Leibniz Universität Hannover

ICOLS 2011

20th International Conference on Laser Spectroscopy

May 30 - June 03
Schlosshotel Münchhausen, Aerzen, Germany

Book of Abstracts

Organizer:
Institute of Quantum Optics, Leibniz Universität Hannover, Germany

Time	Sunday, 29.05.	Monday, 30.05.	Tuesday, 31.05.	Wednesday, 01.06.	Thursday, 02.06.	Friday, 03.06.
from 08.00		**Registration**				
08:45 - 09:00		**Opening Remarks**				
		Optical Clocks and Frequency Standards	**Quantum Computing and Simulation**	**Quantum Gases in Lattices**	**Molecules**	**Opto-Mechanics and Nano-Optics**
09:00 - 09:35		Theodor W. Hänsch	Nathan Lundblad	Randy Hulet	Silke Ospelkaus	Tobias J. Kippenberg
09:40 - 10:15		Hidetoshi Katori	Peter Zoller	Stefan Kuhr	David DeMille	Serge Reynaud
10:20 - 10:55		Till Rosenband	Andrew White	Giovanni Modugno	Michael Drewsen	Arno Rauschenbeutel
10:55 - 11:30		**Coffee Break**				
		Squeezing and Entanglement in Quantum Systems	**Ultra-short Pulses**	**Long-Range Interactions**	**Light, Microscopy**	
11:30 - 12:05		Morgan Mitchell	Katsumi Midorikawa	Tilman Pfau	Monika Ritsch-Marte	**Closing Remarks**
12:10 - 12:45		Tracy Northup	Anne l'Huillier	Michael Köhl	E Wu	**Lunch and Departure**
12:45 - 13:15		**Lunch**		**Lunch**	**Lunch**	
13:15 - 14:15				Departure: 13:15		
		Quantum Simulation, Artificial Fields	**Spectroscopy for Quantum Information**		**Precision Spectroscopy**	
14:15 - 14:50		Nathan Goldman	Matthew Sellars	**Excursion**	Ralf Röhlsberger	
14:55 - 15:30		Fabrice Gerbier	Wes Campell		Peter Rosenbusch	
15:35 - 16:10		Yoshiro Takahashi	Gerhard Rempe		Nathalie Picqué	
16:10 - 16:45	Registration	**Coffee Break**			**Coffee Break**	
		Poster Session	**Poster Session**		**Hot Topics**	
16:45 - 17:00	Reception				W. Vassen	
17:05 - 17:20					Ch. Ospelkaus	
17:25 - 17:40					K. Baldwin	
17:45 - 18:00					J. Billy	
18:05 - 18:20					N. Treps	
19:00 - 20:30		**Dinner**			**Conference Dinner**	
20:30 - 21:30						

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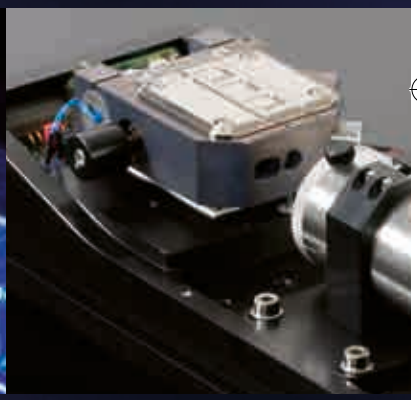

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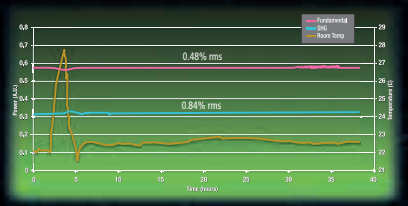

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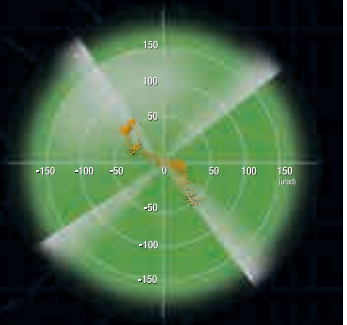

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From Sunday, May 29th, 3 p. m., to Friday, June 3rd, 1 p. m.

Emergency numbers:
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Wifi connection:
There will be only limited internet access at the conference site. We will have a local wireless LAN provided free of charge by Vodafone, realized by 4 access points, each of which can carry up to 32 users. Since the connection is realized by the cell phone network via UMTS, the total bandwidth is limited. At time of registration participants will get information how to get access to this network.

Meals

The conference fee will cover the cost of the technical conference, the proceedings, and the following catering:

Sunday: Reception, mineral water and apple juice

Monday: Lunch, dinner, coffee breaks, mineral water and apple juice, during the poster session soft drinks and beer

Tuesday: Lunch, dinner, coffee breaks, mineral water and apple juice, during the poster session soft drinks and beer

Wednesday: Lunch, coffee break, mineral water and apple juice

Thursday: Lunch, coffee breaks, mineral water and apple juice, conference dinner including soft drinks, beer and wine

Friday: Lunch, coffee break, mineral water and apple juice

Mineral water and apple juice will be available throughout the days.

Excursions

- **Tree top walking**
  Participants have the unique opportunity to discover life in the tree tops – the views, the ecosystem and various animals. With a safe, easy climbing technique, we climb to the tree tops. Several intermediate stops varying in altitude and difficulty are located on the way. This will allow you to select an appropriate level and to progress during the activity. Participants will be grouped into teams of two to support each other and take turns (ca. 3-4 hours) – fully booked.

- **Discover strawberries**
  Did you know what it takes to grow strawberries on over 40 hectares and to deliver them fresh to the market? Watering, bloom and harvesting – you will learn everything about strawberries. After a piece of delicious strawberry cake with locally grown berries, you can shop in the farm or pick strawberries yourself (3 hours)

- **Discover Marienburg castle**
  Discover the Marienburg castle on an interesting guided tour and find out about the history of the Hanoverians, the House of Welf, and the Kingdom of Hannover. Many personal items of the royal family and pieces of historical and cultural importance will introduce you to a different epoch. You will get to the top of the castle tower and enjoy the view of the Leine valley. After the castle tour, there will be a guided tour in a Schnaps distillery including a tasting (4 hours total)

- **Canoe trip**
  Canoeing trip on the Leine river. You will discover the 'Calenberger Land' from the water. (ca. 2-3.5 hours, depending on the length of the tour)

- **City-Tour Hameln**
  Discover the city of the Pied Piper of Hamelin. On a guided tour through the historic old city, you will discover the narrow alleys with the renovated timber frame construction historical buildings and learn about the history of the city and the legend of the Pied Piper. The modern interpretation of the legend, the musical 'Rats', with funny costumes and texts is performed live at 4:30 PM outdoors in Hamelin (ca. 3 hours).

- **Excursion to Volkswagen Commercial Vehicles**
  Trip to Hannover with factory tour.

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Distances between Hameln main station and the ICOLS-hotels

Hotel zur Krone:	1,2 km
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Hotel Stadt Hameln:	1,9 km
Hotel zur Post:	1,7 km
Hotel Christinenhof:	1,6 km
Mercure Hotel:	1,1 km
Rattenfängerhotel Berkeler Warte:	5,7 km
Apartmenthotel:	5,7 km
Schlosshotel Münchhausen:	12,6 km

Bus shuttle to the venue from our recommended hotels will be available.

On Friday, June 3rd, 2011, we will provide a shuttle from the conference site to Hameln station.

Talks Overview

Monday

Optical Clocks and Frequency Standards		
09:00-09:35	Laser Spectroscopy of Hydrogen	Theodor W. Hänsch
09:40-10:15	Synchronous Frequency Comparison of Optical Lattice Clocks to approach the Quantum Limit	Hidetoshi Katori
10:20-10:55	Coherent and incoherent comparisons of Al+ quantum-logic clocks	Till Rosenband
Squeezing and Entanglement in Quantum Systems		
11:30 - 12:05	Quantum metrology with cold atomic ensembles	Morgan Mitchel
12:10 - 12:45	Cavity QED with Single Trapped Ions	T. E. Northup, A. Stute, B. Brandstätter, B. Casabone, D. Habicher, A. McClung, J. Ghetta, J. Reichel, and R. Blatt
Quantum Simulation, Artificial Fields		
14:15 - 14:50	Synthetic Gauge Fields and Topological Phases with Neutral Atoms	Nathan Goldman
14:55 - 15:30	Artificial gauge fields for neutral atoms	Fabrice Gerbier
15:35 - 16:10	Realization of an enlarged spin symmetry of fermions in an atomic gas	Yoshiro Takahashi

Tuesday

Quantum Computing and Simulation		
09:00 - 09:35	Optical lattice-based addressing and control of long-lived neutral-atom qubits	Nathan Lundblad, John Obrecht, Patricia Lee, Malte Schlosser,Radu Chicireanu, Karl Nelson, Ian Spielman, William D. Phillips, and Trey Porto
09:40 - 10:15	Open System Quantum Simulations with Cold Atoms and Ions	Peter Zoller
10:20 - 10:55	Simulating Quantum Systems in Biology, Chemistry, and Physics	Andrew White
Ultra-short Pulses		
11:30 - 12:05	Attosecond Nonlinear Spectroscopy by High-Order Harmonics	Katsumi Midorikawa
12:10 - 12:45	Attosecond Pulse Trains: Generation and Application	A. L'Huillier, J. M. Dahlström, K. Klünder, M. Gisselbrecht, P. Johnsson, J. Mauritsson
Spectroscopy for Quantum Information		
14:15 - 14:50	Demonstration of an efficient quantum memory for light	Morgan Hedges, Jevon J. Longdell, Yongmin Lee and Matthew J. Sellars
14:55 - 15:30	Optical frequency combs for moving beyond resolved sidebands in trapped ion quantum information processing	Wesley C. Campbell, David Hayes, Jonathan Mizrahi, Dzmitry N. Matsukevich, Qudsia Quraishi, Peter Maunz, Crystal Senko, David Hucul, Steven Olmschenk, and Chris Monroe
15:35 - 16:10	Quantum Nonlinear Optics with Single Particles of Light and Matter	Gerhard Rempe

Wednesday

Quantum Gases in Lattices		
09:00 - 09:35	Pairing in Polarized Fermi Gases	Randall G. Hulet, Yean-an Liao, A. Sophie Rittner, and Melissa Revelle
09:40 - 10:15	Single-site-resolved detection and manipulation of atoms in an optical lattice	Stefan Kuhr
10:20 - 10:55	Exploring the physics of disorder with a tunable Bose-Einstein condensate	Giovanni Modugno
Long-Range Interactions		
11:30 - 12:05	Coherent Rydberg excitation in microscopic thermal vapor cells	T. Pfau, H. Kübler, T. Baluktsian, B. Huber, A. Kölle, J. P. Shaffer, R. Löw
12:10 - 12:45	A hybrid system of ultracold atoms and ions	Michael Köhl

Thursday

Quantum Gases in Lattices		
09:00 - 09:35	Ultracold chemistry and dipolar collisions in a quantum gas of polar molecules	Silke Ospelkaus
09:40 - 10:15	Laser Cooling of a Diatomic Molecule	D. DeMille, E.S. Shuman, and J.F. Barry
10:20 - 10:55	Rotational Laser Cooling of Vibrationally and Translationally Cold Molecular Ions	Michael Drewsen
Light, Microscopy		
11:30 - 12:05	How spatial light modulators can advance microscopy and micro-spectroscopy	Monika Ritsch-Marte
12:10 - 12:45	Photon-number resolving detection at infrared wavelengths	E Wu, G. Wu, X. Chen, K. Huang, X. Gu, Y. Jian, M. Ren, Y. Liang, and H. Zeng

Precision Spectroscopy		
14:15 - 14:50	Superradiance, the Collective Lam Shift and EIT in the X-ray Regime	Ralf Röhlsberger
14:55 - 15:30	Spin self-rephasing and very long coherence times	Peter Rosenbusch
15:35 - 16:10	Molecular spectroscopy with laser frequency combs	Theodor W. Hänsch and Nathalie Picqué
Hot Topics		
16:45- 17:05	Spectroscopy of the 1s2s $^3S_1$ – 1s2s $^1S_0$ transition in quantum degenerate helium	R. van Rooij, J.S. Borbely, J. Simonet, M.D. Hoogerland, K.S.E. Eikema, R.A. Rozendaal and W. Vassen
17:05- 17:25	Microwave quantum logic gates for trapped ions	C. Ospelkaus, U.J. Warring, K.R. Brown, Y. Colombe, J.M. Amini, A.C. Wilson, A.M. Meier, E. Knill, D. Leibfried, D.J. Wineland
17:25- 17:45	Quantum Correlations and Atomic Speckle	S.S. Hodgman, R.G. Dall, A.G. Manning, M.T. Johnsson, K.G.H. Baldwin, and A.G. Truscott
17:45- 18:05	Dipolar quantum gases in multi-well potentials	J. Billy, S. Müuller, E. Henn, H. Kadau, P. Weinmann, D. Peter, K. Rzazewski, A. Griesmaier, T. Pfau, M. Jona-Lasinio, L. Santos
18:05- 18:25	Quantum Optics and Quantum Metrology with Femtosecond Optical Frequency Combs	N. Treps, R. Medeiros de Araújo, P. Jian, R. Schmeißner, S. Jiang, O. Pinel, C. Fabre

Friday

Opto-Mechanics and Nano-Optics		
09:00 - 09:35	Cavity Optomechanics: Cooling and quantum measurement of mechanical modes	Tobias J. Kippenberg
09:40 - 10:15	The Casimir Effect: Quantum Optics in Vacuum	Astrid Lambrecht and Serge Reynaud
10:20 - 10:55	Trapping and Interfacing Cold Neutral Atoms Using Optical Nanofibers	Arno Rauschenbeutel

Theodor W. Hänsch
Max-Planck-Institute of Quantum Optics, Garching, and
Faculty of Physics, Ludwig-Maximilians-University, Munich, Germany

Laser Spectroscopy of Hydrogen

The simple Balmer spectrum of atomic hydrogen has provided the Rosetta stone for deciphering the strange laws of quantum physics during the early 20th century. Four decades ago, Doppler-free laser spectroscopy opened a new chapter in the exploration of hydrogen. The pursuit of ever higher resolution and measurement accuracy has inspired many experimental advances, from laser cooling of atomic gases to the laser frequency comb technique for measuring the frequency of light. In the near future, precision spectroscopy of hydrogen may reach a precision of 16 or 17 decimal digits. However, the determination of fundamental constants and experimental tests of fundamental physics laws are now hindered by our insufficient knowledge of the rms charge radius of the proton. Recently, a laser measurement of the 2S-2P Lamb shift of muonic hydrogen has yielded an independent precise new value of the proton radius which differs by five old standard deviations from the official CODATA value. This discrepancy is subject of intense current discussions and it is stimulating plans for future precision experiments.

Synchronous Frequency Comparison of Optical Lattice Clocks to approach the Quantum Limit

Hidetoshi Katori[1,2]

[1]*Department of Applied Physics, Graduate School of Engineering, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan.*
[2]*ERATO Innovative Space-Time Project, Japan Science and Technology Agency, Bunkyo-ku, Tokyo 113-8656, Japan.*

The essential physics in the research of atomic clocks is found in their frequency comparison, which allows investigations of the constancy of the fundamental constants [1, 2], their coupling to gravity [2], and the examination of the relativity. While single-ion optical clocks demonstrate supreme frequency uncertainty of 0.8×10^{-17} [3], the necessary averaging time as long as $\tau \approx 1\times10^{5}$ s is limited by the quantum projection noise (QPN); therefore the clocks' stability becomes a serious experimental concern for further reducing the uncertainty down to 1×10^{-18}.

An optical lattice clock was proposed to improve the clock stability as $1/\sqrt{N}$ by applying a large number N of atoms [4]. However, its stability was so far limited by the Dick effect introduced by the frequency noise of a probing laser. By operating two clocks synchronously to reject the Dick effect [5] in the frequency comparison, we demonstrated the Allan standard deviation of $5\times10^{-16}/\sqrt{\tau}$/s, which allowed to explore 1×10^{-17} uncertainty in $\tau \approx 1{,}600$ s. We discuss possible impacts of the synchronous clock interrogation scheme, such as in the investigations of the fundamental constants and the relativistic geodesy by comparing two clocks operated in distant places.

[1] T. Rosenband *et al.*, *Science* **319**, 1808 (2008).

[2] S. Blatt *et al.*, *Phys. Rev. Lett.* **100**, 140801 (2008).

[3] C. W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, and T. Rosenband, *Phys. Rev. Lett.* **104**, 070802 (2010).

[4] H. Katori, in *The 6th Symposium on Frequency Standards and Metrology*, edited by P. Gill (World Scientific, Singapore, 2002), pp. 323.

[5] S. Bize *et al.*, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **47**, 1253 (2000).

Coherent and incoherent comparisons of Al^+ quantum-logic clocks*

Till Rosenband†
National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305
(Dated: January 30, 2011)

The $^1S_0 \leftrightarrow {}^3P_0$ clock-resonance frequencies of two Al^+ ions are compared by two methods. In the first, two separate optical clocks are constructed with accuracies of 2.3×10^{-17} and 8.6×10^{-18} [1]. The ions in these clocks share no quantum coherence, and their resonance frequencies are compared with a statistical uncertainty of 7.0×10^{-18} after 165,000 s of averaging ($2.8 \times 10^{-15}\sqrt{s/\tau}$ instability). Stability is limited by laser decoherence, which constrains the clocks' probe-times to 150 ms. The clocks are applied to measure a height change of 37 ± 15 cm via the gravitational red-shift [2].

In the second method, two Al^+ ions in one trap are excited by a single laser beam, and clock-state superpositions evolve coherently for up to 5 s [3, 4]. Small frequency differences are measured with a fractional stability of $3.7 \times 10^{-16}\sqrt{s/\tau}$, and a lifetime-limited stability of $1.4 \times 10^{-16}\sqrt{s/\tau}$ may be attainable (see Fig. 1). The technique does not improve time-keeping stability, but speeds-up the measurement of small frequency-shifting effects by several orders of magnitude. Quality factors of 6.7×10^{15} are observed (Fig. 1 inset).

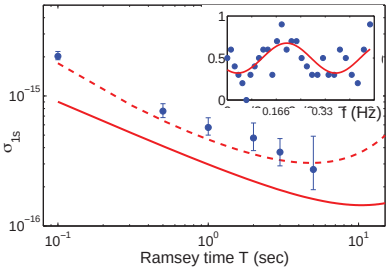

FIG. 1. Observed (points) and expected (dashed line) frequency-measurement stability (extrapolated to 1 s) for various Ramsey free-evolution times, when two Al^+ ions are coherently compared. The solid line is the lifetime-limited stability when only the maximum-slope of the Ramsey signal is probed. Inset: Ramsey signal where the free-evolution time is 3 s (1.121×10^{15} Hz oscillation frequency).

[1] C. W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, and T. Rosenband, Phys. Rev. Lett. **104**, 070802 (Feb 2010).
[2] C. W. Chou, D. B. Hume, , T. Rosenband, and D. J. Wineland, Science **329**, 1630 (2010).
[3] M. Chwalla, K. Kim, T. Monz, P. Schindler, M. Riebe, C. F. Roos, and R. Blatt, Applied Physics B: Lasers and Optics **89**, 483 (Dec. 2007), arXiv:0706.3186-[quant-ph].
[4] C. W. Chou, D. B. Hume, M. J. Thorpe, D. J. Wineland, and T. Rosenband, ArXiv e-prints(Jan. 2011), arXiv:1101.3766-[quant-ph].

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Quantum metrology with cold atomic ensembles

Morgan W. Mitchell*

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www.quantumoptics.es

Quantum metrology uses quantum features such as entanglement and squeezing to improve the sensitivity of quantum-limited measurements. Long established as a valuable technique in optical measurements such as gravitational-wave detection, quantum metrology is increasingly being applied to atomic instruments such as matter-wave interferometers, atomic clocks, and atomic magnetometers. Several of these new applications involve dual optical/atomic quantum systems, presenting both new challenges and new opportunities.

I will describe an optical magnetometry system which achieves both shot-noise- and projection-noise-limited performance, allowing study of optical magnetometry in a fully-quantum regime.[1,2] The versatility of this system allows us to design both linear and non-linear atom-light couplings, with potential application in generation of squeezing and sub-projection-noise measurement.[3] In particular, we have recently developed a method for generating metrologically-advantageous optical nonlinearities and performed the first interaction-based quantum-noise-limited measurements of atomic magnetisation.[4] With this technique we implement a non-linear metrology scheme proposed by Boixo et al. with the surprising feature of precision scaling better than the $1/N$ Heisenberg limit.[5]

Using this interaction-based measurement, we demonstrate a sensitivity scaling as $1/N^{3/2}$ over nearly two orders of magnitude in N, in good agreement with the Boixo theory and our own simulations of the optical response,[6] as shown in Figure 1. I will also discuss briefly the relationship between this nonlinear metrology and more traditional, i.e., linear, quantum metrology.

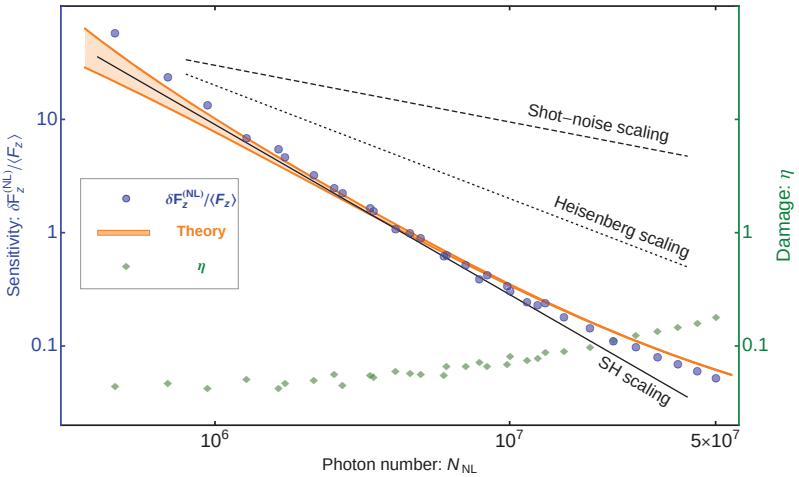

Fig. 1. Sensitivity scaling beyond the "Heisenberg limit" by interaction-based quantum metrology. In a system of N_{NL} interacting photons, with the interaction proportional to the magnetisation F_z of an ensemble of cold rubidium-87 atoms, a polarisation-rotation measurement indicates F_z with a precision scaling as $N_{\mathrm{NL}}^{-3/2}$. Also shown is the probe-induced damage to the atomic state, which for large N_{NL} causes deviation from the ideal scaling.

References

1. M. Koschorreck, M. Napolitano, B. Dubost and M. W. Mitchell, *Phys. Rev. Lett.* **104** (2010).
2. M. Koschorreck, M. Napolitano, B. Dubost and M. W. Mitchell, *Phys. Rev. Lett.* **105** (2010).
3. S. R. de Echaniz, M. Koschorreck, M. Napolitano, M. Kubasik and M. W. Mitchell, *Phys. Rev. A* **77**, p. 032316 (2008).
4. M. Napolitano and M. W. Mitchell, *New J. Phys.* **12**, p. 093016 (2010).
5. S. Boixo, A. Datta, M. J. Davis, S. T. Flammia, A. Shaji and C. M. Caves, *Phys. Rev. Lett.* **101**, p. 040403 (2008).
6. M. Napolitano, M. Koschorreck, B. Dubost, N. Behbood, R. J. Sewell and M. W. Mitchell, *Nature (in press) arXiv:1012.5787v1* (2011).

Cavity QED with Single Trapped Ions

T. E. Northup,[1] A. Stute,[1] B. Brandstätter,[1]
B. Casabone,[1] D. Habicher,[1] A. McClung,[1] J. Ghetta,[1]
J. Reichel,[2] P. O. Schmidt,[1,3] and R. Blatt[1,4]

[1]*Institut für Experimentalphysik, Universität Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria*
[2]*Laboratoire Kastler Brossel, ENS/UPMC-Paris 6/CNRS, 24 rue Lhomond, 75005 Paris, France*
[3]*QUEST Institute for Experimental Quantum Metrology, PTB and Leibniz University of Hannover, 38116 Braunschweig, Germany*
[4]*Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Otto-Hittmair-Platz 1, 6020 Innsbruck, Austria*

Laser spectroscopy is typically a method for investigating the structure and dynamics of atoms and molecules; in the context of cavity quantum electrodynamics, we can instead use laser spectroscopy to probe an "atom-cavity molecule." Here, an atom and the quantized cavity field share excitation quanta, and we can thus observe and control the interactions of single atoms and single photons.

Trapped ions are particularly suited for these measurements because they can be spatially localized to dimensions much smaller than an optical wavelength and can be confined for up to several days. However, trapping ions inside of optical cavities presents a challenge, as the dielectric surfaces of high-finesse mirrors may significantly alter the confining potential seen by the ion. As a result, cavity QED implementations with ion traps have not yet succeeded in reaching the single-atom strong-coupling regime accessed by neutral-atom experiments.

We present vacuum-stimulated Raman spectroscopy performed in the Innsbruck ion-cavity experiment, which operates in an intermediate coupling regime. We have previously demonstrated spectroscopy

of the atom-cavity system in which population is transferred between the ground $4S_{1/2}$ and metastable $3D_{3/2}$ states of a ^{40}Ca ion [1]. By addressing individual Zeeman transitions from these spectra, we have demonstrated a deterministic single-photon source [2], and the tunable parameters of the Raman system also allow us to probe the quantum-to-classical transition in a single-ion laser [3]. The optical $^{40}Ca^{+}$ transition used as a qubit in quantum information experiments connects the ground $4S_{1/2}$ state to the $3D_{5/2}$ rather than the $3D_{3/2}$ state; we have recently implemented cavity-assisted Raman transitions between these two qubit states. Thus, we now have the capability to coherently manipulate and detect the states of individual ions within the cavity, paving the way for experiments including atom-photon entanglement and generation of photonic cluster states.

In addition, we discuss ongoing development of a new experiment in which we plan to achieve strong coupling between single ions and the cavity field. In this experiment, fiber-based mirrors are used to construct a high-finesse cavity with a small mode volume; the cavity is then integrated with a miniaturized linear Paul trap. In the long term, integration of fiber-based devices with ion traps is a promising approach to constructing scalable quantum networks.

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[1] C. Russo et al., Appl. Phys. B **95**, 295 (2009).
[2] H. G. Barros et al., New J. Phys **11**, 103004 (2009).
[3] F. Dubin, Nature Physics **6**, 350 (2010).

Synthetic Gauge Fields and Topological Phases with Neutral Atoms

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In quantum mechanics, the effect of a magnetic field on a charged particle can be formulated in terms of a general mathematical object, the geometric phase [1]. As a corollary, systems of neutral particles that exhibit non-trivial Berry's phases could in principle reproduce the physics of charged particles in a magnetic field. Interestingly, these specific geometric phases can be elegantly engineered in cold-atom systems [2, 3], where they can be controlled by external electromagnetic fields with space-dependent features [4, 5].

In this framework, reproducing the two-dimensional electron gas in a magnetic field with neutral atoms is particularly attractive, as it will certainly deepen our understanding of the topological quantum Hall states [6–8]. Hence synthetic magnetic fields offer an ideal playground to explore topological phases of matter with ultra-cold atoms [9]. Besides, more general gauge fields can be considered in such setups and could simulate spin-orbit coupling and other non-Abelian gauge fields. This outstanding possibility leads to the physics of topological insulators [10] and would allow experimentalists to explore the quantum spin Hall effect [11] and axion electrodynamics [12] in a highly controllable environment. In this talk, I will give a brief introduction to the synthetic gauge fields that can be realized in optical lattices. I will then describe how such setups produce different families of topological order and surprising relativistic behaviors.

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[1] M. V. Berry, Proc. R. Soc. Lond. A **392,** 45 (1984).
[2] M. Lewenstein, A. Sanpera, V. Ahufinger, B. Damski, A. Sen (De), and U. Sen, Adv. Phys. **56,** 243 (2007).
[3] I. Bloch, J. Dalibard, and W. Zwerger, Rev. Mod. Phys. **80,** 885 (2008).
[4] Y.-J. Lin, R. L. Compton, K. J. Garcia, J. V. Porto, I. B. Spielman, Nature, **462** 628 (2009).
[5] J. Dalibard, F. Gerbier, G. Juzeliunas, P. Ohberg, preprint arXiv:1008:5378v1.
[6] D. J. Thouless, M. Kohmoto, M. P. Nightingale, and M. den Nijs, Phys. Rev. Lett. **49**, 405 (1982).
[7] M. Kohmoto, Ann. Phys. **160**, 343 (1985).
[8] M. Hafezi, A. S. Sorensen, M. D. Lukin and E. Demler, Europhys. Lett. **81**, 10005 (2008).
[9] T. D. Stanescu, V. Galitski and S. Das Sarma, Phys. Rev. A **82**, 013608 (2010)
[10] M. Z. Hasan and C. L. Kane, Rev. Mod. Phys. **82**, 3045 (2010)
[11] N. Goldman, I. Satija, P. Nikolic, A. Bermudez, M. A. Martin-Delgado, M. Lewenstein and I. B. Spielman, Phys. Rev. Lett. **105**, 255302 (2010).
[12] A. Bermudez, L. Mazza, M. Rizzi, N. Goldman, M. Lewenstein, and M. A. Martin-Delgado, Phys. Rev. Lett. **105**, 190404 (2010).

Artificial gauge fields for neutral atoms

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Ultracold gases of bosons and fermions are now considered as model systems where the physics of strongly interacting many-body systems, traditionally oriented towards condensed matter physics, can be investigated with good control over the microscopic model and over its parameters. In condensed matter, the orbital coupling of electrons to a magnetic field leads to many fascinating phases, in particular to the integer and fractional quantum Hall effects for quasi-two dimensional electronic systems in strong magnetic fields, or to the recently discovered topological insulators. For a quantum-mechanical system, this coupling reduces to the phase picked up by the particle when moving in space (the Aharonov-Bohm effect). I will review several proposals where a phase is instead directly imprinted on a neutral atom by laser beams, leading to the same orbital physics even in absence of electrical charge and therefore realizing an "artificial magnetic field" felt by the atoms. I will describe in particular how ultra-narrow optical clock transitions (as found in alkaline-earth or in Ytterbium atoms) combined with spin-dependent optical lattices can be used to produce strong artificial magnetic fields and strong interactions at the same time, and how this could lead to "quantum-Hall" atomic phases.

REALIZATION OF AN ENLARGED SPIN SYMMETERY OF FERMIONS IN AN ATOMIC GAS

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The study of ultracold dilute gases is undoubtedly one of the most interesting research fields. In particular, an ultracold gas of ytterbium (Yb) is remarkable in that it offers many interesting possibilities. In addition to the existence of extremely narrow intercombination transitions and rich varieties of stable isotopes, there is also a unique feature for the spin degrees of freedom that all the scattering lengths for different spin components are the same for fermionic isotopes of ^{171}Yb and ^{173}Yb. This leads to an enlarged spin symmetry of SU(2I+1) [1,2] of fermions with nuclear spin I, where rich quantum phases are predicted[1,2,3].

In this presentation, we report the realization of a novel Fermi system with an enlarged spin symmetry of SU(6) in a cold atomic gas of ^{173}Yb with nuclear spin I=5/2[4]. While the achievement of quantum degeneracy of ^{173}Yb with 6 spin components was already reported [5], an important technique of the separate imaging of the nuclear spin components was not developed. Recently we have made this possible by exploiting an optical Stern-Gerlach effect using a spatially inhomogeneous laser beam.

By loading the SU(6) Fermi gas of ^{173}Yb into a 3D optical lattice, we investigate the metallic state to Mott insulator transition. We find results suggesting an adiabatic cooling in the lattice expected for SU(6) systems, and the formation of SU(6) Mott state. The similar cooling effect is also observed in the repulsively interacting Bose-Fermi mixture of spinless boson of ^{174}Yb and the SU(6) Fermi system of ^{173}Yb, which enables us to realize novel phases of dual Mott insulators of bosons and fermions[6]. We also note that this thermodynamics is quite different from the case of

attractively interacting Bose-Fermi mixture which shows considerable heating in the lattice.

In addition, we successfully cool the mixture of two fermionic isotopes of ^{171}Yb with the nuclear spin I=1/2 and ^{173}Yb below the Fermi temperatures [4]. The same scattering lengths for different spin components between the isotopes make this mixture featured with the novel SU(2)$\times$SU(6) symmetry. The mixture is also loaded into a 3D optical lattice to implement the SU(2) $\times$ SU(6) Hubbard model. In particular, we find interaction-induced suppression of Bloch oscillations for the mixture in the 3D lattice.

In the future, we plan to probe the realized quantum phases by high-resolution laser spectroscopy using the ultra-narrow intercombination lines, and also to study novel quantum phases by exploiting optical tuning of inter-atomic interaction [7, 8].

Acknowledgement

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References

1. M. A. Cazalilla, *et al*, *New. J. Phys.* **11**, 103033 (2009).
2. A. V. Gorshkov *et al*, *Nature. Phys.* **6**, 289 (2010).
3. C. Wu *et al*, *Phys. Rev. Lett*. **91**, 186402 (2003).
4. S. Taie, *et al., Phys. Rev. Lett*. **105**, 190401 (2010).
5. T. Fukuhara, *et al., Phys. Rev. Lett*. **98**, 030401 (2007).
6. S. Sugawa, *et al.*, arXiv 1011.4503v2.
7. K. Enomoto, *et al., Phys. Rev. Lett.* **101**, 203201(2008).
8. R. Yamazaki, *et al., Phys. Rev. Lett.* **105**, 050405(2010).

Optical lattice-based addressing and control of long-lived neutral-atom qubits

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The design of many proposed quantum computational platforms is driven by competing needs: isolating the quantum system from the environment to prevent decoherence, and easily and accurately controlling the system with external fields. Neutral-atom optical-lattice architectures provide environmental isolation through the use of states that are robust against fluctuating external fields, yet external fields are nevertheless essential for qubit addressing. Here we demonstrate the selection of individual qubits with external fields, despite the fact that the qubits are in field-insensitive superpositions. We use a spatially inhomogeneous external field to map selected qubits to a different field-insensitive superposition, minimally perturbing unselected qubits, despite the fact that the addressing field is not spatially localized. We show robust single-qubit rotations on neutral-atom qubits located at sites within a double-well configuration with minimal dephasing of neighboring qubits. This precise coherent control is an important step forward for lattice-based neutral-atom quantum computation, and is quite generally applicable to state transfer and qubit isolation in other architectures using field-insensitive qubits. Additionally this double-well proof-of-principle work should be quite applicable in the single-site addressability regime currently being explored by several groups. Additionally we present work demonstrating the near-elimination of the differential light shift for various qubit transitions, using a novel scheme balancing differential shifts with residual vector light shifts of nominally field-insensitive transitions. For details see references [1–6]

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[1] N. Lundblad, J. M. Obrecht, I. B. Spielman, and J. V. Porto, Nat. Phys. **5**, 575 (2009), test.
[2] C. Zhang, S. L. Rolston, and S. D. Sarma, Phys. Rev. A **74**, 042316 (2006).
[3] N. Lundblad, M. Schlosser, and J. V. Porto, Phys. Rev. A **81**, 031611 (2010).
[4] A. Derevianko, Phys. Rev. Lett. **105** (2010).
[5] A. Derevianko, Phys. Rev. A **81**, 051606 (2010).
[6] R. Chicireanu, K. D. Nelson, S. Olmschenk, N. Lundblad, A. Derevianko, and J. V. Porto, arXiv:1010.1520 (PRL in press) (2010).

Open System Quantum Simulations with Cold Atoms and Ions

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A universal quantum simulator is a controlled quantum device that reproduces the dynamics of any other many-particle quantum system with short-range interactions. This dynamics can refer to both coherent Hamiltonian and dissipative open-system evolution. While impressive progress has been reported in isolating the systems from the environment and coherently controlling their many body dynamics in both quantum computing and quantum simulation, we will focus here on the engineering the *open system* dynamics of many particles by a controlled coupling to an environment.
We will discuss both the basic theoretical concepts [1,2] as well as their physical implementation with cold Rydberg atoms [3] and ions [4]. In particular, for a system of trapped ions we report the first realization of a toolbox for simulating an open quantum system with up to five qubits [4].
Using a quantum computing architecture with trapped ions, we combine multi-qubit gates with optical pumping to implement coherent operations and dissipative processes. We illustrate this engineering by the dissipative preparation of entangled states, the simulation of coherent many-body spin interactions and the quantum non-demolition

measurement of multi-qubit observables. We conclude with an outlook on prospects for open-system quantum simulation and computation.

[1] S. Diehl A. Micheli, A. Kantian, B. Kraus, H. P. Büchler and P. Zoller, *Nature Physics* **4**, 878 (2008)
[2] B. Kraus, H. P. Büchler, S. Diehl, A. Kantian, A. Micheli, and P. Zoller, Phys. Rev. A **78**, 042307 (2008)
[3] H. Weimer, M. Müller, I. Lesanovsky, P. Zoller and H.P. Büchler, *Nature Physics* **6**, 382 (2010)
[4] J. T. Barreiro, M. Müller, P. Schindler, D. Nigg, T. Monz, M. Chwalla, M. Hennrich, C. F. Roos, P. Zoller and R. Blatt, submitted for publication

Simulating Quantum Systems in Biology, Chemistry, and Physics

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In principle, it is possible to model any physical system exactly using quantum mechanics; in practice, it quickly becomes infeasible. Recognising this, Richard Feynman suggested that *quantum systems* be used to model *quantum problems* [1]. For example, the fundamental problem faced in quantum chemistry is the calculation of molecular properties, which are of practical importance in fields ranging from materials science to biochemistry. Within chemical precision, the total energy of a molecule as well as most other properties, can be calculated by solving the Schrödinger equation. However, the computational resources required to obtain exact solutions on a conventional computer generally increase *exponentially* with the number of atoms involved [1, 2]. In the late 1990's an efficient algorithm was proposed to enable a quantum processor to calculate molecular energies using resources that increase only polynomially in the molecular size [2–4]. Despite the many different physical architectures that have been explored experimentally since that time—including ions, atoms, superconducting circuits, and photons—this appealing algorithm has not been demonstrated to date.

Here we take advantage of recent advances in photonic quantum computing [5] to present an optical implementation of the smallest quantum chemistry problem: obtaining the energies of H_2, the hydrogen molecule, in a minimal basis [6]. We perform a key algorithmic step—the iterative phase estimation algorithm [7–10]—in full, achieving a high level of precision and robustness to error. We implement other algorithmic steps with assistance from a classical computer, and explain how this non-scalable approach could be avoided. We also provide new theoretical results which lay the foundations for the next generation of simulation experiments using quantum computers.

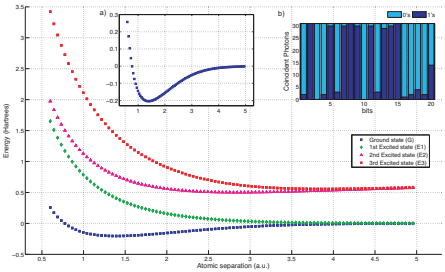

FIG. 1: **Measured results from photonic quantum algorithm: H_2 potential energy curves in a minimal basis.** Each point is obtained using a 20-bit photonic iterative-phase-estimation algorithm (IPEA) and employing n=31 samples per bit (repetitions of each iteration). Every case was successful, achieving the target precision of $\pm(2^{-20}\times 2\pi)\ E_{\rm h}\sim 10^{-5}\ E_{\rm h}$. Curve G (E3) is the low (high) eigenvalue of $\hat{H}^{(1,6)}$. Curve E1 is a triply degenerate spin-triplet state, corresponding to the lower eigenvalue of $\hat{H}^{(3,4)}$ as well as the eigenvalues $\hat{H}^{(2)}$ and $\hat{H}^{(5)}$. Curve E2 is the higher (singlet) eigenvalue of $\hat{H}^{(3,4)}$. Measured phases are converted to energies E via $E=2\pi\phi+1/r$, where the last term accounts for the proton-proton Coulomb energy at atomic separation r, and reported relative to the ground state energy of two hydrogen atoms at infinite separation. **Inset a):** Curve G rescaled to highlight the bound state. **Inset b)**: Example of raw data for the ground state energy obtained at the equilibrium bond length, 1.3886 $a.u.$. The measured binary phase is ϕ=0.0100101110101100000 which is equal to the exact value, in our minimal basis, to a binary precision of $\pm 2^{-20}$.

We also report on our recent results in simulating quantum systems in material science—phase transitions in topological insulators—and in biology—light-harvesting molecules in photosynthesis. Together this body of work represents early experimental progress towards the long term goal of exploiting quantum information to speed up calculations in biology, chemistry and physics.

[1] R. P. Feynman, International Journal of Theoretical Physics **21**, 467 (1982).
[2] S. Lloyd, Science **273**, 1073 (1996).
[3] D. Abrams and S. Lloyd, Physical Review Letters **79**, 2586 (1997).
[4] C. Zalka, Proceedings of the Royal Society of London A **454**, 313 (1998).
[5] B. P. Lanyon, M. Barbieri, M. P. Almeida, T. Jennewein, T. C. Ralph, K. J. Resch, G. J. Pryde, J. L. O'Brien, A. Gilchrist, and A. G. White, Nature Physics **5**, 134 (2009).
[6] B. P. Lanyon, J. D. Whitfield, G. G. Gillet, M. E. Goggin, M. P. Almeida, I. Kassal, J. D. Biamonte, M. Mohseni, B. J. Powell, M. Barbieri, et al., Nature Chemistry **2**, 106 (2010).
[7] D. A. Lidar and H. Wang, Physical Review E **59**, 2429 (1999).
[8] A. Aspuru-Guzik, A. Dutoi, P. Love, and M. Head-Gordon, Science **309**, 1704 (2005).
[9] K. R. Brown, R. J. Clark, and I. L. Chuang, Physical Review Letters **97**, 050504 (2006).
[10] C. R. Clark, K. R. Brown, T. S. Metodi, and S. D. Gasster, arXiv:0810.5626 (2008).

Attosecond Nonlinear Spectroscopy by High-Order Harmonics

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There has been growing interest in applying high-order harmonic fields to atomic/molecular physics in the XUV region. However, the application of ultra-boardband nature of HH spectra has not been explored yet. We have proposed and demonstrated Attosecond Nonlinear Fourier Transform Spectroscopy for investigating the ionization/dissociation pathway imduced by a two or more photon process with high-order harmonics. The unique feature of this method is the use of the autocorrelation technique for measuring the pulse shape of an attosecond pulse train (APT) and relies on the extremely broad harmonic spectra of the APT ranging from visible to extreme ultraviolet region. This spectroscopy would be also beneficial for other intense extreme ultraviolet-soft X-ray light sources, such as X-ray free electron lasers, which are utilized for exploring the nonlinear interaction of high-energy photon with matter, because we can eliminate the strong background signals due to ions or electrons produced by one-photon absorption if we apply this spectroscopy.

Attosecond Pulse Trains: Generation and Application

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When atoms are exposed to intense laser radiation, electrons in the ground state may tunnel ionize, acquire energy from the field, and recombine, leading to the generation of attosecond pulses with broad bandwidth. When this process is repeated many times, the emitted radiation takes the form of a frequency comb, with peaks at odd harmonics of the laser field. The first part of this presentation will describe some of the attosecond tools that are being developed ranging from single attosecond pulses to pulse trains with one or two pulses per laser cycle and the techniques used to characterize them.

One of the most interesting properties of attosecond pulses is that their short pulse duration allows us to measure both phase and amplitude of an unknown wave function or wave packet by pump-probe interferometric methods [1,2], giving us access to the temporal dynamics of the process that led to this wave-packet. In this presentation, we will describe some of these applications, and in particular recent results concerning measurement of single photoionization dynamics using an attosecond pulse train [3].

[1] M. Swoboda et al., Phys. Rev. Lett. 104, 103003 (2010)
[2] J. Mauritsson et al., Phys. Rev. Lett. 105, 053001 (2010)
[3] K. Klünder et al., submitted to Phys. Rev. Lett.

Demonstration of an efficient quantum memory for light

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Storing and retrieving a quantum state of light without corrupting the information it carries is an important challenge for the field of quantum information processing. Classical measurement and reconstruction strategies for storing light are limited in the measurement process by the Heisenberg uncertainty principle. There has been significant effort directed towards the development of quantum memories capable of storing information with a fidelity higher than this classical limit. Successful demonstrations of non-classical storage to date have operated with low efficiencies, less than 17%, and have been limited to the storage of weak quantum states with pulses containing less than a few photons [1-5]. In this talk we report on the efficient quantum storage of light using a memory based on a rare-earth doped crystal. The memory exhibits low noise operation and an efficiency of up to 69%, enabling the demonstration of storage and recall, above the classical limit, of weak coherent states at the single photon level and bright states containing on average more than 100 photons. Further, the memory is shown to operate in the more stringent no-cloning regime for states containing up to 30 photons.

The memory is based on a gradient echo technique [6,7] operating on the 606 nm optical transition in Pr^{3+}:YSO. A narrow spectral feature, 100kHz wide, is prepared using persistent spectral hole burning. An applied electric field gradient Stark-shifts this feature linearly as a function of depth along the propagation direction, creating a 1.8 MHz wide feature with 13 dB of absorption. An optical pulse absorbed by this feature is recalled by reversing the applied field gradient. Homodyne detection was used to analyze the output of the memory.

[1] Appel J., et al., Physical Review Letters **100**, 093602 (2008).

[2] Chaneliere T. et al., Nature **438**, 833-6 (2005).

[3] Lvovsky A. et al., Physical Review Letters **102**, 203601 (2009).

[4] Choi K. et al., Nature **452**, 482 (2004).

[5] Honda, K et al., Physical Review Letters **100**, 093601 (2008).

[6] Kraus B., et al., Phyical Review A **73**, 020302 (2006).

[7] Alexander A., Physical Review Letters **96**, 043602 (2006).

Optical frequency combs for moving beyond resolved sidebands in trapped ion quantum information processing

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One of the key tools for current experiments using trapped atomic ions as quantum information processors is the ability to resolve the sidebands in the spectrum that arise due to the (quantized) motion of the atoms in the trap. As the system is scaled up to include more ions, the spectrum becomes more densely populated with transitions and the resolution of individual sidebands requires longer interaction times and suffers from laser-induced decoherence. We are seeking to address these difficulties by using mode-locked lasers to perform qubit operations via stimulated Raman transitions. For weak pulses, coherent accumulation of transition amplitude from pulse to pulse allows us to demonstrate a comprehansive set of quantum computing operations (including an ion-ion entangling gate) at a far-detuned laser wavelength that induces extremely low decoherence [1]. For strong pulses, a single pulse performs single-qubit operations in about 50 ps [2]. Coherent accumulation from a small number of strong pulses should enable us to perform multi-qubit operations that address multiple sidebands simultaneously, permitting entangling gates on timescales much shorter than a motional period [3]. Taken to the short-time-duration extreme, ultrafast gates based on state-dependent momentum kicks should scale easily to more qubits [4, 5].

References

1. D. Hayes *et al.*, "Entanglement of Atomic Qubits Using and Optical Frequency Comb," Phys. Rev. Lett. **104**, 140501 (2010).
2. W. C. Campbell *et al.*, "Ultrafast Gates for Single Atomic Qubits," Phys. Rev. Lett. **105**, 090502 (2010).
3. Shi-Liang Zhu, C. Monroe, and L.-M. Duan, "Arbitrary-speed quantum gates within large ion crystals through minimum control of laser beams," Europhys. Lett. **73**, 485 (2006).
4. J. J. García-Ripoll, P. Zoller, and J. I. Cirac, "Speed Optimized Two-Qubit Gates with Laser Coherent Control Techniques for Ion Trap Quantum Computing," Phys. Rev. Lett. **91**, 157901 (2003).
5. L.-M. Duan, "Scaling Ion Trap Quantum Computation through Fast Quantum Gates," Phys. Rev. Lett. **93**, 100502 (2004).

Quantum Nonlinear Optics with Single Particles of Light and Matter

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Nonlinear optics with high-intensity lasers and macroscopic media has been a frontier field since the early days of the laser. Nonlinear optics, in particular, has revolutionized laser spectroscopy by opening up new wavelength regimes and providing new measurement techniques to overcome the limitations of linear optics.

Nonlinear optics is not limited to high photon fluxes and bulk crystals. With our increasing ability to realize decreasingly smaller systems and thus achieve strong coupling between light and matter it is now possible to explore nonlinear optics with single atomic and photonic quanta. In fact, the optical nonlinearities obtainable with a single atom inside a high-finesse optical resonator can be many orders of magnitude larger than related nonlinear coefficients of macroscopic media. A recent example is cavity-assisted electromagnetically induced transparency (cavity EIT) where the transmission of a weak probe laser through an optical resonator is blocked by a single atom but unblocked when the atom is irradiated with a suitable control laser [1]. The ability to efficiently control the propagation of single photons is a first step towards the realization of an optical quantum memory which can capture, store and release single photonic quantum states better than

can be achieved classically, sine qua non for distributed quantum networks and quantum repeaters.

Single particles also offer possibilities not shared by systems consisting of many particles. Most notable, genuine quantum mechanical effects become important [2], opening up the field of quantum nonlinear optics with novel phenomena which are not a mere extrapolation of classical phenomena into the quantum realm. Examples include the effects of photon blockade [3] and its unblocking by means of a two-photon gateway [4], characterized by strong photon anti-bunching and photon bunching, respectively, in the transmission of a probe laser through an optical cavity containing a single atom. The possibility to produce pairs of photons with a single-atom system offers intriguing perspectives for the generation of quadrature-squeezed light beams. This extends the ability of a single atom to generate non-classical light without intensity noise towards light with reduced amplitude or phase fluctuations. Moreover, the controlled interaction between two propagating photons via a single atom is a good starting point for the implementation of photonic quantum gates.

The most recent achievement in this emerging field of optical physics will be discussed.

[1] M. Mücke *et al.*, Nature **465**, 755 (2010); T. Kampschulte *et al.*, Phys. Rev. Lett. **105**, 153603 (2010).
[2] I. Schuster *et al.*, Nature Physics **4**, 382 (2008).
[3] K. M. Birnbaum *et al.*, Nature **436**, 87 (2005).
[4] A. Kubaneck *et al.*, Phys. Rev. Lett. **101**, 203602 (2008).

Pairing in Polarized Fermi Gases

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Ultracold atoms have been established as powerful tools for the investigation of complex many-body phenomena. Parameters such as interaction and dimensionality are readily varied. I will discuss experiments on the pairing of spin-polarized ^{6}Li atoms in both 3D and 1D geometries. Spin-polarization of ultracold atoms is accomplished by creating an imbalanced population of two hyperfine levels, a scenario with direct correspondence to magnetized superconductors, and perhaps to the cores of neutron stars. Spin-polarized ultracold atomic gases are excellent candidates for creating the elusive Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) modulated superfluid state. The FFLO state is characterized by pairs with non-zero center of mass momentum.

In 3D, we find phase separation between a fully paired core and the surrounding unpaired atoms, but no evidence for the FFLO state [1]. Theory predicts that FFLO is ubiquitous in 1D, however, and we have performed a 1D experiment to verify these predictions. An array of one-dimensional tubes are formed by imposing a two-dimensional optical lattice on the atoms. We find that phase separation also occurs in 1D, but in contrast to 3D the central core is always partially polarized, while the outer wings are either fully paired or fully polarized, depending on the overall degree of spin polarization [2]. The experimental phase diagram agrees well theory. Although not directly observed in the

experiment, theory predicts that the partially polarized phase is the FFLO state.

We are currently attempting to directly observe the non-zero momentum FFLO pairs in a time-of-flight experiment. In addition, we are investigating the cross-over from 1D to 3D behavior as the depth of the optical lattice is decreased. The current status of these experiments will be reported.

References:

[1] G.B. Partridge, W. Li, R.I. Kamar, Y.A. Liao, and R.G. Hulet, *Science* **311**, 503 (2006).

[2] Y.A. Liao, A.S.C. Rittner, T. Paprotta, W. Li, G.B. Partridge, R.G. Hulet, S. Baur, and E.J. Mueller, *Nature* **467**, 567 (2010).

Single-site-resolved detection and manipulation of atoms in an optical lattice

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Ultracold atoms in optical lattices are a versatile tool to investigate fundamental properties of quantum many body systems. In particular, the high degree of control of experimental parameters has allowed the study of many interesting phenomena such as quantum phase transitions and quantum spin dynamics.

Here we demonstrate how such control can be extended down to the most fundamental level by detecting the atoms individually and by manipulating their spins at specific sites of an optical lattice. Using a high-resolution optical imaging system, we were able to obtain fluorescence images of strongly interacting bosonic Mott insulators with single-atom and single-site resolution [1]. From our images, we fully reconstructed the atom distribution on the lattice and identified individual excitations with high fidelity. This method allows precise in-situ temperature and entropy measurement from single images.

In order to address the atoms in the lattice, we used an off-resonant laser beam focused by the high-resolution imaging system onto individual lattice sites [2]. It shifts the addressed atoms into resonance with an external microwave field that induces a spin-flip. Our scheme yields sub-diffraction-limited resolution, well below the lattice spacing. We created arbitrary spin patterns in our Mott insulators by sequentially addressing selected lattice sites after freezing out the atom distribution. In addition, we directly monitored the tunnelling quantum dynamics of single atoms in the lattice prepared along a single line and observed that our addressing scheme leaves the atoms in the motional ground state.

Our results open the path to a wide range of novel applications from quantum dynamics of spin impurities, entropy transport, implementation of novel cooling schemes, and engineering of quantum many-body phases to quantum information processing.

[1] J. F. Sherson, C. Weitenberg, M. Endres, M. Cheneau, I. Bloch, S. Kuhr, *Single-atom-resolved fluorescence imaging of an atomic Mott insulator,* Nature **467**, 68 (2010).

[2] C. Weitenberg, M. Endres, J. F. Sherson, M. Cheneau, P. Schauß, T. Fukuhara, I.Bloch, S. Kuhr, *Single-spin addressing in an atomic Mott insulator*, arXiv:1101.2076v1 (Nature, in press).

Exploring the physics of disorder with a tunable Bose-Einstein condensate

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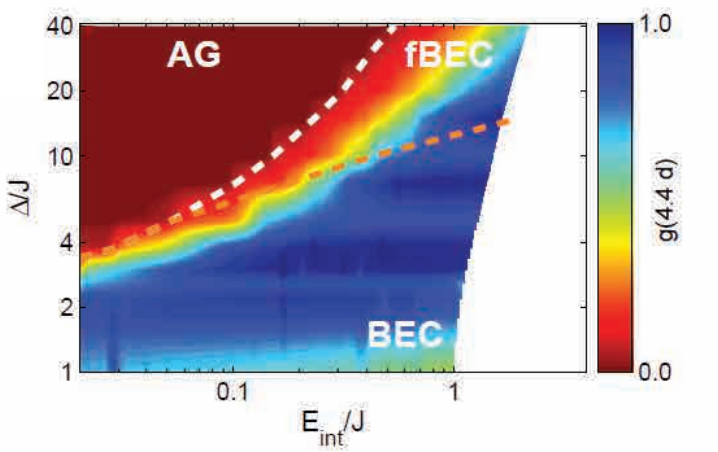
The combination of disorder and nonlinearities determines the transport properties of many physical systems, including normal conductors and superconductors, biological systems, or light in disordered nonlinear media. While a full understanding of the interplay of disorder and nonlinearities has long been sought, the lack of complete control over experimental parameters in most systems makes systematic investigations difficult, and there are still several open questions.

I will describe how in recent experiments [1-3] we have employed Bose-Einstein condensates with tunable interactions in combination with optical potentials to address some of the open questions, related for example to the transport properties and to the transition from insulating to superfluid phases. In particular, we have observed the crossover from an Anderson insulator to a BEC induced by a repulsive interaction by studying the momentum distribution and the correlation function. In addition, we have characterized the subdiffusive transport dynamics that arises from

the interplay of interaction and disorder. I will also discuss prospects for further experiments in the regime of strong interaction.



Correlation of neighbouring states of a Bose-Einstein condensate in a quasiperiodic lattice.

[1] Delocalization of a disordered bosonic system by repulsive interactions, B. Deissler, M. Zaccanti, G. Roati, C. D'Errico, M. Fattori, M. Modugno, G. Modugno, M. Inguscio, Nature Physics 6, 354-358 (2010).
[2] Correlation function of weakly interacting bosons in a disordered lattice, B. Deissler, E. Lucioni, M. Modugno, G. Roati, L. Tanzi, M. Zaccanti, M. Inguscio, G. Modugno, arXiv:1010.0853.
[3] Observation of subdiffusion of a disordered interacting system, E. Lucioni, B. Deissler, L. Tanzi, G. Roati, M. Modugno, M. Zaccanti, M. Inguscio, G. Modugno, arXiv:1011.2362.

Coherent Rydberg excitation in microscopic thermal vapor cells

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Abstract: We show that coherence times of ~ 100 ns are achievable with coherent Rydberg atom spectroscopy in micrometre-sized thermal vapour cells making them robust and promising candidates for scalable quantum devices like single-photon sources.

OCIS codes: 020.5780 Rydberg states; 270.1670 Coherent optical effects

The coherent control of mesoscopic ensembles of atoms and Rydberg atom blockade are the basis for proposed quantum devices such as integrable gates and single-photon sources [1]. To date, impressive experimental progress has been limited to ultracold atoms [1]. Here, we show that coherence times of ~100 ns are achievable with coherent Rydberg atom spectroscopy in micrometre-sized thermal vapour cells [2]. We investigate coherent phenomena like Rabi oscillations to the Rydberg states by pulsed excitation on the nanosecond time scale. Our results demonstrate that microcells with a size on the order of the blockade radius (~2 μm), at temperatures of 100–300 °C, are robust and promising candidates for investigating low-dimensional strongly interacting Rydberg gases, constructing quantum gates and building single-photon sources. We present our fabrication technique for microstructured vapor cells [3] and discuss future directions.

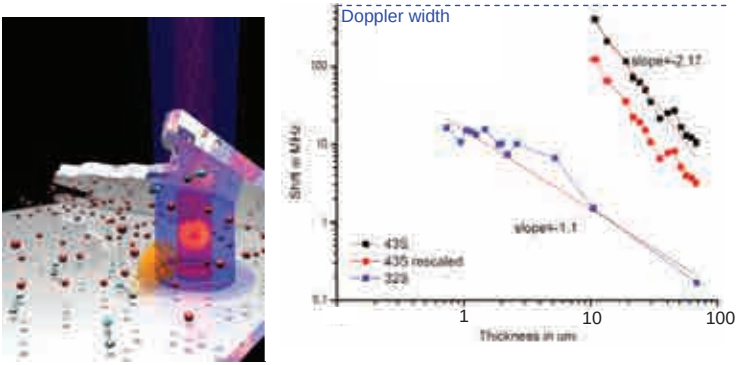

Fig. 1: Rydberg atoms are excited in thermal Rb vapor confined in a wedge cell by narrow band two photon excitation (left). As the atoms interact with the wall the spectroscopic lines shift and broaden (right). For 43 S state the broadening reaches the Doppler width at cell thicknesses of ~ 10 micrometer. Choosing a state which avoids polariton resonances in the confining material this effect can be drastically suppressed. For the 32 S state cell thicknesses down to 1 micrometer shift and broaden the line only by ~20 MHz (right). For comparison the 43S data is rescaled to the 32S situation by their dipolar coupling strength to the surface.

[1] M. Saffman, T. G. Walker, and K. Molmer, "Quantum information with Rydberg atoms´´, *Reviews of Modern Physics* **82**, 2313 (2010) and references therein.
[2] H. Kübler, J. P. Shaffer, T. Baluktsian, R. Löw, and T. Pfau, "Coherent Excitation of Rydberg Atoms in Thermal Vapor Microcells", *Nature Photonics* ***4****, 112 (2010)*
[3] T. Baluktsian, C. Urban, T. Bublat, H. Giessen, R. Löw, and T. Pfau, "Fabrication method for micro vapor cells for alkali atoms" *arXiv:1002.121, Opt. Lett.* ***35****, 1950 (2010)*

A hybrid system of ultracold atoms and ions

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In recent years, ultracold atoms have emerged as an exceptionally well controllable experimental system to investigate fundamental physics, ranging from quantum information science to simulations of condensed matter models. Here we go one step further and explore how cold atoms can be combined with other quantum systems to create new quantum hybrids with tailored properties. We will report on experiments in which we have for the first time deterministically placed a single trapped ion into an atomic Bose Einstein condensate[1]. A trapped ion, which currently constitutes the most pristine single particle quantum system, can be steered with nanometer precision within the atomic cloud and can be observed and manipulated at the single particle level. In the created single-particle/many-body composite quantum system we show sympathetic cooling of the ion, observe chemical reactions of single particles in situ[2], and demonstrate local addressing of the neutral atom cloud.

[1] C. Zipkes, S. Palzer, C. Sias, and M. Köhl, Nature 464, 388 (2010).
[2] C. Zipkes, S. Palzer, L. Ratschbacher, C. Sias, and M. Köhl, Phys. Rev. Lett. 105, 133201 (2010).

Ultracold chemistry and dipolar collisions in a quantum gas of polar molecules

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Ultracold polar molecular quantum gases promise to open new research directions ranging from the study of ultra-cold chemistry, precision measurements to novel quantum phase transitions. Based on the preparation of high-phase space density gases of polar KRb molecules [1-3]. I will discuss the control of dipolar collisions and chemical reactions of polar molecules in a regime where quantum statistics, single scattering partial waves, and quantum threshold laws play a dominant role [4]. In particular, I will point out the crucial role of electric dipole-dipole interactions [5] and external confinement [6] in determining the chemical reaction rate. Finally, I will discuss prospects of reaching quantum degeneracy in bialkali samples of polar molecules and prospects for these systems as novel dipolar quantum many-body systems.

[1] K. K. Ni, S. Ospelkaus, M. H. G. de Miranda, et al., Science 322, 231 (2008).
[2] S. Ospelkaus, K. K. Ni, M. H. G. de Miranda, et al., Faraday Discussions 142, 351 (2009).
[3] S. Ospelkaus, K. K. Ni, G. Quemener, et al., Phys. Rev. Lett. 104, 030402 (2010).
[4] S. Ospelkaus, K. K. Ni, D. Wang, et al., Science 327, 853 (2010).
[5] K. K. Ni, S. Ospelkaus, D. Wang, et al., Nature 464, 1324 (2010).
[6] M. H. G. de Miranda, A. Chotia, B. Neyenhuis et al, arXiv: 1010.3731 (2010).

Laser Cooling of a Diatomic Molecule

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Laser cooling and trapping of atoms has led to revolutionary advances in atomic physics. The more complex internal structure of molecules makes cooling them to the ultracold regime much more difficult than for atoms. However, this same structure makes molecules interesting for a wide variety of applications ranging from precision measurement to quantum computation to quantum chemistry. Here, we report experiments demonstrating the first direct laser cooling of a molecule [1]. This work builds on our recent results showing the ability to apply large optical forces to strontium monofluoride (SrF) molecules via photon scattering [2]. As in that work, here we use optical cycling on the $X^2\Sigma^+$ (v=0, N=1) $\leftrightarrow$ $A^2\Pi_{1/2}$(v=0, N=0) transition of SrF to apply significant forces. SrF is chosen for several reasons [3]: a) the highly diagonal Franck-Condon factors of its X$\leftrightarrow$A transition mean that only two vibrational repump lasers are required to scatter $>10^5$ photons; b) the short lifetime of the A state (τ_A = 24 ns) enables large scattering rates; c) the wavelengths need to drive the cycling and repumping transitions are accessible with standard diode lasers. Use of the X(N=1)$\leftrightarrow$A(N=0) transition eliminates rotational branching [4]; dark Zeeman sublevels of the X(N=1) state are remixed into the optical cycle by a static magnetic field, and radiofrequency sidebands on the lasers address all hyperfine substructure. A slow, cryogenic buffer gas-cooled beam of SrF is used to achieve adequate signal size and long interaction time with the cooling laser.

We have demonstrated 1-D transverse cooling of the SrF beam. The molecular beam is intersected at right angles by multiple passes of the laser beams. Downstream, an image of laser-induced fluorescence from the molecules reveals their spatial distribution, which is strongly correlated with their transverse velocity distribution. We have observed both Doppler and Sisyphus-type

cooling effects, depending on the geometry and detuning of the cooling lasers. We see a reduction in the velocity distribution by a factor of 10 or more, and estimate the final 1-D temperature to be $T_D \approx 5$ mK in the case of Doppler cooling and $T_S \approx 300$ μK for Sisyphus cooling. Our observations are consistent with scattering of 500-1000 photons, limited by the finite interaction time. We see negligible loss of population when both the X(v=1) and X(v=2) vibrational levels are repumped into the cycle, consistent with predictions based on calculated Franck-Condon factors. Transverse cooling of this type may be useful for precision measurements using molecular beams; in addition, our results clearly indicate the viability of laser slowing and cooling of the molecular beam, opening a path to trapping and direct cooling of SrF to the ultracold regime

References

[1] E.S. Shuman, J.F. Barry, and D. DeMille, Nature **467**, 820 (2010).

[2] E.S. Shuman, J.F. Barr, D.R. Glenn, and D. DeMille, Phys. Rev. Lett. **103**, 223001 (2009).

[3] M.D. DiRosa, Eur. Phys. J. D **31**, 395 (2004) suggested use of similar species e.g. CaH.

[4] B.K. Stuhl *et al.*, Phys. Rev. Lett. **101**, 243002 (2008).

Rotational Laser Cooling of Vibrationally and Translationally Cold Molecular Ions

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Stationary molecules in well-defined internal states are of broad interest in both physics and chemistry. Through high-resolution spectroscopy, fundamental physics can be tested and lead to, e.g., improved values of the electron-to-proton mass ratio [1], new boundaries on the electron electric dipole moment [2] and observation of the potential evolution of the fine structure constant over time [3]. Translationally and internally cold molecules have as well been considered promising candidates for qubits in new quantum computing senarios [4], and molecular ions could in the future likely become an excellent alternative to atomic qubits in the realization of a practical ion trap based quantum computer due to favourable internal state decoherence rates. In chemistry, state prepared molecular targets are an ideal starting point for uni-molecular reactions, including coherent control of photofragmentation through the application of various laser sources [5,6]. In cold bi-molecular reactions, where the effect of even tiny potential barriers becomes significant, experiments with state prepared molecules can yield important information on the details of the potential curves of the molecular complexes [7,8,9]. Furthermore, in order to learn more about the chemistry in interstellar clouds, astrochemists can benefit greatly from direct measurements on cold reactions in laboratories [9].

Working with MgH^+ molecular ions in a linear Paul trap, we routinely cool their translational degree of freedom by sympathetic cooling with Doppler laser cooled Mg^+ ions. Giving the time for the molecules to equilibrate internally to the room temperature blackbody radiation, the vibrational degree of freedom will freeze out, leaving only the rotational degree of freedom to be cooled.

We report here on the implementation of a new technique for laser-induced rotational ground-state cooling of vibrationally and translationally cold MgH^+ ions [10]. The scheme is based on excitation of a single rovibrational transition [11], and it should be generalizable to any diatomic polar molecular ion, given appropriate mid-infrared laser sources such as a quantum cascade laser are available.

In recent experiments, a nearly 15-fold increase in the rotational ground-state population was obtained, with the resulting ground-state population of 36,7±1,2 %, equivalent to that of a thermal distribution at about 20 K. The obtained cooling results imply that, through this technique, cold molecular-ion experiments can now be carried out at cryogenic temperatures in room-temperature set-ups.

References

[1] Koelemeij, J. C. J., Roth, B., Wicht, A., Ernsting, I. and Schiller, S., *Phys. Rev. Lett.* **98,** 173002 (2007).
[2] Hudson, J. J., Sauer, B. E., Tarbutt, M. R. and Hinds, E. A., Phys. Rev. Lett. **89**, 023003 (2002).
[3] Hudson, E. R., Lewandowski, H. J., Sawyer, B. C. and Ye, J, Phys. Rev. Lett. **96**, 143004 (2006).
[4] DeMille, D, Phys. Rev. Lett. **88**, 067901 (2002).
[5] Rice, S. A. and Zaho, M. *Optical control of molecular dynamics* (Wiley, New York, 2000).
[6] Shapiro, M. and Brumer, P. W. *Principles of the Quantum Control of Molecular Processes* (Wiley, New York, 2003).
[7] Willitsch, S., Bell, M. T., Gingell, A. D. and Softley, T. P., Phys. Chem. Chem. Phys. **10**, 7200 (2008).
[8] Krems, R. V., Phys. Chem. Chem. Phys. **10**, 4079 (2008).
[9] Smith, I. W. M., *Low temperatures and cold molecules* (Imperial College Press, London, 2008).
[10] Staanum, P. F., Højbjerre, K., Skyt, P.S., Hansen, A. K. and Drewsen, M., Nat. Phys. **6**, 271 (2010).
[11] Vogelius, I. S., Madsen, L. B. and Drewsen, M., Phys. Rev. Lett. **89**, 173003 (2002).

How spatial light modulators can advance microscopy and micro-spectroscopy

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High-resolution liquid crystal panels with micron-sized individually addressable pixels, also known as spatial light modulators (SLMs) can improve optical imaging in a many ways. Placed in a Fourier plane, they can act as an effective Fourier filter to emulate various contrast enhancing techniques, such as dark-field, phase contrast, or spiral phase contrast.

Toggling between these methods is as simple and fast as replacing the grey-level image on the SLM. Moreover, this can be combined with SLM-based optical trapping, allowing one to hold the measured specimen in free space while it is being imaged. Or, SLMs can shape the excitation beams and tailor the phase matching for wide-field CARS microscopy and micro-spectroscopy.

Photon-number resolving detection at infrared wavelengths

E Wu, G. Wu, X. Chen, K. Huang, X. Gu, Y. Jian, M. Ren, Y. Liang, and H. Zeng

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Photon-number-resolving detection is of great importance in various applications, such as the demonstration of fundamental quantum optics experiment, the practical quantum information process and even the low-light-level detection in biophotonics. In this talk, different methods to realize photon-number resolving detection at infrared wavelengths will be discussed, including InGaAs/InP avalanche photodiode (APD) in subsaturated mode and single-photon upconversion.

By self-balancing technique to cancel the spike noise which was caused by the gating pulse on the APD, the gain on the APD could be lowered to make the detector work in non-saturated mode while keeping the same detection sensitivity at single photon level. In this way, the difference of the detector's response for different incident photon flux would be observed. Figure 1 shows the histogram of the peak output voltage when the average detected photon number was 1.5 photons per pulse.

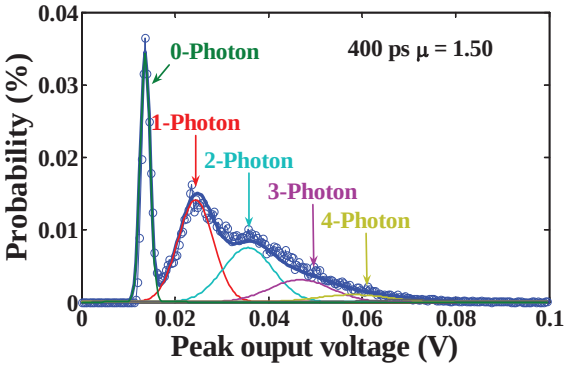

Fig.1 Photon-number resolving detection realized by InGaAs/InP avalanche photodiode.

Another demonstration of photon number resolving detection at infrared wavelengths is based on the single-photon frequency upconversion. The photon number resolving detection at 1.04 μm was realized by coincidence frequency upconversion by converting infrared signal photons into the visible regime where a Si-MPPC could be harnessed. Figure 2 shows the experimental setup of the system and the photon-number resolving performance of the frequency upconversion detector.

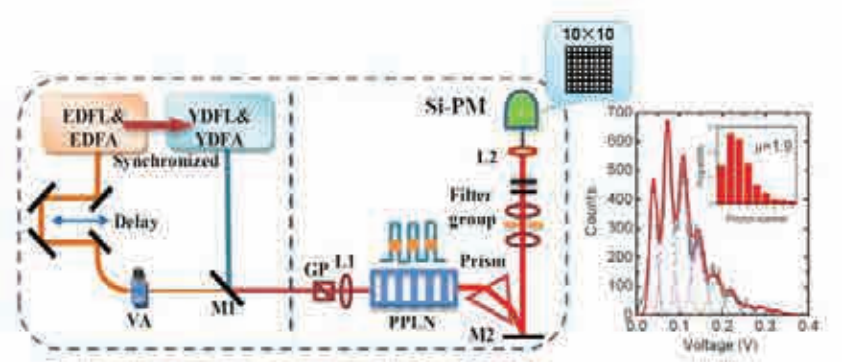

Fig.2 Experimental setup of photon number resolving detection via coincidence frequency upconversion and the histogram of the peak output voltage of the detector.

[1] E. Waks, E. Diamanti, B. C. Sanders, S. D. Bartlett, and Y. Yamamoto, "Direct observation of nonclassical photon statistics in parametric down-conversion," Phys. Rev. Lett. **92,** 113602 (2004).
[2] B. E. Kardynal, Z. L. Yuan, and A. J. Shields, "An avalanche-photodiode-based photon-number-resolving detector," Nature Photonics **2**, 425 (2008).
[3] G. Wu, Y. Jian, E Wu, H. Zeng "Photon-number-resolving detection based on InGaAs/InP avalanche photodiode in the sub-saturated mode," Optics Express **17**, 18787 (2009).
[4] E. Pomarico, B. Sanguinetti, R. Thew, and H. Zbinden, "Room temperature photon number resolving detector for infrared wavelengths," Opt. Express **18,** 10750-10759 (2010).
[5] M. T. Rakher, L. Ma, O. Slattery, X. Tang, and K. Srinivasan, "Quantum transduction of telecommunications-band single photons from a quantum dot by frequency upconversion," Nature Photon. **4,** 786–791 (2010).
[6] X. Gu, K. Huang, Y. Li, H. Pan, E Wu, and H. Zeng, "Temporal and spectral control of single-photon frequency upconversion for pulsed radiation," Appl. Phys. Lett. **96,** 131111 (2010).

Superradiance, the Collective Lamb Shift and EIT in the X-ray Regime

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The interaction of many identical two-level atoms with a common radiation field leads to a profound modification of the temporal, directional and spectral characteristics of their collective emission compared to that of a single atom. A prominent example is the phenomenon of superradiance that manifests as a strong acceleration of the collective spontaneous emission [1]. A multitude of superradiant and other cooperative optical phenomena have then been studied in the regime of visible light, particularly after short-pulsed laser systems became available for time-resolved studies. Later it was noticed that the superradiant emission goes along with a radiative shift of the transition energy, the collective Lamb shift [2,3]. In the optical regime this shift appeared to be extremely difficult to observe due to its small magnitude and atom-atom interactions masking it.

The availability of pulsed x-ray sources (synchrotron storage rings and X-ray lasers) and nuclear two-level systems with transition energies of several 10 keV a.k.a. Mössbauer isotopes, makes it possible to study cooperative effects also in the regime of hard X-rays. The outstanding energy resolution of the Mössbauer effect enables one to analyze spectral properties of the cooperative emission with very high accuracy. Recently, we succeeded to observe the collective Lamb shift for single-photon superradiant emission from ensembles of ^{57}Fe atoms [4], see Fig. 1. An essential feature of this experiment is the use of a planar low-Q cavity in which the ^{57}Fe atoms were embedded and from which the X-rays were resonantly reflected under grazing angles of a few mrad [5].

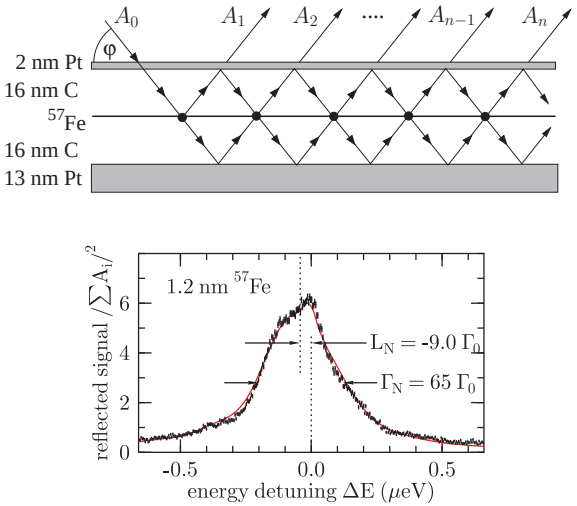

Fig. 1. Top: Geometry of a planar x-ray cavity to study the properties of superradiant cooperative emission from an ultrathin layer of ^{57}Fe atoms embedded in the center of the guiding layer. Bottom: Measured spectral response from a 1.2 nm thick layer of ^{57}Fe embedded in the cavity. Superradiant emission manifests as a homogeneous spectral broadening of 65 times the natural linewidth Γ_0. The collective Lamb shift is the displacement of the center of mass of the curve by -9.0 Γ_0.

In this presentation I will discuss cooperative effects in resonant x-ray scattering, involving nuclear and inner-shell resonances as two-level systems. Special emphasis will be given to cooperative emission from *extended* ensembles of resonant atoms. In this case a spectral response is predicted that resembles very closely that of a three-level system with electromagnetically induced transparency.

[1] R. H. Dicke, Phys. Rev. **93**, 99 (1954).
[2] R. Friedberg, S. R. Hartmann, and J. T. Manassah, Phys. Rep. C **7**, 101 (1973).
[3] M. O. Scully, Phys. Rev. Lett. **102**, 143601 (2009).
[4] R. Röhlsberger, K. Schlage, B. Sahoo, S. Couet and R. Rüffer, Science **328**, 1248 (2010).
[5] R. Röhlsberger, J. Mod. Opt. **57**, 1979 (2010)

Spin self-rephasing and very long coherence times

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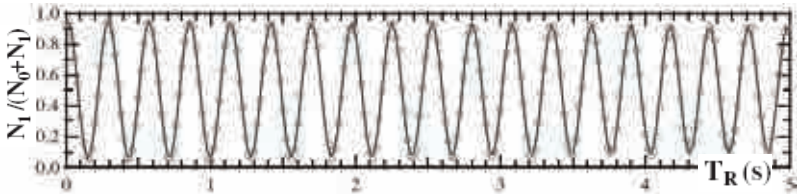
Atomic clocks, nuclear magnetic resonance and other precision techniques are based on the coherent manipulation of an ensemble of spins ½. Highest sensitivity requires narrow linewidth and good signal-to-noise i.e. long coherence times and the interrogation of many spins. Usually these are contradictory as interactions destroy coherence and field gradients create dephasing. Known mechanisms to battle dephasing include experimental techniques like spin-echo or interaction-driven *random* fluctuations leading to motional narrowing and exchange narrowing.

Here we present a new *deterministic* mechanism that may be seen as a continuous intrinsic spin-echo. In contrast to exchange narrowing, the exchange interaction results in a *deterministic* rotation of two spins around their sum. Many of such "identical spin rotations" (ISR) eventually result in spin-rephasing. The mechanism's simple ingredient, the exchange interaction, is of such fundamental nature that a wide observation of our mechanism is expected.

We perform Ramsey spectroscopy on the ground state of ultracold ^{87}Rb atoms magnetically trapped on a chip in the Knudsen regime. The compensation of 2nd order Zeemann effect and mean field shift is employed to reduce field inhomogeneities over the sample to 80 mHz [1]. This should limit the 1/e contrast decay time to about 3 s in agreement with previous work, while decay times of 58+/-12 s are actually observed [2]. Furthermore, slightly off the compensation point, we observe contrast revivals increasing with atom density, which reveal our mechanism as deterministic and interaction driven. Solving a kinetic equation for the spin variables based on the ISR, we obtain good agreement with the data. Our findings are reminiscent of earlier calculations for a trapped gas which predict localized

polarization revivals and synchronization within spatial domains in the hydrodynamic regime. This similarity bares a first indication of the general nature of our mechanism.



The long coherence times open a truly new approach in many applications such as precision spectroscopy atomic sensors and quantum information processing. We present our trapped atom clock on a chip currently showing a frequency stability of $8\ 10^{-13}$ at 1s in a compact set-up [3,4]. Technical improvements under way aim towards the full exploitation of the long coherence times, which should gain another factor of 5.

[1] P. Rosenbusch, Appl. Phys. B, **95**, 227 (2009)
[2] C. Deutsch et al., Phys. Rev. Lett, **105**, 020401 (2010)
[3] C. Lacroute et al., IEEE Trans. Ultrason. Ferroelectr. Freq. Control **57**, 106 (2010).
[4] F. Ramirez-Martinez et al, Advances in Space Research **47** (2011) in print

Molecular spectroscopy with laser frequency combs

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Through the development of optical frequency comb techniques, the elaborate previous frequency-chain schemes for optical frequency measurements, which only worked for selected frequencies, have been replaced by a set-up of the size 1x1 m^2, good for precision measurements of any frequency, and even commercially available. A true revolution in optical frequency measurements has occurred, paving the way for the creation of all-optical clocks with a precision that might approach 10^{-18}. A decade later, laser frequency combs are now common equipment in all frequency metrology-oriented laboratories. Such combs have become enabling tools for a growing tree of applications, from attosecond science to molecular spectroscopy.

Recent experiments of multi-heterodyne frequency comb Fourier transform spectroscopy (also called dual-comb spectroscopy) have demonstrated that the precisely spaced spectral lines of a laser frequency comb can be harnessed for the rapid and sensitive acquisition of highly multiplexed spectra of molecules. In one such experiment, an absorbing molecular gas was placed inside an optical cavity that is matched to the laser resonator so that it is simultaneously resonant for each comb line. The sensitivity to weak absorption is thus much enhanced because the effective path-length is increased, as in cavity ring-down spectroscopy. The information encoded by this interrogating comb needs then to be retrieved by a spectrometer. This is achieved by heterodyning the interrogating comb with a second comb, which serves as a reference: the light transmitted by the cavity is superimposed on a second frequency

comb with slightly different repetition frequency. A single fast photodetector then produces an output signal with a comb of radio frequencies due to interference between pairs of optical comb lines.

Even the first proof-of-principle experiments, carried out in the near-infrared region, have demonstrated a very exciting potential of dual-comb spectroscopy without moving parts for ultra-rapid and ultra-sensitive recording of complex broad spectral bandwidth molecular spectra. With Ytterbium-based fiber frequency combs emitting around 1040 nm and a recording time of only 18 μs, the crowded weak overtone spectrum of ammonia, a molecule of planetological and environmental interests, was resolved for the first time in this region. Compared to conventional Michelson-based Fourier transform spectroscopy, recording times could be shortened from seconds to microseconds, with intriguing prospects for spectroscopy of short lived transient species or for hyperspectral imaging. The resolution improves proportionally to the measurement time. Therefore longer recordings allow high resolution spectroscopy of molecules with extreme precision, since the absolute frequency of each laser comb line can be known with the accuracy of an atomic clock.

Most of the strong fundamental molecular vibration frequencies are located in the mid-infrared spectral region (2 - 20μm), which is referred to as the fingerprint region. Mid-infrared spectroscopy proves an efficient tool for the determination of the structure of molecules, the quantitative analysis of complex mixtures, the investigation of dynamic systems, biomedical spectroscopy, micro-spectroscopy and hyperspectral imaging, and the study of many types of interfacial phenomena. Developing mid-infrared dual-comb Fourier transform spectroscopy is therefore a demanding but highly desirable task. A proof-of-principle demonstration of dual-comb Fourier transform spectroscopy with ceramic Cr^{2+}:ZnSe femtosecond oscillators that are directly emitting in the 2.45 μm region has been reported.

Spectroscopy of the 1s2s $^3S_1$ – 1s2s $^1S_0$ transition in quantum degenerate helium

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We have observed the 1557-nm magnetic dipole transition between the two metastable states of neutral helium, i.e. the 1s2s $^3S_1$ and 1s2s $^1S_0$ states, 19.8 resp. 20.6 eV above the $1s^2$ $^1S_0$ ground state. This transition had never been observed before as it has an Einstein coefficient of 10^{-7} s^{-1}, fourteen orders of magnitude smaller than for the 1083 nm transition from 1s2s $^3S_1$ to 1s2p $^3P_{0,1,2}$, most prominently used for frequency metrology in helium. The 8 Hz natural linewidth of the transition is due to the 20 ms lifetime of the 1s2s $^1S_0$ state. We observed the transition in both helium isotopes.

We use an experimental setup designed for the production of a Bose-Einstein condensate of ^{4}He [1] as well as a degenerate Fermi gas of ^{3}He [2] in a cloverleaf magnetic trap. The quantum degenerate gases, at T ~1μK, are produced in the long-lived (~8000 s) 1s2s $^3S_1$ state and up to 10^6 atoms (^{4}He or ^{3}He) are transferred to a crossed dipole trap at 1557 nm. The transition is excited shifting the frequency of part of the output of the narrowband 1557-nm fiber laser with an AOM. Atoms in the upper state are anti-trapped and therefore leave the trap. The number of trapped atoms and the temperature are measured after time-of-flight on a microchannel plate detector.

The fiber laser frequency is measured beating part of its output with a mode of a femtosecond frequency comb laser, locked to a GPS-controlled Rb clock. Exciting the transition for ~3s we observe a

linewidth of ~80 kHz, limited by the laser frequency stability over that time scale. We measured the transition frequency as a function of laser power to extrapolate the AC Stark shift to zero and corrected for the linear Zeeman shift applying rf transitions between magnetic substates. Mean-field shifts for ^{4}He are measured to be negligible at our level of precision.

We determined an absolute transition frequency for ^{4}He (J=1$\rightarrow$0) of f_4 = 192510702145.8 (1.8) kHz and for ^{3}He ((J, F)=(1,3/2)$\rightarrow$(0,1/2)) of f_3 = 192504914426.4 (1.5) kHz, i.e. a precision of 8×10^{-12}. Present-day QED theory for two-electron atoms is accurate at the 3 MHz level for the absolute energies of the metastable states and at the 0.7 kHz level for the isotope shift [3]. Our results on the absolute frequencies agree with theory and present a big challenge for theorists to calculate higher-order terms. From the isotope shift (incorporating the known hyperfine structure of ^{3}He) we determine the difference in mean-square nuclear charge radius between ^{4}He and ^{3}He to be Δr_c^2=1.019 (11) fm^2.

[1] A.S. Tychkov *et al.*, Phys. Rev. A**73**, 031603 (2006).
[2] J.M. McNamara *et al.*, Phys. Rev. Lett. **97**, 080404 (2006).
[3] G.W.F. Drake, K. Pachucki, private communication (2010).

Microwave quantum logic gates for trapped ions

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Most current schemes for Quantum Information Processing (QIP) with trapped ions implement quantum logic gates through a laser-induced state-dependent interaction between ions held in the same trap. We describe experiments in surface-electrode traps [1] that explore alternative ideas to these well-established techniques. We experimentally demonstrate a microwave near-field approach to quantum logic gates with trapped ions [2], where oscillating magnetic fields and field gradients from microwave currents propagating in the electrodes of a surface-electrode trap are used to implement single- and multi-qubit quantum logic gates. This approach has several important potential advantages with respect to operation fidelity and reduced complexity. To demonstrate the speed of single-qubit operations, we show that it is possible to implement pi pulses with durations less than 20 ns. We show how gradients of the microwave field enable coupling between motional and internal states of the ions and implement motional sideband transitions. We demonstrate microwave sideband cooling of a two-ion rocking mode [3]. Finally, we present the realization of an entangling two-qubit gate using a bichromatic

microwave magnetic gradient field. In connection with our recent experiments on coupled quantized harmonic oscillators [4], these results open up new experimental perspectives for quantum simulation, novel entangling schemes for QIP and for precision spectroscopy.

This work has been supported by IARPA, DARPA, NSA, ONR, and the NIST Quantum Information Program.

References

[1] S. Seidelin, J. Chiaverini, R. Reichle, J. J. Bollinger, D. Leibfried, J. Britton, J. H. Wesenberg, R. B. Blakestad, R. J. Epstein, D. B. Hume, W. M. Itano, J. D. Jost, C. Langer, R. Ozeri, N. Shiga, and D. J. Wineland, Phys. Rev. Lett. **96**, 253003 (2006)

[2] C. Ospelkaus, C. E. Langer, J. M. Amini, K. R. Brown, D. Leibfried, and D. J. Wineland, Phys. Rev. Lett. 101, 090502 (2008)

[3] C. Ospelkaus, U. Warring, Y. Colombe, K. R. Brown, J. M. Amini, D. Leibfried, and D. J. Wineland, arXiv:1104.3573 [quant-ph] (2011)

[4] K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried and D. J. Wineland, Nature **471**, 196 (2011); see also M. Harlander, R. Lechner, M. Brownnutt, R. Blatt and W.Hänsel, Nature **471**, 200 (2011)

Quantum Correlations and Atomic Speckle

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Atoms coherently output-coupled from a Bose-Einstein condensate (BEC) form a coherent beam of matter waves – an atom laser. Most condensates are confined in a magnetic potential, where to achieve maximum flux, the atom laser beam is outcoupled from the centre of the BEC. These atoms in the atom laser beam originate from the highest density region of the BEC and experience a large repulsive force (mean field repulsion) via s-wave interactions. These interactions strongly distort the atom laser beam, yielding a non-ideal spatial profile with a double-peaked structure [1,2].

One method to alleviate this problem is to use an optically trapped BEC. An atom laser is then created by simply reducing the optical power, and letting the atoms fall out of the spatial minimum of the trap where the atomic density is low. Further, by not extinguishing the optical trap completely, the atom laser beam experiences a weak confining potential that acts like an optical fibre to guide the atoms.

Here we demonstrate near-single-mode guiding of a metastable helium (He*) atom laser in an optical dipole potential using a far-detuned laser beam [3]. Atoms cooled to ~1 μK in a magnetic trap are transferred to an optical trap aligned in the vertical direction, where evaporative cooling takes place and a BEC is achieved. Subsequent lowering of the optical potential by a factor of ~ 100 in 10 ms releases the atoms into the guide, and they fall under gravity until they strike a multi-channel plate (MCP) and are imaged. The process is adiabatic, allowing the atoms in the BEC to transfer smoothly from the ground state of the trap to the ground state of the guide. As the atoms progress down the guide, they are adiabatically cooled before eventually falling out of the guide and onto the MCP.

When a thermal atomic cloud is loaded into the guide, a much larger, multimode, transverse spatial profile results. Intensity variations are also present corresponding to speckle in a multimode guided laser beam, and which average to a smooth profile over

subsequent realizations of the experiment. This is the first transverse spatial measurement of a speckle pattern arising from matter waves.

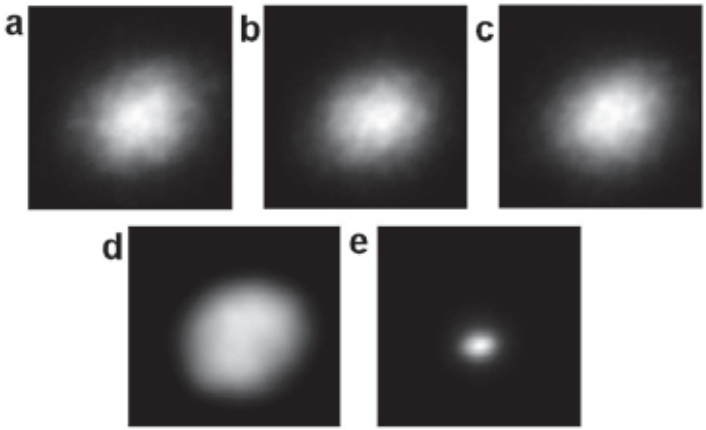

Fig. 1: Same scale: (a-c) Guided thermal atom speckle patterns for 3 data runs. (d) Average over 20 runs yielding a smooth pattern. (e) BEC guided in the lowest order mode, with a gaussian profile.

To further test the speckle hypothesis, we use the unique single-atom detection capabilities of He* to directly measure the quantum statistics [4] of the guided atoms. We employ a delay-line detector [5] that yields the position and arrival time of atoms striking the MCP, which we used previously to measure the 2nd- and 3rd-order correlation functions for ultracold He* atoms [6]. We show that when thermal atoms are loaded into the dipole guiding potential, clear atom bunching is detected (the famous Hanbury Brown and Twiss effect), indicating that multimode guiding is occurring and is associated with matter-wave speckle [7]. When a BEC is loaded into the guide, the atom bunching disappears, consistent with propagation of a coherent matter wave in the lowest-order mode of the guide.

References

[1] J.-F. Riou et al., *Phys. Rev. Lett.*, **96**, 070404 (2006).
[2] R. G. Dall, et al., *Opt. Express* **15**, 17673 (2007).
[3] R.G. Dall et al. *Physical Review A* **81**, 011602(R) (2010).
[4] M. Schellekens et al., *Science* **310**, 648 (2005).
[5] A.G. Manning et al., *Optics Express* **18**, 18712 (2010).
[6] S.S. Hodgman et al., *Science* **331**, 1046 (2011).
[7] R.G. Dall et al., *Nature Communications* to be published 19 April 2011.

Dipolar quantum gases in multi-well potentials

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Recent years have shown an increasing interest in the design and study of novel quantum phases. In this respect, cold quantum gases play a central role through the high level of control they provide, in particular over the inter-particle interactions. Beside the tunable contact interaction, long-range and anisotropic dipolar interactions (DI) are now available in atomic and molecular systems. For instance, repulsive electric DI between two heteronuclear molecules have been used to control chemical reactions.
Here we show that the DI can stabilize an otherwise unstable many-body system. For this, we investigate the stability of a dipolar Bose-Einstein condensate sliced into several pancake-shape clouds by a deep 1D optical lattice. We find the system to be stable at negative scattering length up to -17 Bohr radii, due to the repulsive dipolar on-site interaction. In addition, our experimental results show a good agreement with mean-field calculations, revealing significant attractive inter-site interactions mediated via long-range DI.
This inter-site coupling is of particular interest in the realization of new quantum phases. For instance, for a dipolar BEC in a triple-well potential, it gives rise to intriguing self-organized structures [1]. In order to study such a multi-well system, we plan a new experimental apparatus with major upgrades compared to the current setup.

[1] T. Lahaye *et al.*, Phys. Rev. Lett. **104**, 170404 (2010).

Quantum Optics and Quantum Metrology with Femtosecond Optical Frequency Combs

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Multimode Gaussian quantum light includes all kinds of multimode squeezed and/or multipartite quadrature entangled states, in addition to coherent light. It is a very general and powerful quantum resource that is now currently produced in various laboratories in the world, and is successfully used in various applications to quantum information processing [1]. For that purpose, one need to generate cluster states, and in the regime of co-propagating mode this can be performed via linear operation and/or detection system modal adaptation [2]. In contrast to non-classical states based on the manipulation of Fock states, such quantum light can be produced with very high values of the mean photon number N. As all the limits in parameter estimation scale with some inverse power of N, "bright" multimode Gaussian light is a very good candidate for applications to quantum metrology, more precisely to improve the performance of the estimation of a parameter p that is encoded on the spatio-temporal variation of a light beam.

We present here an approach based on the use of femtosecond optical frequency combs as information carrier, where the shape of the comb –or of pulses in the time domain – is the mode basis for information processing. We first demonstrate the experimental generation of multimode non-classical light generation using a synchronously pumped optical parametric oscillator [3]. Multimode behaviour is shown through the measurement of the intensity correlation matrix in the frequency domain, and the extraction of the eigenmodes of the system.

We then consider the same system for quantum metrology, and in particular parameter estimation such as time delay of dispersion fluctuations. We have determined the ultimate sensitivity in the estimation of any kind of parameter p, with Gaussian light, using a Quantum Cramér Rao approach and shown that it can be reached through homodyne detection where the local oscillator is pulsed shaped in order to match the eigenmode of the measurement. We show how to derive limits for space-time positioning or dispersion measurement using frequency combs, and how the non-classical modes produced in the experiment could be used to improve further these limits beyond the standard quantum limit [4]. Current status of experimental demonstration is then presented.

[1] M. Yukawa, R. Ukai, P. van Loock, and A. Furusawa, Phys Rev a **78**, (2008).
[2] S. Braunstein, Phys Rev A **71**, 055801 (2005).
[3] G. Patera, N. Treps, C. Fabre, and G. J. de Valcarcel, Eur Phys J D **56**, 123-140 (2010).
[4] B. Lamine, C. Fabre, and N. Treps, Phys Rev Lett **101**, - (2008).

Cavity Optomechanics: Cooling of a Micromechanical Oscillator into the Quantum Regime

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Abstract: Using optical sideband cooling, a micromechanical oscillator is cooled to a phonon occupancy of 2 phonons, corresponding to a probability of finding it in its quantum ground state more than 25% of the time.

The control of low-entropy quantum states of a micro-oscillator could not only allow researchers to probe quantum mechanical phenomena—such as entanglement and decoherence—at an unprecedentedly large scale, but also enable their use as interfaces in hybrid quantum systems. Preparing and probing an oscillator in the conceptually simplest low-entropy state, its quantum ground state, has now become a major goal in Cavity Optomechanics [1]. However, to experimentally achieve this goal, two challenges have to be met: its effective temperature T has to be reduced sufficiently so that $\hbar\Omega_m > k_B T$ ($\hbar$ is the reduced Planck constant, k_B the Boltzman constant, and Ω_m the mechanical resonance frequency). Second, quantum-limited measurements of the oscillator's displacement must be performed at the level of the zero-point displacement fluctuations $x_{zpf} = \sqrt{\hbar/2m\Omega_m}$. Using conventional cryogenic refrigeration, a nanomechanical oscillator has recently been cooled to the quantum regime and probed by a superconducting qubit to which it was coupled through its specific piezoelectric properties [2].

Here, we demonstrate a different technique, applying optical sideband cooling [3] to a cryogenically precooled silica toroidal optomechanical micoresonator (Fig. 1). This versatile technique, conceptually similar to laser cooling techniques known in atomic physics, can be applied to a wide range of opto- and electromechanical systems which exhibit parametric coupling of high-quality electromagnetic and mechanical modes.

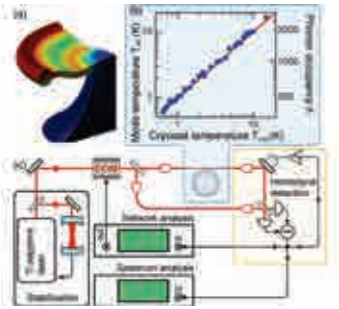

Fig. 1 Cooling a micromechanical oscillator. (a) High-Q mechanical and optical modes are co-located in a silica microtoroid, and are mutually coupled by radiation pressure exerted by the mechanical mode. (b) Thermalization of the mechanical mode to the temperature of the 3He gas in the cryostat down to an occupancy of 200 quanta. (c) Optical setup used for displacement monitoring of the mechanical mode, based on homodyne analysis of the light re-emerging from the optical resonance.

With a resonance frequency of $\Omega_m/2\pi$=72 MHz of the mechanical radial breathing mode (RBM), and an optical linewidth of $\kappa/2\pi$=6 MHz, the used toroidal resonator resides deeply in the resolved sideband regime, as required for ground-state cooling [4]. Thermalizing the resonator to a 850-mK cold ^{3}He buffer gas, the RBM is already cooled to an occupation of 190 quanta as

determined by noise thermometry (Fig. 1). A low-noise cooling laser (λ~780 nm) is subsequently coupled to a whispering gallery mode (WGM) using a tapered fiber. Figure 2 shows the optically measured mechanical resonance frequency and damping when the detuning Δ of the cooling laser is tuned through the lower mechanical sideband of the (split) optical WGM at a power of 2 mW [5]. The strong modification of the oscillator's properties can be modeled with the well-understood radiation pressure-induced dynamical backaction. This allows extracting the additional mechanical damping due to defects in the glass described as an ensemble of two-level systems (TLS) [6]. Its strong temperature dependence enables an independent determination of the toroids' temperature, which can be compared to the noise temperature of the mechanical mode (Fig. 2c). We find excellent agreement between the two methods. At a higher cooling laser power (4 mW) both methods congruently yield a minimum occupation below 10 quanta, corresponding to a >10% probability to find the oscillator in its quantum ground state.

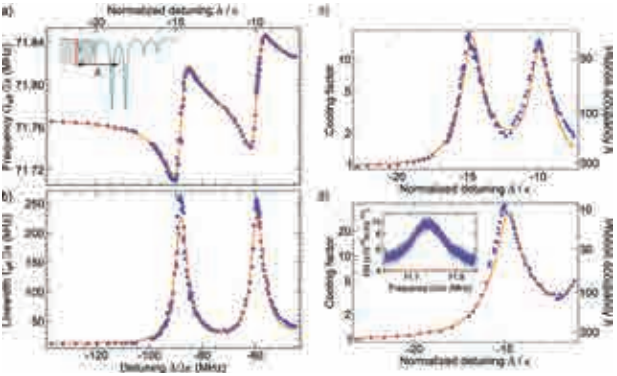

Fig. 2: Cooling results. Resonance frequency (a) and linewidth (b) of the RBM when a 2 mW-power cooling laser is tuned through the lower mechanical sideband of the split optical mode (inset). Blue points are measured data extracted from the recorded spectra of thermally induced mechanical displacement fluctuations, solid lines are a coupled fit based on dynamical backaction and TLS-induced effects. c) Cooling factor (temperature reduction induced by sideband cooling) and phonon occupation of the RBM as a function of normalized detuning as determined by noise thermometry (points) and from a dynamical backaction model, taking into account possible optical heating of the structure and TLS-induced effects.

Further optimization of the silica toroids for stronger optomechanical coupling and lower dissipation enabled cooling the resonator deeper into quantum regime to an average occupancy of only 2 quanta. Moreover we achieved at low occupancy the regime of strong coupling [7]. This constitutes an important step towards the coherent manipulation of the quantum state of the mechanical oscillator.

[1] T. J. Kippenberg, K. J. Vahala, "Cavity Optomechanics: Back-action at the meso-scale," Science **321**, 1172-1176 (2008)
[2] A. D. O'Connell *et al.*, "Quantum ground state and single-phonon control of a mechanical resonator," Nature **464**, 697-703 (2010)
[3] A. Schliesser, R. Rivièrere, G. Anetsberger, O. Arcizet, T. J. Kippenberg, "Resolved-sideband cooling of a micromechanical oscillator," Nature Physics **4**, 417-419 (2008)
[4] I. Wilson-Rae, N. Nooshi, W. Zwerger, T. J. Kippenberg, "Theory of Ground State Cooling of a Mechanical Oscillator Using Dynamical Backaction," Phys. Rev. Lett. **99**, 093901 (2007)
[5] R. Rivière, S. Deléglise, S.Weis, E. Gavartin, O. Arcizet, A. Schliesser, T. J. Kippenberg, "Optomechanical sideband cooling of a micromechanical oscillator close to the quantum ground state," *submitted*. Preprint at arXiv:1011.0290
[6] O. Arcizet, R. and Rivière, A. Schliesser, G. Anetsberger, T. J. Kippenberg, "Cryogenic properties of optomechanical silica microcavities," Phys. Rev. A **80,** 021803(R) (2009)
[7] S. Gröblacher, K. Hammerer, M .R. Vanner, M. Aspelmeyer, "Observation of strong coupling between a micromechanical resonator and an optical cavity field," Nature **460**, 724-727 (2009)

The Casimir Effect: Quantum Optics in Vacuum

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The Casimir effect is a jewel with many facets[1]: It is an observable mechanical effect of vacuum fluctuations, which deserves attention as a prediction of quantum field theory. It has connections with the puzzles of gravitational physics through the problem of vacuum energy or the tests of the gravity law at short ranges. And Casimir and closely related Van der Waals forces, which are dominant at micron or sub-micron distances, have strong relations with atomic and molecular physics, condensed matter and surface physics, chemical and biological physics, micro- and nano-technology[2].

Considering a pair of perfectly flat and perfectly reflecting parallel plates at zero temperature, Casimir found a simple universal expression for the force. But it is clear that this idealization does not describe real experiments[3]. The effect of imperfect reflection of the metallic mirrors used in the experiments has to be taken into account carefully[4]. The correction to the Casimir expression associated with thermal

[1] P.W. Milonni, *The quantum vacuum* (Academic, 1994); S.K. Lamoreaux, *Resource Letter* in Am. J. Phys. 67 850 (1999).
[2] H.B. Chan *et al*, Science 291 1941 (2001); E. Buks, M.L. Roukes, Europhys. Lett. 54 220 (2001); H.B. Chan *et al*, Phys. Rev. Lett. 101 030401 (2008); A. Lambrecht, Nature 454 836 (2008).
[3] M. Bordag, U. Mohideen, V.M. Mostepanenko, Phys. Rep. 353 1 (2001); R.S. Decca *et al*, Annals Phys. 318 37 (2005); Phys. Rev. D 75 077101 (2007).
[4] A. Lambrecht, S. Reynaud, Euro. Phys. J. D 8 309 (2000).

fluctuations at ambient temperature is also important and it is correlated to the effect of imperfect reflection[5].
Precise experiments are performed between flat or nano-structured plates and a sphere. Up to recently, the estimation of the force in these geometries was done through the Proximity Force Approximation (PFA) which amounts to average the force calculated in the parallel plate geometry over the distribution of local inter-plate distances. Pushing the theory beyond PFA has been done in the past few years[6] and it is now possible to calculate the Casimir force between metallic plates and spheres coupled to electromagnetic vacuum at any temperature[7].
The talk will summarize recent developments in the field of Casimir physics and give the current status in the comparison between theory and experiment after years of improvements in both measurements as well as theoretical evaluations.

[5] M. Boström, B.E. Sernelius, Phys. Rev. Lett. 84 4757 (2000); I. Brevik, S.A. Ellingsen, K. Milton, New J. Phys. 8 236 (2006); G.-L. Ingold, A. Lambrecht, S. Reynaud, Phys. Rev. E 80 041113 (2009).
[6] A. Lambrecht, P.A. Maia Neto, S. Reynaud, New J. Phys. 8 243 (2006); T. Emig, R.L. Jaffe, J. Phys. A 41 164001 (2008); O. Kenneth, I. Klich, Phys. Rev. B 78 014103 (2008); K. Klingmüller, H. Gies, J. Phys. A 41 164042 (2008); A.W. Rodriguez *et al*, Phys. Rev. A 80 012115 (2009).
[7] A. Canaguier-Durand *et al*, Phys. Rev. Lett. 102 230404 (2009); Phys. Rev. Lett. 104 040403 (2010); Phys. Rev. A 82 012511 (2010).

Trapping and Interfacing Cold Neutral Atoms Using Optical Nanofibers

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We have recently demonstrated a new experimental platform for the simultaneous trapping and optical interfacing of laser-cooled cesium atoms [1]. The scheme uses a multi-color evanescent field surrounding an optical nanofiber in order to localize the atoms in a one-dimensional optical lattice about 200 nm above the nanofiber surface. At the same time, the atoms can be efficiently interrogated with probe light which is sent through the nanofiber and which couples to the atoms via the evanescent field. In the resonant case, an ensemble of 2000 trapped atoms almost entirely absorbs this probe field, yielding an optical depth of up to 30, equivalent to an absorbance per atom of 1.5 %. On the other hand, if the probe field is detuned with respect to the atomic transition, the dispersive interaction leads to an optical phase shift of the probe. We detect this phase shift interferometrically and show that it enables a non-destructive measurement of the number of trapped atoms. Finally, profiting from the unprecedented ease of optical access provided by our system, we demonstrate electromagnetically induced transparency of the fiber-trapped atoms.

Our work opens the route towards the direct integration of laser-cooled atomic ensembles within fiber networks, an important prerequisite for large scale quantum communication. Moreover, our nanofiber trap is ideally suited to the realization of hybrid quantum systems that combine atoms with solid state quantum devices. Finally, the use of nanofibers for atom trapping allows one to straightforwardly realize intriguing trapping geometries that are not easily accessible with freely propagating laser beams.

[1] E. Vetsch, D. Reitz, G. Sagué, R. Schmidt, S. T. Dawkins, and A. Rauschenbeutel, "Optical interface created by laser-cooled atoms trapped in the evanescent field surrounding an optical nanofiber", Phys. Rev. Lett. **104**, 203603 (2010).

Poster Overview

Posters may be set up/taken down during lunch on Monday and Tuesday. Material will be provided. The letter preceding the poster number indicates the day of presentation („M“: Monday, „T“: Tuesday).

Monday Poster Session

#	*Title*	*Authors*
M01	A thermal calcium-atom interferometer with a phase resolution of a few milliradian based on a narrow linewidth diode laser	Tomoya Akatsuka, Yoshihiro Mori, Yurie Ohtake, and Atsuo Morinaga
M02	Discrete interferometer with individual trapped atoms	A. Alberti, W. Alt, N. Belmechri, S. Hild, M. Karski, A. Steffen, A. Widera, D. Meschede
M03	Laser cooling with a single laser beam and a planar diffractor	Matthieu Vangeleyn, Paul Griffin, Erling Riis and Aidan Arnold
M04	Ring traps: large-separation interference and a new inductive geometry	A. Dinkelaker, M. Vangeleyn, J. D. Pritchard, P.F. Griffin, E. Riis and A.S. Arnold
M05	The FERRUM Project: Experimentally determined lifetimes of the metastable $c^4D_{5/2}$ and $c^4D_{7/2}$ levels in Cr II	E. Bäckström, S. Mannervik, J. Gurell, P.Royen, H. Nilsson, H. Hartmann, R. Blackwell-Whitehead, L-O. Norlin
M06	Spectral narrowing of electromagnetically induced transparency with pseudo-thermal light	In-ho Bae and Han Seb Moon
M07	Vibrational spectroscopy of sympathetically cooled biomolecular ions	Ch. Wellers, A. Borodin, S. Vasilyev, S. Schiller
M08	Probing the state of a repulsive 1D Bose gas by light scattering	A. G. Sykes, R. J. Ballagh
M09	Laser-induced quantum adsorption of atoms on a surface	Victor Balykin
M10	Measuring the quantum speed limit in the dynamics of a two	M. G. Bason, M. Viteau, D. Ciampini, R. Fazio, V. Giovannetti, N.

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	level system	Malossi, R. Mannella, O. Morsch, E. Arimondo
M11	A photon number discriminator without photon counting	J. Bernu, H.M. Chrzanowski, B.M. Sparkes, B. Hage, A. Lund, T.C. Ralph and P.K. Lam
M12	Sub-Doppler spectroscopy with a vapour confined in an opal	Philippe Ballin, Isabelle Maurin, Athanasios Laliotis, Daniel Bloch
M13	Focused Laguerre-Gauss Beams interacting with an Atom : Transfer of Orbital Angular Momentum and Detector-Dependent Mapping	Vasily V. Klimov, Daniel Bloch, Martial Ducloy, Jose R. Rios Leite
M14	Observing the temperature dependence of the atom-surface interaction in the van der Waals Casimir-Polder regime	Athanasios Laliotis, Thierry Passerat de Silans, Marie-Pascale Gorza, Isabelle Maurin, Philippe Ballin, Martial Ducloy, Daniel Bloch
M15	Photodetachment microscopy to an excited state and accurate electron affinity measurements	C. Blondel, C. Delsart, C. Drag, R.J. Peláez and M. Vandevraye
M16	Correlated atom pairs creation in an optical lattice	Marie Bonneau, Josselin Raudel, Raphael Lopes, jean-Christophe Jaskula, Alain Aspect, Denis Boiron, Chris Westbrook
M17	Determination of the fine structure constant and test of the quantum electrodynamics	Rym Bouchendira, Pierre Cladé, Saïda Guellati-Khélifa, Franois Nez and Franois Biraben
M18	Experimental evidence of a new geometric phase by atom interferometry	S. Lepoutre, J. Gillot, G. Trénec, A. Gauguet, M. Büchner and J.Vigué
M19	Orthogonality catastrophe in an ultra-cold Fermi gas	J. Goold, T. Fogarty, M. Paternostro and Th. Busch
M20	Narrow, long-term stable spectral holes in a Eu^{3+}:Y_2SiO_5 crystal for application to laser frequency stabilization	Q.-F. Chen, A. Troshyn, S. Kayser, S. Vasilyev, A. Yu. Nevsky, S. Schiller
M21	Cesium two-photon transitions and TI:saphire comb Laser	Chien-Ming Wu1, Imreh Gergely, Tze-Wei Liu, You-Huan Chen, Wang-Yau Cheng and Jow-Tsong Shy
M22	Comparing thermal and lasing atomic sources for precision inertial measurement	J. E. Debs, P. A. Altin, T. H. Barter, D. Döring, G. R. Dennis, G. McDonald, N. P. Robins, J. D. Close

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M23	Quantum correlations in molecular dissociation to fermion pairs	M. Ögren, K. V. Kheruntsyan and J. F. Corney
M24	Immiscibility in a Quantum Degenerate Mixture of Rb and Cs	S. L. Cornish, D. J. McCarron, K. L. Butler, D. L. Jenkin, M. P. Köppinger and H. W. Cho
M25	Compact Clock with Trapped Rubidium Atoms	V. Dugrain, C. Deutsch, W. Maineult, J. Reichel and P. Rosenbusch
M26	The equation of state of degenerate quantum gases	U. Eismann, N. Navon, I. Ferrier-Barbut, A. Grier, B. Rem, K. Günter, S. Nascimbène, T. C. Nguyen, S. Piatecki, W. Krauth, F. Chevy and C. Salomon
M27	A powerful 671 nm laser source for trapping lithium	U. Eismann, F. Gerbier, G. Trénec, J. Vigué, F. Chevy and C. Salomon
M28	Gravitational-wave Detection With Matter-wave Interferometers Based On Standing Light Waves	Dongfeng Gao
M29	Canceling the quadrupole shift of single ^{40}ca+ optical frequency standards	Kelin Gao, Hua Guan, Yao Huang, Qu Liu, Jian Cao, Peiliang Liu, Xueren Huang
M30	Airborne matter wave inertial sensing	Remi Geiger
M31	Casimir interaction between a dielectric nanosphere and a metallic plane	Antoine Gérardin
M32	A new Approach to doppler-width thermometry	A. Castrillo, G. Galzerano, L. Moretti, P. Laporta, and L. Gianfrani
M33	Measuring the electron EDM using HfF^+	Matt Grau , Tyler Coffey, Kevin Cossel, Huanqian Loh, Laura Sinclair, Tyler Yahn, Jun Ye, and Eric Cornell
M34	BEC without laser cooling: Loading a Conservative Trap from an Atomic Beam	Markus Falkenau, Valentin V. Volchkov, Jahn Rührig, Hannes Gorniaczyk, Tilman Pfau and Axel Griesmaier
M35	Photonic Band Gaps with Ordered Cold Atoms	A. Schilke, C. Zimmermann, P. C. Courteille and W. Guerin
M36	Ultracold Atoms near Carbon Nanotubes	A. Günther, M. Gierling, P. Schneeweiss, P. Federsel, G. Visanescu, D. Kern, and J. Fortágh

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M37	Generation of W-states in an atomic spin-ensemble coupled to a high-finesse cavity	F. Haas, J. Volz, R. Gehr, J. Reichel and J. Estève
M38	A Single Ion as the Mirror of an Optical Cavity	G. Hétet, L. Slodička, Nadia Röck, M. Hennrich, and R. Blatt
M39	Quantum degenerate mixtures of alkali and alkaline-earth-like atoms	Hideaki Hara, Yosuke Takasu, Yoshifumi Yamaoka, John Doyle, Yoshiro Takahashi
M40	Attosecond control of electrons emitted from a nanoscale metal tip – a new low-power sensor for the carrier-envelope phase	P. Hommelhoff, M. Schenk, M. Krüger, J. Hoffrogge, R. Fröhlich, J. Hammer
M41	Self-estimate the uncertainty of $^{40}Ca^{+}$ Optical frequency standard	Xueren Huang, Hua Guan, Yao Huang, Qu Liu, Jian Cao, Peiliang Liu, Kelin Gao
M42	Optical direct comparison of two ^{87}Sr lattice clocks using a fiber-link of 60km	T. Ido, M. Fujieda, H. Hachisu, M. Kumagai, Y. Li, S. Nagano, N. Shiga, and A. Yamaguchi
M43	Wavelength-Scale Imaging of Trapped Ions for Quantum Information Processing	A. Jechow, E. W. Streed, B. G. Norton, M.J. Petrasiunas, D. Kielpinski
M44	Trapping of Ultracold Atoms in a 10μm-period permanent Magnetic Lattice	S. Jose, L. Krzemien, S. Whitlock, P. Surendran, M. Singh, A. Sidorov, R. McLean and P. Hannaford
M45	Tow-Atom Collisions In An Optical-Lattice-Like Magneto-Optical Trap	Jung-Ryul Kim, Wookrae Kim, Sungsam Kang, Sooin Lim, Myunggyu Hwang, Kyungwon An
M46	Bose-Einstein condensation of paraxial light	J. Klärs, J. Schmitt, T. Damm, F. Vewinger and M. Weitz
M47	Laser Spectroscopy of Atomic Hydrogen: Absolute Frequency Measurements of the 2S - 6S,6D Transitions	J. L. Flowers, P. W. Josephs-Franks, H. A. Klein, C. D. Langham, H. S. Margolis, L. Wright, M. D. Plimmer, P. E. G. Baird and D. J. E. Knight
M48	Strontium Ion Optical Clocks at NPL	Geoffrey Barwood, Patrick Gill, Guilong Huang, Yao Huang and Hugh Klein
M49	Pair correlated matter waves for quantum interferometry	B. Lücke, M. Scherer, J. Kruse, L. Pezze, F. Deuretzbacher, P. Hyllus, O. Topic, J. Peise, W. Ertmer, J. Arlt, L. Santos, A. Smerzi,

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		C. Klempt
M50	Extended coherence time on the clock transition of optically trapped rubidium	G. Kleine Büning, J. Will, W. Ertmer, E. Rasel, J. Arlt, and C. Klempt
M51	Klein-Tunneling of a Quasirelativistic Bose-Einstein Condensate in an Optical Lattice	S. Kling, T. Salger, C. Grossert, and M. Weitz
M52	Diatomic alkaline-earth molecules: spectroscopic data for producing ultracold samples	Horst Knöckel, Asen Pashov, Eberhard Tiemann
M53	From cold atoms to molecules: the spectroscopic modeling	Horst Knöckel, Asen Pashov, Eberhard Tiemann
M54	Simultaneous Ion-atom trapping: Results and Directions	K. Ravi, Seunghyun Lee, A. Sharma, G. Werth, and S. A. Rangwala
M55	Arrow Absorption in the Coherent Population Trapping Resonance with the Parrafine Coated Rb Vapor Cell	Hyun Joon Lee, Ye Jin Yu and Han Seb Moon
M56	A laser-cooled Si atom source for Kane quantum computer	S. A. Lee, W. M. Fairbank, Jr., W. C. Czajkowski, A. R. Gorges, H. R. Kippenhan, J. S. Kluck, J. L. Lyons, S. R. Ronald and J. Zhang
M57	Quantum information experiments with a micro-fabricated, cryogenic, surface-electrode ion trap	A.C. Wilson, K.R. Brown, C. Ospelkaus, Y. Colombe, D. Leibfried, D.J. Wineland
M58	Spectroscopy of the $1s2s\ ^3S_1 - 1s2s\ ^1S_0$ transition in quantum degenerate helium	R. van Rooij, J. S. Borbely, J. Simonet, M. D. Hoogerland, K. S. E. Eikema, R. A. Rozendaal and W. Vassen
M59	Quantum Optics and Quantum Metrology with Femtosecond Optical Frequency Combs	N. Treps, R. Medeiros de Araújo, P. Jian, R. Schmeißner, S. Jian, O. Pinel, C. Fabre

Tuesday Poster Session

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T01	Study of systematic effects for Newtonian gravitation constant measurement in MAGIA experiment	Y.-H. Lien, G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedilli and G. M. Tino
T02	Fast Generation of Single Photons in a Coupled Atom-Cavity System	Sooin Lim, Sungsam Kang, Myounggyu Hwang, Wookrae Kim, Jung-Ryul Kim, Kyungwon An
T03	Crossover from 2D to 3D in a Weakly Interacting Fermi Gas	M. Lingham, K. Fenech, S. Hoinka, P. Dyke, E. Kuhnle, M. Delehaye, H. Hu, P. Hannaford and C. Vale
T04	Random-sampling Ramsey-like spectroscopy in the XUV	R. Eramo, I. Liontos, S. Cavalieri, C. Corsi and M. Bellini
T05	The strontium lattice clock at PTB	Christian Lisdat, Stephan Falke, Thomas Middelmann, Stefan Vogt, Fritz Riehle, and Uwe Sterr
T06	Comparison of strontium optical lattice clocks	J. Lodewyck, l. Lorini, M. Zawada, M. Gurov and P. Lemonde
T07	Ultrahigh Resolution Spectroscopy and Precision Measurements with Low Systematic shift using a Trapped $^{88}Sr^{+}$ Single Ion	A.A. Madej, P. Dubé, J.E. Bernard
T08	Guided transport of ultracold atomic gases of Rb up to a room-temperature dielectric surface	A. L. Marchant, S. H¨andel, T. P. Wiles, S. A. Hopkins, C. S. Adams, and S. L. Cornish
T09	Deceleration of neutral polar molecules in macroscopic traveling traps	Samuel A. Meek, Andreas Osterwalder, Maxwell F. Parsons, Gabriele Santambrogio, Alex Woodham, Georg Hammer, Henrik Haak, and Gerard Meijer
T10	MEMS-based Atomic Magnetometry Devices with 20 $fT_{rms}/\sqrt{Hz}$ Sensitivity	Rahul Mhaskar, Svenja Knappe, and John Kitching
T11	High-order harmonic generation by intensity spikes in a filament	D.S. Steingrube, E. Schulz, T. Binhammer, M.B. Gaarde, A. Couairon, U. Morgner, and M. Kovacev
T12	Superconducting Atom Chip towards Single-mode Atomic Waveguide	Tetsuya Mukai
T13	Demonstration of a hybrid optical clock with lattice-	S. Nagano, H. Hachisu, Y. Hanado, K. Hayasaka, M. Hosokawa, T.

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	confined ^{87}Sr atoms and a singly trapped $^{40}Ca^{+}$ ion	Ido, H. Ito, M. Kajita, Y. Koyama, M. Kumagai, Y. Li, C. R. Locke, K. Matsusbara, N. Shiga, and A. Yamaguchi
T14	Dark and Bright Optical Nanofibres for Cold Atom Experiments	Síle Nic Chormaic, Laura Russell, Mark Daly, and Kieran Deasy
T15	Simulation of trapped Bose-Einstein condensates using phase-space methods	B. Opanchuk, S. Hoffmann, P. D. Drummond
T16	Adiabatic Quantum Computing with Neutral Atoms	Labert Parazzoli
T17	Improved Measurement of the 1S-2S Transition in Atomic Hydrogen	Christian G. Parthey, Arthur Matveev, Janis Alnis, Axel Beyer, Nikolai Kolachevsky, Thomas Udem, and Theodor W. Hänsch
T18	An Array of Integrated Atom Photon Junctions	P.G. Petrov, J. Garvie-Cook, M.Kohnen, R.A. Nyman, E.A. Hinds
T19	Coherent Rydberg excitation in microscopic thermal vapor cells	T. Pfau, H. Kübler, T. Baluktsian, B. Huber, A. Kölle, J. P. Shaffer, R. Löw
T20	Vibrational quantum defect for long range molecules spectroscopy. Coupling detection in Rb_2 and Cs_2 series.	Laurence Pruvost, Haikel Jelassi
T21	Cold atoms in Laguerre-Gaussian laser beams	Vincent Carrat, Bruno Viaris de Lesegno and Laurence Pruvost
T22	Interferometry with BEC in extended free fall	Ernst M. Rasel
T23	Experiments with a fiber-based optical dipole trap for cold Cs-Atoms	D. Reitz, S. B. Arroyo Camejo, S. T. Dawkins, R. Mitsch, E. Vetsch, P. Schneeweiss, and A. Rauschenbeutel
T24	Multispecies kinetic theory of cavity-mediated cooling and selforganisation	Helmut Ritsch
T25	A Microchip Decelerator for Polar Molecules	G. Santambrogio, S. A. Meek, M. Abel, H. Conrad, G. Meijer
T26	Spinor and polar lattice gases	Luis Santos
T27	Towards direct frequency comb spectroscopy using quantum logic	B. Hemmerling, F. Gebert, Y. Wan, Piet O. Schmidt
T28	Resonant Multiphoton Ionization of Aromatic Molecules	J. Strohaber, F. Zhu, R. Nava, N. Hart, F. Pham, A. A. Kolomenskii,

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	Revealed by Intensity Resolved Imaging	H. Schroeder, G. G. Paulus and H. A. Schuessler
T29	Generation of High Harmonics in Argon: Pressure and Energy Dependencies and Influence of Metal Clusters	Alexandre Kolomenskii, James Perkins, Ryan Mueller, Siying Peng, Ricardo Nava, James Strohaber, Gerhard Paulus and Hans Schuessler
T30	A Cryogenic System to Separate Krypton Tracers from Well Gases for Ultra-Sensitive Collinear Fast Beam Laser Spectroscopy	T. Mohamed, R. Nava, J. Strohaber, A. A. Kolomenskii, and H. A. Schuessler
T31	Fast Ion Beam Precision Laser Spectroscopy of Argon II in Collinear and Anti-Collinear Geometries Referenced to a Frequency Comb	V. Lioubimov, M. Wada, M. Ogawa, A. Takamine, T. Nakamura, P. Schury, H. Iimura, K. Okada, Y. Yamazaki, T. Hassan, A. A. Kolomenskii, J. Strohaber, H. A. Schuessler
T32	Metastable Helium Vacuum Gauge	F. Shimizu, K. Shimizu, S. Arai, T. Nakasuji, M. Morinaga, and H. Takuma
T33	MAGIC for Trapped Ions	Ch. Wunderlich, I. Baumgart, M. Johanning, A. Khromova, Ch. Piltz, M. B. Plenio, A. Retzker, B. Scharfenberger, N. Timoney, A. Varon
T34	New insights offered by Penning ionizations into optically trapped metastable ^{4}He atoms	Juliette Simonet, Jerome Beugnon, Michele Leduc
T35	The Calcium BEC at PTB	Sebastian Kraft, Oliver Appel, Max Kahmann, Stephan Schulz, Fritz Riehle, and Uwe Sterr
T36	High precision absolute frequency measurements of hyperfine levels of potassium isotopes for 4s $^2S_{1/2}\rightarrow$6s $^2S_{1/2}$ two photon transition	M. V. Suryanarayana and P.V. Kiran Kumar
T37	Mott Insulator of Multi-component Fermi Gases of Ytterbium in Optical Lattices	Shintaro Taie, Seiji Sugawa, Rekishu Yamazaki, and Yoshiro Takahashi
T38	Negative Group Velocity and Meta-optics for Mater-waves	T. Taillandier-Loize, M. Hamamda, G. Dutier, F. Perales, J. Baudon and M. Ducloy

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T39	Fiber-coupled single ion as an efficient quantum light source	H. Takahashi, A. Wilson, A. Riley-Watson, M. Keller and W. Lange
T40	Methods for Sympathetic Cooling of Polar Molecules with Ultracold Atoms	S. Truppe, S. K. Tokunaga, E. A. Hinds and M. R. Tarbutt
T41	RKR-potential for B-state in molecular iodine	Roelant Van Dierendonck
T42	Nondestructive measurement and Bose-Einstein condensation in a crossed high-finesse optical cavity	T. Vanderbruggen, R. Kohlhaas, S. Bernon, A. Bertoldi, A. Landragin, and P. Bouyer
T43	Spontaneous demagnetization of a dipolar chromium BEC at ultra low magnetic field	Laurent Vernac
T44	Optimal trapping wavelength of Cs_2 and RbCs molecules in an optical lattice	R. Vexiau, M. Aymar, N. Bouloufa, J. G. Danzl, M. J. Mark, H.-C. Nägerl and O. Dulieu
T45	Hyperfine structure of Cs_2 and RbCs excited molecules	O. Kriegelsteiner, R. Vexiau, N. Bouloufa, A. Crubellier, J. G. Danzl, H.-C. Nägerl, O. Dulieu
T46	Laser cooling of atoms by collisional redistribution of fluorescence	U. Vogl, A. Saß, S. Haßelmann, and M. Weitz
T47	Quantum Image Processing and Storage with Four-Wave Mixing	U. Vogl, J. Clark, N. Corzo, Z. Zhou, R. Glasser, Q. Glorieux, A.Marino, and P.D. Lett
T48	Combining Red- and Blue-detuned Optical Potentials to Form a Lamb-Dicke Trap for a Single Neutral Atom	Xiaodong He, Peng Xu, Jin Wang, and Mingsheng Zhan
T49	Development of a 10-meter Atom Interferometer	L. Zhou, Z. Y. Xiong, W. Yang, B. Tang, W. C. Peng, K. Hao, R. B. Li, M. Liu, J. Wang, M. S. Zhan
T50	Double-resonance optical-pumping spectroscopy with a ladder-type cesium atomic system and two-color cesium magneto-optical trap	Junmin Wang, Baodong Yang, Qiangbing Liang, Jun He, Tiancai Zhang, and Kunchi Peng
T51	A new setup for the study of strongly correlated low-dimensional systems	Wolf Weimer, Kai Morgener, Florian Wittkötter, Niels Strohmaier and Henning Moritz
T52	Experimental Demonstration of Interaction of Ultracold	A. D. West, K. J. Weatherill, T. J. Hayward, D. A. Allwood, and I.

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	Atoms with a Periodic Array of Nanomagnetic Domain Walls	G. Hughes
T53	Experimental determination of the ^{24}Mg I $(3s3p)^3P_2$ lifetime	Philip G. Westergaard
T54	Microfabricated scalable monolithic linear ion traps with unit aspect ratio	G. Wilpers, P. See, P. Gill, A.G. Sinclair
T55	Loading an Inductively Coupled Ring Trap	Paul Griffin, Aline Dinkelaker, Matthieu Vangeleyn, Jon Pritchard, Aidan Arnold and Erling Riis
T56	Probe correlation and energy gap of Bloch bands in one dimensional optical lattice by matter wave amplification	Xuzong Chen, Yueyang Zhai, Shifeng Yang, Thibault Vogt, Bo Lu, Xinxin Liu, Xu Xu, Wei Xiong, Xueguang Yue, Qiuyu Guo,Yiqiu Wang, Xiaoji Zhou
T57	Microwave Atomic Clock in the Magic Wavelength Optical Lattice and Magic Wavelength Laser	Yueyang Zhai, Shifeng Yang, Bo Lu, Wei Xiong, Xia Xu, Xuguang Yue, Yiqiu Wang, Xiaoji Zhou and Xuzong Chen
T58	Rapid loading and momentum manipulation by standing wave pulses	Xiaoji Zhou, Xinxin Liu, Wei Xiong, Yueyang Zhai, Shifeng, Yang, Thibault Vogt, Xueguang Yue, Yiqiu Wang, Xuzong Chen
T59	Dipolar quantum gases in multi-well potentials	J. Billy, S. Müller, E. Henn, H. Kadau, P. Weinmann, D. Peter, K. Rzazewski, A. Griesmaier, T.Pfau, M. Jona-Lasinio and L. Santos
T60	Quantum Correlations and Atomic Speckle	S. Hodgman, R. G. Dall, A. G. Manning, M. T. Johnsson, K. G. H. Baldwin and A. G. Truscott

A thermal calcium-atom interferometer with a phase resolution of a few milliradian based on a narrow linewidth diode laser

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Atom interferometers have been developed as sensitive detectors for precision measurements and fundamental tests of quantum physics. Ramsey-Bordé atom interferometers forming a closed trapezoidal trajectory are sensitive to the frequency detuning of lasers, therefore they have been used in high-precision spectroscopy of atomic narrow transitions for optical clocks in which external perturbations causing frequency shifts of the resonance are carefully suppressed, because of their advantages over the single-pulse (Rabi) spectroscopy [1]. On the other hand, Mach-Zehnder atom interferometers comprised of four copropagating traveling laser beams, which have a closed parallelogramatic trajectory, are far less sensitive to frequency fluctuations of the laser [2,3]. These interferometers work like white-light interferometers, therefore they are suitable for measuring a nondispersive atomic phase shift which is independent on the velocity of the atom, like the Aharonov-Casher effect and the Röntgen effect [4].

We have developed a Mach-Zehnder atom interferometer based on the $^1S_0$-$^3P_1(m_J = 0)$ transition at 657 nm of Ca using a thermal atomic beam. In order to suppress the fluctuation of the laser phase caused while an atom interacts with four laser beams, a diode laser was stabilized to a resonance of a high-finesse cavity isolated from acoustic and vibrational noise and heat conduction. The linewidth of the laser was estimated to be narrower than 60 Hz. The phase stability of observed interference fringe (Fig. 1(a)) was improved to 2 mrad at an integration time of 300 ms for each point as shown in Fig. 1(b),

which will allow us to detect the Röntgen effect expected in our experimental setup. For a test of the phase measurement scheme, we evaluated the ac Stark shift on the $^1S_0$-$^3P_1$ transition by applying a laser power near resonance of the $^1S_0$-$^1P_1$ transition at 423 nm. The dipole moment of the 423 nm transition was determined by the phase measurement and it was in good agreement with the known value.

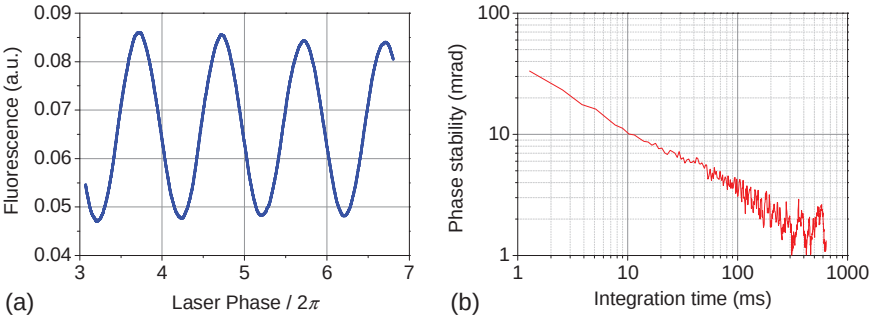

Figure 1. (a) A typical interference fringe plotted by 1000 points. Each point was measured at an integration time of 300 ms. (b) Allan deviation calculated from data set of the differential phase of the interference fringes as a function of the integration time for each point.

The poster presentation will include the spectroscopy of the $^1S_0$-$^3P_1$ transition of a thermal calcium atomic beam, investigation of phase stability of the interference fringe, evaluation of the ac Stark shift induced by the laser power, and prospects for detection of the Röntgen effect.

References

1. V. I. Yudin et al., Phys. Rev. A **82**, 011804(R) (2010).
2. A. Morinaga and Y. Ohuchi, Phys. Rev. A **51**, R1746 (1995).
3. S. Yanagimachi et al., Phys. Rev. A **57**, 3830 (1998).
4. H. Wei et al., Phys. Rev. Lett. **75**, 2071 (1995).

Discrete interferometer with individual trapped atoms

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Coherent control and delocalization of individual atoms is a pivotal challenge in quantum technologies. As a new step on this road, we present an individual atom interferometer that is capable of splitting a trapped Cs atom by up to 10 µm, allowing us to measure potential gradients on the microscale. The atom is confined in a 1D optical lattice, which is capable of performing discrete state-dependent shifts to split the atom by the desired number of wavelengths. We establish a high degree of control, as the initial atom position, vibrational state and spin state can all be prepared with above 95% fidelity. To unravel decoherence effects and phase influences, we have explored several basic interferometer geometries, among other things demonstrating a positional spin echo to cancel background effects. As a test case, an inertial force has been applied and successfully measured using the atomic phase. This will offer us a new tool to investigate the interaction between two atoms in a controlled model system.

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Laser cooling with a single laser beam and a planar diffractor

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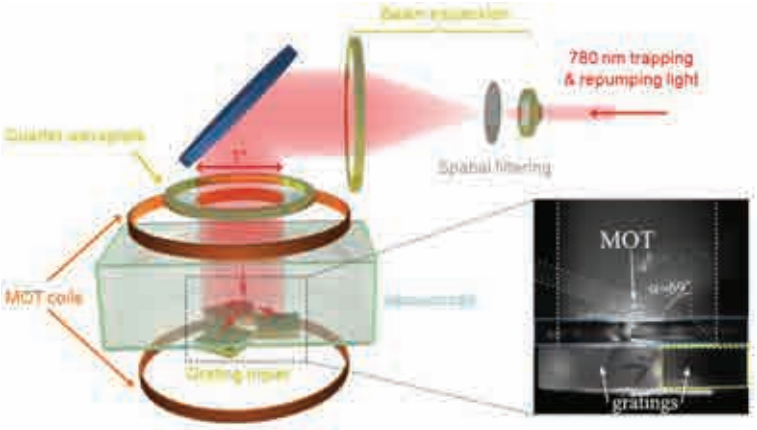
We have realised [1] a shadow-free 4-beam 'pyramidal' magneto-optical trap ideally suited for future microfabrication. A planar triplet of diffraction gratings is used to split and steer a single incoming beam into a tripod of reflected beams, allowing trapping in the four-beam overlap volume. We demonstrate the technique by trapping and subsequently sub-Doppler cooling ^{87}Rb atoms to 30 μK.



[1] M. Vangeleyn, P. F. Griffin, E. Riis and A. S. Arnold, "Single-laser, one beam, tetrahedral magneto-optical trap," Opt. Express **17**, 13601 (2009); M. Vangeleyn, P. F. Griffin, E. Riis and A. S. Arnold, "Laser cooling with a single laser beam and a planar diffractor," Opt. Lett. **35**, 3453 (2010) and references therein.

Ring traps: large-separation interference and a new inductive geometry

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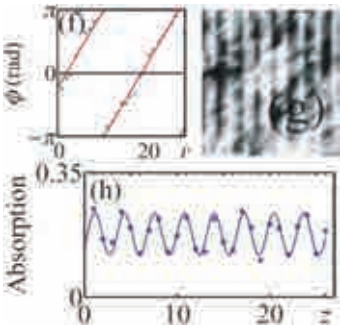
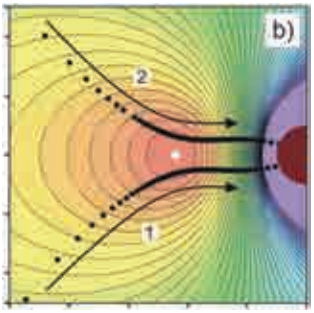
We use magnetic levitation and a variable-separation dual optical plug to obtain clear spatial interference between two condensates axially separated by up to 0.25 mm [1]. Planar fringes are observed using standard (i.e. non-tomographic) resonant absorption imaging.

We also describe our steps toward a new inductively-coupled ring experiment [2] which promises unprecedented smoothness as a result of both the ac mode of operation and the elimination of end effects.





[1] M.E. Zawadzki, P.F. Griffin, E. Riis, and A.S. Arnold, Phys. Rev. A **81**, 043608 (2010).
[2] P.F. Griffin, E. Riis and A.S. Arnold, Phys. Rev. A **77**, 051402(R) (2008).
[3] A.S. Arnold, C.S. Garvie, and E. Riis, Phys. Rev. A **73**, 041606(R), (2006).

The FERRUM Project: Experimentally determined lifetimes of the metastable $c^4D_{5/2}$ and $c^4D_{7/2}$ levels in Cr II

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The FERRUM Project[1] is an ongoing project to get new and accurate atomic data of the iron group elements. In low density astronomical plasma, e.g. the *strontium filament* ejecta of Eta Carinae, radiative decay of long lived metastable states becomes important and can be observed. The measured metastable levels lifetimes can be used together with branching fractions, measured in the astronomical spectrum, to obtain absolute transition rates [2], which in turn can provide information about the abundances of the elements [3].
We report of the lifetimes of the metastable energy levels $3d^4(^3D)\ 4s\ c^4D_{7/2}$ and $c^4D_{5/2}$ in Cr II. They have been measured by time resolved laser spectroscopy. The study has been performed at the CRYRING ion storage ring in Stockholm, Sweden. The lifetimes are found to be 1.37(7) s and 1.28(16) s respectively. Theoretical calculation by Quinet [4] gave the lifetimes 1.40 s and 1.33 s respectively. Another calculation by Nussbaumer et al. [5] gave the lifetimes 1.52 s and 1.61 s respectively.

[1] Johansson, S. et al. Phys. Scr., **T100**, 71, 2002
[2] Gurell, J. et al. A&A. **508**, 525, 2009; Hartman, H. et al. Phys. Scr., **T119**, 40, 2005
[3] Bautista, M.A. et al. Mon. Not. R. Astron. Soc. **393**, 1503, 2009
[4] Quinet, P. Phys. Scr. **55**, 41, 1997
[5] Nussbaumer, H. et al., Astrophys. J. **162,** 589, 1970

SPECTRAL NARROWING OF ELECTROMAGNETICALLY INDUCED TRANSPARENCY WITH PSEUDO-THERMAL LIGHT

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1. Introduction

Electromagnetically induced transparency (EIT) is a useful phenomenon for optical magnetometers, ultraslow light propagation, and quantum memory due to narrow sub-natural linewidth [1-4]. To promise those applications, various properties on the EIT for the used light sources have been studied in a variety of situations such as two coherent lasers, frequency modulated light sources, noisy lasers, and pseudo-thermal light [5, 6]. Particularly, when the noisy-probe light passed though EIT medium, the spectral narrowing of the probe light occurred because the EIT transparency window exhibits narrow band-pass filter for the broad frequency noise [6].

In this paper, we present the spectral narrowing of EIT with a pseudo-thermal probe light based on amplitude noise in the $5S_{1/2}$-$5P_{1/2}$ transition of the Λ-type system of ^{87}Rb atom. We demonstrate that the randomly amplitude modulated EIT is relevant phenomena with noisy laser based on the frequency modulation. We measured the spectral characteristics of EIT with pseudo-thermal probe light, while the heterodyne detection of EIT was performed by measuring beat-note signal between pseudo-thermal EIT and 80 MHz shifted probe light by acoustic-optic modulator.

2. Results

Figure 1(a) shows the EIT spectrum with pseudo-thermal probe light and laser coupling light in the $5S_{1/2}$-$5P_{1/2}$ transition of the Λ-type system of ^{87}Rb atom. This EIT spectrum is measured by the direct transmittance measurement. The pseudo-thermal light and laser were used as probe and coupling light in a resonance with $F = 1 \rightarrow F' = 2$ transition and $F = 2 \rightarrow F' = 2$ transition of the Λ-type system of ^{87}Rb atom, respectively. The pseudo-thermal light was achieved by scattering light from partially

transparent glass, while the glass was rotated with 9.4 m/s. The EIT linewidth was approximated to be 870 kHz, respectively.

We measured the beat-note signal between the probe light after passing through EIT medium and the frequency shifted probe light by an acousto-optic modulator (AOM) at 80 MHz. The measured beat-note signals as a function of probe frequency detuning was shown in Fig. 1(b). The measured spectral width was approximated to be 200 kHz. Even though intensity fluctuation of pseudo-thermal probe light induced broadening of EIT spectrum, the spectral width of the beat-note signal was much narrow more than factor of 4. These results are compatible with narrow EIT spectrum via quantum coherence with noisy laser introduced in Ref [6].

We argue that the direct transmittance spectrum of EIT could be broadened due to intensity fluctuation of pseudo-thermal probe light, but the EIT window should be maintained narrow linewidth as same as that of EIT with coherent light sources.

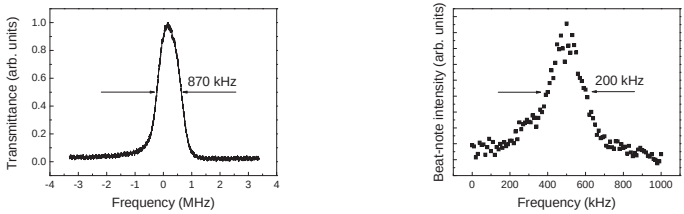

Fig. 1. (a) EIT spectrum with pseudo-thermal probe light and (b) Beat-note signal between EIT and 80 MHz shifted beam as a function of probe detuning.

References

1. K. J. Boller, A. Imamoglu and S. E. Harris, *Phys. Rev. Lett.* **66**, 2593 (1991).
2. Budker and M. V. Romalis, *Nature Physics* **3**, 227 (2007).
3. L.V. Hau, S.E. Harris, Z. Dutton, and C.H. Behroozi, *Nature* **397**, 594 (1999).
4. D. F. Phillips, A. Fleischauer, A. Mair, R. L. Walsworth and M. D. Lukin, *Phys. Rev. Lett.* **86**, 783 (2001).
5. I.-H. Bae, H. J. Lee and H. S. Moon, to be accepted on *J. Opt. Soc. Am. B* (2011).
6. E. E. Mikhailov, V. A. Sautenkov, Y. V. Rostovtsev, A. Zhang, M. S. Zubairy, M. O. Scully, and G. R. Welch, *Phys. Rev. A* **74**, 013807 (2006).

Vibrational spectroscopy of sympathetically cooled biomolecular ions

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In this work we demonstrate, to the first time to our knowledge, vibrational spectroscopy of polyatomic ions that are trapped and sympathetically cooled by laser-cooled atomic ions. We use protonated dipeptide tyrosine-alanine (TAH^+) as a model system, cooled by Barium ions to less then 800 mK. The spectroscopy is performed on the fundamental vibrational transition at 2.74 µm using a continuous-wave optical parameteric oscillator (OPO). Resonant multi-photon IR dissociation spectroscopy (without the use of a UV laser) generates charged molecular fragments, which are sympathetically cooled and trapped and subsequently detected by ion counting. The observed vibrational linewidth indicates that the rotational temperature of the molecular ions is not significantly reduced compared to 300 K ambient temperature.

Photodissociation spectroscopy is a common method for gaining information on structures of molecules, including biomolecules [1], and for studying the energetics of fragmentation [2]. Photodissociation spectroscopy has already been applied to trapped ions, cooled by Helium gas to 300 K or even to 10 K [3]. In this latter case, reduction of the UV laser-induced dissociation by exciting molecules on a vibrational transition is used as a spectroscopic signal. Here we describe the application of vibrational spectroscopy to sympathetically cooled biomolecules. We show that the method of resonant multi-photon IR dissociation (R-IRMPD) spectroscopy is applicable. Here, the resonant absorption of a photon occurs only on one transition. Intramolecular bonds redistribute absorbed energy on a time scale of less than a nanosecond [4]. After that another photon can be absorbed and the process is repeated, thus the molecule collects internal energy until it will be large enough to break molecular bonds. The spectra of the transition obtained under different conditions is here used to answer the question of whether the internal degrees of freedom of the molecules couple, via the ion-ion collisions inside the trap, to the external ones, which are sympathetically cooled to less then 800 mK.

Our experimental setup [5, 6] is shown in Figure 1. It consists of an electrospray ionization source (ESI) [8] for the production of singly or multiply charged gas-phase molecular ions with a mass-to-charge ratio m/z (z is the number of elementary charges), a quadrupole mass filter for the selection of specific molecular species, a RF octopole ion guide to transfer the selected molecular ions from the rough vacuum region of the ESI device to an ultra-high vacuum (UHV) chamber with a typical residual gas pressure of $< 10^{-9}$ mbar, and a linear quadrupole trap in this UHV chamber to store the molecular ions for sympathetic cooling. The preparation of the laser-cooled $^{138}Ba^+$ ion ensembles used for the sympathetic cooling of the molecular ions as well as the required laser setup have been described in [9]. Under appropriate laser-cooling conditions, the barium ions arrange in Coulomb crystals, that can be imaged with an intensified CCD camera (see figure 1). The images contain indirect information on the simultaneously trapped non-fluoresing sympathetically cooled molecular ions and fragment ions. Furthermore, we can mass-selectively extracted ions and count them with an ion detector.

From a solution of 70 pmol/l TAH^+in methanol + water (1:1) + 0.1% formic acid the polyatomic, singly charged ($z = 1$) biomolecules are transferred into the trap and sympathetically cooled within less than 1 min (see Figure 1b)). In a quadrupole trap, ions of different charge-to-mass ratios Q/m arrange radially separated according to their effective radial trap potentials $\Phi(r) \propto Qr^2/m$ [6]. For the (destructive) measurement of the number of ions in the trap, we make use of a mass-to-charge-ratio selective extraction of the ions from the trap: when decreasing the trap RF amplitude U_{RF} the Mathieu stability parameter is reduced and the ions escape from the trap at a mass-to-charge ratio dependent RF amplitude. This leads to an ion extraction mass spectrum as shown in figure 2a). The ratio of TAH^+ fragment ions to the total number of extracted ions (the latter has been tested to be a good measure of the number of ions before photodissociation) is the signal of interest. This is measured as a function of IR wavelength to obtain a spectrum. The compact cw-OPO used as IR source is described in [10]. In IR vibrational spectroscopy of large molecules a significant effect is the thermal population of a very large number of rotational levels, due to their small rotational constant $B \ll k_B T_{rotational}$. This leads to a vibrational transition linewidth on the order $\sqrt{k_B T_{rotational} B}$.

We irradiate the molecules with an IR frequency suitable for the fundamental vibrational transition of the OH group attached to the phenol group [11]. Under conditions of relatively low IR intensity we find partial fragmentation of the original ensemble of TAH^+ for the selected irradiation duration of 3 s (Figure 2 II)). The spectral linewidth is approx. 10 cm^{-1}. This is consistent with the above estimate, if we use $T_{rotational} = 300\,\mathrm{K}$ and $B \simeq 2\,\mathrm{GHz}$‡. At higher irradiation intensity the fragmented fraction increased. For comparison, the spectrum of TAH^+ in absence of laser-cooled Barium ions, but with buffer gas cooling with neutral Helium gas, i.e. at $T_{translation} = T_{rotational} = 300\,\mathrm{K}$ is also shown. The differences in linewidth can be partially explained by saturation effects. There is no evidence for a strong reduction of linewidth upon sympathetic cooling, even though the molecules have been in interaction with the laser-cooled Barium ions for typically 45 s before R-IRMPD. We conclude that even for polyatomic ions, which have relatively low-energy internal modes, there is no efficient coupling to the (cooled) external degrees of freedom, i.e. the time-varying electric fields produced by the collisions between the molecular ions and other trapped atomic or molecular ions are not able to extract from or inject to the molecules significant energy . No such coupling had been observed in sympathetically cooled diatomic molecular ions, either [12].

[1] Correia C F, Balaj P O, Scuderi D, Maître P and Ohanessian G, *J. Am. Chem. Soc.* **130,** 3359-70 (2008)
[2] Dienes T et al, *Mass Spectrom. Rev.* **15,** 163-211 (1996)
[3] Boyarkin O V,Mercier S R, Kamariotis A, and Rizzo T R, *J. Am. Chem. Soc.* **128**, 2816-2817 (2006)
[4] Gregoire G, Gaigeot M P, *Physical Chemistry Chemical Physics*, **9**, 3082-3097 (2007)
[5] Ostendorf A et al, *Phys. Rev. Lett.* **100,** 019904 (2008)
[6] Offenberg D, Zhang C B, Wellers C, Roth B and Schiller S, *Phys. Rev. A* **78,** 061401(R) (2008)
[7] Offenberg D, Wellers Ch, Roth B and Schiller S, *J. Phys. B: At. Opt. Phys.* **42,** 035101 (2009)

‡ Estimated for TAH ions from a database of Anthracene molecules (http://cccbdb.nist.gov/).

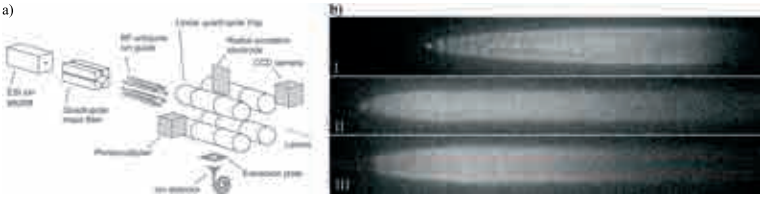

Figure 1. a) Schematic overview of the experimental setup. Protonated molecular ions from an ESI ion source are selected by a quadrupole mass filter and transferred via a RF octopole ion guide to a linear quadrupole trap in a UHV chamber. The trapped ions can be counted by an ion detector below the trap. The laser-cooled $^{138}Ba^+$ ions are imaged with a CCD camera [7]. **b)** Experimental CCD image of a Ba^+ crystal. I) Pure Ba^+ crystal II) Same crystal after loading with TAH^+, which surrounds the Ba^+ crystal and compresses it. III) Crystal after infrared vibrational excitation and photodissociation of the TAH^+ molecules. Light fragment ions are trapped close to the trap axis and show up indirectly as a darker region (marked in red).

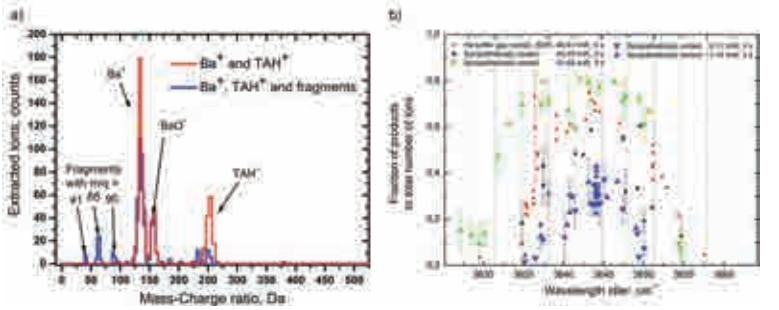

Figure 2. a) Red: Extraction spectra for an ensemble of laser-cooled Barium ions and sympathetically cooled TAH^+. Blue: Same, but after irradiation by the cw-OPO on the vibrational transition. **b)** Vibrational spectrum of polyatomic TAH^+ for the case of sympathetic cooling ($T \simeq 0.8$ K, green, black, blue) and buffer gas - cooling ($T = 300$ K)

[8] Fenn J B, Mann M, Meng C K, Wong S F and Whitehouse C M, *Science* **246,** 64-71 (1989)

[9] Roth B, Ostendorf A, Wenz H and Schiller S, *J. Phys.* B **38,** 3673-85 (2005)

[10] Vasilyev S, Gollnick H.-E, Nevsky A, Grisard A, Lallier E, Gérard B, Jimenez J, Schiller S, *Appl. Phys B* **100**, 737–747 (2010)

[11] Stearns, J A, Guidi M, Boyarkin O V, and Rizzo T R, *J. Chem. Phys.*, **127**, 154322-7 (2007)

[12] Koelemeij J C J, Roth B, Wicht A, Ernsting I and Schiller S, *Phys. Rev. Lett.* **98**, 173002-4 (2007)

Probing the state of a repulsive 1D Bose gas by light scattering

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The state of a uniform repulsive 1D Bose gas of density n is determined by two parameters, the collision interaction strength and the temperature. An important characterisation of the state is provided by the two-body correlation function $g^{(2)}(r) = \langle\hat{\Psi}^\dagger(0)\hat{\Psi}^\dagger(r)\hat{\Psi}(r)\hat{\Psi}(0)\rangle/n^2$, for which analytic expressions have been given for a wide range of the two controlling parameters[1]. A key feature of the system is that the short range correlation behaviour ranges from antibunching ($g^{(2)}(0) = 0$), which occurs in the Tonks gas[2 , 3] regime (high interaction strength and low temperature), to bunching ($g^{(2)}(0) = 2$), which occurs in the thermal regime (low interaction strength and high temperature). A number of schemes have been proposed to measure these correlations (e.g. see reference [1] and and references therein), and in this paper we present a theoretical treatment of an alternative method based on weak field light scattering. Using a formalism similar to Mekhov et al [4], we show that the quadrature variances of the scattered light intensity provide a signature that distinguishes the major regimes of behaviour of the 1D Bose gas.

[1] A. G. Sykes *et al.*, Phys. Rev. Lett. 100,160406 (2008)
[2] B. L. Tolra *et al.*, Phys. Rev. Lett. 92,190401 (2004)
[3] T. Kinoshita *et al.*, Science, 305, 1125 (2004)
[4] Igor. B. Mekhov *et al.*, Phys. Rev. A 76,053618 (2007)

Laser-induced quantum adsorption of atoms on a surface

Victor Balykin

– no abstract available –

MEASURING THE QUANTUM SPEED LIMIT IN THE DYNAMICS OF A TWO LEVEL SYSTEM

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The ability to accurately control a quantum system is a fundamental requirement for the implementation of any protocol in quantum information processing. In addition, in order to avoid decoherence, it is desirable to realise these quantum manipulations in the shortest possible time. Quantum optimal control is an indispensable tool with which to minimise this time [1]. Quantum mechanics sets a fundamental limit to how short this can be, dictated by the Schrödinger evolution [2].

To experimentally probe the limits of quantum control, a Bose-Einstein condensate (BEC) is loaded into an optical lattice formed by two counter-propagating beams. The lattice is subjected to an inertial force by modulating the frequency of one of these beams [3]. This modulation allows external control of the quantum system.

The BEC in the lattice is well described by a two-level system defined by the two lowest Bloch bands. The time-evolution of the condensate realises a paradigm in quantum mechanics, the Landau-Zener problem. Optimal control of the acceleration of the condensate allows the gap to be crossed, without inducing Landau-Zener transitions, in a minimum time.

The results of various protocols for controlling the time evolution of the BEC are presented in figure 1. We study three different types of time evolution. Using a linear Landau-Zener sweep, the time taken

to achieve ever greater adiabaticity diverges. The composite protocol, partly composed of an on-resonant Rabi oscillation, minimises the transition time, approaching the quantum speed limit. It is not adiabatic throughout the protocol, rather the final adiabaticity is prioritised. The protocol of *Roland and Cerf* [4] corresponds to the local adiabatic case. This approach dictates a lower bound on the adiabaticity at each point of the sweep.

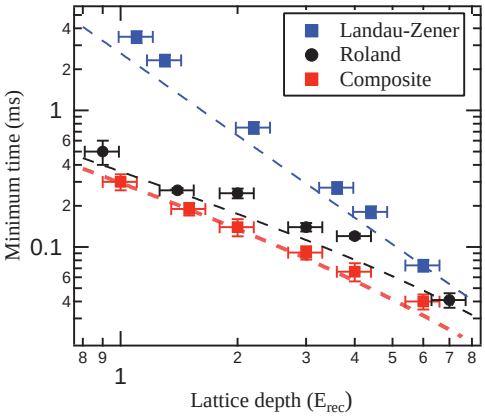

FIGURE 1. Time taken to achieve a 90% efficient population transfer for various protocols as a function of lattice depth.

REFERENCES

[1] I. Walmsley and H. Rabitz, Phys. Today **56**, 43 (2003). L.B. Levitin, Int. J Theor. Phys. **21** , 299 (1982).
[2] K. Bhattacharyya, J. Phys. A **16**, 2993 (1983).
[3] O. Morsch, J. H. Müller, M. Cristiani, D. Ciampini, and E. Arimondo, Phys. Rev. Lett. **87**, 140402 (2001).
[4] J. Roland and N.J. Cerf, Phys. Rev. A **65**, 042308 (2002); .

A photon number discriminator without photon counting.

J. Bernu, H.M. Chrzanowski, T. Symul, B.M. Sparkes, B. Hage, A. Lund, T.C. Ralph and P.K. Lam

Non-Gaussian states form a vital resource for many quantum information protocols. Continuous variable techniques thanks to their high detection efficiency and compatibility with existing telecom infrastructures are a good candidate for these quantum information protocols. However, the usual continuous variable toolbox, which includes Gaussian resources, linear optics and homodyne detections, is insufficient to produce such states due to the absence of extreme nonlinearity. As a result, many groups have integrated photon counting to herald the successful preparation of a non Gaussian quantum states, which can then be characterised using homodyne detection. These 'hybrid' experiments face the challenges arising from simultaneously measuring both the wave and particle properties of light. Here we demonstrate a new purely homodyne based technique for photon number discrimination allowing us to characterise non-Gaussian states. We show the versatility and efficacy of this photon-counting-free technique by experimentally reconstructing one, two and three photon subtracted squeezed vacuum states as well as Fock states.

For more details:

http://arxiv.org/abs/1102.5566

http://arxiv.org/pdf/1103.4199v2

Sub-Doppler spectroscopy with a vapour confined in an opal

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We report on the study of dilute vapours confined in the sub-micrometric interstitial regions of an opal of glass nanospheres, and demonstrate sub-Doppler optical resonances in linear spectroscopy, for a large panel of irradiation angles.

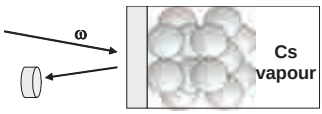
Our experiments are performed on Cs vapour cells in which a window is covered with a film made of several layers of ~ 1µm glass spheres. When irradiating the covered window with a laser, the scattering in the opal makes the transmission very weak ($< 10^{-2}$ for the considered size of glass spheres and opal thickness), but a reflected beam is observable. A striking observation is that the, in the vicinity of the Cs resonances (λ_1 = 894 nm, λ_2 = 852 nm), the reflection spectrum exhibits sub-Doppler structures – whose contrast can be enhanced by a FM technique. These sub-Doppler structures (figure), obtained in *linear* spectroscopy, appear for a large range of incidence angles. This markedly differs from our previous investigations with extremely thin cells (see *e.g.* [1]), allowing a 1D confinement, with sub-Doppler structures restricted to normal incidence.

These sub-Doppler structures are clearly induced by the 3D vapour confinement, and they can be considered as reminiscent, *in the optical domain*, of the Dicke narrowing [2] known to yield Doppler-free signals when the atomic motion is confined to less than a wavelength (usually observed in the *r.f.* domain, with a confinement imposed by collisions to a buffer gas). Our present investigations, eventually involving a pump-probe scheme, aim at distinguishing the signature of the true interstitial regions of the opal, and of the intermediate region between the flat window and the first layer of the opal. The lineshapes exhibit a strong polarization dependence, indicating that various propagating regimes are explored.

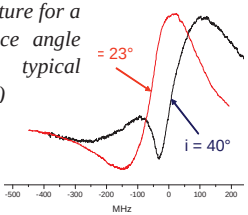
Work partly supported by ANR "Mesoscopic gas" (08-BLAN-0031-01) and by ECOS-Sud (U08E01). We thank S. Ravaine group (CRPP-Bordeaux) for the opal preparation.

[1] G. Dutier *et al.*, Europhys. Lett., **63**, 35 (2003)
[2] R. H. Dicke, Phys. Rev. **89**, 472 (1953)

Principle of selective reflection at an opal interface



Appearance of a sub-Doppler structure for a large incidence angle (here 40 °, typical range 30-60 °)



Focused Laguerre-Gauss Beams interacting with an Atom : Transfer of Orbital Angular Momentum and Detector-Dependent Mapping

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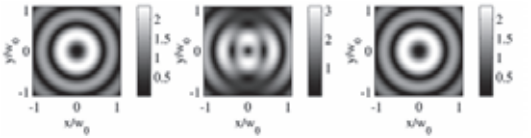
Laguerre-Gauss (LG) beams are of a particular interest owing to their orbital angular momentum [1]. We have shown that these fields, described by a phase factor exp (i$l\varphi$), with φ the azimuthal angle, and l an integer, are not truly hollow [2] in spite of a null electric field on-axis. Indeed, the vector nature of the fields imposes an on-axis longitudinal electric field for $l = \pm 1$, a magnetic field for $l = \pm 2$, and other gradients for $|l| \geq 2$. These effects are quantitatively important for strongly focused beams.

While quantum optics usually assumes a point-like electric field detector, relying on an electric dipole transition (E1), the magnetic energy on-axis (for $l = \pm 2$). requires for its measurement a magnetic field detector (based upon a M1 transition). In the same manner, a gradient field detector, based upon an E2 transition, provides a signal in the "hollow" region of the beam. In spite of weak transition probability of non E1 transitions – usually "nearly forbidden" at optical frequencies-, these detection methods allow to analyze how a higher-than-unity angular momentum of a LG beam is transferred to an elementary quantum atomic system. These considerations also establish that the mapping of a LG beam is detector-dependent.

Pushing further the analysis, we have shown that the interplay of polarization and topological charge (or of spin and angular momentum), modifies the apparent size of (strongly focused) LG beams, even for an E1 transition. This eventually leads to a breaking of the cylindrical symmetry for a linearly polarized LG beam (see fig.1, and [3]), and to a local chiral selectivity. Extension of these results to the near-field domain in the vicinity of nano-emitters is now under investigation.



Mapping in the waist plane of a linearly (x) polarised LG beam, assuming $l = +2$, a waist defined by $kw_0 = 6$, and $p=6$ for the number of radial nodes. The detection relies on an E1 ($S \rightarrow P$) transition: from left to right, with resolution of Zeeman substates $M= -1 , 0, +1$.

Work partly supported by CAPES-COFECUB (456-04) and CNRS-RFBR "PICS 5813"

[1] L. Allen *et al.*, Phys. Rev. A **45**, 8185-8189 (1992)
[2] V.V. Klimov *et al.*, Opt. Express **17**, 9718 (2009)
[3] V.V. Klimov *et al.*, submitted

Observing the temperature dependence of the atom-surface interaction in the van der Waals Casimir-Polder regime

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The long-range atom-surface interaction, experimentally accessible for the last years, attracts a lot of interest, as connected to the Casimir effect, and sensitive to quantum fluctuations in a vacuum/boundary system. Testing its dependence upon temperature, which modifies the fluctuations, is experimentally challenging. Enhancement of these effects was predicted when the vacuum temperature differs from the surface temperature, and observed for the first time on a Rb BEC, 6-10 μm from the wall [1].

Alternately, a highly excited atom, with numerous neighbouring levels, becomes highly sensitive to temperature when some virtual transitions fall in the domain of *thermal* infrared. It becomes a quantum probe for the near-field blackbody radiation.

Selective reflection spectroscopy is particularly convenient to test the Casimir-Polder (C-P) atom-surface interaction in the electrostatic van der Waals (vW) regime on an excited state, as it probes the spatial dependence of the energy of atomic transitions in a vicinity $\sim \lambda/2\pi$ (typically ~100 nm) from the surface. To analyze temperature effects, it is sufficient to heat-up the window of the vapour cell, while keeping constant the vapour density – usually controlled by the temperature of a reservoir-. In experiments at 672 nm to probe Cs($7D_{3/2}$) at a sapphire interface (after prior pumping to $6P_{1/2}$), we observe an increase in the vW attraction with the equilibrium temperature, in agreement (fig.1) with the prediction. The increased attraction mostly originates in the temperature-increased density of vacuum photons. The nearly resonant coupling, between the 7D-5F transition (~10.8 μm) and the thermal sapphire surface excitation (~12.2 μm, corresponding to 1200 K), brings also its own contribution, in spite of the limited temperature range of our experiments.

[1] J. Obrecht *et al.*, Phys. Rev. Lett., **98**, 0632201 (2007)

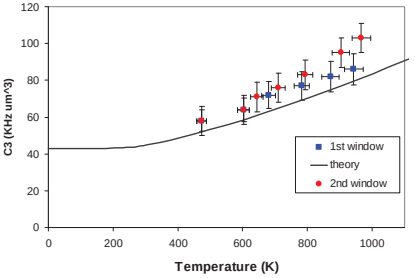

Fig. 1 *Temperature dependence of the vW coefficient of Cs(7D) at the interface with a sapphire window. The experiments were conducted on two windows, and on different spots of those windows, to eliminate possible spurious effects related to surface defects.*

Photodetachment microscopy to an excited state and accurate electron affinity measurements

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Implementation, on the photodetachment microscope, of a cesium sputtering ion source made it possible to study detachment of P^- and Se^- ions. The former was photodetached to the upper thresholds corresponding to the excitation of the $3s^2 3p^3\ ^2D^o$ doublet.

For both atomic species, photodetachment microscopy still produces free electron interferograms that can be analyzed so as to provide a measure of the photoelectron energy with interferometric accuracy. In the case of Phosphorus, the five measured thresholds make it possible to give an experimental value of the two fine-structure intervals of the ground ^3P of P^-, the $^2D_{5/2}-^2D_{3/2}$ interval of the neutral and *e.g.* the $^3P_2 \rightarrow ^2D_{3/2}$ (^3P lowest level to ^2D lower level) detachment energy. Determination of the electron affinity appears now limited by the present-state accuracy of the $3s^2 3p^3\ ^2D^o$ excited levels [1]. The obtained figure of $6\,021.79(8)\,cm^{-1}$, or 0.746607(9) eV, nevertheless offers a 1/6 reduction of the uncertainty of the electron affinity of Phosphorus, with respect to the previous measurement at $6\,022.35(51)\,cm^{-1}$ or 0.74668(6) eV [2].

In the case of Selenium, a preliminary analysis yields a new measurement of the electron affinity at $16\,297.28(2)\,cm^{-1}$, or 2.02060(1) eV, slightly less than the admitted value of $16\,297.8(2)\,cm^{-1}$ or 2.02067(2) eV [3]. A final value will be given at the conference.

References

[1] N. Svendenius, Physica Scripta **22** (1980) 240-287
[2] P. Andersson *et al.*, J. Phys. B: At. Mol. Opt. Phys. **40** (2007) 40974107
[3] N.B. Mansour *et al.*, Nucl. Instrum. Meth. B **32** (1988) 313-316

Correlated atom pairs creation in an optical lattice

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Spontaneous four wave mixing (SFWM) of matter waves is a promising source of non-classical atomic pairs states. The obtained states are similar to the twin photons states generated through parametric down-conversion, widely used in quantum optics. The atoms produced through SFWM are correlated in momentum [1] and exhibit sub-shot noise relative number fluctuations [2]. This source could be interesting for atomic interferometry under standard quantum limit, and also for demonstration of entanglement of the pairs in an EPR way. Since these experiments require recombinaison of modes, the ability to select a few output modes and the atom number in each mode are important.

In the presented experiment, the SFWM process takes place in a 1D optical lattice, whose dispersion relation enables to choose the output modes of this process : for an initial momentum k_0 of the atoms, pairs of atoms are spontaneously generated with the momenta k_1 and k_2 that fullfill the phase-matching conditions given by energy and momentum conservation (see figure 1.a), as predicted by [3] and observed in [4].

A metastable helium BEC is adiabatically loaded into a 1 recoil energy deep lattice, which is hold about 1 ms. This lattice is formed by two counterpropagating beams, whose relative detuning determines its velocity in the lab frame. We detected the atoms after a 300 ms time of flight and reconstruct their initial momentum distribution in 3D.

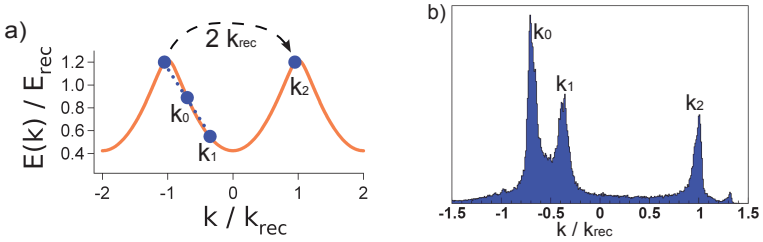

FIGURE 1 – a) Dispersion relation of the atoms in a 1D optical lattice, along the lattice axis : due to phase-matching conditions given by energy and momentum conservation, only pairs of momenta k1 and k2 can be generated from a BEC with momentum k0 in the lattice frame.
b) After the tof, we reconstruct the momentum distribution. The projection along the lattice axis shows 3 peaks, corresponding to the initial BEC (at $k_0 = -0.7k_{rec}$) and to the atoms scattered at k_1 ($-0.39k_{rec}$) and k_2 ($0.99k_{rec}$).

As shown on fig 1.b, this distribution exhibits 3 clouds, formed respectively by the atoms from the BEC, and the atoms scattered in k_1 and k_2. The measured values of k_1 and k_2 for different k_0 are in remarquable agreement with the expected momenta. Computing the second-order correlation function in momentum, we show that indeed the clouds in k_1 and k_2 are correlated. Thus, we demonstrated that atomic SFWM in a lattice is an efficient way of producing pairs of correlated atoms in selected output modes.

References

[1] A.Perrin et al., *PRL* **99**, 150405 (2007)

[2] J.-C.Jaskula et al., *PRL* **105**, 190402 (2010)

[3] K.M.Hilligsoe and K.Molmer, *PRA* **71**, 041602(R), (2005)

[4] G.K.Campbell et al., *PRL* **96**, 020406 (2006)

Determination of the fine structure constant and test of the quantum electrodynamics

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The fine structure constant α is a dimensionless constant which describes the strength of the electromagnetic interaction. It was introduced for the first time in 1916 by A. Sommerfeld as $\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}$ where e is the elementary charge, ϵ_0 the vacuum permittivity, $\hbar$ the reduced Planck constant and c the speed of the light.

Its determination is made in different domains of physics but the value of α is mainly deduced from the combination of quantum electrodynamics calculations with measurements of the electron anomaly done at Harvard University by Gabrielse's Group. So to test QED calculation, an independant determination of α is required.

In this poster, we will present our experiment carried out at the Kastler Brossel Laboratory in Paris. Basically, the experiment consists on a Doppler shift measurement of the recoil velocity ($v_r = \frac{\hbar k}{m}$) on an atom which absorbs a photon. Such a measurement yield to a highly precise determination of the ratio h/m between the Planck constant and the atomic mass. The fine structure constant is related to ($v_r = \frac{\hbar k}{m}$) through the relation:

$$\alpha^2 = \frac{2R_\infty}{c}\frac{A_r(Rb)}{A_r(e)}\frac{h}{m_{Rb}} \tag{1}$$

where R_∞ is the Rydberg constant, $A_r(e)$ and $A_r(Rb)$ are respectively the relative masses of electron and Rubidium atom known with relative uncertainties of few 10^{-10}.

The principle consists on measuring the velocity variation measurement of an ultra cold atomic sample using velocity-selective Raman transitions.The velocity variation is induced by a coherent acceleration using the technique of Bolch oscillations to transfer a large number of recoils to atoms.

Thanks to a new experimental set up, we succeed to improve our last measurement by a factor of about seven [1] and we measured α with a relative uncertainty of $6,6 \times 10^{-10}$.

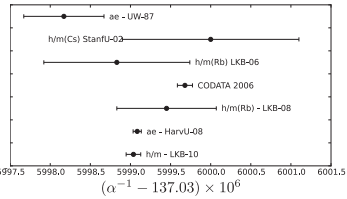

Figure 1: Different determinations of α

References

[1] R. Bouchendira *et al.*, Phys. Rev. Lett **106**, 080801 (2011).

Experimental evidence of a new geometric phase by atom interferometry

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An intriguing aspect of quantum mechanics is that the propagation of a particle can be modified by external electric or magnetic fields, even in the absence of classical forces. A famous example is the Aharonov-Bohm effect [1], predicted in 1959 and rapidly detected: in an electron interferometer, the fringe phase is modified by the vector potential even if the magnetic field vanishes at the place of the electron trajectories. This is the first member of the rich family of geometric phases in physics [2]. There are two effects closely related to the Aharonov-Bohm effect: the Aharanov-Casher effect [3], a geometric phase which appears when a magnetic dipole propagates in a electric field, and the He-McKellar-Wilkens (HMW) effect [4,5], a geometric phase which appears when an electric dipole moment propagates in a magnetic field $\boldsymbol{B}$. These two effects are connected by electric-magnetic duality. While the Aharanov-Casher has been detected by several different experiments, the HMW phase, predicted in 1993, has still never been observed. This phase is given by:

$$\phi_{EB} = -4\,\pi\varepsilon_0\,\alpha \oint \boldsymbol{E}\cdot\frac{(\boldsymbol{v}\times\boldsymbol{B})ds}{\hbar v}$$

where α is the electric polarisability and $\boldsymbol{v}$ the particle velocity.

We have built an experiment to detect the HMW phase, using our Mach-Zehnder atom interferometer [6]. This interferometer is based on a thermal lithium atomic beam and laser diffraction in the Bragg regime. It provides high quality signals and an excellent phase sensitivity of *~15* mrad/√Hz. The spatial separation between the two interferometer arms, ca. 100 μm, is sufficient to insert a stretched aluminum foil (a "septum") between these arms. We can thus build a double capacitor to apply opposite electric fields up to E ≈ ± *0.8* MV/m on the two arms while a coil produces an homogeneous magnetic field up to B ≈ ±*0.015* Tesla. The electric field is horizontal

while the magnetic field is vertical in order to maximize the HMW phase shift.

The HMW phase shift is expected to appear as a supplementary phase which is not the sum of the phase shift due to the electric field alone and of the one due to the magnetic field alone. We have collected a large date set and we have detected a phase shift which is a linear function of the EB product (see figure 1). However, some spurious phases occur, resulting from small defects of the setup which induces inhomogeneity of the electric and magnetic fields.

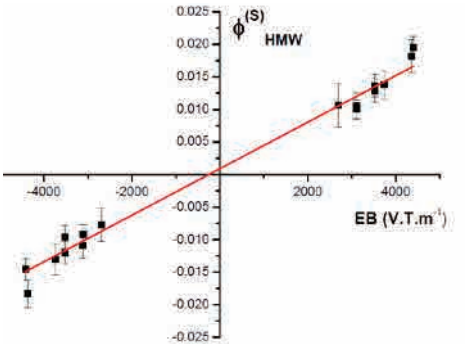

Figure 1: $\phi^{(S)}_{HMW} = (\phi_{E,B} - \phi_{E,-B})/2$ *is plotted as a function of EB. This combination cancels spurious phases and doubles the HMW phase shift.*

Acknowledgements: We want to thank M. Jacquey and H. Jelassi for their participation in early phases of this work, the lab technical staff for their help and CNRS INP, ANR (grant ANR-05-BLAN-0094) and Région Midi Pyrénées for financial support.

References

[1] Y. Aharonov and A. Bohm, Phys. Rev. **115**, 485 (1959).
[2] A. Shapere and F. Wilczek, Geometric phases in physics (World Scientific ed. 1989).
[3] Y. Aharonov and A. Casher, Phys. Rev. Lett. **53**, 319-321 (1984)
[4] X.-G. He and B.H.J. McKellar, Phys. Rev. A **47**, 3424 (1993).
[5] M. Wilkens, Phys. Rev. Lett. **72**, 5 (1994).
[6] A. Miffre, M. Jacquey, M. Büchner, G. Trénec and J. Vigué, Eur. Phys. J. D **33**, 99 (2005).

Orthogonality catastrophe in an ultra-cold Fermi gas

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In the past decade ultra-cold quantum gases have emerged as ideal candidates for designing controllable experiments to simulate effects in condensed matter physics. This success is likely to receive another boost due to the recent emergence of a fundamental new class of hybrid experimental systems. In these, two separate, ultracold atomic systems are combined in such a way that their coupling can be externally controlled and their states independently measured, therefore allowing detailed investigations into the theory of quantum interactions and decoherence. Existing examples of such systems are single spin impurities embedded in ultracold Fermi gases and the combination of single neutral atoms or single ions with Bose-Einstein condensates. They offer the possibility for controlled simulation of many different system-environment models synonymous with condensed matter physics and non-equilibrium statistical physics.

In our work we show that a fundamental and well known quantum many-body effect, the Anderson orthogonality catastrophe, can play an important role in ultra-cold, coupled systems. We consider a single two-level system embedded into a harmonically trapped, ultra-cold Fermi gas and demonstrate how the overlap between the many-body wavefunctions of the Fermi sea before and after a transition in the qubit vanishes as the number of particle increases. This signals the onset of the catastrophe and we show that it can be observed by looking at the dynamical features of the quantum bit alone. Our study identifies the orthogonality catastrophe as a significant effect even in mesoscopic systems and it represents a prime example of how properties of an out-of-equilibrium systems with many degrees of freedom can be inferred by looking at a single auxiliary particle.

We highlight the relationship between the Loschmidt echo and the retarded Green's function - typically used to formulate the dynamical theory of the catastrophe - and demonstrate that the orthogonality catastrophe can be triggered and characterized by local operations on the qubit. We demonstrate how the expected broadening of the spectral function can be observed using Ramsey interferometry on the qubit.

Narrow, long-term stable spectral holes in a Eu^{3+}:Y_2SiO_5 crystal for application to laser frequency stabilization

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Frequency stabilized lasers are of importance for a variety of scientific and industrial applications. Present-day laser stabilization techniques utilize various types of the frequency references e.g. atomic or molecular transitions, or high-finesse optical resonators. Another type of frequency reference is an ensemble of optical centers in a solid at cryogenic temperature. Appealing features of the latter are absence of Doppler broadening, large signal-to-noise ratio and low sensitivity to environmental disturbance. Even if only one suitable optical center species and a single transition is identified for frequency stabilization, this would suffice to provide frequency-stable radiation over essentially the complete optical range, since a frequency comb can be employed for transfer.

In this work we study some fundamental properties of narrow persistent spectral holes in a particular system, Europium ions doped in an yttrium silicate crystal. Our measurements are performed at very high resolution in the time domain, using, for the first time, to our knowledge, an ultra-stable and narrow-linewidth laser. We achieve long-lived holes with width as low as 6 kHz, the lowest relative linewidth reported so far for long-lived holes.

Hole burning spectroscopy (HBS) is well-established technique that allows to overcome limitations imposed by inhomogeneous broadening of absorption lines and to study narrow optical transitions in solids. The technique has also proposed and implemented for numerous applications, e.g. optical data storage and processing, quantum computing and laser stabilization [1]. The Eu^{3+}:Y_2SiO_5 system exhibits one of the narrowest optical resonances in a solid and hence was thoroughly studied during the past decades [2]. A homogeneous linewidth of 122 Hz for $^7F_0$ - $^5D_0$ transition at 580 nm was measured in the time domain using the photon echo technique. However, high-resolution measurements of HBS of Eu^{3+}:Y_2SiO_5 in the frequency domain have been more limited in scope, and have always been limited by the linewidth of the used laser sources. A solid-state laser source at 580 nm based on a cw-OPO was developed some time ago and used for HBS [3]. More recently, it has become possible to replace that source by a frequency-doubled diode laser. Indeed, by coincidence the 580 nm wavelength is very close to the $^1S_0$ - $^3P_0$ clock transition at atomic Yb. We used the high-performance clock laser for an Yb optical lattice clock with 1 Hz linewidth and 1 Hz/sec frequency drift [4] to characterize the Eu^{3+}:Y_2SiO_5 crystal as a potential HBS frequency reference.

An uncoated Y_2SiO_5 crystal doped with 0.1% Eu^{+3} was cooled in a pulse tube cryostat (T_{min} = 3 K). The laser and the cryostat, located in different laboratories, were connected by 80 m long single-mode optical fiber. The spectral holes were burned during ~10 s at ~ mW/cm^2 intensity and then the spectra were obtained by scanning the attenuated laser through the hole. Lock-in detection of the transmitted signal was used. Minimun delay between the burning and the reading was about 10 s. Important parameters of spectral holes (linewidth, lifetime, sensitivity to temperature variations) were evaluated.

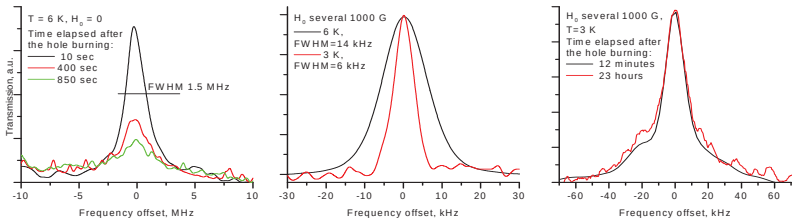

Fig. 1 Spectral holes in Eu^{3+}:Y_2SiO_5 (for clarity, peak heights are normalized to one and peak positions are shifted so as to overlap). Left: a continuously weakening spectral hole in zero magnetic field. Center: two different persistent spectral holes in strong field at 3 K and 6 K. Right: the same hole measured at two times after burning.

Our experiments revealed a considerable difference between the linewidths determined by photon echoes on a short timescale (≤ ms) and those directly measured in the frequency domain, seconds to hours after burning. Furthermore, parameters of the holes (linewidth, lifetime) strongly depend on the magnetic field H_0.A hole width of 1.5 MHz was measured at H_0 = 0 a few seconds after burning and further increased in time (2 kHz/s) , as illustrated in Fig. 1 on the left. The holes became indistinguishable on the inhomogeneous background after few tens of minutes. This observation indicates the existence of slow spectral diffusion in Eu^{3+}:Y_2SiO_5 occurring on a rather long time scale. The introduction of a magnetic field on the order of several 1000 G (we used a strong permanent magnet) resulted in two orders of magnitude sharper spectral structures (center and right plot). The width of the holes burned at 3 K was as low as 6 kHz, while burning at 6 K we found increased widths of 14 kHz (center plot). Furthermore, the spectral holes became much more stable in time. We found no significant degradation in the width of a burnt hole during one day at 3 K, as shown in Fig. 1 right.

In the next experiment we burned the spectral hole at 3 K and read the spectra of this hole while the temperature of the crystal was slowly increased to 4 K and then decreased back to 3 K. The results are summarized in Fig. 2. Alteration of the crystal's temperature results in shift of the hole's central frequency, broadening and deformation of its shape. However, all those effects are almost reversible: the blue line shows the spectrum obtained at 3 K after 45 minutes of temperature cycling. In Fig. 2 right, we show the measured temperature shift of the hole's central frequency (f_C, red) and linewidth (Δf, blue). The solid

lines show fits of the experimental data to power functions. Coupling to phonons results in $f_C \propto T^4$ and $\Delta f \propto T^7$ temperature dependence [2]. Our observations agree with the expected behavior for the frequency shift f_C . The value of 30 Hz/mK at 3 K is very small, and a crystal temperature stabilization to the 1 μK level plus a laser power stabilization are projected to be able to ensure an instability below the $1x10^{-16}$ level. The measured dependence for the linewidth Δf is of second-order in T. This discrepancy compared to theory and the observed slow spectral diffusion implies an extra mechanism for broadening. Possibly this may be due to the interaction of the Eu^{3+} ions with a distribution of low-lying energy states that are thermally activated at low temperatures [5], or to a (reversible) change in the magnetic field distribution within the crystal.

In conclusion, we obtained and characterized narrow and robust spectral structures in $Eu^{3+}:Y_2SiO_5$ crystal using the HBS technique. Holes with spectral widths of 6 kHz and 14 kHz were burned and measured at 3 K and 6 K respectively. To our knowledge these are the narrowest long-lived (hours) resonances observed in the frequency domain in a solid. The signal-to-noise ratio was not optimized so far but is already reasonable. We believe that optimization of the present setup (at 3 K and optimized magnetic field [6]) will allow to decrease the linewidth to a few kHz. We are now working on improvements, such as stabilization of the optical fiber, optimization of the magnet and of the optical setup. In the near future we also plan to measure precisely the frequency stability of the hole using a frequency comb.

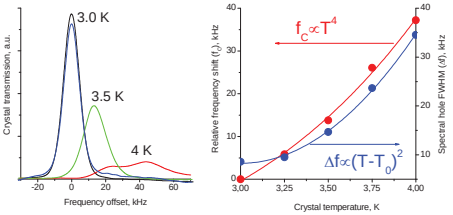

Fig.2 Reversible hole shift and broadening (left) and their temperature dependencies (right). Explanations: see text.

References

1. G. J. Pryde et al, Journal of Luminescence **98**, 309 (2002)
2. F. Könz et al., Phys. Rev. **B 68**, 085109 (2003)
3. T. Petelski et al., Opt. Lett. **26**, 1013 (2001)
4. S. Vogt et al. arxiv 1010.2685
5. M. J. Sellars et al., J. Opt. Soc. Am. **B 11**, 1468 (1994)
6. J.J. Longdell et al., Phys. Rev. B **74**, 195101 (2006)

CESIUM TWO-PHOTON TRANSITIONS AND TI:SAPPHIRE COMB LASER

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1. Absolute frequencies of cesium 6S-8S, 6S-6D hyperfine transitions

The frequency variation of cesium atom 8S transition, if happened to be observable, offers an evidence in clarifying either the variation of nuclear size [1] or fine structure constant α (by comparing with the other transition frequency of different atoms [2]), either of which supports the theories of unifying gravitation force with the other interaction [3]. Especially the transition frequency of cesium 8S state in this report is very near the 411-nm clock frequency (ytterbium ion $^2D_{5/2}$ state) [4]. By using a self-reference comb laser, we obtained the frequencies of cesium-stabilized diode lasers. They are ($6S_{1/2} \rightarrow 8S_{1/2}$): F=3→F'=3 364,507,238,394 (9) kHz ; F=4 →F'=4 364,503,080,327 (7) kHz , at 75^0C cold finger temperature and 90^0C cell wall temperature. The preliminary values are consistent with previous results from Max Planck Institute [5] after taking pressure shift into consideration. Frequency measurements on $6S_{1/2}$-$6D_{5/2,3/2}$ hyperfine transitions are now on going. By precisely determine the hyperfine constants, we would be able to deduce the magnetic octupole moment of ^{133}Cs nucleus for the supplement material of the controversial conclusions between atomic experiment and nucleus model [6].

2. Hand-size optical frequency references of Ti:sapphire comb laser

To generalize the applications of the aforementioned cesium-stabilized diode laser systems, we aggregated the cesium cell inside the laser cavity of an ECDL (extended cavity diode laser). We also sophisticatedly inspect the possible mutual influences between absorber and laser cavity such as mode-pulling, gas lensing and spectral symmetry, and so on. We did not find any obvious influence on laser cavity that was due to two-photon absorber, of which readers should refer reference 7 for the detailed inspection. Our hand-size-scheme lasers possess the following good features in terms of being trustable optical frequency references: 1. Absolute frequencies are known; 2. No linear Zeeman shift (6S→8S, 822 nm); 3. Only one natural abundant ^{137}Cs isotope; 4. Stable and robust [7]. In our laboratory, we are currently using the 822-nm and 884-nm cesium-stabilized lasers to be the frequency references of our mode-lock Ti:sapphire laser. We are grateful to the financial support from NSC 96-2112-M-001 -022-MY3, Taiwan.

References

1. T. H. Dinh, A. Duning, A. Dunning, V. A. Dzuba and V. V. Flambaum, Phys. Rev. A **79**, 054102 (2009)
2. V. A. Dzuba, V. V. Flambaum and J. K. Webb, , Phys. Rev. A **59**, 230 (1999).Coddington.
3. V. V. Flambaum, International J. Mod. Phys. A **22**, 4937 (2007)
4. P. Taylor, M. Roberts, S. V. Gateva-Kostova, R. B. M. Clarke, G. P. Barwood, W. R. C. Rowley and P. Gill, , Phys. Rev. A **56**, 2699 (1997).
5. P. Fendel, S. D. Bergeson, Th. Udem and T. W. Hansch, Opt. Lett. **32**, 701 (2007)
6. V. Gerginov, A. Derevianko and C. E. Tanner, Phys. Rev. Lett., **91**, 072501 (2003)
7. Y.-H. Chen, T. –W Liu, C. M. Wu, C. –C. Lee, C. K. Lee and W. –Y. Cheng, Opt. Lett. **36**, 76 (2011)

Comparing thermal and lasing atomic sources for precision inertial measurement

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In principle, a light bulb and laser that have the same photon flux will yield the same precision in many shot noise limited optical measurements. In practice, it is the classical properties of optical lasers, their brightness, coherence, and low phase and amplitude noise that enable the shot noise limit to be achieved at high flux. In atom optics, high-brightness lasing atomic sources based on Bose Einstein condensates (BECs) have been largely rejected by the precision measurement community due to low flux and due to the assumption that their comparatively high density will lead to dephasing that can limit precision. Here we present the first experimental comparison between a thermal atom inertial sensor [1-3] and an atom-laser based inertial sensor. We find that dephasing in an expanded BEC will not limit the precision of inertial measurements, and that large momentum transfer (LMT) beam-splitting [4-7] with lasing sources gives higher fringe visibility in our apparatus and potentially higher flux than a thermal source employing LMT beam-splitting. As is commonly the case in optical interferometry, we observe a significant increase in visibility when using a lasing atomic source instead of a thermal one in an identical setup. There are three possibilities available to increase the current sensitivity of cold atom inertial sensors, increase the flux, increase the momentum transferred by the beamsplitters, and/or squeeze the quantum noise. For a classical source, the signal to noise ratio of an inertial measurement increases as the square root of the flux and increases linearly with the momentum imparted by the beamsplitters. It is these two parameters that we focus on in this work. To date, cold atom inertial sensing has been dominated by thermal sources typically at a temperature on the order of 1 micro-Kelvin or less. Currently, the average flux of thermal sources is two orders of magnitude higher than the best BEC and atom lasers sources [8,9]. This corresponds to only a factor of 10 in signal to noise and may well be recovered using high visibility LMT beam-splitting and squeezing with a lasing atomic source. The question of which source, thermal or lasing, to use in these sensors is an important question and is the major topic of the work we present here. We address this question with a cold atom gravimeter.

1. M. Kasevich and S. Chu, *Measurement of the gravitational acceleration of an atom with a light-pulse atom interferometer*, Applied Physics B: Lasers and Optics **54**, 321, (1992).
2. A. Peters, K. Y. Chung and S. Chu, *High-precision gravity measurements using atom interferometry*, Metrologia, **38**, 25 (2001).
3. H. Müller , S. Chiow, S. Herrmann, S. Chu, K. Y. Chung, *Atom-interferometry tests of the isotropy of post-newtonian gravity*, Phys. Rev. Lett., **100**, 031101 (2008).
4. J. H Denschlag et. al, *A bose-einstein condensate in an optical lattice,* Journal of Physics B: Atomic, Molecular and Optical Physics, **35**, 3095, (2002).
5. H. Müller, S. Chiow, Q. Long, S. Herrmann, and S. Chu, *Atom interferometry with up to 24-photon-momentum-transfer beam splitters*, Phys. Rev. Lett. **100**, 180405, (2008).
6. H. Müller, S. -w Chiow, S. Herrmann and S. Chu, *Atom interferometers with scalable enclosed area,* Phys. Rev. Lett. **102**, 240403, (2009).
7. P. Cladé, S. Guellati-Khelifa, F. mc Nez, F. mc Biraben, *Large momentum beam splitter using bloch oscillations,* Phys. Rev. Lett, **102**, 240402, (2009).
8. K.M.R van~der Stam, E. D. van Ooijen, R. Meppelink, J. M. Vogels and P. van~der Straten, *Large atom number bose-einstein condensate of sodium,* Review of Scientific Instruments, **78**, 013102 (2007).
9. M. A. Kasevich, plenary talk, 41st winter colloquium on the Physics of Quantum Electronics, Snowbird, Utah, Jan 2011.

Quantum correlations in molecular dissociation to fermion pairs

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We calculate the growth of correlations in a Fermi gas formed by dissociation from a molecular condensate, following the rapid quench through a Feshbach resonance. The exact quantum many-body dynamics are numerically simulated by means of a Gaussian phase-space representation [1]. We quantify deviations of atom-atom pair correlations from Wick's factorization scheme, and show that atom-molecule and molecule-molecule correlations grow with time, in clear departures from pairing mean-field theories.

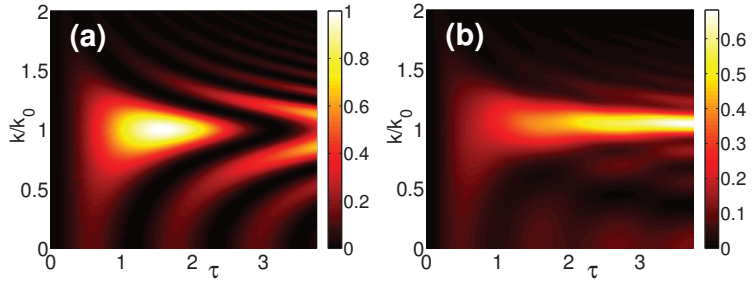

Figure 1: 1
The *exact* fourier-mode populations of the dissociated atom field. (a) Pauli-blocked regime with $N_0 = 10^4$ atoms; (b) Depleted pump regime with $N_0 = 100$ atoms.

The accuracy for higher-order correlations is demonstrated by comparison with a standard matrix representation for small systems of 10 molecules and 10 atomic modes. We then give results for systems of $10^2 - 10^4$ molecules and 10^3 atomic modes, illustrating the potential capability of the phase-space representation for first-principles quantum dynamical simulations for fermionic systems of realistic sizes in current experiments.

The Gaussian phase-space method provides an exact solution to quantum dynamics, as long as sampling error can be controlled. It can be viewed as providing the quantum corrections, through additional stochastic terms, to different mean-field approaches.

Extensions of this method to implement s-wave scattering interactions will allow us to study non-equilibrium dynamics in a broader class of fermionic model systems of current experimental interest, such as the Fermi Hubbard model and the BEC-BSC crossover problem.

References

[1] M. Ögren, K. Kheruntsyan and J. F. Corney, *First-principles quantum dynamics for fermions: Application to molecular dissociation*, Europhysics Letters **92**, 36003 (2010)

Immiscibility in a Quantum Degenerate Mixture of Rb and Cs

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Quantum degenerate mixtures of two or more atomic species open up many new research avenues, including the formation of ultracold heteronuclear molecules [1]. Such molecules possess permanent electric dipole moments which give rise to anisotropic, long range dipole-dipole interactions. These interactions differ greatly from the isotropic, short-range contact interaction commonly encountered in quantum degenerate atomic gases and consequently offer novel applications in quantum information processing [2] and simulation [3]. Recently, great successes have been achieved in the creation of high phase space density molecular gases by combining magneto-association on a Feshbach resonance with stimulated Raman adiabatic passage (STIRAP) to transfer the molecules to the ro-vibrational ground state [4–6]. The pre-requisite to this approach is the attainment of a high phase space density atomic mixture. Here we present the realisation of a quantum degenerate mixture of ^{87}Rb and ^{133}Cs following a novel approach in which the ^{133}Cs gas is sympathetically cooled. Initially $\sim 4\times10^8$ ^{87}Rb atoms and $\sim 2\times10^7$ ^{133}Cs atoms are collected in an ultra high vacuum magneto-optical trap (MOT) and transferred into a magnetic quadrupole trap. Forced RF evaporation is used to cool the ^{87}Rb atoms, while interspecies elastic collisions ensure that the ^{133}Cs atoms are cooled sympathetically. This cooling is ceased once the Majorana losses become significant. The mixture is then transferred into an optical dipole trap formed at the intersection of two crossed laser beams by simply ramping down the gradient of the quadrupole trap to ~ 30 Gcm^{-1}. The atoms are subsequently transferred to their absolute internal ground states. By reducing the depth of the dipole trap further evaporation and sympathetic cooling allow us to produce two species Bose-Einstein condensates containing $\sim 2\times10^4$ atoms of each species. Preliminary observations of the degenerate mixture reveal immiscible behavior via a dramatic spatial separation of the two species. Altering the initial composition of the mixture allows the production of pure single species ^{133}Cs condensates of up to 6×10^4 atoms.

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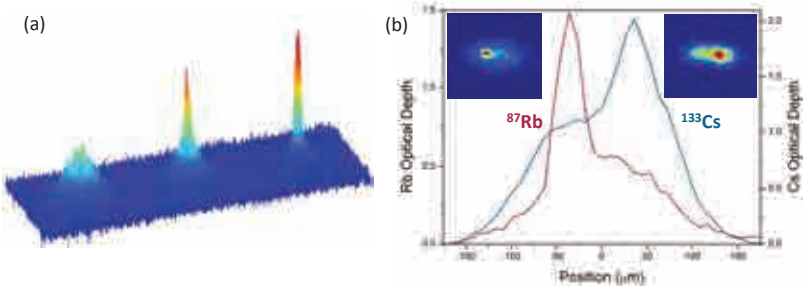

FIG. 1: (a) The observation of Bose-Einstein condensation in a gas of ^{133}Cs atoms as the system is cooled below the transition temperature. (b) The observation of phase separation in a quantum degenerate mixture of ^{87}Rb and ^{133}Cs.

[1] *Cold and ultracold molecules: science, technology and applications*, L.D. Carr, D. DeMille, R.V. Krems, J. Ye, New J. Phys. **11**(5), 055049 (2009).

[2] *Quantum Computation with Trapped Polar Molecules*, D. DeMille, Phys. Rev. Lett. **88**, 067901 (2002).

[3] *A toolbox for lattice-spin models with polar molecules*, A. Micheli, G.K. Brennen, P. Zoller, Nat. Phys. **2**, 341 (2006).

[4] *A High Phase-Space-Density Gas of Polar Molecules*, K.K. Ni, S. Ospelkaus, M.H.G. de Miranda, A. Pe'er, B. Neyenhuis, J.J. Zirbel, S. Kotochigova, P.S. Julienne, D.S. Jin, J. Ye, Science **322** (5899), 231 (2008).

[5] *Quantum Gas of Deeply Bound Ground State Molecules*, J.G. Danzl, E. Haller, M. Gustavsson, M.J. Mark, R. Hart, N. Bouloufa, O. Dulieu, H. Ritsch, H.C. Nägerl, Science **321** (5892), 1062 (2008).

[6] *An ultracold high-density sample of rovibronic ground-state molecules in an optical lattice*, J. Danzl, M.J. Mark, E. Haller, M. Gustavsson, R. Hart, J. Aldegunde, J.M. Hutson, H.C. Nägerl, Nature Phys. **6**, 265 (2010).

Compact Clock with Trapped Rubidium Atoms

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We investigate the use of magnetically trapped, cold clouds of ^{87}Rubidium atoms to realise an atomic clock in a compact set-up [1]. Our two trapped clock states $|F,m_f\rangle = |1,-1\rangle$ and $|2,1\rangle$ define a two-photons transition which is first-order insensitive to magnetic field fluctuations around a magic field of 3.23 Gauss. Compensation of the second order Zeeman shift and the meanfield shift minimizes the spatial inhomogeneity of the clock transition frequency [2]. Under this condition very long coherence times of 58 s +/- 12s have been measured and explained by a new mechanism of self rephasing of the pseudo spin associated to the two level system [3].
Compactness of the setup is achieved by use of a specially designed atom chip that allows to perform the whole clock cycle from cooling to interrogation in a $(5cm)^3$ Pyrex cell. The microwave signal used for interrogation is carried by a coplanar waveguide on the chip while an additional DC current in the central wire of this guide provides transverse confinement for the atoms. Special microwave synthesis chain and ultra-low noise current sources were designed to meet the metrology requirements [4].
We present measurements of the clock stability of $6.5\ 10^{-13}$ at 1 s , one order of magnitude better than the best commercial atomic clocks. This is achieved by interrogating 25 000 atoms cooled to 170 nK with a 12 s cycle time. We also present the design and characterization of a special atom source that could be used to both reduce the cycle time and increase the number of interrogated atoms, allowing a gain on the clock stability of a factor 3 while preserving the compactness of the setup. Furthermore, to improve our two-states detection scheme we investigate an adiabatic rapid passage from the $|1,-1\rangle$ state to the untrapped $|2,0\rangle$ state, giving yet a transfer efficiency of 98.9 %.

[1] P. Treultein et al., “Coherence in Microchips Traps”, Phys. Rev. Lett., 92, 203005 (2004).
[2] P. Rosenbusch, “Magnetically trapped atoms for compact atomic clocks”, Appl. Phys. B, 95, 227 (2009).
[3] C. Deutsch et al., “Spin Self-Rephasing and Very Long Coherence Times in a Trapped Atomic Ensemble”, Phys. Rev. Lett, 105, 020401 (2010).
[4] C. Lacroute et al., “Preliminary results of the Trapped Atom Clock on a Chip”, IEEE TUFFC, 57, 106 (2010).

The equation of state of degenerate quantum gases

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One of the greatest challenges in modern physics is the understanding of the behavior of ensembles of strongly interacting particles like neutron star matter or electrons in metals. A key point is the thermodynamics of those systems, which are fully characterized by the Equation of State (EoS).
We developed a general method to probe the pressure of locally homogeneous ultracold gases with high precision [1]. This allows stringent tests of many-body theories.
First, we focus on the finite-temperature EoS of the unpolarized unitary Fermi gas. We show that the low-temperature properties of the strongly interacting normal phase are well described by Fermi liquid theory and we localize the superfluid transition.
Second, we address the zero-temperature EoS of the spin-polarized system. Surprisingly, despite of strong interactions, the polarized phase behaves as a mixture of two ideal gases: a Fermi gas of majority atoms and a non-interacting gas of dressed quasi-particles, the Fermi polarons [2].
Finally, we measure the zero-temperature EoS of the homogeneous Bose gas [3]. For increasing repulsive interactions our data shows a clear departure from mean-field theory and provides a quantitative test of the many-body corrections first predicted in 1957 by Lee, Huang and Yang.

[1] S. Nascimbene, N. Navon, K. Jiang, F. Chevy, C. Salomon, Exploring the Thermodynamics of a Universal Fermi Gas. Nature **463**, 1057 (2010).

[2] N. Navon, S. Nascimbene, F. Chevy, C. Salomon, The Equation of State of a Low-Temperature Fermi Gas with Tunable Interactions. Science **328**,729 (2010).

[3] N. Navon, S. Piatecki, K. Günter, B. Rem, T. C. Nguyen, F. Chevy, W. Krauth and C. Salomon, Dynamics and Thermodynamics of the Low-Temperature Strongly Interacting Bose Gas. arXiv: 1103.4449v1

A powerful 671 nm laser source for trapping lithium

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The lithium atomic species is of great interest for cold atom experiments and the study of quantum degenerate gases. However, a powerful yet reliable light source to address the atomic D-line transitions at 671 nm was not available so far. We present an all solid-state single-mode laser source emitting 670 mW of narrowband light frequency-locked with respect to any of the D-lines [1].
The design is based on a diode-pumped Nd:YVO_4 single-mode ring laser, operating on the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition near 1342 nm. The infrared light is frequency doubled in an external enhancement cavity using periodically poled Potassium Titanyl Phosphate (ppKTP). Doubling efficiencies of up to 86% are obtained, resulting in a diffraction-limited beam.
We characterize the system in terms of linewidth, relative intensity noise and long-term stability. Implementation in our group's quantum gas experiment presented in [2] is ongoing. Finally, we discuss prospects for further output power scaling to the multi-Watt range.

[1] U. Eismann , F. Gerbier, C. Canalias, A. Zukauskas, G. Trénec, J. Vigué, F. Chevy and C. Salomon. An all-solid-state laser source at 671 nm for cold atom experiments with lithium. arXiv: 1103.5841v1

[2] S. Nascimbène, N. Navon, K. J. Jiang, L. Tarruell, M. Teichmann, J. McKeever, F. Chevy and C. Salomon. Collective Oscillations of an Imbalanced Fermi Gas: Axial Compression Modes and Polaron Effective Mass, Phys. Rev. Lett. **103**, 170402 (2009).

Gravitational-wave Detection With Matter-wave Interferometers Based On Standing Light Waves

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Abstract

We study the possibility of detecting gravitational-waves with matter-wave interferometers, where atom beams are split, deflected and recombined totally by standing light waves. A detection scheme was proposed. Considered current technologies and their future improvements, it is possible for our proposed detector to reach a high sensitivity at a much lower cost. It can be a good candidate scheme for building future gravitational-wave detectors.

Canceling the quadrupole shift of single ^{40}ca+ optical frequency standards

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One method to eliminate quadrupole shift in optical frequency measurements is averaging three pairs of the Zeeman transition frequencies, which acquires the intensities of the chosen components to be nearly the same. However, that is not the common case. The method used for adjusting the intensities of the components is changing the direction of propagation and the beam polarization of the probe laser. The lock of the laser can last for more than 10 hours after adjusting the system, while the quadrupole shift is cancelled in the experiments.

PACS numbers: 32.30.Jc, 06.30.Ft, 32.80.Qk, 37.10.Ty

For the optical transitions have large line quality factors Q [1], optical frequency standards are expected to replace the microwave standard in Cs as in the definition of the SI second. Recently, the best evaluation of the frequency inaccuracy reported is about 8.6×10^{-18} with Al^+ [2], which has surpassed Cs-fountain clocks observably. Other high accuracy optical standards based on a single ion have been developed, with an inaccuracy in the order of 10^{-15} in Sr^+ [3], and Ca^+ [4].

The $^{40}Ca^+$ has a simple energy level scheme which has good potential accuracy and low systematic shifts. The “clock” transition is the electric quadrupole $4s\ ^2S_{1/2} - 3d\ ^2D_{5/2}$ transition at 729 nm, which has a natural linewidth of 0.2 Hz [5].

Full details of the laser cooling, trapping detecting and probing systems used in this work are reported in previous work [6, 7, 8]. Briefly, loaded by ionizing at neutral Ca atom beam with electron bombardment, a single ion of $^{40}Ca^+$ is trapped and cooled in a miniature Paul ring trap. The excess micromotion amplitude of the ion is precisely detected by rf-photon correlation method [9]. According to recent experiments, an ion can stay in the trap for 15 days after perfect compensation.

The clock transition is observed by the electron-shelving method [9]. A pulse-light sequence is introduced to observe the clock transition spectrum in order to avoid ac Stark shift. The quantum jump spectrum is derived after certain circles.

Besides the ac Stark shift, there are some other effects that need to be eliminated, the biggest one of which is the quadrupole shift. Fortunately, this effect can be cancelled by averaging three pairs of the Zeeman components in the optical frequency measurement [3].

However, it is not easy locking to three pairs of the Zeeman components in the same time, since the relative intensities of the observed Zeeman components are usually different and sometimes some of the components are missing. Then the locking of the laser to the ion is not stable.

The relative intensities of the observed Zeeman components for the quadrupole transition are given in Tab.1. [10]

Tab.1. Relative intensity of the line [10]

m_J	m'_J	intensity
1/2 (-1/2)	-3/2 (3/2)	1/6 Q_2
-1/2 (1/2)	-5/2 (5/2)	5/6 Q_2
1/2 (-1/2)	-1/2 (1/2)	1/3 Q_1
-1/2 (1/2)	-3/2 (3/2)	2/3 Q_1
1/2 (-1/2)	1/2 (-1/2)	1/2 Q_0

where

$$Q_0 = 6sin^2\theta\cos^2\theta\cos^2\phi$$
$$Q_1 = \cos^2 2\theta\cos^2\phi + sin^2\phi\cos^2\theta \quad (1)$$
$$Q_2 = sin^2\theta(\cos^2\theta\cos^2\phi + sin^2\phi)$$

Here θ is the angle between the direction of propagation of the laser and the direction of *B* field, and Φ is the angle between the direction of *B* field and the direction of the laser beam polarization.

In order to get a perfect lock, the intensities of the Zeeman components which we choose are required to be equal. Then the angle θ and Φ is determined according to Tab.1.

In practice, the magnetic field is firstly compensated to be smaller than 10 nT, which means the ten components of the Zeeman profile in all are separated by less than 800Hz. Then the proper angle θ is achieved by changing the current of the three pairs of coils. Finally the polarization of the 729 laser beam is adjusted to get a best profile of the transitions.

After adjusting the system, the lock of the laser can last for more than 10 hours. The quadrupole shift is cancelled during the optical frequency measurements.

In the paper, based on the relative intensity formula, the intensities of the observed Zeeman components are adjusted by changing the direction of propagation and the beam polarization of the probe laser. Then the laser can be firmly locked to the ion by averaging frequencies of three pairs of the Zeeman components so that the quadrupole shift of the ion is cancelled.

References

[1] R. J. Rafac, B. C. Young, J.A. Beall, et al., Phys. Rev. Lett., 2000, **85**(12):2462
[2] C. W. Chou, D.B. Hume, J. C. J. Koelemeij, et al., Phys. Rev. Lett., 2010, **104**(7):070802
[3] H. S. Margolis, G. P. Barwood, G. Huang, et al., Science, 2004, **306**:1355
[4] M. Chwalla, J. Benhelm, K. Kim, et al., Phys. Rev. Lett., 2009, **102**(2):023002
[5] P. A. Barton, C. J. S. Donald, D. M. Lucas, et al., Phys. Rev. A, 2000, 62(3):032503
[6] Shu Hua-Lin, Guan Hua, Huang Xue-Ren, et al., Chin. Phys. Lett., 2005, **22**:1641
[7] Shu Han-Lin, Guo Bin, Guan Hua, et al., Chin. Phys. Lett., 2007, **24**:1217
[8] Liu Qu, Huang Yao, Cao Jian, et al., Chin. Phys. Lett., 2011, **28**:013201.
[9] D. J. Berkeland, J. D. Miller, J. C. Bergquist, et al J. Appl. Phys. , 1998, **83**(10):5025
[10] Paul Taylor, Ph.D thesis. University of Oxford, 1996, 96-98.

Airborne matter wave inertial sensing

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Inertial sensors relying on atom interferometry offer a breakthrough advance in a variety of applications, such as inertial navigation, gravimetry or ground and space based tests of fundamental physics. These instruments require a quiet environment to reach their performance and using them outside the laboratory remains a challenge. I will report the first operation of an airborne matter wave accelerometer set up aboard a 0-g plane and operating during the standard gravity (1-g) and microgravity (0-g) phases of the flight. I will explain how it is possible to detect inertial effects more than 300 times weaker than the typical acceleration fluctuations of the aircraft. I will also describe the 0-g operation of the matter wave sensor and discuss the extension of our experiments to airborne and spaceborne tests of the Universality of Free Fall with cold atoms.

Casimir interaction between a dielectric nanosphere and a metallic plane

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We study the Casimir interaction between a dielectric nanosphere and a metallic plane, using the multiple scattering theory. Exact results are obtained with the dielectric described by a Sellmeier model and the metal by a Drude model. Asymptotic forms are discussed for small spheres and large or small distances. The well-known Casimir-Polder formula is recovered at the limit of vanishingly small spheres, while an expression that behaves better at small distances is found for any finite value of the radius. The exact results are of particular interest for the study of quantum states of nanospheres in the vicinity of surfaces.

A NEW APPROACH TO DOPPLER-WIDTH THERMOMETRY

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Doppler-width thermometry is a relatively new method for determining the absolute temperature of a gaseous system at thermodynamic equilibrium. Soon after its first implementation [1], this method appeared to be very promising, with the advantage of being conceptually simple, applicable to any gas at any temperature, in whatever spectral region. It consists in retrieving the Doppler width from the highly-accurate observation of the absorption profile corresponding to a given atomic or molecular line. There is presently a strong interest in new primary thermometric methods, likely to be employed for highly-accurate determinations of the Boltzmann constant (k_B), in view of a possible new definition of the unit kelvin.

After a proof-of-principle experiment performed on CO_2 molecules at 2 μm [2], we moved to a second generation experiment with the ambitious goal of reaching the target accuracy of 10^{-6} [3]. Performed on water molecules at 1.38 μm, this new experiment is based upon a pair of offset-frequency-locked extended-cavity diode lasers. Such a technique ensures extreme levels of accuracy in controlling and measuring any variation of the laser frequency around a given absolute reference [4].

The accurate line shape modelling is an indispensable prerequisite for an improved determination of k_B. Besides the Doppler effect, other mechanisms can influence the line profile and they all contribute to the overall width. Very recently, speed dependence effects have been clearly evidenced in the near-IR spectrum of self-colliding $H_2{}^{18}O$ molecules, at pressures between 40 and 500 Pa [5]. This makes more challenging the retrieval of the Doppler width from high-quality absorption spectra, with the required accuracy. In fact, a proper treatment of speed-dependence of collisional parameters would require quantum mechanical scattering calculation that are still prohibitively complex for triatomic molecules.

Here, we discuss a new strategy for Doppler-width thermometry that results to be much more relaxed with respect to the line-shape problem. Instead of determining the Doppler width from the fit of a single spectrum, it is retrieved from a set of spectra, recorded at different gas pressures with exactly the same temperature, exploiting the relationship between the line-center absorbance and the integrated absorbance. Line fitting is performed by using the semiclassical model known as speed-dependent Voigt profile with hypergeometric dependence of the collisional parameters on the absorber speed [5]. This model ensures a refined interpolation of the absorption spectra, thus allowing one to determine the quantities of interest with a relative accuracy limited only by the noise level. First results will be presented and the implications for an improved determination of k_B will be discussed.

[1] C. Daussy *et al.*, Phys. Rev. Lett. **98**, 250801 (2007).
[2] G. Casa *et al.*, Phys. Rev. Lett. **100**, 200801 (2008).
[3] A. Castrillo *et al.*, C. R. Phys. **10**, 894-906 (2009).
[4] A. Castrillo *et al.*, Opt. Expr. **18**, 21851-21860 (2010).
[5] M.D. De Vizia *et al.*, Phys. Rev. A, in press (2011).

MEASURING THE ELECTRON EDM USING HFF$^+$

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Trapped molecular ions provide large effective electric fields and long electron spin coherence times for the search for an electron electric dipole moment (eEDM). In particular, the $^3\Delta_1$ state of HfF$^+$ has been proposed as a candidate for the eEDM search. To create HfF$^+$, we optically excite a supersonic beam of neutral HfF with two photons to an autoionizing state, and then perform laser-induced fluorescence to detect the state of the resultant HfF$^+$ ions. Additionally, because the spectroscopic energy levels of HfF$^+$ are not well known, we must perform broad survey spectroscopy in an ion sensitive manner. We report on our efforts to understand the autoionization process for efficient state preparation of HfF$^+$ ions, on our implementation of massively parallel direct frequency comb velocity modulation spectroscopy, and on our general progress towards an eEDM measurement. This work is funded by the US National Science Foundation and Marsico Endowed Chair.

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BEC without laser cooling: Loading a Conservative Trap from an Atomic Beam

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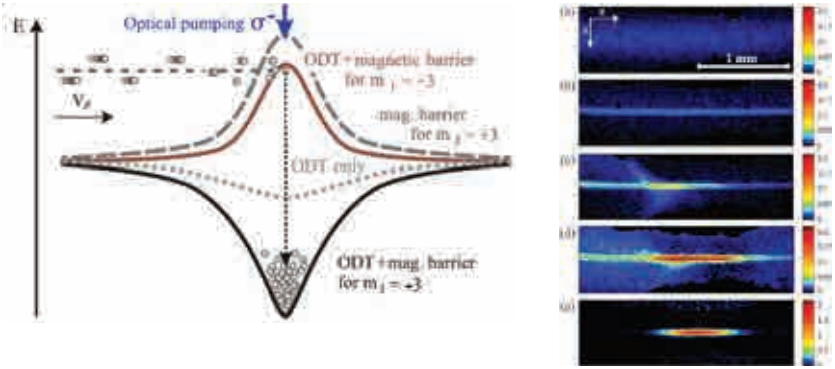

Left) Illustration of the dissipative loading scheme. A Superposition of an optical dipole trap (ODT) and a local magnetic field confines the atoms radially. Along the z direction (i.e. the symmetry axis of the guide) the hybrid potential can be either repulsive or attractive depending on the atom's magnetic sublevel. Arriving atoms are in the low-field seeking state. The magnetic field thus acts as a barrier. At the position of the barrier's maximum, the atoms are pumped to the high-field seeking absolute ground state while the directed kinetic energy is dissipated. Right) In-trap absorption images of the atoms accumulating in the hybrid trap.

We have realized a scheme for the fast accumulation and Bose-Einstein condensation of ^{52}Cr atoms in a conservative potential loaded from a magnetically guided atomic beam [1]. Without laser cooling on a cycling transition, one dissipative step involving optical pumping allows us to load atoms at a rate of $2 \cdot 10^7$ atoms per second into the trap. The trapped cloud reaches a collisionally dense regime within less than 100 ms and we produce a Bose-Einstein condensate by subsequent evaporative cooling in less than 5 seconds. This constitutes a new approach to quantum degeneracy where Bose-Einstein condensation can in principle be reached without the need of a closed cycling transition. The much less restictive requirement of a transition suited for pumping between low- and high-field-seeking states should make this scheme applicable to a wider range of atomic - and possibly also molecular - species that are otherwise hard to cool.

[1] Falkenau et al. PRL 106, 163002 (2011)

Photonic Band Gaps with Ordered Cold Atoms

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We report experiments about the photonic properties of cold atoms ordered in one-dimensional optical lattices.

First, we experimentally investigate the Bragg reflection of light at such 1D lattices. Cold rubidium atoms are trapped in a tunable laser standing wave and probed by a weak near-resonant beam under a small incident angle with the lattice. By a fine tuning of the lattice periodicity, we can reach the regime of multiple reflection due to the refractive index contrast between atomic layers, yielding an unprecedented high reflectance efficiency of 80%.

This result is explained by the occurrence of a *photonic band gap* in our system, in accordance with previous predictions [1,2]. We show indeed that despite the practical limitations of such cold-atoms systems (finite length, unperfect periodicity, losses), a strong reduction of the local density of states is induced by the periodic index modulation [3].

In a second experiment, we investigate the situation where the atoms, still trapped in the lattice, are pumped by an external laser so as to produce gain [4]. In pump-probe experiments, we observe a large Raman gain simultaneously in both transmitted and Bragg-reflected waves or large phase-conjugated reflection due to four-wave-mixing, depending on the pumping configuration. Moreover, without any probe beam, we observe a strong, conical light emission, whose angle is related to the lattice wavelength consistently with the Bragg condition. This is the analogue of a *distributed feedback laser*, only made of cold atoms.

[1] I. H. Deutsch, R. J. C. Spreeuw, S. L. Rolston and W. D. Phillips, Phys. Rev. A **52**, 1394 (1995).
[2] M. Artoni, G. La Rocca and F. Bassani, Phys. Rev. E **72**, 046604 (2005).
[3] A. Schilke, C. Zimmermann, P. W. Courteille and W. Guerin, arXiv: 1101.3469.
[4] W. Guerin, F. Michaud and R. Kaiser, Phys. Rev. Lett. **101**, 093002 (2008).

Ultracold Atoms near Carbon Nanotubes

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Hybrid quantum systems, which combine ultracold atoms with solid state devices, have attracted considerable attention in the last few years. We report on our experimental efforts towards the realization of such systems based on ultracold atoms near carbon nanotubes.

We present recent experimental data taken on the contact interaction between ultracold atoms and carbon nanotubes. Free standing single nanotubes, periodic structures, and carpets of nanotubes are vertically grown on the surface of an atom chip. Using a novel, cold atom scanning probe microscope, we are able to measure the surface topography of these nano-structures and to laterally resolve a single carbon nanotube. Spatially overlapping ultracold thermal clouds or Bose-Einstein condensates with such a single nanotube, we record atom losses and measure the inelastic scattering cross section between ultracold rubidium atoms and the carbon nanotube. From the scattering data we derive the velocity dependent scattering radius of the nanotube and gain information about the fundamental Casimir-Polder interaction. In addition, we describe a novel atom detector based on field ionization of ground state atoms near carbon nanotubes and subsequent ion counting.

Generation of W-states in an atomic spin-ensemble coupled to a high-finesse cavity

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A "W-state" of N two-level systems is a symmetric, coherent superposition of N states, where exactly one particle is excited and the other particles are in the ground state: $\frac{1}{\sqrt{N}}(|1000...\rangle + |0100...\rangle + |0010...\rangle + ...)$.
These states are a promising resource for quantum information processing and metrology applications.
Here, we report the scalable generation of W-states encoded in the hyperfine structure of neutral ^{87}Rb-atoms in a high-finesse fiber Fabry-Perot cavity. We verify the entanglement by measuring the Husimi-Q distribution along two orthogonal axes, which allows to reconstruct the density matrix of the prepared state.

We prepare ensembles of 3 to 20 atoms in the $|0\rangle = |F = 1, m_F = 1\rangle$ hyperfine ground state with an accuracy of ± 2 atoms and load them into the TEM 00 mode of a high-finesse cavity resonant to the $|F = 2\rangle \rightarrow |F' = 3\rangle$-transition. After the ensemble is prepared, a weak microwave pulse resonant to the $|F = 1, m_F = 1\rangle \rightarrow |1\rangle = |F = 2, m_F = 2\rangle$ transition is applied, which leads to the transfer of a single atom to $|1\rangle$ and therefore to the creation of a W-state with a probability $p = 0.2$. The success of the microwave pulse is monitored by measuring the transmission of the cavity and the sequence is repeated if it was not successful. We have previously shown that the use of the cavity allows us to detect an atom in $|1\rangle$ with high fidelity and negligible spontaneous emission, thus preventing the destruction of the entangled state.

We demonstrate the generation of W-states consisting of 3, 9 and 18 atoms. We use the cavity detection scheme and a maximum likelihood analysis to reconstruct the density matrix, yielding a preparation fidelity of approximately 30%.
The main limitation of this preparation scheme is due to hyperfine state detection errors, which could easily be reduced by using a cavity with lower losses and higher cooperativity . Using improved mirror coatings, such cavities have been recently produced in our group.

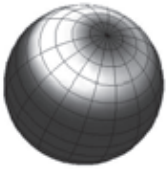

Figure 1: Reconstruction of the generated W-state on the Bloch-sphere for an ensemble of 9 atoms.

A Single Ion as the Mirror of an Optical Cavity

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By tightly focussing a probe field onto an ion trapped in front of a distant mirror, we observe a modulation of the vacuum Rabi constant and demonstrate the operation of a single-ion as an optical mirror.

The modification of the vacuum by boundaries and its effect on atomic properties, as for example the Lamb shift, is probably the most central topic in quantum mechanics and is widely investigated experimentally. In order to reach a strong light-matter coupling, most studies usually make use of very high finesse cavities. A more recent research area also investigates the direct coupling of tightly focussed light onto atoms in free space [1–4]. We recently undertook work with single trapped ions where we show the direct extinction of a laser field and electromagnetically induced transparency from a single atom [5]. The strong confinement offered by Paul traps, the readily available sideband cooling techniques and the ability to perform efficient and deterministic quantum gates [6], make single ions good candidates for free space quantum communication.

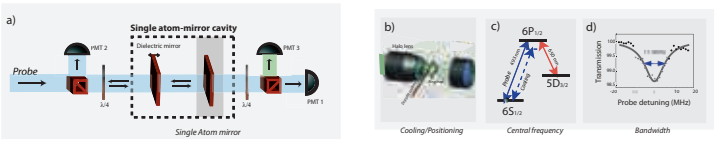

FIG. 1: a) Schematics of the single ion-mirror set-up. The probe field is transmitted through the dielectric mirror and reflected by the atom, thus forming a cavity. The intensity of the probe going through the cavity is measured on transmission by PMT1 and on reflection by PMT2. PMT3 is used for measuring the ion fluorescence. b),c),d) show the main properties of the single atom operated as a mirror : Positioning, central frequency of the probe field, and transmission/reflection bandwidth, respectively.

We present a first step towards merging the field of cavity QED with free space coupling, using an ion trap apparatus. We set-up a novel atom-mirror system where a weak probe field is tightly focussed onto a single trapped ion at the focus of a lens-mirror set-up. This allows strong free space atom-light interaction. The atomic properties are then modified by a single mirror in a regime where the probe field intensity is already significantly altered by the atom alone. We show that the mirror-induced change in the vacuum mode density around the atom can modulate the atom's coherent coupling to the probe and the total spontaneous decay, so that the atom behaves as the mirror of a cavity. Such a set-up furthermore enables us to demonstrate the first order coherence between the back-scattered field and the driving laser. Finally, we show that the contrast of the transmitted signal does not depend on the lens aberrations and transverse atomic motion, allowing us to observe almost full suppression of the coupling of the probe light to the ion.

In the set-up of Fig. 1 we consider the atom as an optical reflector. Figure b), c) and d) show the positioning, central optical frequency for reflection, and transmission bandwidth of the atom mirror respectively. We use a single $^{138}Ba^{+}$ ion in a ring Paul trap [7]. For strong extinction of a laser field by the ion in free space, we use a weak probe beam resonant with $S_{1/2}$ to $P_{1/2}$ transition, and spatially filtered using a single-mode fiber to guarantee a Gaussian spatial profile at the input of the high-numerical aperture lens. As shown Fig. 1 b), The probe beam is overlapped with the dipole emission pattern of the ion using a custom-designed objective with a numerical aperture (NA) of 0.4, corresponding to an $\epsilon = 4\,\%$ fraction of the full solid angle.

The operation of our ion-mirror system is shown in Fig. 2-a) using a 99.7% reflective mirror. As the mirror position is scanned, we observed sinusoidal oscillations of the power detected by PMT1. These results reveal that the elastic back-scattered field is indeed interfering with the transmitted probe, and that the ion is well within the Lamb-Dicke regime. Fig. 2-b) shows the fluorescence rate measured on PMT3 in the same experimental conditions but with the probe field blocked. The modulation of the fluorescence rate here is due to a self-interference of the single photons emitted by the atom [8]. We then perform another experiment where we replace the high reflectivity mirror by a 35/65% mirror in order to measure the ion's influence on the back-reflected field of the cavity. The results are shown Fig. 2 d) and c), where we display the reflected and transmitted powers respectively. With the transmitted power at

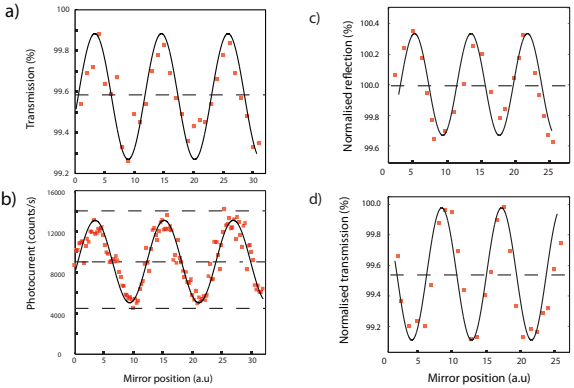

FIG. 2: Experimental results : a) shows the transmission of the probe through the single atom-mirror system as a function of the mirror position. Here the dielectric mirror is 99.7 % reflective. b) is the single photon interference fringe measured on PMT3. c) shows a plot of the normalized intensity of the probe after being reflected off the cavity, with a 35/65% reflective/transmissive dielectric mirror. d) is the corresponding normalized transmission of the probe as a function of the mirror position. In a) and d), the dashed line corresponds to the transmission of the probe when the mirror is slightly misaligned. In c) it corresponds to its reflection when the ion is removed.

its minimum, the reflected power is maximal, as is predicted for a Fabry-Pérot cavity.

Although treating the ion as a reflector gives an intuitive understanding of the effects, the modulation of the transmission of the probe through such a single atom-mirror should be interpreted as QED-induced changes of the emission and coupling rates. Theoretically, when the atom is at a node, and with a high numerical aperture lens, the spontaneous decay tends to zero [9]. The transmission would be possible only for a very narrow probe frequency range, which together with the change of the atom-light light coupling, effectively means a narrow transmission profile, so that the system will behave as a Fabry Pérot cavity. In our experiment, we observed a change of the vacuum Rabi frequency $|g_{k_0}|^2$ of the atom in the probe mode, due to the modification of the vacuum field density by the mirror. Deviations from the sinusoidal shape would be visible for a lens covering a solid angle of more than 10%.

In conclusion, we showed the operation of a single atom as an optical mirror in a Fabry-Perot like cavity. Our investigations are performed in a regime where a significant fraction of the power of a probe field can be affected by the atom. This regime allows us to realize an experiment where both the properties of an atom as a reflector, and the modification of the atom-light coupling constant can play a role. Although a simple cavity interpretation lend itself naturally to a description of our experiment, a more general QED interpretation should be preferred for an unambiguous discrimination of the involved mechanisms in more general scenarios. We showed that here, in the on resonance, and Born-Markov approximations, both interpretation are equivalent.

[1] M. K. Tey et al., Nat Phys **4**, 924 (2008).
[2] G. Wrigge et al., Nat Phys **4**, 60 (2008).
[3] A. N. Vamivakas et al., Nano Letters **7**, 2892 (2007).
[4] A. A. Abdumalikov et al., Phys. Rev. Lett. **104**, 193601 (2010).
[5] M. Stobińska, G. Alber, and G. Leuchs, EPL **86**, 14007 (2009).
[6] H. Häffner, C. Roos, and R. Blatt, Physics Reports **469**, 155 (2008).
[7] L. Slodička, G. Hétet, S. Gerber, M. Hennrich, and R. Blatt, Phys. Rev. Lett. **105**, 153604 (2010).
[8] J. Eschner, C. Raab, F. Schmidt-Kaler, and R. Blatt, Nature **413**, 495 (2001).
[9] G. Hétet, L. Slodička, A. Glätzle, M. Hennrich, and R. Blatt, Phys. Rev. A **82**, 063812 (2010).

Quantum degenerate mixtures of alkali and alkaline-earth-like atoms

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Ultracold atomic gas mixtures consisting of different elements have many new interesting possibilities such as dipolar physics with polar molecules[1], study of heteronuclear Efimov resonances[2] and quantum simulation of novel quantum phases. To reach these goals, it is desirable to achieve quantum degenerate regime simultaneously in a mixed gas.

We focus on a pair of alkali (Li) and alkaline-earth-like (Yb) atoms, which has unique features different from other bi-alkali systems. Firstly, polar molecules consist of alkali and alkaline-earth-like atoms have not only electric dipole moment but also electron spin degrees of freedom in the electronic ground state ($^2\Sigma_{1/2}$). So LiYb molecules may enable us to implement quantum simulation of lattice-spin models[3]. In addition, the large mass ratio of Yb to Li (~29) enables us to study Efimov trimers LiYbYb, which have a much smaller discrete scaling factor ($e^{\pi/s_0} \sim 4$) than those composed of identical bosons ($e^{\pi/s_0} \sim 22.7$). Furthermore, the mixture with large mass difference loaded into an optical lattice is a good tool for quantum simulation of an impurity system.

With these motivations, we have successfully produced quantum degenerate Bose-Fermi mixture of ^{6}Li-^{174}Yb and Fermi-Fermi mixture of ^{6}Li-^{173}Yb. We have already succeeded in simultaneous MOT of Li and Yb[4]. Then we transferred the atoms from the MOT into an optical dipole trap and cooled them to quantum degenerate regime by sympathetic evaporative cooling. Figure.1 shows the result for Bose-Fermi mixture. For

^{6}Li, the total atomic number N_{Li} is 2.5×10^{4} and temperature T_{Li} is 290±30 nK, corresponding to 0.08±0.01 T_F. For ^{174}Yb, T_{Yb} is 280±20 nK, below the BEC transition temperature T_c = 510 nK. The number of atoms in the condensate is 1.5×10^{4}. In the case of Fermi-Fermi mixture, T_{Li} = 220±40 nK and T/T_F = 0.07±0.02 for ^{6}Li and T_{Yb} = 170±10 nK and T/T_F = 0.52± 0.12 for ^{173}Yb. The equality of the temperatures between the Li and Yb atoms within the experimental error indicates that the Yb cloud provides good thermometry for the very cold Fermi gas of ^{6}Li. The quantum degenerate mixtures of Li and Yb, as realized here, can be the basis for creation of ultracold molecules with electron spin degrees of freedom, studies of novel Efimov trimers, and impurity probes of superfluid systems.

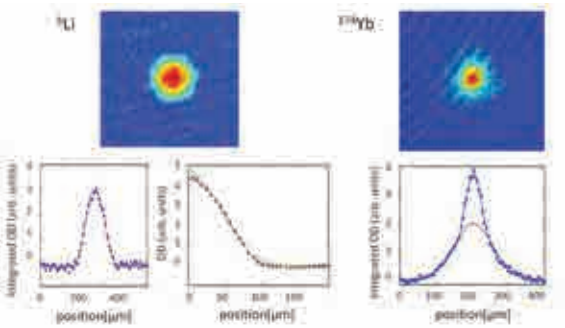

Fig.1 TOF absorption images of Bose-Fermi mixture of ^{6}Li and ^{174}Yb. For ^{6}Li, lower left is the integrated optical density and lower right is the azimuthally averaged distribution. For ^{174}Yb, lower is the integrated OD. Expansion time is 1 ms for ^{6}Li and 16 ms for ^{174}Yb.

References

[1] K. –K. Ni *et al.* , Science **322**, 231 (2008)
[2] G. Barontini *et al.* , Phys. Rev. Lett. **103**, 043201 (2009)
[3] A. Micheli *et al.* , Nature Phys. **2**, 341 (2006)
[4] M. Okano *et al.* , Appl. Phys. B **98**, 691 (2010)

Attosecond control of electrons emitted from a nanoscale metal tip – a new low-power sensor for the carrier-envelope phase

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Before the invention of the frequency comb, possibilities were discussed on how to control the carrier-envelope phase of short laser pulses. One idea proposed was to employ the photoemission current of electrons in the so-called optical tunneling regime [1]. In this regime, the electron emission follows quasi-statically the driving laser electric field. Because of the highly non-linear nature of the tunnel process, one would expect a varying tunnel current with varying C-E phase.

In the last decade it has been shown with great success that not only the emission process itself can lead to a strong C-E phase dependent emission current, but that the laser electric field, once the electron "is born" classically, acts on it, in a highly C-E phase dependent manner. In the so-called strong-field regime the electron dynamics is mainly governed by the external laser electric field. For example, the laser field can drive the electron back into the parent atom or ion. When it recombines it generates high harmonic radiation [2]. The electron may also scatter elastically off the parent matter. In that case, the electron can gain more energy in the laser field, which is evidenced by a plateau region in electron spectra.

We have recently observed strong-field effects in photoemission of electrons from sharp tungsten tips [3]. Moreover, for the first time from a solid, we have observed the tell-tale plateau region, clearly evidencing elastic recollision of the liberated electron with the tip. With C-E phase stabilized laser oscillator pulses we have observed pronounced carrier-envelope phase effects in this region [4]. At high energies the current can be almost fully switched with the C-E phase. We also observe a strong C-E phase dependence of the visibility of the peak structure in the plateau (see figure). Absence or presence of spectral interference indicate that plateau electrons primarily originate from either one or two emission windows with a duration of about 450 attoseconds within the pulse. This notion is well-supported by theory models (results of a semiclassical calculation are shown in insets of the figure). Plateau electrons can be fully controlled by the C-E phase with attosecond precision and might serve as a highly sensitive low-power sensor for the C-E phase. We envision a sensor device of the size of a die, working with as little as 100pJ pulse energy (corresponding to 10mW of average power at ~100 MHz repetition rate).

A fraction of the poster will be devoted to our recent demonstration of microwave guiding of low energy (1…10eV) electrons on a planar substrate [5], reminiscent in design of novel planar five-wire structures of ion trappers. With advanced electron emitters we foresee ground-state guiding of electrons in this guide, representing a new quantum device with guided electrons. We are currently in the process of building an integrated beam splitter structure.

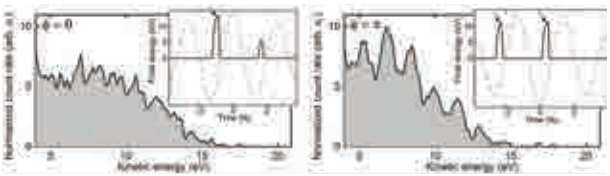

Fig. 1 Normalized count rate vs kinetic energy in the plateau part for two C-E phase angles ϕ. Insets: Final energy vs time from the semiclassical Simple Man's Model (dashed line: laser field). Depending on the phase, one or two classical trajectories (see arrows) predominantly contribute to a high final energy, causing the absence (left) or presence (right) of quantum mechanical interference in the energy domain.

[1] L. Xu, Ch. Spielmann, A. Poppe, T. Brabec, F. Krausz, T. W. Hänsch, Route to phase control of ultrashort light pulses, Opt. Lett. **21**, 2008 (1996)
[2] See contribution by A. L'Huillier et al. to this conference
[3] M. Schenk, M. Krüger, P. Hommelhoff, Phys. Rev. Lett. **105**, 257601 (2010).
[4] M. Krüger, M. Schenk, P. Hommelhoff, *submitted for publication* (Feb. 2011).
[5] J. Hoffrogge, R. Fröhlich, M. A. Kasevich, P. Hommelhoff, scheduled to appear in May 6, 2011 issue of PRL

Self-estimate the uncertainty of $^{40}Ca^{+}$ Optical frequency standard

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Recently progress on the evaluation of systematic frequency shifts are reported in the development of the single trapped $^{40}Ca^{+}$ optical frequency standard .The systematic uncertainty of the 4s $^{2}S_{1/2}$–3d $^{2}D_{5/2}$ clock resonance is around 1.0×10^{-15}. An Allan deviation of less than 6.0×10^{-15}at 2000 s is obtained using a femtosecond laser frequency comb referenced on an active H-Maser.

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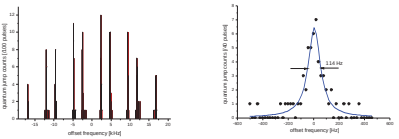
A single Ca^{+} ion has been proposed to be one of the candidates of the future frequency standards [1,2, 3,]. Optical frequency standard based on Ca^{+} is being developed by the Quantum Optics and Spectroscopy Group in Innsbruck University Austria, the National Institute of Information and Communications in Japan (NICT) and University of Provence in France. The uncertainty of the absolute frequency measurement was evaluated to be 2.4×10^{-15} with referenced to the transportable Cs fountain clock of LNE-SYRTE by Innsbruck Group was reported[4] and a measurement with a 10^{-14} uncertainty level was reported with the Paul trap and Doppler cooling by NICT [5].

In this paper, we report a detailed study of the systematic uncertainty of the 4s $^{2}S_{1/2}$–3d $^{2}D_{5/2}$ clock transition frequency based on the single $^{40}Ca^{+}$ ion with 1.0×10^{-15}. This result shows that the $^{40}Ca^{+}$ optical clock can reach an accuracy level competitive with Cs-fountains, while the potential stability for the system is far greater. Meanwhile, an Allan deviation of less than 6.0×10^{-15}at 2000 s is obtained using a femtosecond laser frequency comb referenced on an active H-Maser.

Full details of the laser cooling, trapping system, detecting and probing systems used in this work are reported in previous work [6, 7]. Briefly, a single $^{40}Ca^{+}$ ion is trapped and cooled in a miniature Paul ring trap. The distance between two endcaps z_0=1.4 mm ,the radius of ring electrode r_0=0.8 mm. Two other electrodes perpendicular with each other are set in the ring plane to compensate the ion's excess micromotion. A trapping rf of 450 V_{op} is applied to the ring at a frequency of 9.8 MHz. Based on measurements of the ion motion sideband spectra, the secular frequencies of the trap were to be ω_x ; ω_y ; $700kHz$ and ω_z ; $1.5MHz$, respectively.

Typically, approximately 10 μW of the 397 nm cooling laser power are focused on the single ion with a spot size of about 40 μm and a typical linewidth of 10 MHz, for the 866 nm repumping laser, 600 μW of power with 60 μm of size and less than 10 MHz of linewidth; for the 854 nm quenching laser, 150 μW of power with 60 μm of size and 10 MHz of linewidth; and for the 729 nm clock laser, 40 nW of power with 100 μm of size, respectively. Both the 397nm and 866nm lasers are stabilized to the 729 nm laser using two different transfer cavities. The "clock" laser at 729 nm is a commercial Ti: sapphire laser, which is locked to a temperature-controlled high-finesse Fabry-Perot cavity (Zerodur material) using PDH method [8]. A linewidth of about 10 Hz was measured from the heterodyne beatnote with a home-made diode laser stabilized to another high-finesse ULE cavity. The 729 nm laser is locked to the clock transition, which is observed by the electron-shelving method [9], by the "4 points locking scheme" [10, 11] using a double passed AOM with another function generator for inducing a feedback offset frequency to measure the stability or do the measurements of systematic shifts [12].

The 729 nm laser is locked to six chosen Zeeman transition to do the measurements: ΔM_J=0, ΔM_J=±1, ΔM_J=±2 one after another to null the electric quadrupole shift, i.e., the laser is locked to in inner most components for the first 6 seconds, after that the laser is locked to the second inner most components for 6 seconds, and then the inner pair of ΔM_J=±2 components. The offset frequency between the probe laser and the ion "clock" transition line center is measured by a double passed AOM, which shifts the laser frequency to match the transition. The required AOM frequencies are updated every 40 cycles of pulses, which cost about 1.5 s.



a) b)

FIG. 1. a) Ten components of the Zeeman profile $4s\ ^2S_{1/2}$-$3d\ ^2D_{5/2}$ clock transition with the whole separation of 34 kHz in the magnetic field of about 0.43 μT; b) One of the M_J =0 component which was achieved with the 729 nm scanning step of 6 Hz, the fitted curve is the Lorentzian fit and yields a linewidth of 114(11) Hz.

There are a variety of potential sources of systematic shift which might be associated with the quadrupole 729 nm $4s\ ^2S_{1/2}$–$3d\ ^2D_{5/2}$ "clock" transition in a laser cooled trapped $^{40}Ca^+$ ion as follows.

TABLE I. The systematic frequency shifts and their associate errors in Hz and the uncertainty in units of 10^{-15}.

Effect	Shift (Hz)	Error (Hz)	Fractional error (10^{-15})
2nd order Doppler shift due to thermal motion	-0.006	0.003	0.01
2nd order Doppler shift due to micromotion	-0.02	0.02	0.05
Stark shift due to thermal motion	0	<0.001	<0.001
Stark shift due to micromotion	0	<0.001	<0.001
Ac Stark shift due to 397 nm	0	<0.001	<0.001
Ac Stark shift due to 866 nm	0	<0.001	<0.001
ac Stark shift due to 854 nm	0	<0.001	<0.001
ac Stark shift due to 729 nm	0.23	0.36	0.87
Blackbody radiation shift	0.35	0.02	0.05
Servo error and shift	0.11	0.03	0.07
2nd order Zeeman shift	0	<0.001	<0.001
Electric quadrupole shift	0	0.23	0.56
Total shift	0.47	0.41	1.0

From the systematic shift errors considered above, it appears that detail experiments with $^{40}Ca^+$ optical frequency could lead to an accuracy of better than 10^{-16}. In that the electric quadrupole shift and the ac Stark shift with 729 nm laser are dominating the uncertainty budget, and the uncertainty of the electric quadrupole shift is so large, mainly due to the large statistic error. So our probe laser needs to be improved further, especially on the nonlinear drift and the linewidth, we also need to set up another $^{40}Ca^+$ optical clock to do the comparison of the two traps to achieve a better Allan deviation. Finally We should use the Cs fountain as reference clock to calibrate the H-maser for the measurement of the absolute frequency of the $4s\ ^2S_{1/2}$–$3d\ ^2D_{5/2}$ transition of single calcium ion.

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[1]P. Barton *et al*., Phys. Rev. A **62**, 032503 (2000).
[2] C. Champenois *et al*., Phys. Lett. A **331**, 298 (2004).
[3] M. Kajita *et al*., Phys. Rev. A **72**, 043404 (2005).
[4] M. Chwalla *et al*., Phys. Rev. Lett. **102**,023002 (2009).
[5] K. Matsubara *et al*., Appl. Phys. Express **1,** 067011 (2008).
[6] H. L. Shu *et al*., Chin. Phys. Lett. **22,** 1641 (2005).
[7] H. L. Shu *et al*., Chin. Phys. Lett. **24,** 1217 (2007).
[8] H. Guan *et al*., Opt. Commum. **284,** 217 (2011).
[9] H. Dehmelt, IEEE Trans. Instrum. Meas. **31,** 83 (1982).
[10] J. E. Bernard *et al* Phys. Rev. Lett. **82,** 3228(1999).
[11] G.. Barwood *et al* 2001 IEEE Trans. Instrum. Meas. **50** ,543(2001).
[12] Q. Liu *et al*., Chin. Phys. Lett. **28** ,013201 (2011).

Optical direct comparison of two ^{87}Sr lattice clocks using a fiber-link of 60km

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The community of time and frequency standards has begun a serious discussion toward the redefinition of the second. In the discussion, one important issue to be resolved is how to transfer the highly stabilized optical signal to remote sites. Developing the transfer technique will also enable the accurate comparison of two physically separated clocks. The confirmation of the identical frequency reduces the possibility that residual common systematic shift is hidden in in-house frequency comparisons.

In case of the distance shorter than 100km, the transfer using optical fiber network is the most promising [1]. While the fiber suffers the change of its optical length due to mechanical vibrations or temperature fluctuations, the amount of the phase shift imposed on the transmission path can be detected at the local site by obtaining a heterodyne beat between the local signal and transmitted signal partly reflected back from the remote site. Since the ^{87}Sr lattice clock in National Institute of Information and Communications Technology (NICT) has lately started its operation and a dark fiber link between NICT and Univ. of Tokyo (UT) is available, we for the first time performed the remote comparison of two lattice clocks based on the common atomic transition.

The ^{87}Sr lattice clock developed in NICT employs a conventional 1D configuration. The observed spectral width of the clock transition is 12Hz (FWHM). The short term stability of the clock laser is 5×10^{-15}, limited by the insufficient reduction of the sensitivity of the cavity length to the seismic vibration. According to the evaluation of the systematic shifts, the uncertainty originated from the atomic system is 5.2×10^{-16} in total, where AC stark shift, 2nd order Zeeman shift, black body radiation shift, and density shift contribute in same level.

Schematic diagram of the direct comparison is shown in Fig. 1. The optical frequency of the clock laser at NICT is linked to the communication band by stabilizing the frequency-doubled CW laser of 1538nm to one tooth of Ti:Sa comb,

which is locked to the clock laser at 698nm. Part of the 1538nm CW laser at NICT is transferred to the UT using the fiber-noise compensation system described above. The received signal at UT is amplified by EDFA, frequency doubled, and then the nearest comb component of the Ti:S frequency comb at UT is locked to the doubled 769nm. The differential frequency of two lattice clocks is indicated at UT from the beat frequency obtained between the clock laser and the frequency comb. The frequency difference clearly showed the differential gravity shift due to the 55m difference of the elevations. Correcting systematic shifts, the residual difference of the intrinsic atomic resonance was in sub-Hz level. In addition, the overall relative stability turned out to be 5×10^{-15} and 3×10^{-16} at 1s and 2000s, respectively.

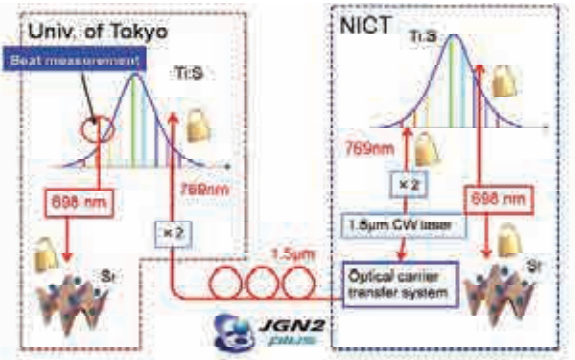

Fig.1 Schematic diagram of the fiber link between NICT and University of Tokyo

[1] P. A. Williams, W. C. Swann, and N. R. Newbury, “High-stability transfer of an optical frequency over long fiber-optic links” J. Opt. Soc. Am. B **25** 1284 (2008).

Wavelength-Scale Imaging of Trapped Ions for Quantum Information Processing

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Laser cooled trapped atomic ions are a nearly ideal system to test fundamental atomic and quantum physics at very high precision. All degrees of freedom of trapped ions can be controlled at the quantum level. Thus, they have been used for studies in many fields of modern physics e.g. quantum computing (QC) and quantum information processing (QIP). A clear roadmap exists for achieving large scale QIP [1, 2] including the use of phase Fresnel lens (PFL) arrays as a scalable optical interconnect [3].

In the work presented here, we employed an ion trap formed by two tungsten needles with a tip diameter of about 10 µm and a spacing of approximately 300 µm. $^{174}Yb^{+}$ was loaded into the trap by isotope selective photo-ionization from an atomic beam. The ions were laser cooled with an all diode laser system.

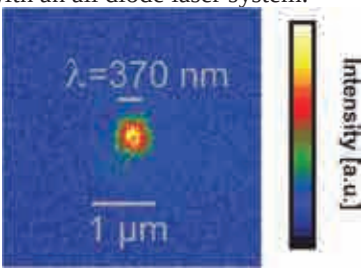

Fig. 1. Image of a single ion obtained with a PFL integrated in UHV of a needle ion trap.

The PFL had a focal length of f = 3 mm = and a NA = 0.64, which corresponds to 12 % of the total solid angle. The RF needles were positioned with nanopositioning translation stages such that the

PFL collimated the light scattered from the trapped ions and imaged onto a cooled CCD camera using a magnifying telescope. An image of a single ion on the CCD camera is shown in Fig. 1 a, where the horizontal axis is the needle axis. The size of the ion image (FWHM) was calculated using Gaussian fits through the data. The ion extent was 434 nm ± 9 nm in the vertical axis and 475 nm ± 9 nm in the horizontal axis. This represents an improvement of an order of magnitude over our previous results [4]. The high image resolution allowed us to resolve temperature, micromotion and linewidth effects by visual detection only.

In summary we have successfully demonstrated trapping and laser cooling of ions in close proximity to an integrated microfabricated PFL, with ion image resolution on the order of the wavelength of the scattered light. To our knowledge, our imaging resolution of 440 nm is the highest ever achieved for a single atom. This high resolution enables the possibility of individual addressing and individual readout of the ions by lasers, as required for large-scale ion-trap QIP [5]. Furthermore our architecture stands out by excellent scalability and the ability to be manufactured at low costs in high quantities. The collection efficiency is comparable to state of the art in QIP [4]. While our approach mainly targets large-scale QIP with trapped ions, it can be easily transferred to neutral atoms and solid state QIP applications [6].

References

[1] D. Kielpinski, C.R. Monroe, and D.J. Wineland, "Architecture for a large-scale ion-trap quantum computer," Nature **417,** 709 (2002)

[2] J. M. Amini, H. Uys, J. H. Weseberg, S. Seidelin, J. Britton, J. J. Bollinger, D. Leibfried, C. Ospelkaus, A. P. VanDevender and D. J. Wineland "Toward scalable ion traps for quantum information processing," NJP **12** 033031 (2010)

[3] E. W. Streed, B. G. Norton, J. J. Chapman, and D. Kielpinski, "Scalable, efficient ion-photon coupling with phase Fresnel lenses for large-scale quantum computing," Quant. Inf. Comp. **9** 0203-0214 (2009)

[4] E. W. Streed, B. G. Norton, A. Jechow, T. J. Weinhold and D. Kielpinski, "Imaging of trapped ions with a microfabricated optic for quantum information processing," Phys. Rev. Lett. **106**, 010502 (2011)

[5] L.-M. Duan and C. Monroe,"Colloquium: Quantum networks with trapped ions," Rev. Mod. Phys. 82, 1209 (2010).

[6] J. P. Hadden, J. P. Harrison, A. C. Stanley-Clarke, L. Marseglia, Y.-L. D. Ho, B. R. Patton, J. L. O'Brien, and J. G. Rarity, " Strongly enhanced photon collection from diamond defect centers under microfabricated integrated solid immersion lenses," Appl. Phys. Lett. 97, 241901 (2010).

TRAPPING OF ULTRACOLD ATOMS IN A 10 μm-PERIOD PERMANENT MAGNETIC LATTICE

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Optical lattices produced by the interference of laser beams have been used extensively to carry out various experiments in fundamental physics. These include studies of the superfluid to Mott insulator quantum phase transition, lower-dimensional quantum gases and quantum entanglement in quantum information. Magnetic lattices provide a promising alternative to optical lattices and have the potential advantages of low technical noise, low heating rates and highly stable and reproducible potentials; of being able to tailor geometries of arbitrary shape such as triangular-based and honeycomb lattices; and of being ideally suited for mounting on an atom chip for practical devices [1,2].

We report here the trapping and cooling of ^{87}Rb atoms in a 1D permanent magnetic lattice constructed from TbGdFeCo magnetic film on a 10 μm-period grooved structure on an atom chip. Previously, ^{87}Rb atoms in the weak field-seeking $|F = 2, m_F = +2\rangle$ state were successfully loaded into the 1D magnetic lattice [1]. Heating due to adiabatic compression in the tight traps and insufficient axial confinement limited the temperature of the trapped atoms to ~ 300 μK and the trap lifetime to ~ 0.5 s. We have now implemented controlled axial confinement in the 1D magnetic lattice and optically pumped the atoms into the $|F = 1, m_F = -1\rangle$ weak-field-seeking ground state to reduce losses due to three-body recombination. After a first evaporative cooling, ~ 10^6 atoms at ~ 10 μK in a Z-wire trap initially located ~ 600 μm below the chip surface, are brought closer to the magnetic lattice by ramping down the Z-wire current. At a current of 18 A the Z-wire trap merges with the magnetic lattice and a second evaporation is conducted which transfers the ore atoms into the magnetic lattice. In this way ~ 3×10^5 atoms in the $|F = 1, m_F = -1\rangle$ state are loaded into ~ 100 lattice sites at ~8 μm below the chip surface with a trap lifetime of ~ 12 s. Radiofrequency spectroscopy measurements indicate an atom temperature of 1-2 μK which

is close to the calculated BEC transition temperature of 1.5 μK for 2000 atoms. With improved magnification of the detection optics and using *in situ* absorption imaging, we can spatially resolve the individual clouds in the 10 μm-period magnetic lattice (Figure 1).

Future plans include obtaining a clear signature of the BEC transition in the multiple traps of the magnetic lattice and implementing a 2D magnetic lattice, with periods down to ~1 μm to perform quantum tunnelling experiments in a magnetic lattice on an atom chip.

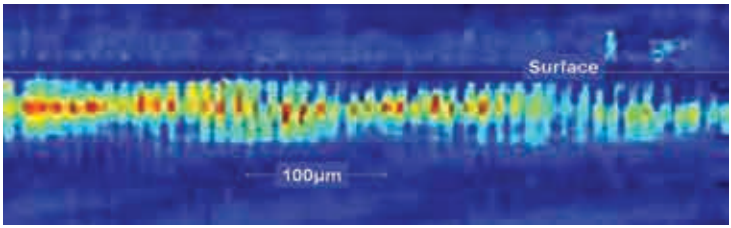

Figure 1. Side view in situ absorption image of ^{87}Rb F=1 atoms trapped in a 10 μm-period 1D magnetic lattice. (Pixel size: 3 μm)

References

1. M. Singh, M. Volk, A. Akulshin, A. Sidorov, R. McLean and P. Hannaford, *J. Phys. B.* **41**, 065301 (2008).
2. S. Whitlock, R. Gerritsma, T. Fernholz and R. Spreeuw, *New J. Phys*. **11**, 023021 (2008).

TWO-ATOM COLLISIONS IN AN OPTICAL-LATTICE-LIKE MAGNETO-OPTICAL TRAP

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In a trap of cold atomic cloud, two atoms can escape the trap by an inelastic collision mediated by a photon. The higher the density of atomic cloud is, the more atoms can collide, and thus the number of atoms in the trap will be limited. There are several proposals to suppress two-atom collision events. One is to capture the atoms in an optical lattice and thus to decrease their chance of getting close to each other. However, in an optical lattice, atoms can tunnel to neighboring sites[1], and moreover, the small volume of a micro potential site may increase the two-atom collision rate inversely proportional to the trap volume. In order to resolve these conflicting pictures, we performed an experiment where we trapped a few ^{85}Rb atoms in an optical lattice formed in a phase-stabilized magneto-optical trap and measured the two-atom collision rate[2]. Varying experimental conditions, we can study the suppression and enhancement of collisions in optical lattices. In this presentation, we will report the results so far and compare them with Monte-Carlo simulations.

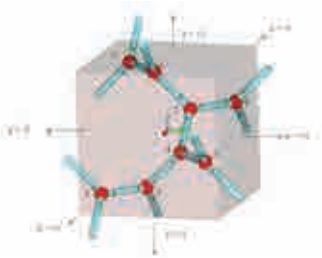

Figure 1. The unit cell of optical lattice

References

1. W. Kim, C. Park, J.-R. Kim, Y. Choi, S. Kang, S. Lim, Y.-L. Lee, J. Ihm, and K. An, "Tunneling-induced spectral broadening of a single atom in a three-dimensional optical lattice" *et al., Nano Lett.* **11**, 729 (2011).
2. Y. Choi, S. Yoon, S. Kang, W. Kim, J.-H. Lee, and K. An, "Direct measurement of loading and loss rates in a magneto-optical trap with atom-number feedback",, *Phys. Rev.* **A76**, 013402 (2007).

Bose-Einstein condensation of paraxial light

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Photons have played a vital role for the experimental realization of Bose-Einstein condensation in ultracold atomic gases. To cool down matter to sufficiently low temperatures fundamentally new, on optical techniques relying cooling and trapping techniques had to be developped. Considering their supportive role for atomic BECs it seems natural to ask if photons can undergo a BEC in their own right. Typically this question is negated with reference to black body radiation - presumably the most omnipresent Bose gas at all. For black body radiation not only the spectral distribution of photon energies depends on temperature but also their total number. Temperature and photon number cannot be tuned independently - if the temperature of the photon gas is lowered then also the photon number will decrease (Stefan-Boltzmann law). However a number-conserving thermalization process was experimentally observed for a two-dimensional photon gas in a dye-filled optical microcavity (Fig. 1) [1]. Here we report the observation of a Bose-Einstein condensate of photons in this system [2]. The cavity mirrors provide both a confining potential and a non-vanishing photon mass, making the system formally equivalent to a two-dimensional gas of trapped, massive bosons. The photons thermalize to the temperature of the dye solution (room temperature) by multiple scattering with the dye molecules. Upon increasing the photon density, we observe the following BEC signatures: the photon energies have a Bose-Einstein distribution including a massively populated ground-state mode (Fig. 2, 3); the phase transition occurs at the expected photon density and exhibits the predicted dependence on cavity geometry; and the ground-state mode emerges even for a spatially displaced pump spot.

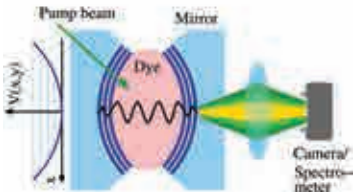

Fig. 1

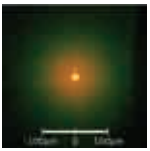

Fig. 2

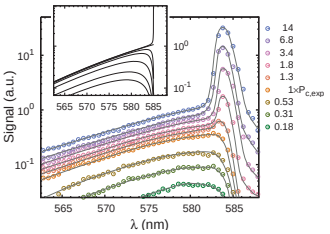

Fig. 3

[1] J. Klaers, F. Vewinger and M. Weitz, *Nature Phys.* **6**, 512 (2010)
[2] J. Klaers, J. Schmitt, F. Vewinger and M. Weitz, *Nature* **468**, 545 (2010)

Laser Spectroscopy of Atomic Hydrogen: Absolute Frequency Measurements of the 2S - 6S,6D Transitions

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The Rydberg constant is determined by comparing measured transition frequencies in atomic hydrogen and deuterium to the theoretical expressions for the energy levels and is currently known to 6.6 parts in 10^{12}. Although the 1S - 2S transition frequency is known much more accurately[1], other transition frequencies must be measured with higher precision to disentangle quantum electrodynamic (QED) and nuclear size effects. Significantly, a recent measurement of the proton charge radius by spectroscopy of muonic hydrogen[2] lies almost five standard deviations away from the CODATA recommended value, implying either that the calculations of QED effects in atomic hydrogen or muonic hydrogen are incorrect or incomplete, or that the accepted value for the Rydberg constant is incorrect. New high-accuracy measurements of transition frequencies in atomic hydrogen have an important part to play in understanding the source of this discrepancy.

At NPL we have recently made the first absolute frequency measurements of the 2S - 6S,6D transitions in hydrogen, which have previously only been studied by comparison with the 1S - 3S transition[3]. The transitions are studied by Doppler-free two-photon spectroscopy on a metastable hydrogen atomic beam in a collinear geometry[4]. The two-photon transitions are excited using a frequency-stabilized Ti:sapphire laser and the absolute frequency measurements are carried out using a femtosecond optical frequency comb.

The largest sources of systematic frequency shift are the second-order Doppler shift and the ac Stark shift. The velocity distribution of the metastable atoms has been measured by using a 656 nm extended cavity diode laser to observe the Doppler-broadened single-photon 2S - 3P transition, using co- and counter-propagating laser beams that are collinear with the metastable beam. The ac Stark shift is determined by recording two-photon spectra at different laser intensities. For each spectrum, we fit a theoretical line profile that takes into account the light shift and the saturation of the transition, the velocity distribution of the metastable atoms and the hyperfine structure of the upper state.

This work was funded by the UK Department for Business, Innovation and Skills (BIS) as part of the National Measurement System (NMS) "Pathfinder" programme.

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[1] T. W. Hänsch et al., "Precision spectroscopy of hydrogen and femtosecond laser frequency combs", Phil. Trans. Roy. Soc. A, **363**, p. 2155–2163, 2005.

[2] R. Pohl et al., "The size of the proton", Nature, **466** 213–217 (2010).

[3] S. Bourzeix et al., "High resolution spectroscopy of the hydrogen atom: determination of the 1S Lamb shift", Phys. Rev. Lett., **76** 384–387 (1996).

[4] J. L. Flowers et al., "The NPL Rydberg constant experiment", IEEE Trans. Instrum. Meas. **56** 331–335 (2007).

Strontium Ion Optical Clocks at NPL

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Optical frequency standards offer a step improvement of one to two orders of magnitude in the ability to realise the SI second[1]. The NPL strontium ion optical clock project[2] is targeted on creating systems with better performance than microwave clocks, for both space[3] and terrestrial environments. Recent activities have centred on compact transportable system development and long-term unattended operation with quantum-limited performance. One ring and two end-cap $^{88}Sr^{+}$ trap systems based on the $^{2}S_{1/2}$ - $^{2}D_{5/2}$ 674 nm optical-clock quadrupole transition are under development. By comparing the end-cap traps, we have demonstrated single-ion stability of 7 parts in 10^{16} at 1000 seconds.

Cooling radiation at 422 nm is generated by single-pass frequency doubling of an ECDL diode laser in PPKTP. Two DFB lasers are used: one, at 1092 nm, drives ions out of the metastable $^{2}D_{3/2}$ level and a second, at 1033 nm, drives the ion out of the $^{2}D_{5/2}$ state following excitation by the 674 nm clock laser. Both DFB diodes have integral Peltier coolers in a TO3 can. Photo-ionisation of strontium is accomplished with both a 405 nm diode laser and 461 nm radiation that is produced by single-pass frequency doubling of a 922 nm ECDL laser in PPKTP. The compact trap, which has a 1.5 mm ring electrode and flat AR-coated windows, yields single-ion $^{88}Sr^{+}$ line profiles with a S/N ratio of better than 10:1. The small volume is pumped by a 2 l/sec ion pump. A 12 mm diameter photomultiplier was installed and two layers of magnetic shielding were fitted to reduce stray magnetic field variations to a negligible level. The overall volume of the delivery optics and magnetically shielded vacuum chamber of the compact trap system is more than an order of magnitude smaller than the NPL Sr^{+} and Yb^{+} end-cap trap optical clock systems.

Optical pumping was demonstrated with computer-controlled shuttering of linear and circularly polarised 422 nm laser cooling beams, in order to increase ground state preparation efficiency. Computer monitoring and laser-lock error recovery routines have been implemented; these allow continuous data taking for up to 60 hours. The 674 nm clock lasers, locked to ULE cavities, reach stabilities of 2 to 3 parts in 10^{15} between 1 and 500 s, with the linear and quadratic drifts removed. Cold-ion clock-transition linewidths of 9 Hz have been observed corresponding to the Fourier transform-limit of the 100 ms probe pulses used. Calculations indicate that, in five hours, with a 200 ms probe pulse, one should be able to achieve relative frequency stabilities of parts in 10^{17}.

This work was funded by the UK Department for Business, Innovation and Skills (BIS), as part of the National Measurement System (NMS) "Pathfinder" programme. Discussion with collaboration partners and colleagues at WIPM, ESA, JPL and NPL is gratefully acknowledged.

[1] H.S. Margolis, "Optical Frequency Standards and Clocks", Contemporary Physics **51** (1) 37-58 (2010).

[2] G.P. Barwood, P. Gill, G. Huang and H.A. Klein, "Observation of a sub-10 Hz linewidth $^{88}Sr^{+}$ $^{2}S_{1/2}$ - $^{2}D_{5/2}$ clock transition at 674 nm", IEEE TIM **56** 226-229 (2007).

[3] Patrick Gill, Helen Margolis, Anne Curtis, Hugh Klein, Stephen Webster and Peter Whibberley, "Optical Atomic Clocks for Space", Tech. Supporting Doc. ESTEC/Contract 21641/08/NL/PA (Nov. 2008): http://www.npl.co.uk/upload/pdf/atomic_clocks_space.pdf

Pair correlated matter waves for quantum interferometry

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Matter wave optics with ultra cold samples has reached the point where nonclassical states can be prepared and their fascinating properties can be explored. In optics, parametric down conversion is routinely used to generate light with squeezed observables as well as highly entangled photon pairs. The applications of these nonclassical states range from fundamental tests of quantum mechanics to improved interferometers and quantum computation. Therefore, it is of great interest to realize such nonclassical states with matter waves. Bose-Einstein condensates with non-zero spin can provide a mechanism analogous to parametric down conversion, thus enabling the generation of nonclassical matter waves. The process acts as a two-mode parametric amplifier and generates two clouds with opposite spin orientation consisting of the same number of atoms. At a total of ~10000 atoms, we observe a squeezing of the number difference of -8 dB below shot noise, including all noise sources. A microwave coupling between the two modes allows for analysis of the created state towards sub-shot-noise interferometry.

Extended coherence time on the clock transition of optically trapped rubidium

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The definition of the second is provided by microwave fountain clocks. Besides the quest for highest accuracy, applications ranging from navigation to communication technology demand more stable and compact atomic frequency standards. The stability of all interferometric clocks is limited by the duty cycle, the ratio between interrogation and cycle time. The interrogation time of fountain clocks is limited by their principle of operation, preventing a compact realization. This limitation could be overcome by using trapped atomic ensembles instead of fountains.

However, in a trapped ensemble the confining potential is generally different for the two states defining the clock transition. This results in a differential frequency shift which is necessarily inhomogeneous across the trapped ensemble. Hence, the atoms experience a slightly different phase evolution in each trap state. This dephasing mechanism leads to a loss of contrast of the interferometer signal and thus limits the interrogation time. In a special magnetic confinement, for which the inhomogeneity of the Zeeman shift is canceled by the density shift, it was shown that the collisional interaction can be used to induce spin self-rephasing [1]. This effect inhibits dephasing and induces characteristic contrast revivals, mediated by collisional interaction.

We show that spin self-rephasing is applicable in an optical potential for the magnetically insensitive clock states. We demonstrate a coherence time of 21s – the longest ensemble coherence time measured so far. The coherence time is achieved in a Ramsey sequence on the ^{87}Rb hyperfine transition, a secondary representation of the second. We show that both the inhomogeneity of the differential light shift and the inhomogeneity of the density shift can be overcome by spin self-rephasing. Furthermore, we evaluate the applicability of spin self-rephasing for atomic microwave clocks and demonstrate a stability of 2.4×10^{-11} at one second, which is limited by technical noise. We predict a 300 fold stability enhancement for a purpose-built apparatus with standard technical improvements, which enters the stability range of most atomic fountain clocks in a potentially much more compact setup. Our findings prove the fundamental nature of spin self-rephasing which is independent of the type of trap and the magnetic quantum number. Thus, its applicability might be extended to optical lattice clocks as well as quantum information with atomic ensembles.

[1] C. Deutsch et al., Phys. Rev. Lett. **105**, 020401 (2010).

Klein-Tunneling of a Quasirelativistic Bose-Einstein Condensate in an Optical Lattice

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In the area of solid state physics, it has been demonstrated that electrons in graphene can behave as relativistic particles, although the electron velocity is orders of magnitude below the speed of light [1]. The dispersion relation in this material near the Fermi energy is linear, i.e. quasirelativistic. Here we report a proof-of-principle quantum simulation of relativistic wave equation predictions with ultracold atoms in an optical lattice [2]. Our experiment is based on rubidium atoms in a Fourier-synthesized lattice potential consisting of an optical standing wave with spatial periodicity $\lambda/2$, where λ denotes the laser wavelength, and a higher spatial harmonic with $\lambda/4$ spatial periodicity. For a suitable choice of relative phases and amplitudes of the harmonics, the dispersion relation, see Fig. 1, in the region between the first and second excited Bloch band becomes linear, as known for ultrarelativistic particles. In theoretical work it has recently been shown that the dynamics of atoms in the bichromatic lattice near the crossing between the first two excited bands can be formally described using a one-dimensional Dirac-

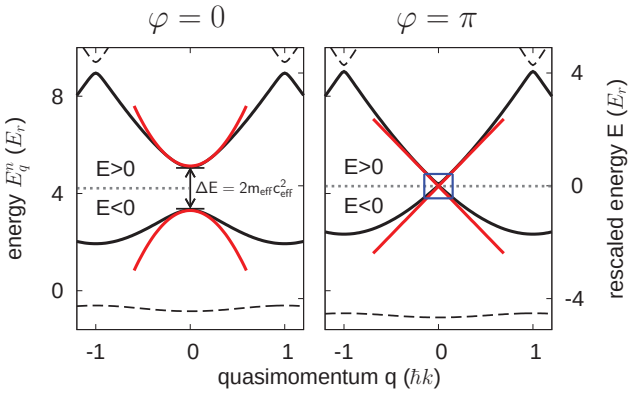

Fig. 1: *Dispersion relation resulting from bichromatic optical lattice. Left: Schrödinger-like, quadratic dispersion. Right: linear, relativistic dispersion.*

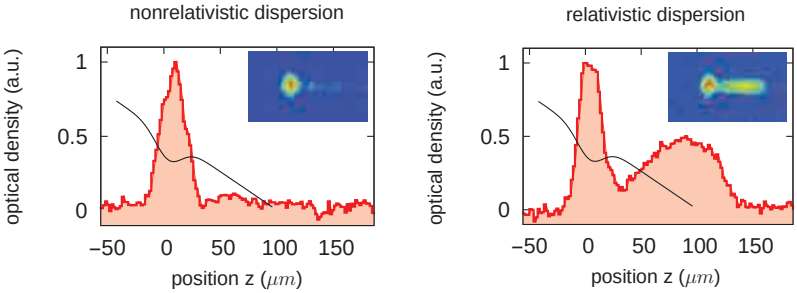

Fig. 2: *Dynamics of the condensate in presence of barrier. Left: Schrödinger-like, dispersion and reflection, right: relativistic, dispersion and Klein-tunneling.*

like wave equation [3]. We have experimentally demonstrated both the transmission of atoms through a potential barrier for the case of a linear dispersion relation, i.e. Klein-tunneling, and the usual reflection of atoms by the barrier for the case of a quadratic, i.e. Schrödinger-like, dispersion in an excited Bloch band [2], see Fig. 2. In other work, Bloch-Zener oscillations, the coherent superposition of Bloch oscillations and Landau-Zener tunnelling, and a Stückelberg interference pattern in the two-band lattice system has been observed [4]. For the future, we expect that ultracold atoms in variably shaped optical lattices allow quantum simulations of a wide range of effects of both linear and nonlinear Dirac-dynamics.

References

[1] M.I. Katsnelson, K.S. Novoselov, and A.K. Geim, Nature Phys. **2**, 620 (2006).

[2] T. Salger, S. Kling, C. Grossert, and M. Weitz, to be published.

[3] D. Witthaut, T. Salger, S. Kling, C. Grossert, and M. Weitz, arXiv:1102.4047.

[4] S. Kling, T. Salger, C. Grossert, and M. Weitz, Phys. Rev. Lett. **105**, 215301 (2010).

Diatomic alkaline-earth molecules: spectroscopic data for producing ultracold samples

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Cold molecules and their efficient creation are a hot topic of present research. Most investigations, however, focus on alkalis, for which the electronic structure and interatomic potentials have been intensively studied spectroscopically as well as by ab initio methods.
Diatomic molecules based on alkaline-earth metal atoms lack hyperfine structure in contrast to alkaline atoms, thus their spectral and interaction structure is much simpler. Experimentally, however, only for few homonuclear alkaline earth metal dimers enough spectroscopic information is available to construct reliable interatomic potentials. Moreover, for the cases Ca_2 and Sr_2, which we investigated spectroscopically, substantial discrepancies exist between experiment-based potentials and those from ab initio calculations, especially for electronically excited states.
Thus the knowledge base for creation of cold molecules from alkaline earth atoms, which must involve molecular ground states and excited states as well, is much less reliable than for the case of alkalis.
We will present results of our spectroscopic investigations on the examples of Mg_2, Ca_2 and Sr_2, discussing the experimental method and various approaches with their benefits or drawbacks for modelling the data by potential energy curves. We will also add information on what is known about other dimer combinations of alkaline earth metal like CaMg and of electronically similar atoms like Hg and Yb.

From cold atoms to molecules: the spectroscopic modeling

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Cold molecules and their efficient creation are a hot topic of present research. While first demonstrations of their production were for homonuclear alkali dimers like Cs_2, now heteronuclear alkali diatomics like e.g. KRb have risen recent interest. One important property stimulating this activity is their permanent electric dipole moment giving rise to long range anisotropic interactions.

Knowledge of the interaction potentials of the colliding cold atoms, of which the molecules are synthesized, is very important for the understanding of the formation process and for improving its efficiency. During recent years we have investigated spectroscopically many diatomic combinations of alkali atoms. With the simple spectroscopic method of laser induced fluorescence recorded by a Fourier-transform spectrometer high resolution data were gained. The molecular ground electronic states were characterized almost up to the dissociation limit. Moreover by employing mixed singlet-triplet excited molecular levels it was possible in various cases to record fluorescence simultaneously to the molecular ground singlet $X^1\Sigma^+$ and triplet $a^3\Sigma^+$ states, so that the relative position of the levels involved is measured directly.

From such investigations and including, where available, atomic cold collision data from other sources precise model potentials for the ground electronic states for nearly all combinations of alkali atoms over relevant ranges of internuclear distances were constructed,

which consistently also describe the observed singlet–triplet coupling by hyperfine interaction.

The collected spectroscopic data also contain information on the excited molecular states, which can be starting points for finding

efficient pathways for creation of cold molecules from cold atoms. Essentially an excitation process from a deeply bound level in the molecular ground state with fluorescence into a vibrational level of the triplet ground state close to the atom pair limit is just the reverse of forming a deeply bound cold molecule from a molecule in a triplet level close to the ground state asymptote, which could have been created via e.g. a Feshbach-resonance collision of two cold atoms.
The methods of spectroscopy and modelling of the data will be explained, and the application of the models will be discussed.

Simultaneous Ion-atom trapping: Results and Directions

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We present an experiment that simultaneous traps alkali ions and the parent atom with spatial overlap. Such an experiment opens up the possibility of studying various phenomena such as elastic and inelastic collisions, formation of molecules and molecular complexes, sympathetic cooling to name a few. For alkali atom daughter ion species, the interaction is mediated via a doublet molecular potential and processes like resonant charge exchange collision are reaction channels of particular interest. We present an experimental apparatus that has been designed and constructed with the view of probing such interactions and to provoke chemistry of ultra-cold dilute gases with and in the presence of ions. We have successfully cooled and trapped Rubidium (Rb) atoms in a Magneto-Optical Trap which is spatially overlapped with a trapped ion cloud of Rb^+. Some signatures of ion-atom interaction have been observed on this setup. Recent results and the general future directions of the experiment will be presented in this poster.

NARROW ABSORPTION IN THE COHERENT POPULATION TRAPPING RESONANCE WITH THE PARAFFINE COATED Rb VAPOR CELL

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Busan 609-735, Korea

1. Introduction

Electromagnetically induced absorption (EIA) which is the opposite phenomenon of electromagnetically induced transparency (EIT) has been investigated in the resonance on a $F_g \rightarrow F_e = F_g + 1$ in the Hanle configuration. Many previous experiments related with EIT and EIA in Hanle configuration use a pure Rb vapor cell and Rb vapor cell with buffer gas. Recently, A. Huss *et al.* reported coherent population trapping (CPT) resonances by means of level-crossing type in the presence of additional transverse magnetic fields [1] and *Yu et al*. reported the level-crossing absorption with the sub-natural linewidth in the buffer gas contained Rb vapor cell [2].

Most atomic coherence experiment use an alkali-metal vapor contained in a glass cell. Because atomic coherence is generally destroyed when atom collide with the walls of the cells, wall relaxation, commonly cells filled with buffer gas are used. Another technique for reducing wall relaxation is using an anti-relaxing coating on the cell. In anti-relaxation coated cell such as paraffin-coated cell, despite of collision on the wall of the anti-relaxation coated cell the atomic coherence between two ground states may be maintained because the anti-relaxation coated cell are free from the wall collision and the buffer gas collision.

In this paper, we present effect of transverse magnetic fields in ^{87}Rb D_1 line with a paraffin coated Rb vapor cell. The absorption spectra were investigated according to the laser polarization. In addition, the Hanle spectrum was calculated numerically using full density matrix equations for the relevant magnetic sublevels of the hyperfine levels.

2. Results

Figure 1 shows the Hanle spectra with paraffin coated cell in the F=2→ F'=1 transition with varying the polarization of the laser field, where the

degree is the angle between the direction of initial linear polarization and the fast axis of the quarter-wave plate. While the polarization of the laser field is changed from the linear to the circular ($0^o \rightarrow 45^o$). A distinct absorption spectrum with a narrow spectral width of 0.2 mG was observed in the condition of circular polarization. In the paraffin coated Rb cell, the spectral linewidth is more narrow by 2-order than that in buffer gas cell due to the repeated interaction. The absorption spectrum is the result of a redistribution of the ground-state populations caused by the transverse magnetic field but, not an atomic coherence effect due to two-photon coherence. When there is a weak transverse-residual-magnetic field, the atomic magnetic momentum is changed around the zero value of the z-axis magnetic field directed to the laser's propagation.

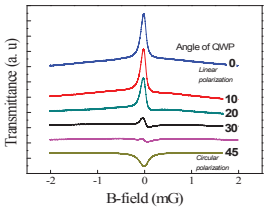

Fig. 1. Laser polarization dependent CPT features.

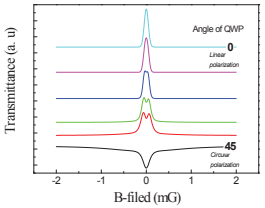

Fig. 2. Numerically calculated CPT signals according to the laser polarization

References

1. A. Huss, R. Lammegger, L. Windholz, E. Alipieva, S. Gateva, L. Petrov, E. Taskova, and G. Todorov, J. Opt. Soc. Am. B **23**, 1729 (2006).
2. Ye Jin Yu, Hyun Jun Lee, In-Ho Bae, Heung-Ryoul Noh, and Han Seb Moon, Phys. Rev. A **81**, 023416 (2010)

A laser-cooled Si atom source for Kane quantum computer

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In 1998 Bruce Kane proposed a solid state quantum computer architecture that has the potential to be scalable to kilo-qubits or even mega-qubits.[1] It utilizes an array of single ^{31}P dopant atoms embedded in a ^{28}Si lattice. Each ^{31}P atom has nuclear spin 1/2 and acts as a qubit. The challenge for this concept is the placement of one and only one ^{31}P atom at each site, ~10 nm below the surface and separated ~20 nm, with about 1 nm precision in the Si substrate. To avoid ion straggling, the P ions should be deposited at low energy, ~100 eV. Even the best commercial ion guns do not have sufficiently small phase space to accomplish this task. Deposition of one and only one ion in a site is also problematic.

A laser cooled and trapped single atom in a magneto optic trap, followed by resonant photo-ionization, provides a deterministic ion source with a small enough phase space to achieve the required precision in deposition [2]. Current laser technology does not allow for the direct cooling and trapping of P atoms, as the transition at 177 nm is in the vacuum ultraviolet region. However, the $3s^2 3p^2\ ^3P_2 \rightarrow 3s3p^3\ ^3D^o_3$ transition in silicon at 221.7 nm is a cycling transition that may be used for the laser cooling and trapping of silicon atoms. In particular, the radioactive isotope ^{31}Si would beta decay after deposition into ^{31}P. Such a deterministic single ion source of ^{31}Si could provide the desired ^{31}P qubits for a Kane quantum computer. (Fig. 1)

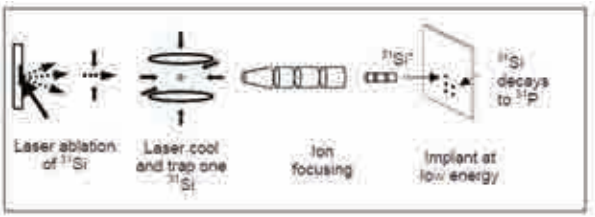

Fig. 1. Schematic diagram of scheme to place ^{31}P in Si with nm precision.

We have determined the hyperfine A-coefficients and isotope shifts for the cooling transition of the stable Si isotopes, using a 221.7 nm laser with a Si atomic beam.[3] A resonance fluorescence spectrum is shown in Fig. 2. From the measured values and the magnetic moment of ^{31}Si, the hyperfine transitions in ^{31}Si can be estimated to about 100 MHz. Laser cooling and trapping of all four isotopes of Si are possible, using the frequencies indicated by the arrows in Fig. 3. It is particularly favorable that when ^{31}Si is being

cooled and trapped, the stable Si isotopes are being heated will not be trapped. Thus very high isotopic selectivity is possible.

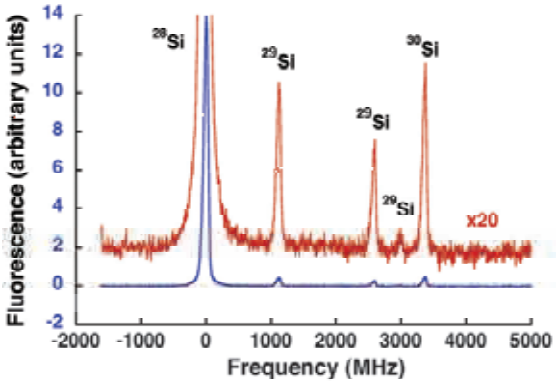

Fig. 2 Resonance fluorescence spectrum of the stable isotopes of Si at 221.7 nm.

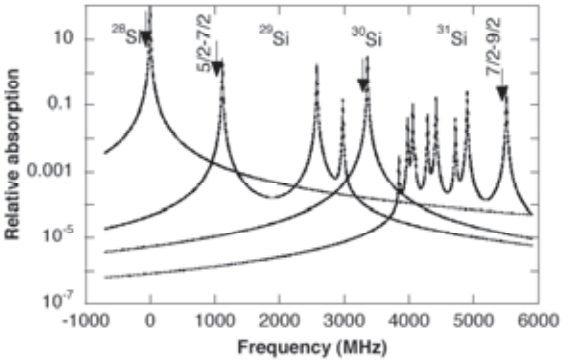

Fig. 3 Predicted line positions for Si isotopes

To convert the atoms into ions, we have investigated the resonance ionization spectrum from the excited $3s3p^3\ {}^3D°_3$ state and determined the ionization cross section near threshold. The magneto-optic trapping of Si atoms is underway, and the ion optics for extraction of single Si^+ ions and low energy implantation into a Si substrate is being designed. Our goal is to deposit an array of ^{31}P atoms and to image it by scanning probe microscopy.

This work is supported by the W. M. Keck Foundation.

1. B. E. Kane, *Nature* **393**, 133-137 (1998).
2. S. B. Hill and J. J. McClelland, Appl. Phys. Lett. **82**, 3128 (2003). J. L. Hanssen, J. J. McClelland, E. A. Dakin and M. Jacka, Phys. Rev. A **74**, 063416 (2006).
3. S. A. Lee and W. M. Fairbank, Jr., Phys. Rev. A **82**, 042515 (2010).

Quantum information experiments with a micro-fabricated, cryogenic, surface-electrode ion trap*

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Although the basic components of a quantum information processor using trapped ions have been demonstrated, scaling to large numbers of qubits and operations so that algorithms and simulations of practical importance can be implemented remains a major challenge. This is a technically challenging because it requires significant improvements in the precision with which quantum states of ions are prepared, manipulated and measured. Solutions are multi-disciplinary – involving micro-fabrication, cryogenics, integrated photonic devices, as wells as materials and surface science. Here we report progress from experiments that address a range of these issues. We use a micro-fabricated, cryogenic, surface-electrode ion trap, with two closely-spaced independently controlled potential wells. In the first experiment with this new apparatus, we implement a scheme for coupling two ions trapped in separate wells, and demonstrate tunable energy exchange at approximately the single quantum level [1]. A second experiment investigates errors in single qubit gates (rotations) with the use of randomized bench-marking [2].

*Supported by IARPA, DARPA, NSA, ONR and the NIST Quantum Information Program

[1] Brown, K.R., Ospelkaus, C., Colombe, Y. Wilson A.C., Leibfried, D., & Wineland, D.J., *Coupled quantized mechanical oscillators*, Nature, **471**, 196 (2011)
[2] Knill, E., Leibfried, D., Reichle, R., Britton, J., Blakestad, R.B., Jost, J.D., Langer, C., Ozeri, R., Seidelin, S., & Wineland, D.J., *Randomized benchmarking of quantum gates*, Phys. Rev. A **77**, 012307 (2008)

Study of systematic effects for Newtonian gravitation constant measurement in MAGIA experiment

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The development of atom interferometry receives much interest in many applications because of its high sensitivity. Accelerometers based on atom interferometry have been proposed or implemented for fundamental physics experiments [1] as well as many applications such as metrology [2], geophysics and so on [3].

We will present the experiment for measuring of the gravitational constant G in MAGIA experiment [4]. The experiment is based on a Raman light-pulse atom interferometry gravity gradiometer detecting the gravitational field generated by a well characterized set of source masses (FIG. 1).

In order to achieve the proposed goal of 10^{-4} accuracy on determination of G, we proceeded a series of the scrutinies on several system parameters which the source masses induced ellipse angle might be susceptible to. Besides to the aforementioned studies, we recently explored a systematic shift related to different source masses positions and it could not be easily suppressed by the current differential

measurement scheme. The details will be presented in the conference.

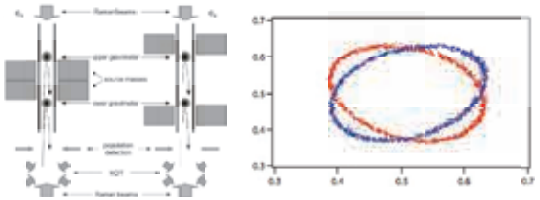

FIG. 1 Left: simplified apparatus; Right: The ellipses for different source masses configurations

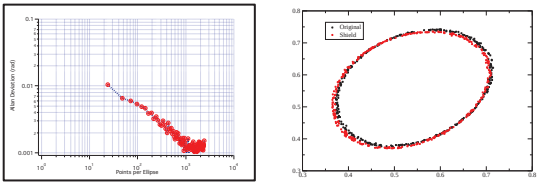

FIG. 2 Left: Allan variance for the phase angle of the ellipses; Right: The ellipses for magnetically unshielded and shielded platforms.

[1] H. Müller et al., "A precision Measurement of the Gravitational Redshift by the Interference of Matter Waves", Nature Phys. **463** 926 (2010).

[2] M. Cadoret et al., "Atom Interferometry Based on Light Pulses: Application to the High Precision Measurement of the Ratio h/m and the Determination of Fine Structure Constant", Euro. Phys. J. Spec. Top. **172** 121 (2009).

[3] M. de Angelis et al., "Precision Gravimetry with Atomic Sensors", Meas. Sci. Technol. **20** 022001 (2009).

[4] G. Lamporesi et al., "Determination of the Newtonian Gravitational Constant Using Atom Interferometry", Phys. Rev. Lett. **100** 050801 (2008).

FAST GENERATION OF SINGLE PHOTONS IN A COUPLED ATOM-CAVITY SYSTEM

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The controlled generation of single photons is one of the important issues in quantum information since a single photon can be used for a flying qubit. It has been realized with various systems including coupled atom-cavity systems, which have advantages of high collection efficiency and well-defined spatial profile of generated photon. We have performed the single photon generation in an atom-cavity system with ^{85}Rb atoms and a Fabry-Perot cavity[1].

The schematic of our experimental setup is shown in Figure 1(a). In our experiment, the atom-cavity coupling constant, atomic decay rate and the cavity decay rate were given by $\{g_0, \gamma, \kappa\} = 2\pi \times \{16, 3, 19\}$MHz, respectively, which were in a moderate coupling regime. A single ^{85}Rb atom in the cavity was excited by a π-pulse pumping laser, and it generated a single photon into the cavity mode by the atom-cavity interaction. The generated photon was emitted out of the cavity and detected by a single photon counting module. Our cavity parameters were optimized for high efficiency and fast repetition rate up to 10 MHz, which is faster than the previous records[2].

In this poster, the experimental results including the temporal single-photon wave packet and the intensity correlation of generated photons (Figure 1(b)) will be presented, and the progress to make our system more efficient will also be discussed.

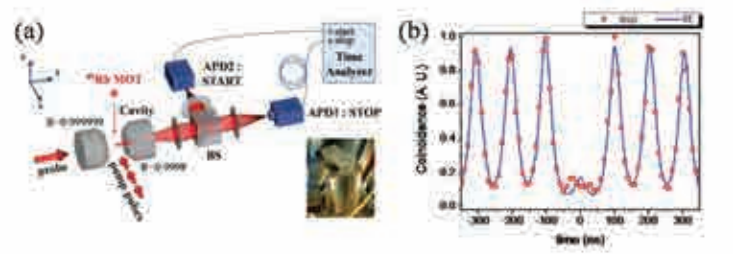

Figure 1: (a) Experimental setup. ^{85}Rb atoms from a magneto-optical trap (MOT) were released to the cavity. When one of those atoms traversed the cavity mode, it was pumped with a π-pulse laser. **(b) Intensity correlation of generated photons.** The suppression of coincident detection indicates single photon generation.

References

1. Sungsam Kang, Sooin Lim, Myounggyu Hwang, Wookrae Kim, Jung-Ryul Kim, and Kyungwon An, *"Controlled generation of single photons in a coupled atom-cavity system at a fast repetition-rate"*, Opt. Express **19**, 2440 (2011).

2. J. Bochmann, M. Mücke, G. Langfahl-Klabes, C. Erbel, B. Weber, H. P. Specht, D. L. Moehring, and G. Rempe, *"Fast Excitation and Photon Emission of a Single-Atom-Cavity System"*, Phys. Rev. Lett. **101**, 223601 (2008)

CROSSOVER FROM 2D TO 3D IN A WEAKLY INTERACTING FERMI GAS

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The dimensionality of an ultracold quantum gas can vastly affect the properties it displays, leading to a great deal of interest in lower dimensional systems. In two dimensions, the transition to superfluidity is a Berezinskii-Kosterlitz-Thouless (BKT) [1,2] phase transition. This is identified by the pairing of vortices with opposite circulation and has been observed in Bose gases [3]. Other phenomena that occur in two-dimensional systems include confinement-induced resonances and a two-body bound state for arbitrarily weak attractive interactions [4,5].

We present the characterisation of the crossover from two dimensions to three dimensions in a weakly interacting Fermi gas of ^{6}Li atoms, trapped in a single oblate optical harmonic trap [6]. The dimensionality of the system is dependent on the atom number as this determines the number of harmonic states occupied in the tightly confined transverse dimension. As we increase the atom number above a critical number N_{2D}, higher transverse states become occupied as Pauli exclusion and the aspect ratio of the trap limit the number of particles that can occupy the transverse ground state. For atom numbers above N_{2D}, the gas enters a quasi-2D regime where the shell structure in the growth rate of the cloud size becomes evident. A trap with an aspect ratio of 60 was used in these studies, leading to N_{2D} of approximately 1800. Figure 1 shows the evolution of the aspect ratio of the trap as the atom number increases from the 2D ($N < 1800$) to quasi-2D regimes. The inset shows the gradient of the aspect ratio which highlights the steps associated with the occupation of new transverse shells.

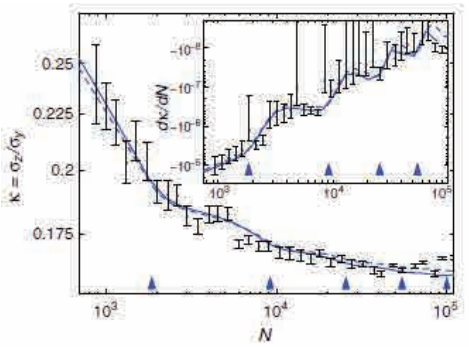

Figure 1: Measured aspect ratio of the atom cloud versus atom number in the 2D-3D crossover regime (points) and theoretical predictions for a weakly interacting (solid line) and ideal (dashed line) Fermi gas. The arrows predict where the higher transverse states are accessible. Inset: Gradient of the experimental and theoretical aspect ratios.

We will also present our progress towards creating a new two-dimensional trap using a blue detuned TEM01 mode optical dipole trap [7,8]. This will provide independent control over both the transverse and radial trapping frequencies, offering a much higher aspect ratio. As the critical atom number N_{2D} is proportional to the square of the aspect ratio, this will enable the production of much larger atom clouds in the true two-dimensional regime.

[1] V. L. Berezinskii, *Sov. Phys. JETP* **34**, 610 (1972)

[2] J. M. Kosterlitz and D. J. Thouless, *J. Phys. C* **6**, 1181 (1973)

[3] Z. Hadzibabic et al., *Nature* **441**, 1118 (2006)

[4] D. S. Petrov and G. V. Shlyapnikov, *Phys. Rev. A* **64**, 012706 (2001)

[5] T. Bergeman et al., *Phys. Rev. Lett*. **91**, 163201 (2003)

[6] P. Dyke et al., *Phys. Rev. Lett.* **106**, 105304 (2011)

[7] N. L. Smith et al., *J. Phys. B: At. Mol. Opt. Phys.* **38**, 223-235 (2005)

[8] T. Meyrath et al., *Opt. Express*, **13(8)**, 2843-2851 (2005)

Random-sampling Ramsey-like spectroscopy in the XUV

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Extending high-resolution spectroscopy to the vacuum- and extreme-ultraviolet regime (xuv) is highly desirable. High-order harmonic (HOH) generation from intense fs laser pulses, with its table-top character, is an effective and attractive tool to produce coherent radiation in this spectral region. Its main limitation for application to high-resolution spectroscopic studies, its inherently broad bandwidth, has been recently overcome by utilizing time-delayed pulse replicas to excite the targeted atomic system, in analogy to the Ramsey scheme of separated oscillatory fields [1].

In the approach discussed here, the required xuv pulse pair is created by splitting an amplified IR laser pulse in a Michelson interferometer before HOH generation in a gas jet [2-4]. An experiment performed on high-lying bound states of Argon [4], measuring Ramsey quantum fringes in the excitation signal at delays larger than 100 ps, has demonstrated a potential resolving power, in the xuv, higher than the best currently attainable ones in synchrotron facilities. However, if precise xuv frequency measurements are to be performed, one needs to accurately follow all the atomic quantum interferences over a long time interval. In the xuv spectral region this is far from trivial. In fact, since such measurements are performed in a slow ion/electron count regime, it is easily seen that they demand prohibitively long acquisition times that, in turn, pose severe constraints on the overall stability of the system.

Here we demonstrate a novel method theoretically proposed by our group [5], to overcome these constraints and make measurement times substantially shorter. By acquiring Ramsey fringes only over a limited subset of randomly-chosen delay intervals in the whole range T, which is dictated by the given target spectral resolution, we are able to perform the first high-precision absolute measurement of an xuv atomic transition frequency using a simple pulse-splitting interferometer.

References:

1. N. Ramsey, Phys. Rev. **78**, 695 (1950)

2. S. Cavalieri, R. Eramo, M. Materazzi, C. Corsi and M. Bellini, Phys. Rev. Lett. **89**, 133002 (2002)

3. A. Pirri, E. Sali, C. Corsi, M. Bellini, S. Cavalieri and R. Eramo, Phys. Rev. A **78**, 043410 (2008)

4. I. Liontos, S. Cavalieri, C. Corsi, R. Eramo, S. Kaziannis, A. Pirri, E. Sali and M. Bellini, Opt. Lett. **35**, 832 (2010)

5. R. Eramo, M. Bellini, C. Corsi, I. Liontos and S. Cavalieri, Phys. Rev. A, *to be published* (2011)

The strontium lattice clock at PTB

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Optical clocks using optical reference transitions in neutral atoms or single ions have achieved a level of accuracy and stability that opens new fields of interdisciplinary research. At a fractional accuracy level beyond 10^{-16} relativistic geodesy with a resolution better than a meter starts to become relevant. The time dependence of fundamental constants can be tested with laboratory experiments, results can be compared with theory predictions and astrophysical results.

At PTB we build an optical clock with neutral ^{87}Sr atoms that are confined in a one dimensional optical lattice which is operated at the magic wavelength where no net light shift appears on the clock transition. Recently we have performed the first frequency measurement of our lattice clock against one of PTB's primary caesium fountain clocks. The measured frequency has an uncertainty of 1×10^{-15} and is in good agreement with the results achieved by other institutes. The lattice clock itself contributes with a systematic uncertainty of 1.5×10^{-16} to the measurement uncertainty. We have inferred a stability of the lattice clock of better than $3\times10^{-15}\cdot(\tau/\mathrm{s})^{-0.5}$.

One large contribution to the uncertainty budget is the ac-Stark shift of the Sr clock transition by the ambient black body radiation. Currently we investigate methods to reduce this effect by interrogation of the atoms in a cryogenic environment or by

better characterisation of the atomic response to the black body radiation. We believe that these investigations will push the accuracy of Sr lattice clocks to the 10^{-17} level.

Besides the development of laboratory clocks we build a transportable lattice clock that will be used for first optical clock comparisons between laboratories beyond the accuracy of Cs fountain clocks. The transportable lattice clock will also be used as demonstrator for relativistic geodesy measurements.

The support by the Centre of Quantum Engineering and Space-Time Research (QUEST), funding from the European Community's ERA-NET-Plus Programme (Grant No. 217257), and by the ESA and DLR in the project Space Optical Clocks is gratefully acknowledged.

Comparison of strontium optical lattice clocks

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Optical lattice clocks have already proven to be good candidates for next generation atomic clocks. They combine both a high number of atoms that enables high frequency stabilities, as well as high accuracy due to the confinement of the atoms in a dipole trap. In the recent years, steady improvements have been achieved in optical lattice clock with strontium atoms.

A major concern about lattice clocks is the light shifts induced by the trapping potential on the atomic transition, and it has been previously shown that for a relatively shallow trapping potential (10 recoil energies Er), the effect of the scalar and hyper-polarizability terms could be controlled down to 10^{-17}.

The recent comparison between two Sr optical lattice clocks that has been built at SYRTE enabled us to measure with unprecedented accuracy all the trap induced effects, and to push further down the limit these effects place on the ultimate accuracy of optical lattice clocks. We could observe for the first time the vector and tensor

shifts on the clock transition, and put a more stringent limit on the hyperpolarizability effect.

The higher order E2/M1 effect that were recently discussed as a concern for the accuracy of lattice clocks were also investigated. We could put a higher bound on this effect that rules out this concern.

The results presented here show that Sr optical lattice clocks can reach the 10^{-17} accuracy level even for traps as deep as a few 100 Er.

Given these results, we present the first comparison results between the two strontium devices and comparisons with the microwave frequency standards at SYRTE.

Ultrahigh Resolution Spectroscopy and Precision Measurements with Low Systematic shift using a Trapped $^{88}Sr^{+}$ Single Ion

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ABSTRACT

For a number of years, one of the highest spectral resolutions with the lowest level of perturbation have been obtained using single, trapped, and laser cooled atomic ions [1]. A number of these systems have been studied as potential future optical atomic clocks and a few systems have been selected as secondary reference frequencies for the realization of the SI second. In addition, these systems represent a unique test-bed for studying subtle physical phenomena at the highest accuracy. We present recent results aimed at obtaining ultra-accurate measurements of the $^{88}Sr^{+}$ single-ion system. Using the developed NRC ultrastable probe laser system at 445 THz (674 nm), resolution of the single ion lineshape has been obtained below 5 Hz. Measured instabilities of the probe laser against the ion reference have shown a value of 5×10^{-16} at 3000 s averaging time [2]. Recently, a new miniature ion trap of the endcap design having a characteristic endcap spacing of 0.54 mm has been developed. Loading of the trap is performed solely using photo-ionization laser sources at 461 nm and 405 nm. This reduces the neutral atom flux on the trap

structure by three orders of magnitude compared to electron impact ionization, and significantly improves the stability of the system to maintain the ion with minimal Stark and time dilation shifts associated with ion micromotion. Minimization of the ion micro-motion along three orthogonal directions is now performed by observation using integrated total fluorescence via a photon counting photomultiplier and a photon counting CCD imaging camera. Continuous laser cooling and ion containment times of over 30 hr have now been achieved. Stable single ion signals of the order of 10^4 counts per second are observed using high collection efficiency optics with a signal to background ratio of > 50. We anticipate that the new trap will have uncertainties on the systematic shifts approaching 10^{-17} in the near term. Discussions on the evaluation of critical parameters such as micromotion induced shifts and blackbody radiation shift will be provided. The performance of the new system will allow the exploration of gravity's influence on the ion transition frequency at the sub-m level. In collaboration with a team from the Canadian Geodetic Survey Division, mapping of absolute gravitational force and a survey determination of the trap system above the earth's geoid are being performed in preparation for studies examining the system's contribution to International Atomic Time (TAI) and measurements of gravitational red-shift. An overview of the proposed measurement system will be presented at the meeting.

REFERENCES

[1] H. G. Dehmelt, IEEE Trans. Instrum. Meas. **IM-31**, 83 (1982).

[2] P. Dubé, A.A. Madej, J.E. Bernard, L. Marmet, and A.D. Shiner, Appl. Phys. B **95**, 43–54 (2009).

Guided transport of ultracold atomic gases of Rb up to a room-temperature dielectric surface

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Precise measurements of the interactions between an atom and a solid surface are of fundamental interest and may, in the future, set new limits on short range corrections to gravity due to exotic forces beyond the Standard model [1]. Ultracold atoms represent a new and elegant tool to probe atom surface interactions [2–4] as a result of the unprecedented control with which they can be manipulated. One approach is to study the reflection of atoms from the surface. In this context, small and well defined velocities of the atoms can be achieved using advanced laser cooling and launching techniques. Additionally, a controlled evanescent wave can be used to tailor the potential seen by the atom in the vicinity of the surface. Reflection of ultracold atoms in the ground state has been studied [2], exhibiting anomalous reflection. Our goal is to use a BEC with attractive interactions in the form of bright-matter wave solitons to perform reflection experiments from the surface. Their non-dispersing spatial extent may overcome the problem of anomalous reflection and, coupled with precise control of the velocity of the solitons, will enable a detailed study of the

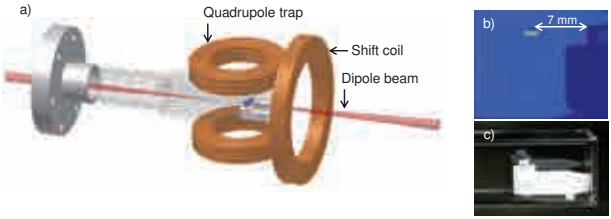

FIG. 1: a) Schematic of the experimental setup. A single dipole beam is delivered through the back surface of a glass prism. Axial confinement along the beam is provided by a magnetic quadrupole trap. A single coil positioned behind the prism is used to produce a bias field to shift the location of the quadrupole field zero. b) False colour absorption image of atoms trapped near the prism surface. The mount on which the prism sits is also shown. c) Photograph of the prism within the glass cell.

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atom-surface potential. Here we present a simple technique for the production of ultracold gases near a room temperature surface. Our approach involves guided transport of ultracold Rb atoms up to a room temperature surface in a hybrid trap using a dipole trap combined with a magnetic quadrupole trap.

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[1] *Probing submicron forces by interferometry of Bose-Einstein condensed atoms*, S.Dimopoulos, A.A.Geraci, Phys. Rev. D **68**, 124021 (2003).

[2] *Low Velocity Quantum Reflection of Bose-Einstein Condensates*, T. A. Pasquini, M. Saba, G.-B. Jo, Y. Shin, W. Ketterle, D. E. Pritchard, Phys. Rev. Lett. **97**, 093201 (2006).

[3] *Direct Measurement of Intermediate-Range Casimir-Polder Potentials*, H. Bender, Ph. W. Courteille, C. Marzok, C. Zimmermann, S. Slama , Phys. Rev. Lett. **104**, 083201 (2010).

[4] *Coherent Reflection of He Atom Beams from Rough Surfaces at Grazing Incidence*, Bum Suk Zhao, H. Christian Schewe, Gerard Meijer, Wieland Schöllkopf, Phys. Rev. Lett. **105** (133203) (2010).

Deceleration of neutral polar molecules in macroscopic traveling traps

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A decelerator is presented in which neutral polar molecules are guided and decelerated using the principle of traveling electric potential wells, such that the molecules are confined in stable three-dimensional traps throughout. The traps can be translated electronically to match the initial velocity of a molecular beam, and by increasing or decreasing the frequency of the applied waveforms, the traps and the molecules contained within them can be accelerated or decelerated [1].

Calculations indicate that the phase space acceptance at constant velocity is a factor of three higher than in the state-of-the-art switched Stark decelerator presented in reference [2]. The calculations also indicate that, during deceleration, the same relative phase space acceptance is maintained for an acceleration which is a factor of three higher. Time-resolved measurements of the transverse spatial distribution after the exit of the decelerator test the validity of these calculations and the influence of imperfections in the construction and the applied waveforms. Such measurements should also indicate how much of this phase space acceptance can practically be filled using the available molecular beam.

This decelerator is also ideally suited to the deceleration of molecules with a low rotational constant, such as heavy diatomic molecules. In the low rotational states of such molecules, the levels that are initially low field seeking undergo avoided crossings with levels from the next higher rotational state at relatively low electric field strengths and become high field seeking at stronger fields. In standard switched Stark decelerators, where the electric fields exceed 100 kV/cm, molecules in these states cannot be decelerated, but because the molecules in this decelerator never move into regions where the electric fields exceed 30 kV/cm, the molecules can remain low field seeking throughout the entire device. Efforts are underway to decelerate YbF and WC molecules, which are both of great interest for experiments searching for an electron electric dipole moment [3,4].

[1] A. Osterwalder *et al. Phys. Rev. A*, 81:051401(R), 2010
[2] L. Scharfenberg *et al. Phys. Rev. A*, 79:023410, 2009
[3] J. J. Hudson *et al. Phys. Rev. Lett.*, 89:023003, 2002
[4] J. Lee *et al. Journal of Modern Optics*, 56:2005–2012, 2009

MEMS-based Atomic Magnetometry Devices with 20 $fT_{rms}/\sqrt{Hz}$ Sensitivity

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We present an MEMS-based atomic optical magnetometer [1] based on optical pumping of alkali vapor in a micromachined silicon vapor cell. The cell is filled with ^{87}Rb and Nitrogen buffer gas and is heated to 430K to obtain atomic density of 10^{20} m^{-3}. The alkali vapor is then interrogated with a circularly polarized pump laser beam resonant with the D1 transition in ^{87}Rb. The magnetometer is operated in the so-called Spin-Exchange Relaxation Free (SERF) [2,3] regime. In this regime, the spin-exchange collision rate is higher than the Larmor precession frequency. This leads to very narrow magnetic resonances with FWHM line-widths of less than 50nT at operating temperatures of ~440K in our sensors.

We have demonstrated the sensitivity of the atomic magnetometer sensors of less than 20 $fT_{rms}/\sqrt{Hz}$ at 10Hz using the Single-beam SERF technique [4]. In this poster, we put forth a detailed analysis of the sensor physics and list the operating parameters. The technical and fundamental challenges to increasing the sensitivity and performance of the Single-beam SERF magnetometer are discussed. The construction of the sensor-head using fiber-optic light delivery and techniques for vacuum packaging the vapor cell in a miniature MEMS-based package of volume less than 1 cm^3 are presented. Lastly, we introduce a motion-insensitive, portable, high-sensitivity, multichannel magnetometry system concept based on the Single-beam SERF sensors. Such a system can provide a low-cost, high-performance solution to complement the measurements currently possible only using Superconducting Quantum Interference Devices (SQUIDs).

References:

[1] D. Budker and M. Romalis, Nature Physics **3**, 227 – 234 (2007).

[2] W. Happer and A. C. Tam, Phys. Rev. A **16**, 1877 – 1891 (1977).

[3] J.C. Allred, *et. al*., Phys. Rev. Lett. **89**, 130801 (2002).

[4] V. Shah, et. al., Nature Photonics **1**, 649 – 652 (2007).

High-order harmonic generation by intensity spikes in a filament

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The investigation of ultrafast processes relies on the production of light pulses with durations shorter than the process itself. The shortest pulses which are realized nowadays are of attosecond duration [1] and are synthetized from a coherent extreme-ultraviolet (XUV) spectrum provided via high-order harmonic generation (HHG) by few-cycle driver pulses. These few-cycle pulses are commonly produced by pulse compression in a hollow-core fiber with subsequent dispersion compensation [2]. In this contribution, we propose a new route to isolated attosecond pulse (IAP) production using a femtosecond filament. Our setup combines pulse compression, dispersion management and HHG in a single stage with simple and compact setup [3]. In addition, this novel method provides a highly nonlinear, localized probe for investigation of the filamentation process.

A femtosecond filament results from the balancing effects of Kerr self-focusing and defocusing from free electrons forming a high-intensity light channel which is sustained over distances longer than the natural diffraction limit [4]. Due to the ultrafast spatiotemporal reshaping of the propagating pulses in a filament, intensity spikes well above the equilibrium intensity can occur [5], as depicted in Fig. 1(a). These spikes are intense enough for HHG.

In our experiment, we create a filament using 35-fs, 0.8-mJ pulses loosely focused (f = 2 m) into a semi-infinite gas cell filled with 1 atm argon. The exit of the cell establishes a steep gradient from atmospheric to vacuum pressure to couple out high-order harmonic radiation generated inside the filament. Due to the small absorption length in atmospheric argon, the

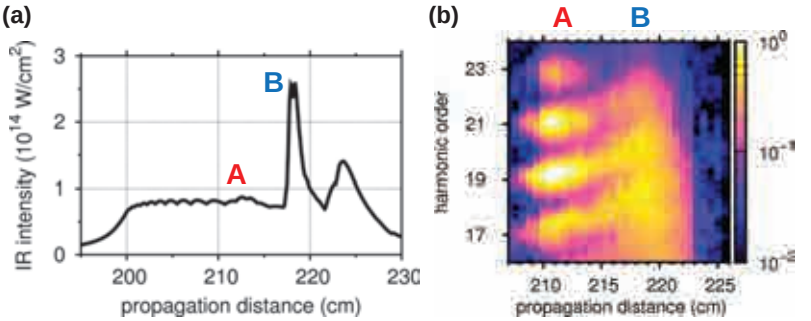

Fig. 1 (a) Calculated intensity evolution versus propagation distance inside a femtosecond filament with the occurrence of three intensity spikes. (b) Experimental harmonic spectra versus propagation distance in the filament. The harmonic intensity is encoded by the color. The two regions A and B of high yield are attributed to the corresponding intensity spikes in (a).

origin of harmonic radiation is close to the exit of the cell and can be scanned through the filament by translating the filament. Measured harmonic spectra versus the propagation distance in the filament are illustrated in Fig. 1(b). Two distinct regions (A, B) of high conversion efficiency are identified, and attributed to HHG by intensity spikes in the filament in agreement with numerical calculations (Fig. 1(a)). The first spike A produces a spectrum of resolved harmonics (Fig. 1(b)) corresponding to a multi-cycle pulse. The second spike B generates a continuous harmonic spectrum which suggests that it results from a nearly single-cycle pulse. This interpretation is supported by numerical calculations which predict that the continuous spectrum could be applied for the synthesis of IAPs with durations of 500 as, suggesting an innovative IAP source with simple and compact experimental setup.

References

[1] M. Hentschel, *et al.*, Nature **414**: 509 (2001).
[2] M. Nisoli, *et al*., Opt. Lett. **22**: 522 (1997)
[3] D.S. Steingrube, *et al.*, New J. Phys. **13**: 043022 (2011).
[4] A. Braun, *et al.*, Opt. Lett. **20**: 73 (1995).
[5] M.B. Gaarde and A. Couairon, Phys. Rev. Lett. **103**: 043901 (2009).

Superconducting Atom Chip towards Single-mode Atomic Waveguide

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Atom interferometer is expected to achieve many orders of improvement in phase sensitivity against the optical counterparts. Since the success of laser cooling, the wavelength of atomic matter-wave is enlarged and matter-wave interference is achieved with Bragg scattering of photons and/or micro-fabricated structures. An introduction of Bose-Einstein condensate also significantly improved the practicality of atom interferometers. Although these technical inventions improved the atom interferometry significantly, the sensitivity of atom interferometer is staying behind that of conventional technique for the difficulty in controlling the matter-wave propagation path coherently. For this reason, high sensitive reflection mirrors for atoms or a single mode atomic wave-guide is strongly desired.

A micro magnetic trap with superconducting materials, i.e. superconducting atom chip, is a practical candidate for realizing a sufficiently strong confinement for ultracold neutral atoms, which is necessary for the single-mode atomic waveguide. With a persistent current in a superconducting MgB_2 thin film circuit we have achieved a micro magnetic trap with a strong confinement. The maximum confinement so far achieved is larger than 100 kHz in radial direction with $I = 4.4$ A current and $B_y = 32$ mT. The temperature of the trapped atomic cloud is 30 μK, which is about an order above the single-mode regime.

This research was partly supported by JSPS KAKENHI "Grant-in-Aid for Scientific Research (B), MEXT KAKENHI "Quantum Cybernetics project", and JSPS FIRST Program "Quantum Information Processing Project".

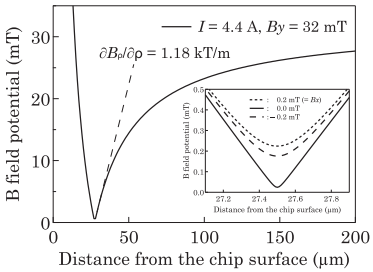

Figure 1: Calculated potential profile along the center of the trap with I = 4.4 A and B_y = 32 mT. The inset shows an expanded profile around the trap minimum.

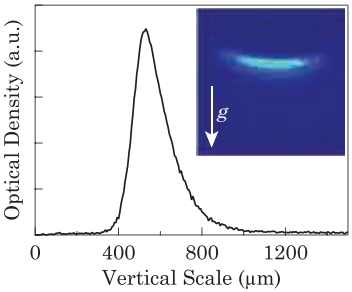

Figure 2: Absorption image of the atomic cloud released from the chip trap with $I = 4.4$ A and $B_y = 32$ mT.

Demonstration of a hybrid optical clock with lattice-confined ^{87}Sr atoms and a singly trapped $^{40}Ca^{+}$ ion

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Optical frequency standards are developed throughout the world to re-define the SI second. The fundamental configuration of most of these standards is a narrow-linewidth clock laser stabilized to a single ion trapped by suitable electric field or neutral atoms confined in an optical lattice, with a clockwork device for the counting and display. A single ion clock is anticipated to achieve the highest accuracy due to its environment free of perturbations by other particles and fields [1]. An optical lattice clock is promised to register the best stability because of its high signal-to-noise ratio (SNR) afforded by an ensemble with a large number of atoms [2]. Thus, one would expect to develop a combination technique that would allow obtaining an optical clock with their advantage. We have demonstrated a hybrid optical clock with ^{87}Sr atoms lattice-confined and a $^{40}Ca^{+}$ ion singly-trapped for:

1. characterization of the control topology
2. feasibility study of precise spectroscopies of different atoms using one "master" clock laser with assistance of a femtosecond laser frequency comb

A clock laser system of our hybrid optical clock consists of an ^{87}Sr lattice clock [3], a femtosecond Ti:sapphire laser frequency comb and a probe laser oscillating at 729nm, which serves as an ultrastable local oscillator to probe the narrow $^{2}S_{1/2}$-$^{2}D_{5/2}$ forbidden transition of $^{40}Ca^{+}$ ion. The master clock laser with the wavelength of 698nm is stabilized to a high finesse ULE cavity and the laser frequency is locked to $^{1}S_{0}$-$^{3}P_{0}$ transition of neutral ^{87}Sr confined in a 1D optical lattice, as shown in Fig.1. Its optical transition spectrum was resolved to be 20Hz linewidth (FWHM). The instability of our lattice clock was found to be $2 \times 10^{-14}/\tau^{1/2}$ from the comparison with the ^{87}Sr lattice clock at Tokyo University. The repetition rate of the self-referencing frequency comb is phase-locked to the master clock laser for bridging between the wavelength (698nm) and others without degradation. The 729nm probe laser is tightly locked to the one mode of the frequency comb; the linewidth of the master laser and instability of the lattice clock are retrieved on the probe laser. It is eventually stabilized to the optical clock transition of the laser-cooled single $^{40}Ca^{+}$ ion confined

in a radio-frequency Paul trap [4]. The frequency control signal extracted from the spectroscopy of $^{40}Ca^{+}$ ion is fed back to an acousto-optic modulator (AOM) placed between the master laser at 698nm and frequency comb to push and pull the frequency of the comb mode.

By probing the clock transition, we have obtained 40Hz linewidth atomic spectra, which are good agreement with those resolved by employing the fundamental configuration. The instability of the hybrid clock was measured by comparing with a cryogenic sapphire oscillator via another Ti:sapphire frequency comb, and it was 3×10^{-14} and 3×10^{-15} at 1s and 100s, respectively. From the operation of the hybrid clock, the clock laser system having a negligible frequency drift was also found to be suitable for the single ion clock, which requires a relatively long measurement cycle for probing pairs of the transitions and long integration period for obtaining its atomic spectra with better SNR. Although the accuracy of the current system is limited by that of $^{40}Ca^{+}$ ion, this combination technique applied to an alkaline-earth-like ion such as $^{27}Al^{+}$ and $^{115}In^{+}$ ion would provide a way to realize an optical clock with the stability and uncertainty of 10^{-18} level.

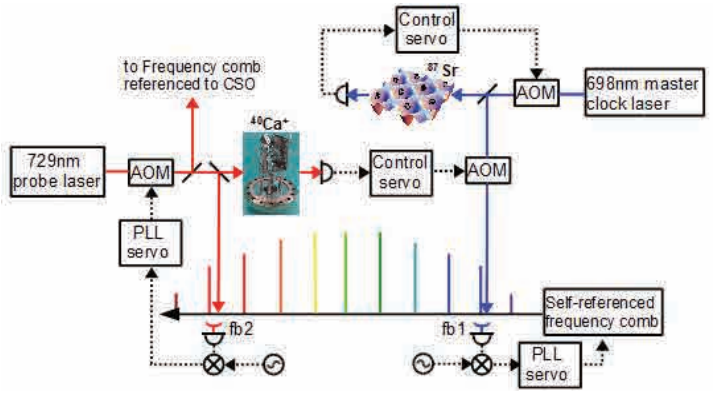

Fig. 1 Control topology of the hybrid optical clock.

[1] C. W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, and T. Rosenband, "Frequency Comparison of Two High-Accuracy Al+ Optical Clocks" Phys. Rev. Lett. **104**, 070802 (2010) .

[2] Y. Y. Jiang, A. D. Ludlow, N. D. Lemke, R. W. Fox, J. A. Sherman, L.-S. Ma, C. W. Oates, "Making optical atomic clocks more stable with 10^{-16} level laser stabilization" Nature Photonics, **5**, 158 (2011).

[3] A. Yamaguchi, N. Shiga, S. Nagano, H. Ishijima, M. Hosokawa and T. Ido "Optical Lattice Clock" 22nd International conference on Atomic Physics.

[4] K. Matsubara, K. Hayasaka, Y. Li, H. Ito, S. Nagano, M. Kajita, and M. Hosokawa, "Frequency Measurement of the Optical Clock Transition of $^{40}Ca^{+}$ Ions with an Uncertainty of 10^{-14} Level" Appl. Phys. Express, **1**, 067011 (2008).

Dark and Bright Optical Nanofibres for Cold Atom Experiments

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Optical nanofibres are narrow cylindrical waveguides fabricated from commercial optical fibre that is reduced in diameter using a heat-and-pull technique [1]. When used in a cold atom setup, they can be used either as dark or bright probes providing a method for determining typical cloud characteristics, such as profile, temperature, loading time and decay time, in a non-destructive way [2]. The nanofibre can also be used to study the spectroscopic behaviour of the trapped atoms.

To use the nanofibre as a dark probe (Fig. 1), we centre the waist region of the fibre, which is approximately 600 nm in diameter, in a cloud of approximately 10^8 ^{85}Rb atoms. The fluorescent photons from laser-cooled atoms in the vicinity of the fibre surface can couple efficiently into the guided modes of the nanofibre. By connecting a suitable low-light level detector to one end of the nanofibre, we can monitor the signal from the cold atomic cloud.

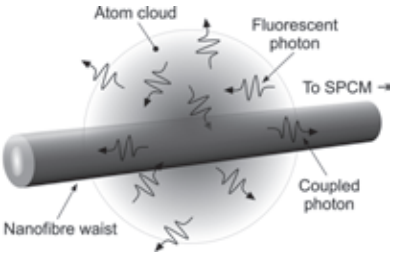

Figure 1: Schematic illustration of a 'dark' optical nanofibre probe. SPCM: Single photon counting module.

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A forced oscillation method [3] is used to measure the average cloud temperature above and below the Doppler limit (of 140 μK) for rubidium using a dark nanofibre. Despite the presence of the relatively hot fibre in the cloud of atoms, we observe temperatures as low as 90 μK.

In a further experiment, a frequency-scanned probe beam is launched through the nanofibre and the resonant light is absorbed at its waist by the atoms. The transmitted probe signal is measured using an avalanche photodiode. We present recent single-photon absorption results which demonstrate surface interaction effects and discuss future work on 2-photon absorption in the cold atomic system.

References

[1] J. Ward, D. O'Shea, B. Shortt, M. Morrissey, K. Deasy and S. Nic Chormaic, *Rev. Sci. Instrum.* **77**, 083105 (2006)

[2] M. J. Morrissey, K. Deasy, Y. Wu, S. Chakrabarti and S. Nic Chormaic, *Rev. Sci. Instrum.* **80**, 053102 (2009)

[3] P. Kohns, P. Buch, W. Süptitz, C. Csambal and W. Ertmer, *Europhys. Lett.* **22**, 517 (1993)

Simulation of trapped Bose-Einstein condensates using phase-space methods

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Atom interferometry is at the heart of many suggested future applications of ultracold atomic physics. Bose-Einstein condensates (BEC) or atom lasers have potential advantages as detectors or sensors, provided one can extract atomic phase information. However, unlike photons, atoms can interact rather strongly, causing dephasing. An intimate understanding of quantum many-body dynamics is essential in understanding the precise nature of interaction-induced dephasing in the measurement process. Progress in this technology therefore requires a quantitative theory of atom interferometry.

Coupled Gross-Pitaevskii equations (GPEs) are widely used to simulate the dynamics of BEC. This method is easy and relatively fast, and it allows one to obtain rather accurate predictions for the evolution of the cloud structure [1]. The problem is that this method produces incorrect results for low number of particles or long evolution times, since it neglects quantum noise. There are ways to improve GPE-based simulations, one of which is the inclusion of quantum noise terms via the Wigner representation.

A crucial issue which is important on the long time-scales of interferometry experiments is the decoherence caused by the effects of dissipation, including both linear and non-linear losses. We include these by means of local, Markovian master equation terms, which include the experimentally observed one-body, two-body and three-body loss coefficients. Two-body losses due to spin-exchange collisions are particularly significant in these experiments, which involve interference between the different hyper-fine levels in the ground state.

Next, we give a simple, yet quantitatively accurate theoretical approach to calculations of atom interferometry using the truncated Wigner representation, which includes both quantum fluctuations in the initial state, and additional quantum noise introduced through dissipation. This method extends the conventional GPEs describing a condensate to include quantum noise effects. The resulting quantum noise can be taken into account by writing the master equation for the condensate and transforming it into one of the quasi-probability representations, like positive-P [2, 3] or Wigner [2, 4]. The resulting equation can then be expressed as a set of stochastic equations, which can be solved numerically. We present the results of such simulations for several types of experiments on ^{8}7Rb condensates [5].

[1] R. P. Anderson, C. Ticknor, A. I. Sidorov, B. V. Hall, Phys. Rev. A, **80**:023603 (2009)

[2] M. J. Steel, M. K. Olsen, L. I. Plimak, P. D. Drummond, S. M. Tan, M. J. Collett, D. F. Walls, and R. Graham, Phys. Rev. A, **58**(6):48244835 (1998)

[3] J. J. Hope, Phys. Rev. A, **64**(5):053608 (2001)

[4] A. Norrie, R. Ballagh, and C. Gardiner, Phys. Rev. A, **73**:043617 (2006)

[5] M. Egorov, R. P. Anderson, V. Ivannikov, B. Opanchuk, P. D. Drummond, B. V. Hall, and A. I. Sidorov, arXiv:1012.3813 (2010)

Adiabatic Quantum Computing with Neutral Atoms

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Sandia National Laboratories

We are developing, both theoretically and experimentally, a neutral atom qubit approach to adiabatic quantum computing (AQC). It has been shown in [1,2] that neutral atoms trapped in optical far off- resonance traps (FORTs) can be used for two-qubit
gates using interactions mediated by electric-dipole coupling of a coherently excited Rydberg state. A similar neutral atom system is attractive for this work due to the long-term coherence of the qubit ground states, the potential of multi-dimensional arrays of qubits in FORT traps and the potential for strong, tunable interactions via Rydberg-dressed atoms [3]. If these arrays can be designed to encode a desirable computation into the system Hamiltonian one could use these tunable
interactions along with single-qubit rotations to perform an AQC. Taking full advantage of Sandia's microfabricated diffractive optical elements (DOEs), we plan to implement such an array of traps and use Rydberg-dressed atoms to provide a controlled atom- atom interaction in atomic cesium. We forecast that these DOEs can provide the functions of trapping,
single-qubit control and state readout resulting in an

important engineering stride for quantum computation with neutral atoms. We will develop this experimental capability to generate a two-qubit adiabatic evolution aimed specifically toward demonstrating the two-qubit quadratic unconstrained binary optimization (QUBO) routine. We are studying the two-qubit QUBO problem to test the immunity of AQC to noise processes in the control interactions as well as dissipation mechanisms associated with the trapping. We are developing our theoretical and experimental capabilities through key collaborations with The University of Wisconsin, NIST and The University of New Mexico.

References:

[1] L. Eisenhower *et al.*, "Demonstration of a neutral atom controlled- NOT quantum gate," Phys. Rev. Lett., **104**, 010503, (2010). [2] T. Wilk *et al.*, "Entanglement of two individual neutral atoms using Rydberg blockade," Phys. Rev. Lett., **104**, 010502, (2010). [3] J.E. Johnson and S. L. Rolston, "Interactions between

IMPROVED MEASUREMENT OF THE 1S-2S TRANSITION IN ATOMIC HYDROGEN

CHRISTIAN G. PARTHEY, ARTHUR MATVEEV, JANIS ALNIS, AXEL BEYER, NIKOLAI KOLACHEVSKY, THOMAS UDEM, AND THEODOR W. HÄNSCH

For the last five decades precision spectroscopy on atomic hydrogen along with hydrogen's calculable atomic structure have been fueling the development and testing of quantum electro-dynamics and have lead to the precise determination of the Rydberg constant and the proton charge radius. Furthermore, the outstanding precision in measuring the $1S - 2S$ transition has been used to set limits on a possible variation of fundamental constants and violation of Lorentz boost invariance. It promises a stringent test of the charge conjugation / parity / time reversal theorem by comparison with the same transition in anti-hydrogen.

Here, we present an improved measurement of the $1S - 2S$ transition with a fractional frequency uncertainty surpassing 5×10^{-15}. A careful analysis of the contributing systematic effects is presented. Among these, the second order Doppler effect and the quadratic ac Stark shift are dominating.

An Array of Integrated Atom Photon Junctions

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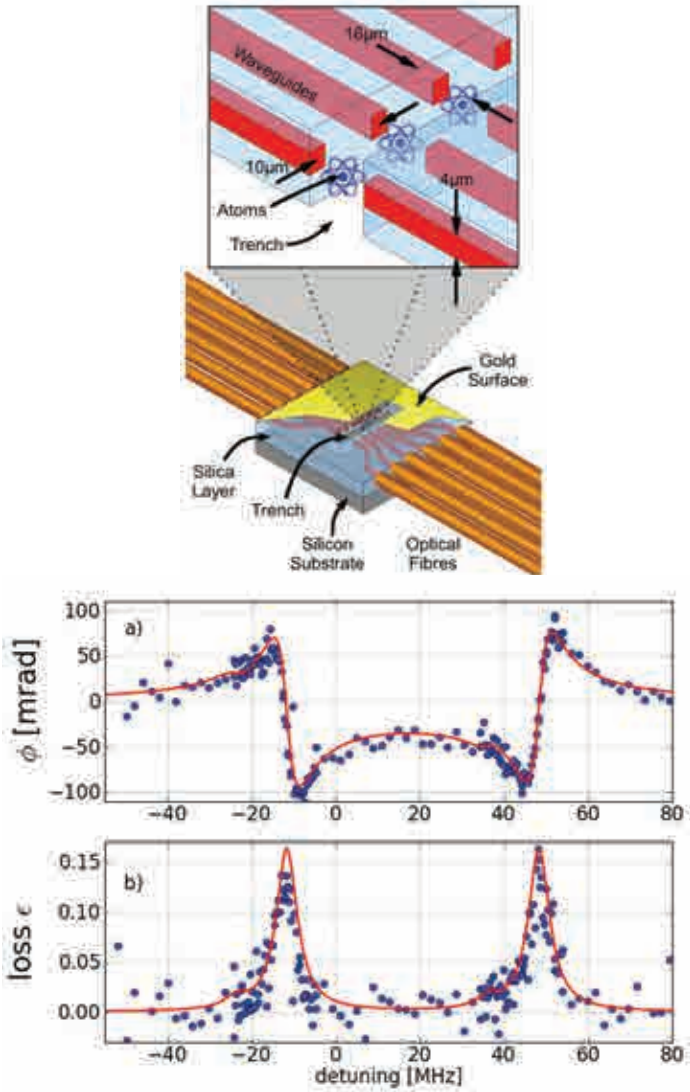
We have constructed a new kind of atom chip using integrated optical waveguide structures. There are 12 buried, single-mode optical waveguides in doped silica, connectorised using V-groove-mounted optical fibres. Light in the waveguides crosses a trench where it can interface with laser-cooled atomic samples (top figure). The waveguides are separated by just 10 μm at the interface, and the beam waist is 2.2 μm. The chip is integrated into a current-carrying sub-chip for magnetic trapping.

Launching cold atoms into the trench, we have used the absorption of light to demonstrate the presence of, on average, less than 1 atom crossing the mode of a waveguide [1]. One atom causes 2% absorption. We have also successfully used fluorescence detection. Conversely, we have used the atoms to probe the intensity and polarisation of the light. With a focused external fluorescence beam, we have imaged an excited-state cloud using the array of waveguides.

We have also developed a two-frequency interferometer to measure atomic density in a magnetic trap non-destructively using phase shifts (bottom figure) [2]. We achieve statistically limited phase noise down to about 700 photons/μs .Observed atomic loss rates conform to a simple rate model of photon scattering, and can be combined with the phase response to form a figure of merit: the more photons are used, the more sensitive the measurement, but the greater the loss. With the figure of merit, we show how to optimise such detection. Smaller beams make for better detection with less loss. We intend to use the technique to make real-time observations of BECs in the trench of the waveguide chip.



References

[1] M. Kohnen et al., *Nature Photonics* **5**, p35 (2011)

[2] M. Kohnen et al., *arXiv:1104.0236v1*

Coherent Rydberg excitation in microscopic thermal vapor cells

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Abstract: We show that coherence times of ~ 100 ns are achievable with coherent Rydberg atom spectroscopy in micrometre-sized thermal vapour cells making them robust and promising candidates for scalable quantum devices like single-photon sources.

OCIS codes: 020.5780 Rydberg states; 270.1670 Coherent optical effects

The coherent control of mesoscopic ensembles of atoms and Rydberg atom blockade are the basis for proposed quantum devices such as integrable gates and single-photon sources [1]. To date, impressive experimental progress has been limited to ultracold atoms [1]. Here, we show that coherence times of ~100 ns are achievable with coherent Rydberg atom spectroscopy in micrometre-sized thermal vapour cells [2]. We investigate coherent phenomena like Rabi oscillations to the Rydberg states by pulsed excitation on the nanosecond time scale. Our results demonstrate that microcells with a size on the order of the blockade radius (~2 μm), at temperatures of 100–300 °C, are robust and promising candidates for investigating low-dimensional strongly interacting Rydberg gases, constructing quantum gates and building single-photon sources. We present our fabrication technique for microstructured vapor cells [3] and discuss future directions.

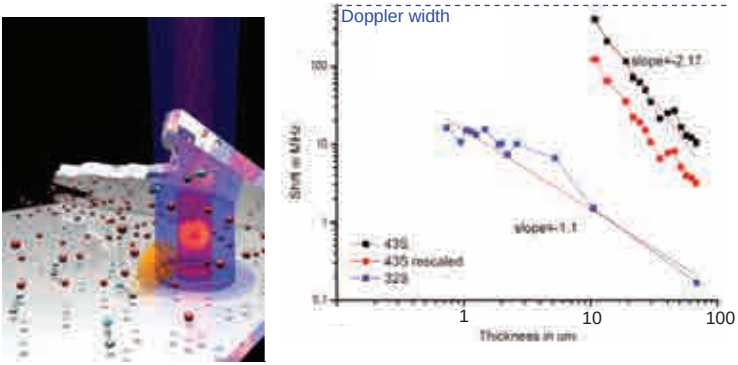

Fig. 1: Rydberg atoms are excited in thermal Rb vapor confined in a wedge cell by narrow band two photon excitation (left). As the atoms interact with the wall the spectroscopic lines shift and broaden (right). For 43 S state the broadening reaches the Doppler width at cell thicknesses of ~ 10 micrometer. Choosing a state which avoids polariton resonances in the confining material this effect can be drastically suppressed. For the 32 S state cell thicknesses down to 1 micrometer shift and broaden the line only by ~20 MHz (right). For comparison the 43S data is rescaled to the 32S situation by their dipolar coupling strength to the surface.

[1] M. Saffman, T. G. Walker, and K. Molmer, "Quantum information with Rydberg atoms´´, *Reviews of Modern Physics* **82**, 2313 (2010) and references therein.
[2] H. Kübler, J. P. Shaffer, T. Baluktsian, R. Löw, and T. Pfau, "Coherent Excitation of Rydberg Atoms in Thermal Vapor Microcells", *Nature Photonics* ***4****, 112 (2010)*
[3] T. Baluktsian, C. Urban, T. Bublat, H. Giessen, R. Löw, and T. Pfau, "Fabrication method for micro vapor cells for alkali atoms" *arXiv:1002.121, Opt. Lett.* ***35****, 1950 (2010)*

Vibrational quantum defect for long range molecules spectroscopy. Coupling detection in Rb_2 and Cs_2 series.

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In the context of cold molecule formation, many routes have been discovered, for example using the photo-association process via a long range excited molecular state. In addition if this state is coupled with another one having a large wavefunction at short range, it results a correct Franck-Condon factor, and so decay to a vibrational ground state.

One of the aims of high resolution photo-association spectroscopy near the dissociation limit is to find such excited states. For that a careful analysis of spectroscopic data is required.

Using the method of the vibrational quantum defect coupled to the Le Roy Bernstein energy law, we are able to detect and quantify coupling between nearly resonant states belonging to different series. Examples are given for Rb_2 and Cs_2 series.

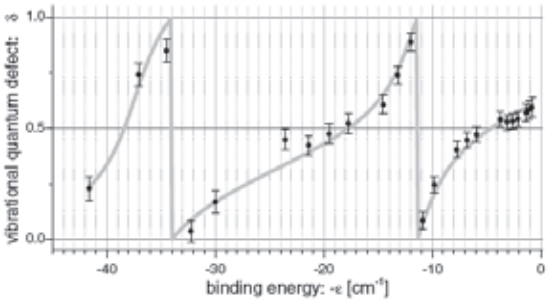

Fig. 1 Analysis of Cs_2 $(6s\text{-}6p_{1/2})0_g^-$: vibrational quantum defect versus energy, and the fitting curve using a coupled series model. Figure of reference 3.

[1] H. Jelassi, B. Viaris de Lesegno and L.Pruvost., Phys. Rev. A **74** p. 012510 (2006).
[2] H. Jelassi, B. Viaris de Lesegno, and L. Pruvost, M. Pichler, W. C. Stwalley, Phys. Rev. A **78**, 022503 (2008).
[3] L. Pruvost and H. Jelassi, J. Phys. B: At. Mol. Opt. Phys. **43**, 125301 (2010).

Cold atoms in Laguerre-Gaussian laser beams

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A Laguerre-Gaussian (LG) laser mode, blue-detuned from the atomic resonance, constitutes a power-law trap for cold atoms because the laser intensity profile varies as $r^{2\ell}$, where ℓ is the order of the LG mode.

We have shown that very accurate LG modes can be generated from a usual Gaussian mode, and applying a phase-hologram with a spatial light modulator and that they can be used to guide cold atoms [1]. The effect which has been experimentally studied versus the order of the mode and the laser detuning, has been quantitatively interpreted by a 2D-capture model.

LG modes or deformed LG modes [2] could be used for other applications, where specific traps are required. For example, a Bose-Einstein condensate realized in a power-law trap is expected to have different properties than the condensate in a harmonic trap [3]. Condition for condensation is less severe and the condensate would be homogeneous.

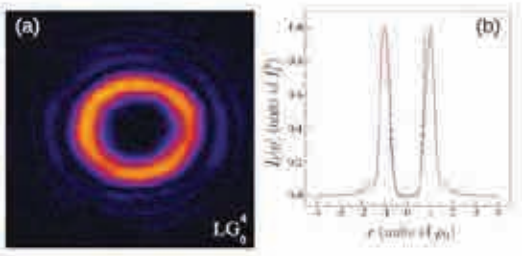

Fig. 1 Holographically-generated Laguerre-Gaussian mode with ℓ=4, and the intensity profile, fitted by a r^8 law near the center.

[1] M. Mestre, F. Diry, B. Viaris de Lesegno, L. Pruvost, Eur. Phys. J. D **57** 1 87-94 (2010).
[2] F Diry, Ch Hazera, B. Viaris de Lesegno, L. Pruvost, "Generation and propagation of polygonal-deformed LG modes by using phase-only holograms", in preparation
[3] A. Jaouadi, N. Gaaloul, B. Viaris de Lesegno, M. Telmini, L. Pruvost, and E. Charron, "Bose-Einstein condensation in dark power-law laser traps", Phys. Rev. A **82**, 023613 (2010).

Interferometry with BEC in extended free fall

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We present a status report about interferometry with extended wave packets at nK energy scales. Motivation is performing tests and measurements of gravity with quantum objects. The experiments reported here use a chip- based atom laser. Measuring the universality of propagation of matter waves touches the foundations of quantum mechanics and one of the pillars of general relativity: Einsteins Equivalence Principle.

Experiments with a fiber-based optical dipole trap for cold Cs-Atoms

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Pulling a standard optical fiber to a diameter of less than the wavelength of the guided light causes the light field to propagate to an essential fraction outside of the fiber as an evanescent wave. This can be used for light-matter interactions in the vicinity of the surface of the fiber.

In our setup, a silica fiber with a diameter of 500nm is used to implement a dipole trap potential for cold cesium atoms with a depth of a few hundred μK, located about 200nm above the surface of the fiber [1]. Here, the trapping potential is created by the superposition of two detuned evanescent light fields, which are coupled into the fiber: The red-detuned field at 1064nm exerts an attractive force onto the atoms towards the fiber, whereas the blue-detuned light field at 780nm prevents them from hitting the fiber surface. In order to confine the atoms not only radially, but also axially the red-detuned trapping light is coupled in from both sides, creating a standing wave along the fiber. This leads – together with the azimuthal confinement due to the azimuthal intensity distribution of the evanescent field of the linear polarized lights – to two one-dimensional optical lattices above and below the fiber in which the atoms are trapped. Typically, 2x2.2mW for the red-detuned light and 25mW for the blue-detuned light are used in this configuration and result in a trap depth of about 400μK and trapping frequencies of about 200kHz, 315kHz, and 140kHz in the radial, axial, and azimuthal direction.

After loading the atoms from a six-beam magneto-optical trap, the transmission of a weak probe beam, launched through the fiber, is used to detect the atoms inside the fiber trap. At resonance, each atom absorbs about 1.5% of the probe light via evanescent field

coupling, yielding a high optical density of up to 30 for about 2000 atoms. Furthermore, the birefringence induced by the arrangement of the trapped atoms above and below the fiber allows us to perform an interferometric measurement of the optical phase shift due to the trapped ensemble [2]. We demonstrate that the off-resonant measurements of this kind are non-destructive with respect to the number of trapped atoms.

Additionally, based on the high optical density, our setup is ideally suited for performing non-linear-optics experiments. Adding a coupling light field into the fiber allows us to coherently prepare the atomic ensemble. First measurements of the Autler-Townes-Effect, showing a splitting of 6MHz with only 30nW of pump power, as well as first preliminary data of electromagnetically induced transparency in the trapped ensemble are presented. These results open the route towards the manipulation and storage of light with coherently prepared fiber-coupled atomic ensembles. Potential applications include fiber-coupled quantum memories and quantum repeaters as well as many-body physics with light-matter quasi-particles.

Finally, we present calculations showing that a fiber-based atom trap allows one to straightforwardly realize extraordinary trapping geometries which are not easily accessible with freely propagating laser beams [3].

References

[1] E. Vetsch, D. Reitz, G. Sagué, R. Schmidt, S. T. Dawkins, and A. Rauschenbeutel, „Optical interface created by laser-cooled atoms trapped in the evanescent field surrounding an optical nanofiber", Phys. Rev. Lett. **104**, 203603 (2010)
[2] S. T. Dawkins, et al., to be submitted
[3] D. Reitz, et al., to be submitted

Multispecies kinetic theory of cavity-mediated cooling and selforganisation

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We present a kinetic theory of several different species of polarisable particles in a transversally-pumped high-Q standing-wave resonator. Within the framework of Vlasov theory (continuous phase space distribution for large particle numbers we determine the instability condition for the homogeneous phase for a fixed set of velocity distributions of the various types of particles.[1] Whereas for a single species the ratio of potential- to kinetic energy needs to be bounded for stability to prevail, in the many-species case it is the *sum* of the individual ratios which has to satisfy this very bound. Therefore, instability is the easier to achieve the more species are involved.

Neglecting statistical fluctuations as well as the field mode input noise, Vlasov's equations allow for an infinite number of stable solutions, no matter whether homogeneous or selforganised. As a remedy to this unphysical degeneracy we include $\sim 1/N$ corrections to obtain selfconsistent, coupled nonlinear Fokker-Planck equations for the phase space distributions of the different species. Their most general equilibrium solution below instability threshold is the q-Gaussian distribution (also called Tsallis distribution), leading e. g. to the Gaussian or the Lorentzian velocity distributions as special cases. The final temperature reached by cavity cooling is limited by half of the cavity linewidth, giving us a dissipation-induced selforganisation condition. If the latter is satisfied, the selforganised phase is reached even if the ensembles are initially stable and the final temperature is modified by the trap frequency. [2]

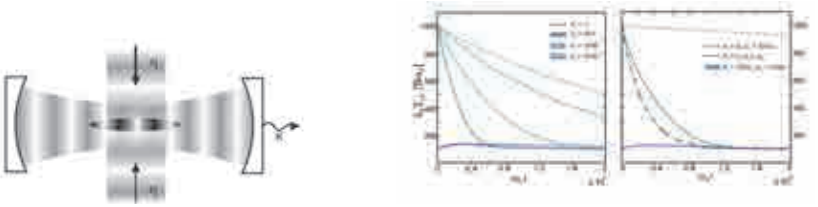

Figure 1: *a) Scheme of particles in a cavity b) Sympathetic cooling of two species*

The work was supported by the Austrian Science Fund FWF (P20391 and F4013).

[1] A Vlasov approach to bunching and selfordering of particles in optical resonators, T. Grießer, H. Ritsch, M. Hemmerling, and G. R. M. Robb, Eur. Phys. J. D **58**, 349 (2010).

[2] P. Domokos and H. Ritsch, Phys. Rev. Lett. **89**, 253003 (2002)

A Microchip Decelerator for Polar Molecules

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The manipulation of polar molecules using the electric fields created by the microscopic electrodes of a microchip is a new and fascinating research field. Microscopic electrodes allow for the creation of large field gradients, i.e. large forces for polar molecules, using only moderate voltages applied to the electrodes. The position of the molecules above a microchip can be controlled with a very high precision. In addition, present-day microelectronics technology makes it possible to integrate multiple tools and devices onto a compact surface area, like lenses, decelerators and traps for polar molecules but also integrated detection elements like radiation sources and optical cavities. All these features make microchip-based devices appealing for experiments on cold molecules under well-controlled conditions. Typical number densities of molecules on a chip are comparable to the densities in macroscopic decelerators but the absolute numbers are still quite low. However, new results in the suppression of loss mechanisms from the microtraps and new chip designs promise intresting improvements in this sense.

Spinor and polar lattice gases

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Institut für Theoretische Physik
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Spinor gases, with various available Zeeman states, and polar gases, with significant or even dominat dipole-dipole interactions, constitute two interesting scenarios for novel physics in ultra-cold gases. In this poster I will present some of our recent works on spinor and polar gases in deep optical lattices. I will on one hand discuss ground-state phases of one-dimensional strongly-correlated spin-3/2 fermions and spin-1 bosons in optical lattices, as well as a possible idea of how to use high-spin fermions to cool spin-1/2 lattice fermions. In a second part I will briefly present recent results on polar lattice gases, including inter-layer superfluidity of fermions in bilayers, entanglement-spectrum properties of the Haldane-insulator phase in one-dimensional polar lattice bosons, spontaneous soliton filamentation in stacks of coupled one-dimensional dipolar BECs, and non-locally induced losses for reactive polar molecules in bilayers.

Towards direct frequency comb spectroscopy using quantum logic

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QUEST Institute for Experimental Quantum Metrology
Physikalisch-Technische Bundesanstalt Braunschweig
and Leibniz University Hannover

We present a versatile spectroscopy apparatus for single trapped atomic and molecular ions with a complex level structure. The lack of a closed cycling transition in these species prevents direct laser cooling and the observation of laser induced fluorescence. The first challenge is solved by sympathetic cooling the external motion of the spectroscopy ion to the absolute ground state by a simultaneously trapped magnesium logic ion. Spectroscopy and repumping from meta-stable states will be performed using a stabilized frequency comb emitting all required optical frequencies. If the comb is resonant with an atomic transition, photons will be scattered, imparting a recoil on the ion crystal for each absorption and emission event. For the parameters in our system, ~10 scattered photons will excite a quantum of motion of the common normal mode. This can be detected with high efficiency on the magnesium ion, providing the spectroscopy signal. We will present numerical simulations of this *photon recoil spectroscopy* for calcium ions. Alternative methods using a cw spectroscopy laser and quantum logic techniques for more complex ions, such as Ti^+ and Fe^+, will be discussed. With the presented system, we will determine isotope shifts of the transition frequencies of these ions, which will help to improve the analysis of quasar absorption spectra for a possible variation of the fine-structure constant [1].
Cooling to the ground state of motion is a requirement of the presented spectroscopy protocols. We therefore present cooling results using a single-source laser system, which consists of a frequency-quadrupled fiber laser that provides all required frequencies for cooling, detection and coherent manipulation of the magnesium logic ion [2].

[1] J. C. Berengut, V. A. Dzuba, V. V. Flambaum, J. A. King, M. G. Kozlov, M. T. Murphy, and J. K. Webb, Arxiv Preprint arXiv:1011.4136 (2010).
[2] B. Hemmerling, F. Gebert, Y. Wan, D. Nigg, I. V. Sherstov, and P. O. Schmidt, arXiv:1010.5664 (2010).

RESONANT MULTIPHOTON IONIZATION OF AROMATIC MOLECULES REVEALED BY INTENSITY RESOLVED IMAGING

J. Strohaber, F. Zhu, R. Nava, N. Hart, F. Pham, A. A. Kolomenskii, H. Schroeder, G. G. Paulus and H. A. Schuessler

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We present experimental results for the ionization of aromatic molecules subjected to intense, ultrashort laser pulses. Measurements of molecular ions were performed using a recently developed technique capable of three-dimensional imaging of ion distributions within the focus of a laser beam [1]. By selecting ions originating from the central region of the focus, where the spatial intensity distribution is nearly uniform, volumetric-free intensity-dependent ionization yields were obtained [2]. The measured data revealed a previously unseen resonant-like multiphoton ionization process. We attribute the kink in the data to stepwise ionization

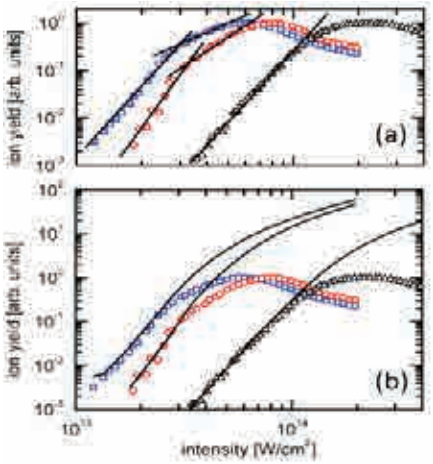

Figure 1. Intensity dependent ion yields: ion yields of aniline (blue squares), benzene (red circles) and xenon (black triangles); (a) ion yields of aniline exhibit a slope of 5 to 2, ion yields of benzene have a slope of 6 to 3 and those of xenon do not show a change in slope. (b) integrated ion yields over a focal volume demonstrate why conventional TOF setups could not have revealed the resonant like behavior in the ion yields curves for aniline and benzene.

through an intermediate state which is characterized for aniline and benzene by changes in the power dependencies. Comparison of benzene, aniline and Xe ion yields demonstrate that the observed intensity dependent structures are not due to geometric artifacts. In the case of aniline, a new "S_2" electronic state is independently discovered.

We used focused sub-50-femtosecond 800-nm pulses, and because (800 nm)/3=266 nm we can access the phenyl S_1 and new "S_2" states with 3 photons in benzene and aniline respectively . The inherently larger bandwidth of femtosecond pulses makes our experiment less sensitive to the exact excitation energy of the S_1 level than in earlier nanosecond work. Another distinctive feature of the present research is found in the high optical pumping rates of ultrashort pulses. These pulses promote efficient parent ion formation of the molecules by exceeding the dissociation/predissociation rates that frustrated parent ion formation for nanosecond pulses and allows the resulting parent ions to be identified with and ion mass spectrometer. To the best of our knowledge, ion yields as a function of peak intensity for ultrashort, 800-nm pulses have only been reported for benzene, but not for aniline molecules. We will point out why the setups used in these previous benzene experiments could not have shown the now revealed resonant enhanced multiphoton ionization (REMPI) aspect of these molecules.

This research is supported by the grants of the Robert A. Welch Foundation (No. A1546), MURI DOD (No.W911NF-07-1-0475) and the National Science Foundation (Nos. 0722800 and 0555568).

References

1. J. Strohaber, C. J. G. J. Uiterwaal, Phys. Rev. Lett. **100**, 023002 (2008).
2. J. Strohaber, A. A. Kolomenskii, and H. A. Schuessler, Phys. Rev. **A 82**, 013403 (2010).

GENERATION OF HIGH HARMONICS IN ARGON: PRESSURE AND ENERGY DEPENDENCIES AND INFLUENCE OF METAL CLUSTERS

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Development of new ultrafast sources of coherent electromagnetic radiation, extending to the XUV spectral range, stimulates interest to high harmonic generation (HHG) process in noble gases. In this process the atoms subjected to intense laser pulses are ionized. The freed electrons oscillate in the incident radiation field and with certain probability recombine with the gas atoms, giving rise to short bursts of electromagnetic radiation, which occur each half a period. Consequently, HHG takes place, which contains mostly odd harmonics. We observed this phenomenon in Ar gas with amplified pulses from a T:Sapphire laser system with a pulse duration 50fs at center wavelength 800nm. The gas jet was formed by a thin metal (Ni) tube with holes produced by the incident laser radiation. The pressure in the middle of the interaction region was about 100 mbar and decreased on both sides of the jet as Ar was ejected in vacuum. The generated high harmonics extended to 29th order (Fig. 1) and were well separated for the used pulse, which contained about 20 periods of the fundamental field. We observed strong dependences of the output of the harmonics on the pressure in the gas jet and the presence of the chirp in the pulse. The energy of the pulses at the fundamental wavelength was varied from 0.5 mJ to 5mJ with corresponding range of laser intensities from 5×10^{14} to 5×10^{15} W/ cm^2. For energies about 0.5 mJ a single amplification stage at 1kHz was employed, and for higher pulse energies a 10Hz laser system with two stages of amplification was used. The observed intensity of high harmonics was increasing with the pump

power in the range of energies used. Estimates show that an efficiency of about 10^{-6} for conversion into XUV radiation was reached.

The conversion efficiency was enhanced manyfold when the gas was mixed with metal clusters and plasma [1] formed during the ablation of the metal tube. In this case also a formation of a broad continuum spectrum was observed. While it was demonstrated that high harmonics exhibit high degree of coherence, the coherent properties of the continuum spectrum are unknown and are the subject of the current investigation. It is pointed out that the effects of highly ionized Ar [2] can be important at high intensities and also the electron recombination with non-parent ions [3] can be responsible for the observed generation of a continuum spectrum.

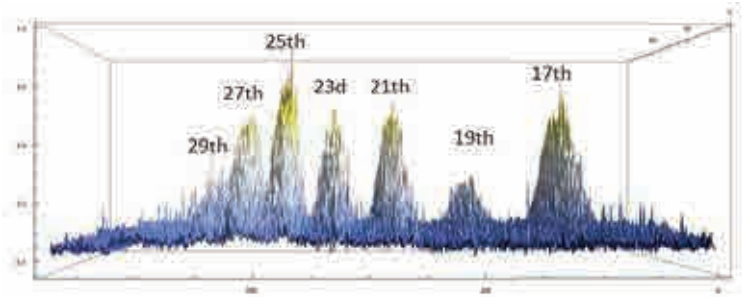

Fig. 1. Observed spectrum with numbers showing orders of high harmonics.

We gratefully acknowledge support by the grants from the Robert A. Welch Foundation (No. A1546), MURI DOD (No.W911NF-07-1-0475) and the National Science Foundation (Nos. 0722800 and 0555568).

References

1. R. A. Ganeev, Laser Physics **18**, 1009 (2008).
2. E. Gibson, et al. Phys. Rev. Lett. **92**, 033001 (2004).
3. S. Ghimire et al. Nature Physics **7**, 138 (2011)

A CRYOGENIC SYSTEM TO SEPARATE KRYPTON TRACERS FROM WELL GASES FOR ULTRA-SENSITIVE COLLINEAR FAST BEAM LASER SPECTROSCOPY

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The noble gas ^{85}Kr is a long lived radio-isotope ($T_{1/2}$=10.7 years) which is being used as a tracer in petroleum reservoirs, since it does not occur naturally and is not subject to chemical or biological reactions. Here we shortly describe our laser spectroscopy apparatus [1] and then present our method for pre-separation of krypton tracers in the well gas samples and measuring krypton isotope ratios.

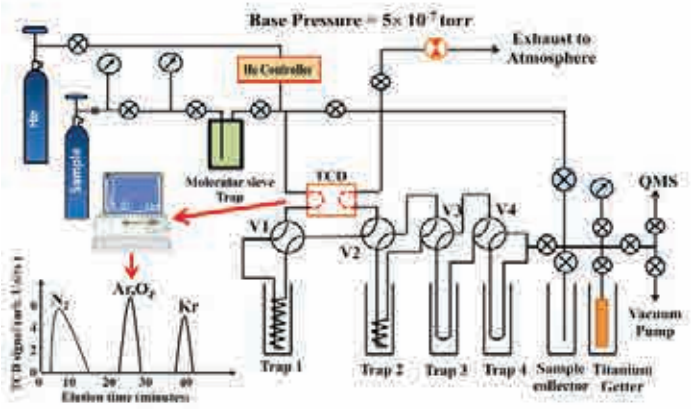

Figure 1. Schematic diagram of the krypton separation system (QMS: Quadrupole Mass Spectrometer; V: 4- ways valve; TCD: Thermal Conductivity Detector).

For this purpose we constructed a portable apparatus for collecting, separating, and enriching of krypton. The device is based on cryogenic trapping of the gases at liquid nitrogen temperatures in consecutive traps. In particular, the apparatus depicted in Fig.1 consists in the first stage of a molecular sieve trap for the elimination of H_20 and CO_2, followed in later stages by several charcoal traps for the collection of krypton and other gases and three stages of gas chromatography to achieve separation and purification of krypton from mainly N_2, O_2, and Ar. Finally small amounts of residual N_2 and other reactive gases still remaining after the third stage of chromatography are removed with a hot Ti sponge getter trap.

A thermal conductivity detector is used to monitor the characteristic elution times of the various components of condensed gases in the traps after warming them gradually from liquid nitrogen to boiling water temperatures. The eluting gases are observed as peaks which allow us to optimize the switching time of the valves between the three stages of gas chromatography in such way that mainly krypton is selected and loaded to the next stages, while removing the other gases to an exhaust using pure He gas for transportation. The krypton separation efficiency is determined using a quadrupole mass spectrometer. A compilation of results will be given for a variety of gas samples taken from petroleum reservoirs and from ambient air.

This research is supported by the Qatar Foundation under the NPRP grant 30-6-7-35.

References

1. R. Nava, H. Schuessler, M. Fahes, and H. Nasrabadi, and A. Kolomenskii, SPE Annual Technical Conference and Exhibition, 4-7 October 2009, New Orleans, Louisiana, SPE 124689.

FAST ION BEAM PRECISION LASER SPECTROSCOPY OF ARGON II IN COLLINEAR AND ANTI-COLLINEAR GEOMETRIES REFERENCED TO A FREQUENCY COMB

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Collinear fast ion beam laser spectroscopy is instrumental for precision absolute frequency measurements. The advantages of the collinear fast beam technique are that it is Doppler-free, and that it introduces an artificial isotope shift, convenient for separation of spectra from different isotopes, which overlap at zero acceleration voltage. The reduction of the Doppler width in the collinear fast beam method is achieved by narrowing the velocity spread of the accelerated ions due to velocity bunching, and the artificial isotope shift has its origin in different velocities of the various isotopes after acceleration. Spectral lines of Ar II ions were measured in parallel and antiparallel geometries of the laser and the ion beams, allowing to retrieve the absolute frequency of the spectral transitions with an exact relativistic expression, namely the square root of the product of the frequencies measured in these collinear and anticollinear configurations [1]. To provide a reference for the laser wavelength, iodine saturation spectroscopy was used. The precision of laser spectroscopy was obtained by observing the beat note between the spectroscopy laser and the corresponding line of a femtosecond laser frequency comb. The fitting of fluorescence line shapes by a Voigt spectral profile, and the error of the measurement are discussed.

This method was employed to measure the transition frequency between the Ar II metastable state $^2G_{7/2}$ and the excited $^2F_{5/2}$ state with the relative transition frequency error 6×10^{-10}.

Typical measured fluorescence lineshapes and positions of the beat notes with the frequency comb are shown in Fig. 1. Figure 2 shows the transition frequencies obtained at different acceleration energies and with almost simultaneous measurements in collinear and anticollinear geometries to reduce the influence of ion source and acceleration voltage instabilities. The data showed close values in the transition frequency, which was determined to be

$$\nu_0 = 485, 573, 619.7 \pm 0.3\text{MHz}.$$

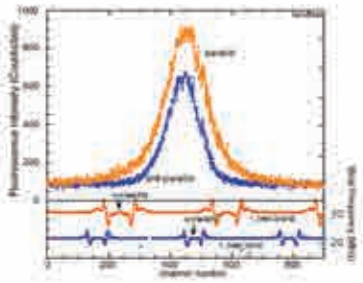

FIG. 1. Laser induced fluorescence spectra of an $^{40}Ar^+$ ion beam with collinear and anticollinear laser radiation. The absolute laser frequencies are obtained from the beat frequencies with the frequency comb.

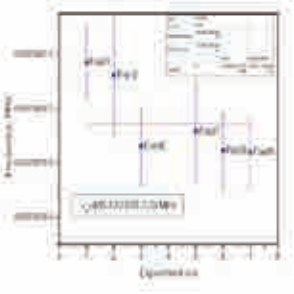

FIG. 2. The frequencies of Ar II $^2G_{7/2}$ - $^2F^0_{5/2}$ transition measured in six independent experimental runs. Voigt line shape was used for fitting.

The obtained accuracy of the transition frequency is a two orders of magnitude improvement compared to previous results [2].

This work is supported by the grants of the Qatar National Research Fund NPRP 30-6-7-35, the National Science Foundation No. 0722800, by the Grants-in-Aid for Scientific Research from the JSPS, by the President's Special Grant of RIKEN, and by the Robert A. Welch Foundation under grant A1546.

References

[1] G. Borghs et al., Opt. Commun. **38**, 101 (1981).
[2] Yu. Ralchenko et al., http://physics.nist.gov (2008).

Metastable Helium Vacuum Gauge

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Standard vacuum gauge uses electrons to ionize residual gas in the vacuum chamber. Typical electron energy is 100eV, and more than 10^{16} electrons are injected in the chamber every seconds. Huge number of electrons and its relatively high energy causes disturbance to ion counts limiting the sensitivity to the order of 10^{-12} torr.

We propose to use laser-cooled metastable helium atoms in the $2s^3S$ state for ionizer instead of electrons. The metastable helium atom has internal energy of 20eV and can ionize any gas except for the ground state helium. It can be kept in the vacuum chamber up to its lifetime of 8000s, which is many orders magnitude longer than the holding time of electrons emitted from the gauge filament. Therefore, very small number of helium atoms will be sufficient to detect high vacuum. The $2s^3S$ helium atom decays to the ground state in space by emitting a spontaneous VUV photon. It may emit a Penning electron if it hits the chamber wall. However, those disturbances should be negligibly small.

By introducing slow metastable helium atoms in a vacuum chamber of 10^{-7} to 10^{-10} torr through a pinhole from a magneto-optical trap, we are currently measuring the ionization and total cross-sections of various gases. From our preliminary cross-section data we estimate that we can measure the vacuum of 10^{-14} torr range in a chamber of several litters which is continuously pumped with the speed of 10 l/s. By magnetically trapping helium atoms the system should be able to measure the mass separated partial pressure using time of flight technique.

This work is partly supported by the grant from Matsuo Foundation.

MAGIC for Trapped Ions

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With trapped ions unsurpassed control of the quantum degrees of freedom of individual particles has been achieved [1]. When contemplating the scalability of trapped ions for quantum information science one notes that the use of laser light for *coherent manipulation* gives rise to fundamental and technical issues [2,3,4]. Recently, laser-less addressing of ions in a magnetic field gradient and Magnetic Gradient Induced Coupling (MAGIC) between ion spins and their motion [5] using radio-frequency radiation has been demonstrated.

We report on the first demonstration of essential features of a trapped ion "molecule" that exhibits spin-spin interactions, due to MAGIC, analogous to J-coupling between nuclear spins in molecules: The coupling strength has been measured as a function of the trapping frequency using two $^{171}Yb^{+}$ ions. Single spins of such an individual pseudo-molecule are addressed and coherently manipulated using microwave radiation. Importantly, these measurements have been carried out with thermally excited ions with a mean quantum number of 50 ± 21 characterizing the excitation of the COM axial mode.

Another line of experiments with trapped $^{171}Yb^{+}$ ions shows that the use of microwave-dressed states as qubits stabilizes them against magnetic field fluctuations and, thus, enhances their coherence time by more than two orders of magnitude [6]. Importantly, these dressed states retain their sensitivity to magnetic gradients and are thus useful for MAGIC. Furthermore, this scheme allows for conditional quantum gates whose performance is not limited by a small Lamb-Dicke parameter (LDP) in microwave- or laser-based schemes. This will allow for reducing the necessary magnitude of a magnetic field gradient (that gives rise to an effective LDP) in microwave-based schemes. Or, viewed differently, with a given LDP η the speed of conditional quantum dynamics can be increased by a factor $1/\eta$. This generic scheme should be applicable to other physical systems, too.

References

[1] R. Blatt, and D. Wineland, Nature **453**, 1008-1015 (2008).
[2] R. Ozeri, et al., Phys. Rev. A **75**, 042329 (2007).
[3] F. Mintert, C. Wunderlich, Phys. Rev. Lett. **87**, 257904 (2001); ibid. **91**, 029902 (2003); C. Wunderlich in *Laser Physics at the Limit*, pp. 261- 271 (Springer, 2002); C. Wunderlich, C. Balzer, Adv. At. Mol. Opt. Phys. **49**, 293-376 (2003).
[4] C. Ospelkaus et al, Phys. Rev. Lett. **101**, 090502 (2008).
[5] M. Johanning et al Phys. Rev. Lett. **102**, 073004 (2009)
[6] N. Timoney et al., arXiv:1105.1146 (2011).

New insights offered by Penning ionizations into optically trapped metastable ^{4}He atoms - Juliette Simonet, Jerome Beugnon, Michele Leduc - *Laboratoire Kastler-Brossel, 24 rue Lhomond, 75005 Paris*

We will present prospective experiments involving metastable Helium atoms (He^*) confined into optical potentials. The large internal energy allows for fast and efficient detection of these atoms on electron multipliers (channeltron or MCP).
It also makes metastable atoms intrinsically fragile and difficult to manipulate since any atomic collision may lead to losses due to Penning ionization:

$$\begin{aligned} He^* + He^* &\rightarrow He + He^+ + e^- \quad (1) \\ &\rightarrow He_2^+ + e^- \quad (2) \end{aligned}$$

The collision rate of this reaction is of the order of 10^{-10} cm^3·s^{-1}, which prevents to achieve the large atomic densities characterising a degenerate gas. However, for Helium, if the colliding partners are spin polarized, the Penning ionization is inhibited as the electronic spin is not conserved between the initial and final states.

In a dipole trap, the magnetic field being a free parameter, its influence on inelastic collision rate constants can be experimentally determined. Following the study of Fedichev *et. al.*[1], we present a new theoretical evaluation integrating the latest

[1] Fedichev, *Phys. Rev. A*, 53, 1447 (1996).

molecular potential available[2]. Such a measurement could provide new informations on the interatomic potential of the $^5\Sigma_g^+$ electronic state.

The deep trapping potential produced by a 1D optical lattice at Λ= 1560 nm allows to reach the strong confinement regime, freezing the atomic motion along one direction. In this reduced dimensionality, both elastic and inelastic collisions are modified and present interesting signature. A prospective study demonstrates that quasi-2D collisional effects could be measured on inelastic Penning collision rates.

The study of strongly correlated many-body systems has motivated many experimental studies. A remarkable example in one dimension is the Tonks-Girardeau (TG) gas, where bosons with strong repulsive elastic interactions minimize their interaction energy by avoiding spatial overlap and hence acquire fermionic properties[3]. He* atoms into a 3D optical lattice also permit to enter a strongly correlated regime. The large Penning inelastic collisions result indeed in a stabilization of the system, suppressing double occupancy of lattice sites and inhibiting the losses (similar effect than in one dimension[4]).

[2]Przybytek, *Journal of Chemical Physics*, 123(13), 134315 (2005).
[3]Paredes, *Nature*, 429, 277 (2004).
[4]Syassen, *Science*, 320, 1329 (2008).

The Calcium BEC at PTB

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Due to their coherence, quantum degenerate gases offer many advantages for precision experiments. Especially, alkaline earth atoms with their non-degenerate ground states and the absence of hyperfine structure are promising candidates for applications in atom interferometry and precision experiments based on sub-Hz spectroscopy.

Despite the large s-wave scattering length of ^{40}Ca of approximately $350a_0$ - $700a_0$ and the correspondingly large three body loss we have achieved Bose-Einstein condensation both in a crossed and in a single-beam optical dipole trap.
For further manipulation of the scattering length, optical Feshbach resonances will be employed. Because of the narrow intercombination line of calcium, optical Feshbach resonances with low inelastic loss rates are expected. In an ongoing experiment the necessary information on the molecular levels near the $^1S_0$-$^3P_1$ asymptote will be obtained by photoassociation spectroscopy.

Our work is supported by the Centre for Quantum Engineering and Space-Time Research (QUEST).

High precision absolute frequency measurements of hyperfine levels of potassium isotopes for $4s\ ^2S_{1/2} \rightarrow 6s\ ^2S_{1/2}$ two photon transition

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Precise knowledge of certain optical frequencies is important for applications in spectroscopy, metrology, in the determination of the fundamental constants and industrial applications. The recent developments in the 1S–2S spectroscopy of muonium with an all-solid-state laser system based on a frequency tripling scheme have led to interest in finding a suitable reference in the region of 730–732 nm, which is about 1⁄6th of the 1S–2S transition interval. In this context, the potassium two-photon transitions such as $4s\ ^2S_{1/2} \rightarrow 6s\ ^2S_{1/2}$ and $4s\ ^2S_{1/2} \rightarrow 6s\ ^2D_{3/2,5/2}$ seem to be ideal candidates as they could be directly linked to hydrogen [1]. We have recently measured isotope shift, hyperfine splittings and absolute frequency for the potassium isotopes for the $4s\ ^2S_{1/2} \rightarrow 6s\ ^2S_{1/2}$ two photon transitions [2]. The isotope shift and hyperfine splittings were measured with sub MHz accuracy. However, the absolute frequencies of the hyperfine components of the ^{39}K and ^{41}K transitions were measured with accuracy of $\pm$ 10MHz using continuous calibration method of wavemeter. In the present work, we have improved the accuracy of the absolute frequencies measures to the tune of 50 KHz using the high resolution Fabry-Perot interferometer. The details of the work will be presented.

References:

1) Yi-Wei Liu and P E G Baird, “Two-photon spectroscopy in potassium,” Meas. Sci. Technol. 12, 740–743 (2001).
2) P.V. Kiran Kumar and M.V. Suryanarayana, “Isotope shift and hyperfine structure measurements of 4s 2S1/2 → 6s 2S1/2 two-photon transition of potassium isotopes”, J. Phys. B: At. Mol. Opt. Phys. 44, 055003 (2011)

Mott Insulator of Multi-component Fermi Gases of Ytterbium in Optical Lattices

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Ultracold atomic gases provide unique opportunity to investigate quantum many-body physics in a novel controlled manner. Fermi gases in optical lattices are especially interesting from the viewpoint of quantum simulation of solid-state electronic systems. Recently, the realization of a Mott insulator of fermionic alkali atoms was reported [1, 2] and experiments proceed toward observation of ordered phases in lattices, which requires further cooling.

We report the first realization of a novel multi-component Mott insulator of atomic Fermi gases in 3D optical lattices using ytterbium (Yb) atoms. The absence of electronic spin in the ground state of Yb atoms gives rise to the novel SU($2I$+1) spin symmetry for their fermionic isotopes with nuclear spin I [3, 4]. Such a high spin symmetry has been difficult to realize in real condensed matter, in spite of much theoretical interest.

We realize the SU(6) symmetric Hubbard system by loading a

degenerate gas of ^{173}Yb (I=5/2) into an optical lattice. In order to verify the formation of Mott insulating region in the optical lattice, we employ the photoassociation method [5, 6], which enables us to measure doubly occupied lattice sites (double occupancy). Significant reduction of double occupancy due to the strong repulsive interaction is observed. In addition, we prove the existence of the Mott gap by observing the resonant enhancement of double occupancy after the periodic modulation of the lattice depth at the frequency close to the on-site interaction [1].

We also observe the Pomeranchuk cooling in optical lattices. During the lattice loading, larger entropy – ln(6) per atom – is absorbed by spin, which results in further cooling compared to the usual SU(2) case [3, 7]. The large growth rate of double occupancy during the lattice modulation [8] indicates the formation of the stable Mott plateau near the trap center.

References

[1] R. Jördens *et al*., Nature **455**, 204 (2008).
[2] U. Schneider *et al*., Science **322**, 1520 (2008).
[3] M. A. Cazalilla *et al*., New J. Phys. **11**, 103033 (2009).
[4] A. V. Gorshkov *et al*., Nature Phys. **6**, 289 (2010).
[5] T. Rom *et al*., Phys. Rev. Lett. **93**, 073002 (2004)
[6] S. Sugawa *et al*., arXiv:1011.4503 (2010).
[7] K. R. A. Hazzard, *et al*., arXiv:1011.0032 (2010).
[8] D. Greif *et al*., Phys. Rev. Lett. **106**, 145302 (2011).

Negative Group Velocity and Meta-optics for Mater-waves

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Similarities and differences between light and matter-wave optics originate in the properties of the associated particle. Since the seminal paper of V.G. Veselago [1], many works have been devoted to optical negative-index media (NIM) and their properties (negative refraction, perfect focussing, etc.). Such artificial media are essentially characterised by a negative value of the optical index, i.e. the reversal of the wave vector with respect to the Poynting vector. What should be the "de-Broglie optics" equivalent of those meta-materials ? For matter waves, the direction of the phase velocity, i.e. wave vector, remains unchanged ; one has to reverse v_g, i.e current density of probability which is the atomic counterpart of the energy flux of light optic. Obviously, such an effect is necessarily transient, so our approach relies on both position- and time-dependent magnetic potentials.

We have shown that a novel class of potentials - "*comoving*" potentials [2] - provides us with a remarkably simple solution to devise negative-index media for matter waves [3]. The calculation of the induced matter-wave phase-shift demonstrates the possibility of producing transient negative group velocities for the atomic wave packet (see figure 1). With an adequate time-dependence of the co-moving field, we can devise cylindrical or spherical "*metalenses*". This phenomenon is due to a narrowing of the wave packet transiently counterbalancing the natural spreading. This is the manifestation of a general property of NIM, i.e. a time reversal effect [4]. This extension of "meta-optics" down to the nanometer wavelength range opens novel applications in atom nano-lithography and interferometry.

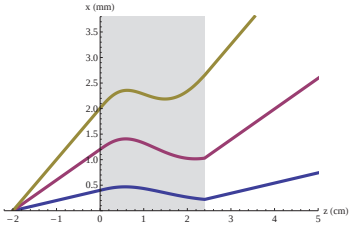

FIGURE 1 – Trajectory of the wave packet center in a comoving potential

A sequence of comoving magnetic potential pulses can induce a new type of slowing technique [5]. Each pulse reduces the velocity by a small but significant amount and it is shown that, by repeating the process two thousands times, the velocity can be lowered from several hundreds m/s down to zero. In the absence of any random recoil process, the initial characteristics of the beam (taking in account purely kinematical effects), as angular aperture, velocity dispersion, etc. should be preserved.

References

[1] V.G. Veselago, Sov. Phys. Usp. **10**, 509 (1968)
[2] R. Mathevet *et al.*, Phys. Rev. A **61**, 033604 (2000)
[3] J. Baudon *et al.*, Phys. Rev. Lett. **102**, 140403 (2009)
[4] M. Hamanda *et al.*, Eur. Phys. J. D **61**, 321 (2011)
[5] M. Hamanda *et al.*, to be published

Fiber-coupled single ion as an efficient quantum light source

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The interaction of light and single atomic particles is of great interest from both a fundamental and an application point of view. In ion-trap science, an efficient coupling between light and ions is beneficial for quantum state detection. Furthermore cavity-QED with trapped ions would realise a deterministic quantum information network [1]. On the other hand, incorporating optical elements in an ion-trap structure to enhance the coupling is challenging, since the presence of dielectrics can affect the trapping potential adversely. An elaborated design of shielding is required to minimise detrimental effects to ions. Therefore only a small number of successful implementations of integrated optics in an ion trap have been reported [2].

We have realized a novel compact system which combines a miniature ion trap with optical fibers [3]. Our trap is of the endcap type. By replacing the central rods with hollow tubes and inserting multimode optical fibers, a single ion is in effect trapped in the gap between the two opposing fiber endfacets (Figure 1). Retracting the fibers by 50 μm makes the overlap between the dielectric fibers and the trapping rf-field negligible. Additionally we confirmed that there is no evidence of charge accumulation on the fiber endfacets by using a single trapped ion as a sensitive probe for stray fields. This demonstrates convincingly the compatibility of ion trapping and optical fiber technology.

Each fiber captures light from an ion with a numerical aperture of 0.34, corresponding to 6% of the full solid angle in total. Resonance fluorescence photons from a trapped ion detected through the fibers show anti-correlated arriving times. This is due to the fact that single ions can only emit a single photon at a time. As shown in Figure 2, the normalised second order correlation function $g^{(2)}(\tau)$ shows strong anti-bunching at $\tau = 0$, attesting to the quality of our system as a single photon source.

Our results show that the endcap-trap geometry is an ideal way to accomodate dielectric optical elements in an ion trap and that it is possible to store a single ion reliably for extended times while keeping it coupled to the fibers. The current setup can be upgraded to a cavity QED experiment by replacing the bare fiber ends with concave and mirror-coated endfacets forming a fiber cavity [4]. The high stability of trapped ions and the small mode volume of a fiber cavity make such a configuration very attractive for realising a deterministic cavity-QED system with strong coupling.

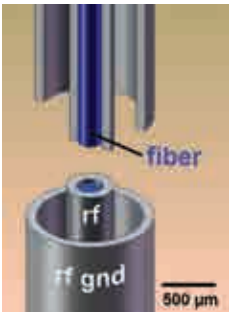

Figure 1: Endcap trap with integrated optical fibers. Half of the upper electrode structure is cut away to reveal the upper fiber.

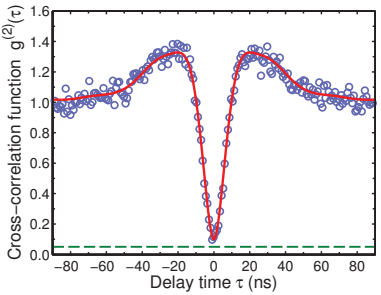

Figure 2: Normalised cross-correlation $g^{(2)}(\tau)$ of photon arrival times at the end of the two fibers.

References

[1] M. Keller, B. Lange, K. Hayasaka, W. Lange, and H. Walther, "Continuous generation of single photons with controlled waveform in an ion-trap cavity system," *Nature* **431**, 1075 (2004).

[2] A. P. VanDevender, Y. Colombe, J. Amini, D. Leibfried, and D. J. Wineland, "Efficient fiber optic detection of trapped ion fluorescence," *Physical review letters* **105**, 23001 (2010).

[3] A. Wilson, H. Takahashi, A. Riley-Watson, F. Orucevic, P. Blythe, A. Mortensen, D. R. Crick, N. Seymour-Smith, E. Brama, M. Keller, and W. Lange, "Fiber-coupled single ion as an efficient quantum light source," *arXiv:1101.5877*.

[4] Y. Colombe, T. Steinmetz, G. Dubois, F. Linke, D. Hunger, and J. Reichel, "Strong atom-field coupling for Bose-Einstein condensates in an optical cavity on a chip." *Nature* **450**, 272 (2007).

T40

Methods for Sympathetic Cooling of Polar Molecules with Ultracold Atoms

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Ultracold polar molecules could be used to simulate strongly interacting quantum systems with well-controlled interactions. To make this possible, methods for cooling polar molecules to ultra-low temperatures are needed, the more general the better. The association of ultracold atoms to form heteronuclear molecules and the direct laser cooling of molecules [1] are limited to just a few species.

Sympathetic cooling of trapped polar molecules with ultracold atoms could be a very general method for cooling. We present numerical simulations of sympathetic cooling in various traps and conclude that a microwave trap offers the best prospects for efficient cooling [2]. In this trap the polar molecules are trapped in an electric field maximum of a microwave field inside a cavity, as proposed in [3]. The molecular cloud is then overlapped with an atomic cloud in a magnetic trap. Since the molecules are trapped in the ground state, losses due to inelastic collisions are suppressed. We have built a high-finesse Fabry-Perot microwave cavity for molecule trapping experiments, and we present a characterisation of the coupling behaviour and quality factor of this cavity.

This trap should be suitable for trapping a wide range of molecules. We have developed a cold, supersonic source of CH molecules which are ideal for Stark deceleration, trapping and cooling experiments. We compare the performance of various CH sources that we have built and tested.

[1] E. S. Shuman, J. F. Barry and D. DeMille. “Laser cooling of a diatomic molecule”, *Nature* **467**, 820-823

[2] S. K. Tokunaga, W. Skomorowski, P. S. Zuchowski, R. Moszynski, J. M. Hutson, E. A. Hinds and M. R. Tarbutt “Prospects of sympathetic cooling of molecules in electrostatic, ac and microwave traps”, Eur. Phys. J. D (in press); arXiv:1012.5029v2

[3] D. DeMille, D. R. Glenn and J. Petricka, “Microwave traps for cold polar molecules*”, Eur. Phys. J. D* **31**, 375 (2004)

RKR-potential for B-state in molecular iodine

Roelant Van Dierendonck

– no abstract available –

Nondestructive measurement and Bose-Einstein condensation in a crossed high-finesse optical cavity

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State-of-the-art atomic detectors such as clocks [1] or inertial sensors [2] have reached the standard quantum limit given by the atomic shot-noise. To go further, the sensitivity can be enhanced either increasing the number of atoms, or reducing the effect of quantum noise. In this context, atomic spin-squeezed states (SSS) [3] have been recently achieved [4–8], and they allowed sensitivity enhancement in atomic clocks [9, 10].

In the purpose of preparing measurement induced SSS we developed a nondestructive heterodyne measurement scheme based on the frequency modulation spectroscopy technique [11]. The main advantages of such a technique is its high rejection of path length fluctuations and its ability to easily reach the shot-noise limit of a weak optical probe thanks to the beating with a strong reference beam. We designed a photodetector limited to the optical shot-noise for an incident power of 500 μW at a beatnote frequency of 2 GHz. We used the detection to nondestructively follow in real-time both Rabi oscillations and a spin-echo sequence [12].

In order to reach a high amount of squeezing, a high optical density is necessary. We thus build an dipole trap, based on standard telecom technologies. Thanks to the optical field enhancement induced by a resonator, a trapping optical power of ~ 250 W can be obtained with only 5 W of incident power at 1550 nm. The arms of the cavity are crossed to keep high trapping frequencies in all spatial dimensions, the beam waist at the crossing point is ~ 100 μm. The geometry of the cavity has been checked *in-situ* using the light-shift tomography technique [13], Fig. 1. About 30.10^6 atoms of ^{87}Rb are trapped and the lifetime is ~ 7 s (limited by the residual pressure of the high vacuum chamber).

We performed evaporative cooling in the trap. When evaporating by simply reducing the optical power we were limited to a phase-space density of a few 10^{-2} since the frequencies at the end of the ramp were too low (~ 50 Hz) which collapses the collision rate. To overcome this problem a dimple was added in the vertical direction in a very similar way that [14]. Even with a low 200 mW optical power in the dimple, the 20 μm waist allows us to keep a transverse frequency of 550 Hz. With such a setup we reach the Bose-Einstein condensation (BEC) after a ramp of 3 s. The BEC contains about 10^4 atoms, the transition temperature is ~ 100 nK, and the final average trap frequency is 250 Hz.

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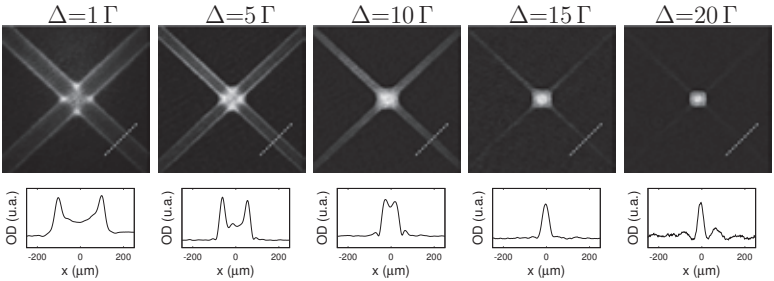
FIG. 1: (Top) Tomographic images of the optical potential setting the probe frequency to different detuning with respect to de D_2 line. (Bottom) Integral optical density obtained by projecting the upper images on the 45 dashed line crossing one arm of the cavity.



[1] G. Santarelli, P. Laurent, P. Lemonde, A. Clairon, A. G. Mann, S. Chang, A. N. Luiten, and C. Salomon, Phys. Rev. Lett. **82**, 4619 (1999).
[2] A. Gauguet, B. Canuel, T. Lévèque, W. Chaibi, and A. Landragin, Phys. Rev. A **80**, 063604 (2009).
[3] M. Kitagawa, M. Ueda, Phys. Rev. A **47**, 5138 (1993).
[4] M. H. Schleier-Smith, I. D. Leroux, and V. Vuletiċ, Phys. Rev. Lett. **104**, 073604 (2010).
[5] J. Appel, P. J. Windpassinger, D. Oblak, U. B. Hoff, N. Kjaergaard, and E. S. Polzik, Proc. Natl. Acad. Sci. USA **106**,10960 (2009).
[6] J. Estève, C. Gross, A. Weller, S. Giovanazzi, and M. K. Oberthäler, Nature **455**, 1216 (2008).
[7] M. F. Riedel, P. Bohi, Y. Li, T. W. Hänsch, A. Sinatra, and P. Treutlein, Nature **464**, 1170 (2010).
[8] Z. Chen, J. G. Bohnet, S. R. Sankar, J. Dai, and J. K. Thompson , Phys. Rev. Lett. **106**, 133601 (2011).
[9] A. Louchet-Chauvet, J. Appel, J. J. Renema, D. Oblack, N. Kjaergaard, and E.S. Polzik, New J. Phys. **12**, 065032 (2010).
[10] I. D. Leroux, M. H. Schleier-Smith, and V. Vuletiċ, New J. Phys. **12**, Phys. Rev. Lett. **104**, 250801 (2010).
[11] T. Vanderbruggen, S. Bernon, A. Bertoldi, A. Landragin, and P. Bouyer, Phys. Rev. A **83**, 013821 (2010).
[12] S. Bernon, T. Vanderbruggen, R. Kohlhaas, A. Bertoldi, A. Landragin, and P. Bouyer, arXiv:1103.1722, submitted to New J. Phys.
[13] A. Bertoldi, S. Bernon, T. Vanderbruggen, A. Landragin, and P. Bouyer, Opt. Lett. **35**, 3769 (2010).
[14] D. Jacob, E. Minoun, L. De Sarlo, M. Weitz, J. Dalibard, and F. Gerbier, arXiv:1104.1009.

Spontaneous demagnetization of a dipolar chromium BEC at ultra low magnetic field

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Several quantum phases are predicted for Bose Einstein condensates made of atoms with a non zero spin, known as spinor condensates. These phases originate from the dominant Van der Walls contact interactions, which are spin-dependent. In the case of alkali atoms, the quantum phases were studied for a constant magnetization, and emerge from an interplay between contact interactions and the quadratic Zeeman effect.
In the case of chromium, the magnetic dipole-dipole interactions are much larger. While they can be neglected for the quantum phase diagram, they allow the magnetization of the condensate to change, so that the linear Zeeman effect comes into play. At "normal" fields, the ground state is ferromagnetic, but for experimentally-challenging low magnetic fields a phase transition to a non-ferromagnetic phase is expected.
We experimentally study the absolute ground state of a spin-3 chromium condensate at magnetic field below 1 mGauss. We evidence a phase transition between a ferromagnetic phase and an unpolarized phase, when the magnetic field is quenched below a critical value Bc. Comparing experiments with a bulk BEC and with an array of 1D quantum gases, we show that Bc depends on the density of the degenerate cloud, and we measure values for Bc in agreement with theoretical predictions. We also show that the magnetization dynamics is governed by magnetic dipole-dipole interactions, and elaborate a simple model to account for the timescale of the demagnetization process at the lowest fields.
Our work opens up the experimental study of quantum magnetism with free magnetization using ultracold atoms.

Optimal trapping wavelengths of Cs_2 and RbCs molecules in an optical lattice

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The present work aims at finding optimal parameters for trapping of Cs_2 and RbCs molecules in optical lattices, with the perspective of creating a quantum degenerate gas of ground-state molecules. We have calculated dynamic polarizabilities of Cs_2 and RbCs molecules subject to an oscillating electric field, using accurate potential curves and electronic transition dipole moments. We show that for some particular wavelengths of the optical lattice, called "magic wavelengths", the polarizability of the ground-state molecules is equal to the one of a Feshbach molecule. As the creation of the sample of ground-state molecules relies on an adiabatic population transfer from weakly-bound molecules created on a Feshbach resonance, such a coincidence ensures that both the initial and final states are favorably trapped by the lattice light, allowing optimized transfer in agreement with the experimental observation.

Hyperfine structure of Cs_2 and RbCs excited molecules

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Unlike ground state alkali-metal diatomics, very little is known about the hyperfine structure of excited electronic states. We present a preliminary analysis of the expected structure of the rovibrational levels of the Cs_2 and RbCs excited electronic states correlated to the lowest $^2S+^2P$ limit based on an asymptotic model for the hyperfine Hamiltonian [1]. We set up potential curves built on long-range atom-atom interaction connected to short-range ab-initio results obtained in our group. The hyperfine structure strongly depends on the projection of the total angular momentum of the molecule, and on the sum of projections of of the total angular momentum of the separated atoms. The comparison with the experimental data recorded in Innsbruck [2] will be presented. The possible interaction of electronic states at short distances due to hyperfine coupling is discussed.

[1] D. Comparat, et al, Eur. Phys. J. D 11, 59 (2000)
[2] J.G. Danzl et al Faraday Disc. 142, 283 (2009)

Laser cooling of atoms by collisional redistribution of fluorescence

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The general idea that optical radiation may cool matter was put forward by Pringsheim already in 1929 [1]. Doppler cooling of dilute atomic gases is an extremely successful application of this concept, and more recently anti-Stokes fluorescence cooling in multilevel systems has been explored in solids. Collisional redistribution of fluorescence is a proposed different cooling mechanism that involves atomic two-level systems [2], though experimental investigations in gases with moderate density have not reached the cooling regime. We have experimentally demonstrated cooling of an atomic gas based on collisional redistribution of fluorescence, using rubidium atoms subject to 200 bar of argon gas pressure [3]. The frequent collisions in the ultradense gas transiently shift a far red detuned laser beam into resonance, while spontaneous decay occurs close to the unperturbed atomic resonance frequency. During each excitation cycle, a kinetic energy of order of the thermal energy $k_B T$ is extracted from the dense atomic sample. We presently achieve cooling in a heated gas from an initial temperature of 410°C down to -120°C temperature in the laser beam focus[4] and explore cooling with high power laser diode stacks. The cooled gas has a density of more than 10 orders of magnitude above the typical values in Doppler cooling experiments. Future prospects of the demonstrated technique can include cryocoolers and the study of homogeneous nucleation in saturated vapour.

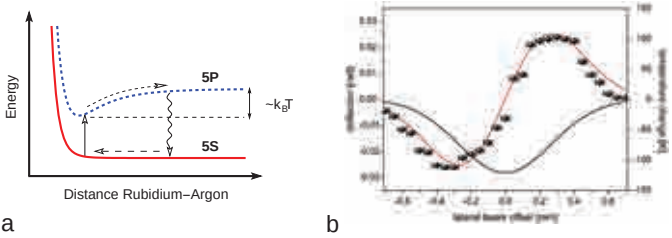

Figure 1: *(a) Simplified scheme of rubidium energy levels during collisions with a buffer gas atom and the cycle of laser cooling by collisional redistribution. Strongly red detuned photons can be absorbed, when a perturber atom approaches the rubidium atom. Reemission is most probable for unperturbed atoms. (b) Deflection spectroscopy signal and derived temperature profile in a laser cooled potassium vapour with argon buffer gas.*

[1] P. Pringsheim, Zeitschrift für Physik **57**, 739 (1929).
[2] P. R. Berman and S. Stenholm, Optics Communications **24**, 155157 (1978).
[3] U. Vogl and M. Weitz, Nature **461**, 70 (2009).
[4] A. Saß, U. Vogl and M. Weitz, Appl. Phys. B **102**, 503 (2011).

Quantum Image Processing and Storage with Four-Wave Mixing

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Quantum correlations and entanglement in multi-mode squeezed fields have recently gained much interest, and can have which have applications in quantum information, quantum imaging, and quantum computing. We use a nondegenerate four-wave mixing process in Rubidium vapor at 795 nm to demonstrate generation of entangled images and multi-mode output beams [1,2,3]. Transferring the quantum correlations from the light to atoms in order to generate correlated atom beams is another interesting prospect. We have built a compact four-wave mixing source of squeezed light, using semiconductor lasers only, for use in such experiments. To allow for the generation of higher multi-mode images we investigate also the use of high power alkali-laser as a high power pump source for the generation of squeezed twin-beams.

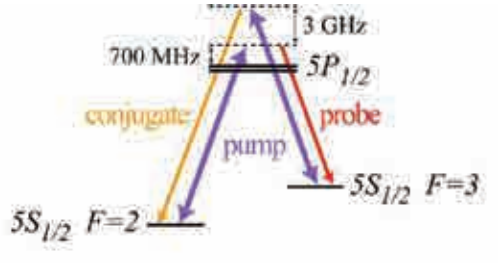

Figure 1: *Used double lambda scheme with the relevant levels of the 85 Rb D1 line.*

[1]C.F. McCormick, V. Boyer, E. Arimondo, and P.D. Lett, Opt. Lett. 32, 178 (2007)
[2]V. Boyer, A.M. Marino, R. C. Pooser, and P. D. Lett, Science 321, 544 (2008)
[3]A. M. Marino, R. C. Pooser, V. Boyer, and P. D. Lett, Nature 457, 859 (2009)

Combining Red- and Blue-detuned Optical Potentials to Form a Lamb-Dicke Trap for a Single Neutral Atom*

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Single neutral atom in optical tweezers is one of the most promising candidates for storing and processing quantum information. But usually the atoms are required to lie in ground state to implement quantum gates based on controlled collisions [1] and to prepare a superposition of two internal states of hyperfine manifold [2]. Unlike single ions in steep Lamb-Dicke traps which can be cooled down using optical sideband cooling [3, 4] or electromagnetically induce transparency (EIT) cooling [5], atoms in optical tweezes are difficult to use these cooling methods for the bigger Lamb-Dicke parameter. Here we propose and demonstrate a scheme of forming a tight trap for a single neutral atom to reduce the Lamb-Dicke parameter to a value that meets the need for Raman sideband cooling or EIT cooling.

This tight trap is a bichromatic far-off resonance optical dipole trap (BFORT). It is formed by overlapping a blue-detuned Laguerre-Gaussian laser beam (LG_0^1)with a red-detuned Gaussian beam. The blue-detuned doughnut beam offers a steep repulsive force for neutral atoms pointing to the optical axis, while the red-detuned Gaussian beam provides an attractive force pointing to the optical axis too. They cooperate and give an ultra steep potential for single neutral atoms eventually.

By moderating blue-detuned potential depth, we can

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increase the oscillation frequency of a single atom trapped in BFORT to 150 kHz compared with 50 kHz in a Gaussian trap (Fig 1). This reduces the Lamb-Dicke parameter from 0.28 to 0.16 which is in a good position to further the atoms down to the ground state by using Raman sideband cooling or EIT cooling. Meantime, the scattering rate of the blue-detuned light is just dependent on the temperature of the atoms, it can be eliminated when the atoms is close to the ground state.

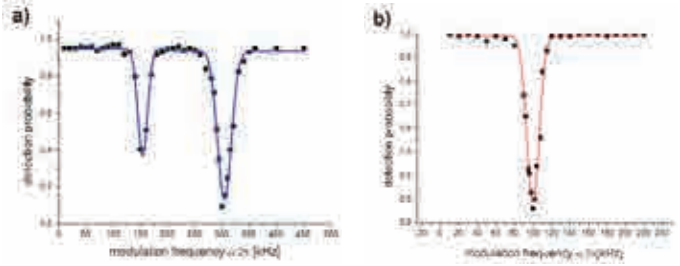

Fig 1. Experimental vibrational spectra of single atoms in the BFORT (a), and a Gaussian FORT (b). The filled squares depict the probability measurement of the single atoms in the traps after the modulation of the potential depth as a function of the modulation frequency. The solid curves are Gaussian fit to the experimental data.

References

1. D. Jaksch, H. -J. Briegel, J. I. Cirac, C. W. Gardiner, and P. Zoller, *Phys. Rev. Lett.* **82**,1975 (1999)
2. M. P. A. Jones, J. Beugnon, A. Gaetan, J. Zhang, G. Messin, A. Browaeys, and P. Grangier, *Phys. Rev. A* **75**, 040301 (2007)
3. F. Diedrih, J. C . Bergquist, W. M. Itano, and D.J. Wineland, *Phys. Rev. Lett.* **62**, 403 (1988)
4. C. Monroe, D. M. Meekhof, B. E. King, S. R. Jefferts, W. M. Itano, and D. J. Wineland, *Phys. Rev. Lett.* **75**, 4011 (1995)
5. C. F. Roos, D. Leibfried, A. Mundt, F. Schmidt-Kaler, J. Eschner, and R. Blatt, *Phys. Rev. Lett.* **85**, 5547 (2000)

Development of a 10-meter Atom Interferometer*

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Atom interferometers have found many applications in fundamental physics, precision measurements and inertial sensing. One of the main parameters that limit the accuracy of atom interferometers is the free flight time *T*. In a typical 1-meter-high fountain type atom interferometer *T* is less than 0.5 s, while for a 10-meter interferometer *T* can be larger than 1 s. High fountain also provides large space separation for atoms in different states. Due to the potential high sensitivity in gravity measurements, this kind of large interferometer is not only a good facility for Equivalence Principle test, but also a possible detector for gravitational wave. 10-meter atom fountain was suggested and is being built in Stanford University [1, 2]. Recently we developed a new type 10-meter atom interferometer [3]. The height of the whole interferometer is 13 m, and the effective height of free falling chamber, which is inside the magnetic shielding cylinder, is 10 m. Three kinds of atoms, Rb, Cs, and Li, are designed to work together in this interferometer, the first fountain of ^{85}Rb was realized and the maximum launch height is 6 m (see Fig. 1). M-Z interference fringe at 2.5 m fountain was observed (shown in Fig. 2). The visibility of 86% is seen from the primary result, more work will be followed step by step.

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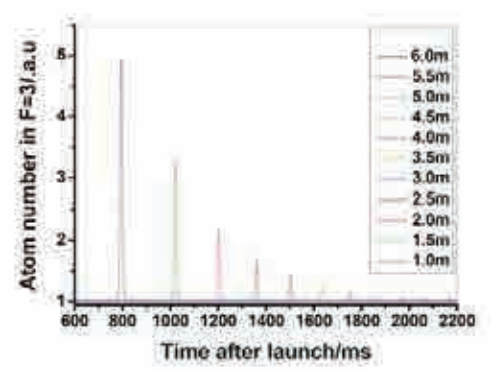

Fig. 1 Fountain signals at different launch heights.

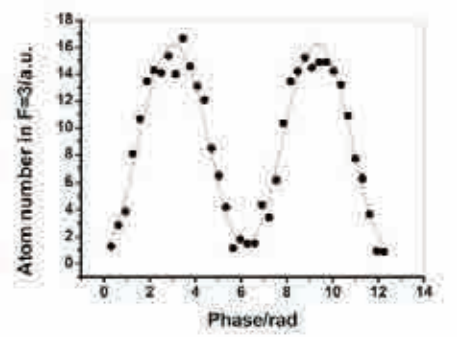

Fig. 2 Interference fringes displayed as dependence of relative population on the phase of Raman lasers.

References

1. S. Dimopoulos, P. W.Graham, J. M. Hogan, M. A. Kasevich, S. Rajendran, *Phys. Rev. D* **78**, 122002(2008)
2. S. Dimopoulos, P. W.Graham, J. M. Hogan, M. A. Kasevich, S. Rajendran, *Phys. Lett. B* **678**, 37(2009)
3. L. Zhou, Z. Y. Xiong, W. Yang, B. Tang, W. C. Peng, K. Hao, R. B. Li, M. Liu, J. Wang, M. S. Zhan, *Gen. Relativ. Gravit.* Online First, 8 March 2011

Double-resonance optical-pumping spectroscopy with a ladder-type cesium atomic system and two-color cesium magneto-optical trap

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We present our experimental investigation of double-resonance optical-pumping (DROP) spectroscopy with cesium (Cs) $6S_{1/2}$ - $6P_{3/2}$ - $8S_{1/2}$ ladder-type system and two-color Cs magneto-optical trap (MOT) which partially employs radiation force due to the transition between the atomic excited states.

There often exist two DROP peaks under off-resonance condition, and their origins are explored in our experiment. One of the two DROP peaks has a narrow linewidth due to atomic coherence for couterpropagating configuration; another has a broad linewidth due to spontaneous decay for copropagating configuration. The two peaks all appear on two-photon resonance if the lower laser which couples the intermediate excited state and the ground state has a single-photon detuning, and the upper laser which couples the higher excited state and the intermediate excited state correspondingly has an opposite single-photon detuning. Thus we can offset lock the upper laser related to the upper transition via the off-resonance DROP spectrum.

We employed this offset locking scheme to control the two-photon frequency detuning of the two-color Cs MOT. We investigated and characterized the two-color Cs MOT. It was found that two-color Cs MOT can efficiently cool and trap Cs atoms on both of the red detuning and the blue detuning from of two-photon resonance. With the red two-photon detuning, the cooling/trapping mechanism can be understood using a two-photon Doppler cooling picture which is similar to the standard MOT. With the blue two-photon detuning, the cooling/trapping mechanism is now not very clear and should be investigated, and it probably can be explained using two-color polarization gradient cooling mechanism. This two-color MOT may be used in the background-free detection of LIF photons of trapped few atoms in MOT, especially in single atoms MOT.

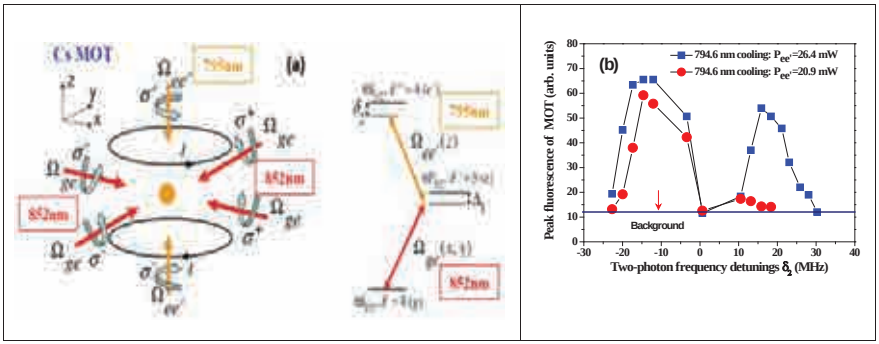

Fig. (a) Schematic diagram of two-color cesium MOT.

Fig. (b) Peak fluorescence of the two-color cesium MOT vs the two-photon frequency detuning δ_2.

T51

A new setup for the study of strongly correlated low-dimensional systems

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We present our new experimental setup for the study of low-dimensional Fermi gases with local control and readout. A gas of fermionic Lithium will be cooled to quantum degeneracy by all-optical means and prepared between two microscope objectives. A novel ring resonator concept will be used for creating two-dimensional systems and the Fermi-Hubbard model. In combination with the excellent optical access this allows us to address non-equilibrium phenomena in strongly correlated systems.

Experimental Demonstration of Interaction of Ultracold Atoms with a Periodic Array of Nanomagnetic Domain Walls

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We present a demonstration of the interaction of ultracold atoms with domain walls through the use of an atomic mirror [1]. Lithographically fabricated permalloy ($Ni_{81}Fe_{19}$) planar nanowires are written onto a silicon substrate; this production method affords a great deal of freedom in device design, c.f. e.g. [2]. Due to their ferromagnetic nature these nanowires can be populated with domain walls. Whilst the behaviour and dynamics of domain walls have been the subjects of much study they are yet to be harnessed by the atomic physics community as tools for investigating new physics.

Nanowires written in a sinusoidal pattern create an analogue to the sinusoidal magnetisation required for an ideal mirror, whilst the small characteristic lengthscale of our device means there is a very rapid decay in the magnetic field strength away from the surface [2].

FIG. 1: Our experimental setup, from left to right: the vacuum chamber housing the experiment, the mount for our nanowire chip and associated coils, the nanowire chip itself - a 5 mm×5 mm silicon substrate with 2 mm×2 mm written area, and an optical microscope images of the nanowires showing their sinusoidal structure.

Using this device we have demonstrated reflection of a cloud of $\sim 10^7$ ^{87}Rb atoms, cooled to 10 μK, and then optically pumped into the $|\mathrm{F} = 2, m_\mathrm{F} = 2\rangle$ weak field seeking state. Atoms in strong field seeking states do not bounce.

Despite being made of permanent magnetic structures the device can be switched on and off. Monte Carlo simulations accurately reproduce the signals

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we observe over a wide range of experimental parameters. We infer properties of the device from the resultant bounce signal. Ongoing work has the goal of examining the nature of Van der Waals potentials at short range.

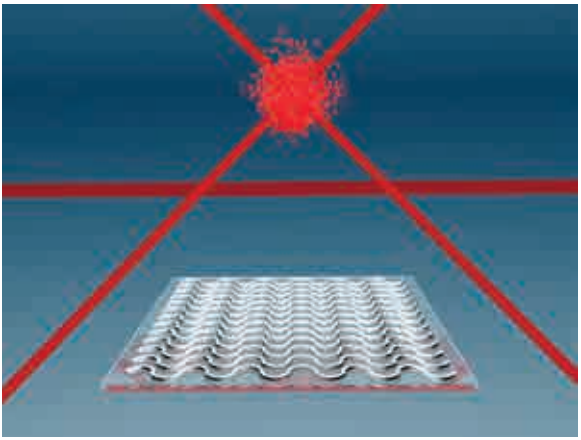

FIG. 2: A schematic of our experimental setup, showing the nanowire array and the MOT formed above the chip, as well as the light sheet used to detect the atoms.

We also present planned work of using these domain walls as the basis for extremely tight and mobile atom traps [3]; due to the large field gradients afforded by our small characteristic length we anticipate trap frequencies into the MHz regime. Due to their basis on a single domain wall it will be possible to transport the atoms within traps along the nanowires.

[1] *Design and characterization of a field-switchable nanomagnetic atom mirror*, T. J. Hayward, A. D. West, K. J. Weatherill, P. J. Curran, P. W. Fry, P. M. Fundi, M. R. J. Gibbs, T. Schrefl, C. S. Adams, I. G. Hughes, S. J. Bending, and D. A. Allwood, J. Appl. Phys. **108**, 043906 (2010)

[2] *Optimized magnetic lattices for ultracold atomic ensembles*, R. Schmied, D. Leibfried, R. J. C. Spreeuw, S. Whitlock, New J. Phys. **12**, 103029 (2010)

[3] *Magnetic atom optics: mirrors, guides, traps, and chips for atoms*, E. A. Hinds and I. G. Hughes, J. Phys. D **32**, R119 (1999)

[4] *Mobile atom traps using magnetic nanowires*, D. A. Allwood, T. Schrefl, G. Hrkac, I. G. Hughes, and C. S. Adams, Appl. Phys. Lett. **89**, 014102 (2006)

Experimental determination of the ^{24}Mg I $(3s3p)^3P_2$ lifetime

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Abstract

We present the first experimental determination of the electric-dipole forbidden $(3s3p)^3P_2 \rightarrow (3s^2)^1S_0$ (M2) transition rate in ^{24}Mg and compare to state-of-the-art theoretical predictions. Our measurement exploits a magnetic trap isolating the sample from perturbations and a magneto-optical trap as an amplifier converting each $^3P_2 \rightarrow {}^1S_0$ decay event into millions of photons readily detected. The transition rate is determined to be $(5.18\pm0.3)\cdot10^{-4}\,\mathrm{s}^{-1}$ corresponding to a $^3P_2$ lifetime of 1930 $^{+120}_{-110}$ seconds. This value is in agreement with recent theoretical predictions.

Microfabricated scalable monolithic linear ion traps with unit aspect ratio

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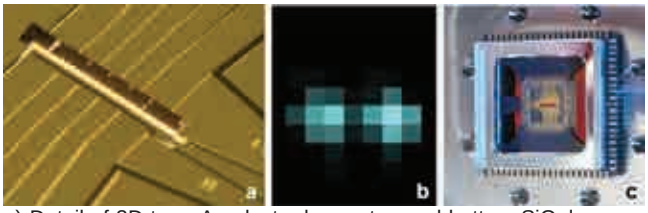
Microfabricated traps are a necessary component to achieve scalability for ion trap QIP. Previous successful traps have included 2D surface traps [1,2], 3D Au coated alumina [3-5], 3D degenerate Silicon [6], monolithic 3D GaAs traps [7].

We have developed and produced a monolithic, microfabricated, scalable linear ion trap with unit aspect ratio. The trap with an ion-to-electrode distance of 240 μm is now operational and used to trap $^{88}Sr^{+}$ ions.



a) Detail of 3D trap: Au electrodes on top and bottom SiO_2 layers which are grown on bulk Si. The Si is used as spacer and in the trapping region is etched through and recessed. The electrodes' Au wraps around the free standing SiO_2 front ends in the trapping region and covers up the dielectric surfaces. b) Two $^{88}Sr^{+}$ ions trapped in the center segment of the trap shown in a. c) A packaged trap chip in the vacuum system with airside dc and rf contacts.

The design is based on SiO_2-on-Si technology [8]. Trap characteristics include

- monolithic 3D trap fabricated using scalable planar processing techniques (no post-processing assembly),

- unit-aspect ratio yielding a deep high efficiency potential,
- low substrate heating.

With a deep trapping potential of up to 5 eV, long uncooled (> 25 min) and cooled trap lifetimes (> 24 h) have been observed. These are believed to be limited by background gas collisions (~ 5/h). High radial motional frequencies of 3.9 MHz with a rf drive ferquency of 23.2 MHz at 420 V amplitude ($q < 0.5$) have been measured. These agree with the high trap efficiencies predicted from trap modelling [8]. A full characterisation of the trap performance including heating rates is under way.

The experiments are carried out in a UHV compatible vacuum system based on the use of a standard ceramic chip carrier. The system provides for

- excellent optical access (> 1.2 π sr),
- a compact electrical feedthrough for rf and dc connections,
- short path lengths from airside to trap center (< 15 mm), enabling electronic filtering outside the vacuum yet in close proximity to trap electrodes.

Further results of the trap characterisation will be presented.

[1] S. Seidelin et al., Phys. Rev. Lett. 96, 253003(2006)
[2] J. Labaziewicz, et al, Phys. Rev. Lett., 100, 013001 (2008).
[3] W.K. Hensinger et al., Appl. Phys. Lett. 88, 034101 (2006)
[4] S. A. Schulz , et al, New J. Phys. 10 , 045007 (2008).
[5] R. B. Blakestad, et al, Phys. Rev. Lett. 102, 153002 (2009).
[6] J. Britton, Appl. Phys. Lett. 95, 173102 (2009)
[7] D. Stick et al., Nature Physics 2, 36 (2006)
[8] M. Brownnutt et al., N. J. Phys. 8, 232 (2006)

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Loading an Inductively Coupled Ring Trap

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We report on experimental progress towards an atom-interferometry experiment in a smooth ring geometry. We have proposed a new form of toroidal trap for ultra-cold and quantum degenerate atomic gases [1]. By applying a time-varying magnetic field about an electrically isolated conducting loop a stable, time-averaged minimum of the magnetic field is formed from the superposition of the applied and induced fields. This geometry resolves the issue of perturbations of the ideal symmetry of the toroidal geometry due to electrical connections and benefits from time averaging of corrugating potentials due to current meandering. We present the status of a new experimental apparatus to use Bose (^{87}Rb) and Fermi (^{40}K) degenerate gases for Sagnac interferometry. We describe the procedure for loading an ultra-cold cloud of atoms into the trapping potential through a moving molasses in a magnetic field. Our laser system for cooling of K and its integration into the project are discussed, along with future development of the project.

[1] "Smooth, inductively coupled ring trap for atoms", P.F. Griffin, E. Riis and A.S. Arnold, Phys. Rev. A **77**, 051402(R) (2008)

Probe correlation and energy gap of Bloch bands in one dimensional optical lattice by matter wave amplification

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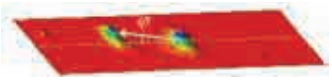
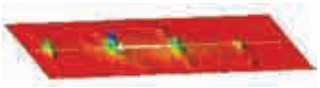
Abstract: Amplification of matter waves was analyzed in an angular condition of resonant light diffraction by a Bose gas released from an optical lattice. We found that competition between superradiant scattering Fig 1(a) 、(b)and matter wave amplification Fig 1(c)、(d) which will be dominated while the optical potential depth increases. The first order mode can be amplified and related distribution of momentum <p> will be oscillated vs the delay time between switch off the optical lattice and switch on the pump laser pulse, see Fig 2. The curve shows the correlation between wave functions of different on site of optical lattice. The energy gap of Bloch bands in one dimensional optical lattice can be measured also by similar approach.

(a)



(b)

(c)



(d)

Fig. 1 (a)configuration for experiment of superradiant scattering in BEC; (b)experimental result for superradiant scattering in BEC; (c) configuration for experiment of Bragg diffraction in optical lattice; (b)experimental result for Bragg diffraction in optical lattice.

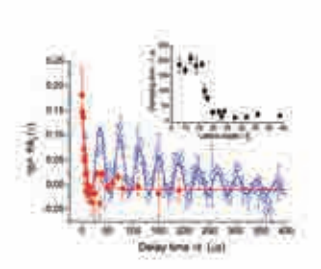


Fig 2 Average momentum calculated from time of flight images. The delay time corresponds to the delay between optical lattice switch off and MWA pump pulseswitch on times.

Microwave Atomic Clock in the Magic Wavelength Optical Lattice and Magic Wavelength Laser

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Abstract: In this paper, the experimental research in Peking University, on realizing a novel atomic clock utilizing the interaction between Bose-Einstein condensate in optical lattices and microwave, is introduced. When the condensate is loaded in the optical lattices with specific wavelength (magic wavelength, shown in Fig. 1), the relative frequency shift of atomic energy level becomes zero. Therefore, the impact of the light frequency shift on atomic clock will be removed, and we can get the atomic clock signal with high precision when putting the atom into the resonance microwave field. We researched and developed by ourselves a whole set of Blue Light Frequency Doubling Laser, including the main vibration, the tapered amplifier and the frequency doubling cavity. A stable (Stabilization Locking Time > 10 hours) and high-power (>150 mW) magic wavelength laser can be obtained in experiment. We developed and mastered a kind of fast and stable frequency stabilization technology, shown in Fig. 2.

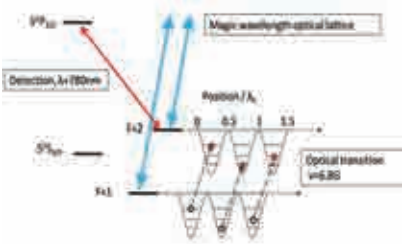

Figure 1 Figure 2

Figure 1: *Microwave Atomic Clock with Magic Wavelength Optical Lattices*
Figure 2: *Structure of frequency stabilization system*

[1] **High-Accuracy Microwave Atomic Clock via Magic Optical Lattice,** Xiaoji Zhou, Xuzong Chen, and Jingbiao Chen, arXiv:physics/0512244 v1, 25 Dec 2005.

[2] **An optical lattice clock,** Masao Takamoto, Feng-Lei Hong, Ryoichi Higashi & Hidetoshi Katori, Nature Vol 435, p321 (2005).

Rapid loading and momentum manipulation by standing wave pulses

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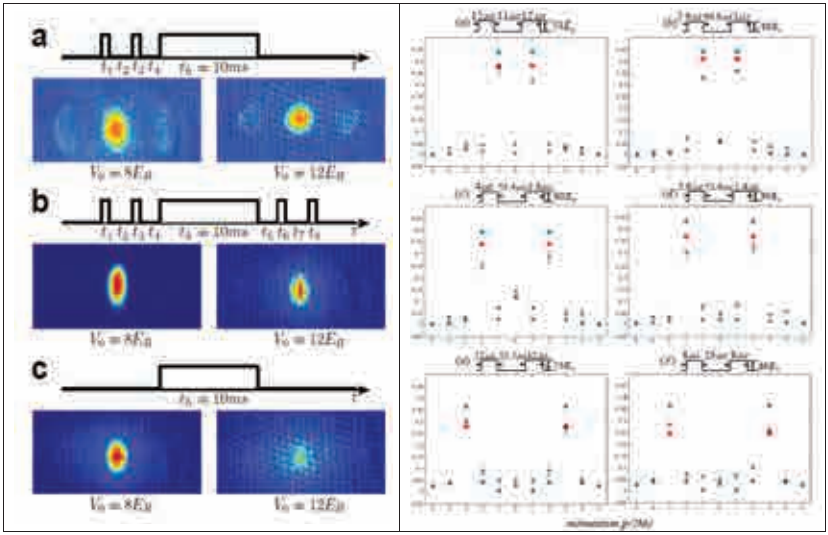
Abstract: We present a scheme for non-adiabatically loading a Bose-Einstein condensate into the ground state of a one dimensional optical lattice within a few tens of microseconds typically, i.e. in less than half the Talbot period. This technique of coherent control is based on sequences of pulsed perturbations and experimental results demonstrate its feasibility and effectiveness. As the loading process is much shorter than the traditional adiabatic loading timescale, this method may find many applications. Furthermore, we demonstrate that a coherent control method based on such sequences of pulses is very efficient for experimentally designing specific momentum states.



Left figures: Absorption images for three different time sequences. As the condensate was released from both the lattice potential and the magnetic trap, it expands freely for $30ms$ and then an absorption image is taken. For each time sequence, we show the results for two lattice depths of $8ER$ and $12ER$. Right figures: Experimental realization of designed momentum states. The expected momentum state is $\pm 2k$ ((a) and (b)), $\pm 4k$ ((c) and (d)) and $\pm 6k$ ((e) and (f)). The pulse sequences are shown above each figure. The black round dots are experimental results. The blue diamond dots are the expectations based on the design. The red square dots are the modified design with momentum width, which agree with the experiments better.

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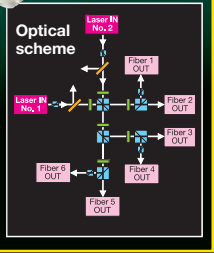
Yb	556	Rb	780
Na	589	Kr	811
Li	671	Cs	852
Sr	689	He	1083
Na	760		

Optical scheme



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