ICOLS 05 Programme

	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
7.30 - 8.50		**Breakfast**	**Breakfast**	**Breakfast**	**Breakfast**	**Breakfast**
8.50 - 9.00		**Welcome**				
9.00 - 9.30		John Hall	Carl Wieman	Jook Walraven	Hot topics	Ferenc Krausz
9.35 - 10.05		Jun Ye	Tilman Pfau	John Bohn		Phil Bucksbaum
10.10 - 10.40		Jim Hough	Bill Phillips	Dave DeMille		Ian Walmsley
10.45 - 11.15		**Coffee**	**Coffee**	**Coffee**	**Coffee**	**Coffee**
11.15 - 11.45		Thomas Udem	Elena Ostrovskaya	Keith Burnett	Hot topics	Jean-Michel Raimond
11.50 - 12.20		Pablo Cancio Pastor	Anna Sanpera	Rudi Grimm		Christoph Becher
12.25 - 12.55		Ryugo Hayano	Peter Drummond	John Thomas		Dave Wineland
13.00 - 14.30	**Arrival and Registration**	**Lunch**	**Lunch**	**Lunch**	**Lunch**	**Lunch**
14.30 - 15.00				**Excursions after lunch or packed lunch**	Mark Kasevich	
15.05 - 15.35					Helen Margolis	
15.40 - 16.10					Hidetoshi Katori	
16.15 - 16.45					Svenja Knappe	
16.45 - 17.15		Saïda Guellati-Khélifa	Gerhard Rempe			
17.20 - 17.50		Stefan Schiller	Arno Rauschenbeutel			
17.55 - 18.25		Vladilen Letokhov	Jakob Reichel			
19.00 - 19.30	**Dinner at leisure**	**Dinner**	**Dinner**	**Followed by Midsummer Night's BBQ**		
19.30 - 20.30					**Banquet**	
20.30 -	**Reception** Norman Ramsey	**Poster Session 1**	**Poster Session 2/ Sponsors' Exhibition**			

Monday 20th June

High Precision Measurements

8.50 **Welcome**
Chairman: Ed Hinds
9.00 **John Hall**
Improving laser coherence
9.35 **Jun Ye**
Precision measurement and coherent control
10.10 **Jim Hough**
Long baseline Gravitational Wave Detectors – status and developments

10.45 Coffee

Chairman: xx
11.15 **Thomas Udem**
Precision spectroscopy of hydrogen and femtosecond laser frequency combs
11.50 **Pablo Cancio Pastor**
Precision spectroscopy of helium
12.25 **Ryugo Hayano**
Precise laser spectroscopy of antiprotonic helium - weighing the antiproton

13.00 Lunch

Afternoon: free

Chairman: xx
16.45 **Saïda Guellati-Khélifa**
Block oscillations of ultracold atoms: a tool for a H/M_{Rb} measurement
17.20 **Stefan Schiller**
Ultracold molecular ions: towards precision spectroscopy of HD^+
17.55 **Vladilen Letokhov**
Astrophysical Laser Spectroscopy

19.00 Dinner

20.30 – **Poster session 1**

Tuesday 21st June

Symposium on Cold Atoms and Molecules

Chairman: xx

9.00 **Carl Wieman**
BEC- the first 10 years

9.35 **Tilman Pfau**
Ultracold chromium: a dipolar quantum gas

10.10 **Bill Phillips**
Experiments with a quantum degenerate Bose gas in one dimension

10.45 Coffee

Chairman: xx

11.15 **Elena Ostrovskaya**
Nonlinear atom optics of Bose Einstein condensates in optical lattices

11.50 **Anna Sanpera**
Cold gases in inhomogeneous and random optical lattices

12.25 **Peter Drummond**
Correlations and collective modes in Fermions on lattices

13.00 Lunch

Afternoon: free

Chairman: xx

16.45 **Gerhard Rempe**
Individual atoms and photons under control

17.20 **Arno Rauschenbeutel**
Controlling strings of single trapped atoms

17.55 **Jakob Reichel**
Atom Chips: coherence and single atoms

19.00 Dinner

20.30 – **Poster session 2/Sponsors' Exhibition**

Wednesday 22nd June

Symposium on Cold Atoms and Molecules

Chairman: xx

9.00 **Jook Walraven**
Bose-Einstein condensates studied with a linear accelerator

9.35 **John Bohn**
Electric-field spectroscopy of weakly-bound molecular dimers

10.10 **Dave DeMille**
Optical production of ultracold polar molecules

10.45 Coffee

Chairman: xx

11.15 **Keith Burnett**
Molecules and correlated pairs in ultracold gases

11.50 **Rudi Grimm**
Experiments on the BEC-BCS crossover in an ultracold Fermi gas of ^{6}Li atoms

12.25 **John Thomas**
Thermodynamical and mechanical properties of a strongly interacting Fermi gas

13.00 Lunch

Afternoon: Excursions

Thursday 23rd June

Hot Topics

Chairman: xx
9.00 **Hot Topics**

10.45 Coffee

Chairman: xx
9.00 **Hot Topics**

13.00 Lunch

Atomic Clocks and Interferometers

Chairman: xx
14.30 **Mark Kasevich**
Inertial navigation sensors based on atom interferometry
15.05 **Helen Margolis**
A strontium ion optical frequency standard with Hz-level uncertainty
15.40 **Hidetoshi Katori**
Optical lattice clock
16.15 **Svenja Knappe**
Microfabricated Atomic Clocks and Magnetometers

19.30 Highland banquet

Friday 24th June

Quantum Control and Quantum Information

Chairman: xx

9.00 **Ferenc Krausz**
Attosecond physics: controlling and tracking electron dynamics on an attosecond time scale

9.35 **Phil Bucksbaum**
Quantum control

10.10 **Ian Walmsley**
Photonic engineering for QIP

10.45 Coffee

Chairman: xx

11.15 **Jean-Michel Raimond**
Giant atoms for explorations of the mesoscopic world

11.50 **Christoph Becher**
Quantum information and cavity QED with trapped ions

12.25 **Dave Wineland**
Quantum control, quantum information processing, and quantum-limited metrology with trapped ions

13.00 Lunch and End of Conference

Abstracts of Oral Presentations

IMPROVING LASER COHERENCE*

MARK NOTCUTT AND JOHN L HALL†

JILA, University of Colorado
Boulder, CO 80309-0440 USA

The convenient approximation of a real laser field by a Coherent State is again a relevant topic of interest, as laser spectroscopy scenarios are being developed in which remarkably long atomic lifetimes and extended interaction times (~100 s) can be enjoyed. Years ago, appropriate locking techniques were shown to allow precise locking to a cavity, even in the milliHz domain, but lab vibrations modulated the cavity length and so the obtained optical frequency. Methods such as mechanical isolation (on a heroic scale) or active anti-vibration approaches are productive such that, by now several groups have developed sources with sub-Hz linewidths. Still, linewidths in the 100 milliHz domain have seemed very challenging – all the margins have been used up. We discuss an improved mounting system for an optical reference cavity, based on implementing vertical symmetry, which provides dramatic reduction in the vibration sensitivity and can yield sub-Hz linewidths on an ordinary optical table in an ordinary lab. Interesting and controlling new issues such as temporally-dependent spatial structure of the EO-modulated probe beam, and thermally-generated mechanical position noise are found to dominate the laser phase errors in the sub-Hz linewidth domain. The theoretical scaling – and the spectral character – of this thermal noise motion of the cavity mirror surfaces have been studied and confirmed experimentally, showing an ~5 $x10^{-17}$ m/Sqrt(Hz) thermal noise amplitude at 1 Hz, with a 1/Sqrt(f) amplitude spectral density. For effective temperature stabilization, multi-point thermal control and dual thermal shells provide stable operation near the ULE thermally-stationary point. Spectral filtering in the optical and vacuum paths are critically important to prevent ambient thermal radiation from entering the inner shell. The observed frequency drift-rates of ~3 Hz/minute are not yet ideally stable, but apparently can be compensated accurately enough to allow 1 radian coherence times to be

* This work is supported in part by the National Institute of Standards and Technology, the Office of Naval Research, NASA, and the National Science Foundation.
† This work has been advanced by useful discussions with J. C. Bergquist, Jun Ye, and L.-S. Ma.

~100 s, after other problems are adequately suppressed. Recent JILA spectra of lattice-trapped cold Sr atoms show very low temperatures (judged by the unequal vibrational sideband strengths) and make us anxious to perfect improved phase-stable laser sources for the $^1S_0 - {}^3P_0$ doubly-forbidden transition at 698 nm. These laser developments are aided by optical comb techniques, allowing useful phase comparison of our lab's several prototype stable laser sources, despite their various different wavelengths.

PRECISION MEASUREMENT AND COHERENT CONTROL

J. YE, R. J. JONES, M. J. THORPE, K. D. MOLL, M. STOWE, A. MARIAN, S. M. FOREMAN, AND F. C. CRUZ*

JILA, National Institute of Standards and Technology, and the Department of Physics, University of Colorado, 440 UCB Boulder, CO 80309-0440, U.S.A.

The application of precisely phase-controlled, broadband, femtosecond lasers on cold atomic samples has yielded precise measurement of atomic structure and dynamics, leading to high resolution and time-dependent spectroscopy. These frequency comb-based precision measurement capabilities may be extended to the EUV spectral region.

Precise phase control of ultra-wide-bandwidth optical frequency combs has produced remarkable and unexpected progress in precision measurement and ultrafast science. In this contribution we will present some of the recent results on precision spectroscopy of ultracold atoms using femtosecond combs and discuss the possibility of extending these scientific endeavors to the EUV region by producing precise comb structure there via extreme nonlinear optics.

We will concentrate on current experiments utilizing phase-stabilized femtosecond lasers for precise measurements and control in ultracold atoms [1]. The wide-bandwidth, phase-coherent optical comb spectrum enables accurate and efficient measurement of the global atomic structure. Coherent pulse accumulation, quantum interference, and associated mechanical actions are monitored in real time, creating the powerful combination of frequency domain precision and time domain dynamics and control. Another development is on ultra-precise optical atomic clock with ultracold Sr atoms [2]. A precisely stabilized comb now enables Hz-wide laser linewidths to be measured and controlled across a frequency gap of 10^{14} Hz, permitting precision spectroscopy of narrow linewidth transitions in Sr atoms loaded in an optical lattice.

To extend the coherent frequency comb structure and related precision measurement capabilities into the deep UV spectral region, we have recently demonstrated high-harmonic generation (HHG) at 100 MHz repetition rates enabled by a femtosecond enhancement cavity. HHG provides a coherent source of vacuum-ultraviolet to soft x-ray radiation. HHG has traditionally relied on high-energy, low repetition rate amplified laser systems to provide the peak intensities needed for ionization of the gas target. The small conversion efficiency of the process, combined with the low repetition rate of amplified

laser systems, results in low average powers in the EUV generation. Furthermore, the use of these sources as precision spectroscopic tools is limited, as the original laser frequency comb structure is lost in the HHG process.

Using a femtosecond laser coupled to a passive optical cavity (Fig. 1), coherent frequency combs in the EUV spectral region are generated via high-harmonics of the laser without any active amplification or decimation of the repetition frequency. We can thus significantly improve the average power conversion efficiency and reduce the system cost and size, while dramatically improving the spectral resolution. Since little of the fundamental pulse energy is converted, a femtosecond enhancement cavity is ideally suited for HHG as the driving pulse is continually recycled after each pass through the gas target. Optical-heterodyne-based measurements reveal that the coherent frequency comb structure of the original laser is fully preserved in the high-harmonic generation process, with the rms phase variation measured to be <1 rad over 1-s measurement time. The presence of the frequency comb structure in the EUV and its extreme spectral resolution will enable similar revolutions in precision measurement, quantum control, and ultrafast science as in the visible region.

*On leave from Instituto de Fisica "Gleb Wataghin", UNICAMP, Campinas, Brazil.

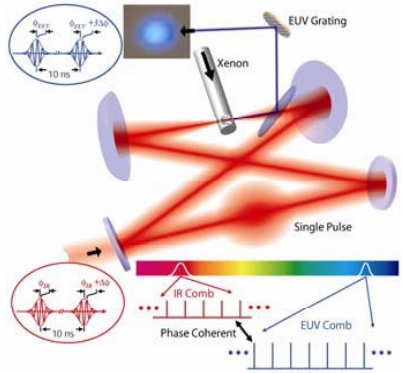

Figure 1: Schematic setup of intracavity HHG. A gas target at the cavity focus enables coherent high-harmonic generation, resulting in a phase-stable frequency comb in the VUV spectral region. The photo inset shows the actual spatial mode profile of the 3rd harmonic coupled out of the cavity.

References

[1] A. Marian et al., *Science* **306**, 2063 (2004); A. Marian et al., submitted for publication (2005).
[2] See contributions by T. Ido et al. and M. M. Boyd et al. at this conference.
[3] R. J. Jones et al., submitted for publication (2005).

LONG BASELINE GRAVITATIONAL WAVE DETECTORS – STATUS AND DEVELOPMENTS

JAMES HOUGH [†]

Institute for Gravitational Research, University of Glasgow, Glasgow G12 8QQ, Scotland, UK

Results are now appearing from the first generation of long baseline gravitational wave detectors that use laser interferometry for motion sensing. In this talk the status of current detectors – LIGO, VIRGO, GEO 600 and TAMA 300 - will be reviewed along with plans for the future. In particular a planned upgrade to the US LIGO detector system will be discussed. Emphasis will be placed on the novel interferometry used in GEO 600, variants of which have relevance for future detectors intended to operate below the standard quantum limit. In addition some of the important factors that are likely to limit the sensitivity of such instruments will be outlined. Of particular importance among these are the mechanical dissipation of the multilayer dielectric mirror coatings which can lead to excess thermal noise and the optical loss of the same coatings which can limit the extent to which quantum noise can be reduced.

[†] for the LIGO Scientific Collaboration.

PRECISION SPECTROSCOPY OF HYDROGEN AND FEMTOSECOND LASER FREQUENCY COMBS

TH. UDEM, P. FENDEL, M. FISCHER, N. KOLACHEVSKY, J. ALNIS, M. ZIMMERMANN, CH. GOHLE, M. HERRMANN, R. HOLZWARTH, AND T. W. HÄNSCH

Max-Planck-Institut für Quantenoptik,
Hans-Kopfermann Strasse 1,
85748 Garching, Germany

A femtosecond frequency comb is a simple and compact tool that allows the phase coherent connection of the radio frequency domain (below 10 GHz) with the optical domain (above 200 THz). It greatly simplified high precision optical frequency measurements and provides the long awaited clockwork mechanism for an all-optical atomic clock. In addition it allows to shape the electric field transients of femtosecond pulses including the phase between the carrier wave and the pulse envelope,

We have used such a frequency comb to measure the absolute frequency of the 1S-2S two-photon transition in atomic hydrogen, i.e. comparing it with the Cs ground state hyperfine splitting. By comparing data taken in 2003 with earlier measurements in 1999 we can set an upper limit on the variation of the 1S-2S transition frequency of (-29 ± 57) Hz within 44 months. To derive limits on the drift rates of fundamental constant such as the fine structure constant, we combine these measurements with the results obtained by S. Bize at NIST and E. Peik at PTB with different optical transitions. This gives precise and separate restrictions for the fractional time variation of the fine structure constant and the Cs nuclear magnetic moment measured in Bohr magnetons. The latter is a measure of the drift rate of the strong interaction.

Furthermore we report on efforts to convert the frequency comb technology to much shorter wavelength. Based on intra cavity high harmonic generation an XUV (up to 60 nm) frequency comb is generated with a repetition rate of 110 MHz useful for high resolution laser spectroscopy in this region.

PRECISION SPECTROSCOPY OF HELIUM

P. CANCIO PASTOR

Istituto Nazionale di Ottica Applicata (INOA) and
European Laboratory for Non-Linear Spectroscopy (LENS)
Largo E. Fermi 6,
I-50125 Firenze, ITALY
E-mail: pcp@inoa.it

Precision spectroscopy of atomic helium has been performed in Florence, since more than ten years. In particular, the 2^3P fine structure (FS) was measured by heterodyne saturated-fluorescence spectroscopy [1]. Recently, by using an optical frequency-comb synthesizer (OFS), we could perform absolute frequency measurements of the $2^3S_1 \rightarrow 2^3P_{0,1,2}$ transitions [2]. Thanks to this set-up, an uncertainty of few kHz could be achieved for the frequency separations, thus obtaining the best Lamb-shift determination in a simple atomic system. Tests of the quantum electrodynamics (QED) theory can be performed by using these high-precision measurements. As a consequence, a precise determination of the FS constant from He spectroscopy can be compared to determinations from other physical systems.

We are presently focusing our experiment to precise frequency measurements in ^{3}He at 1083 nm. As is well known, hyperfine structure and ^{3}He-^{4}He isotopic shift give information about the nuclear structure, and a determination of nuclear charge radii. Such determinations could shed light onto three nucleon forces, relativistic effects and the role of local/nonlocal potentials. Moreover, a new accurate determination of the proton charge radius could also be obtained by comparing the ^{3}He radius and the Tritium one. For the ^{3}He spectroscopy, we have further modified the set-up, by directly phase-locking a 1083 nm diode laser to the OFS. This approach can be easily extended to other optical helium transitions and multi-resonant experiments can provide new precise measurements of frequency differences. Preliminary results for the 2^3P hyperfine structure and of the ^{3}He-^{4}He isotope shift will be discussed as well as the perspectives of the extension of such experimental approach to optical helium transitions.

References

1. G. Giusfredi *et al.*, *Can. J. Phys.,* (2004), in press. F. Minardi *et al.*, *Phys. Rev. Lett.* **82**, 1112 (1999).
2. P. Cancio Pastor *et al.*, *Phys. Rev. Lett.* **92**, 023001 (2004) .

PRECISE LASER SPECTROSCOPY OF ANTIPROTONIC HELIUM - WEIGHING THE ANTIPROTON

R. S. HAYANO*

Department of Physics, University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
E-mail: hayano@phys.s.u-tokyo.ac.jp

An antiprotonic helium ($\overline{p}\mathrm{He}^+$) atom[1] is a metastable ($\tau \sim 3\mu$s) neutral three-body Coulomb system consisting of an antiproton, a helium nucleus, and an electron. It was serendipitously discovered that about 3% of antiprotons stopped in a low-temperature helium gas target automatically form such metastable atoms. Precision laser spectroscopy of $\overline{p}\mathrm{He}^+$ is possible by inducing a laser-resonant transition from a metastable antiproton orbit (such as $(n, l) = (39, 35)$) to a neighbouring short-lived orbit $(n, l) = (38, 34)$, which is about 2 eV below the (39,35) level) using a pulse laser, and by detecting the resonance via a sharp increase in the induced antiproton annihilation. There are about 10 such metastable-unstable pair of levels, with their resonance wavelengths ranging from ultra violet to infrared.

By comparing the experimental results with the state-of-the-art three-body QED calculations[2], antiproton to proton mass and charge comparison has been done to a precision of 10 parts per billion[3], which is currently the most precise test of the CPT symmetry (matter-antimatter symmetry) for baryons[4]. A new series of measurements, using a frequency comb and an improved laser system, is in progress. When completed (and theoretical calculations are revised accordingly), it may become possible to determine the antiproton mass as precise as (or more precise than) the proton mass.

References

1. T. Yamazaki *et al.*, Physics Reports **366**, 183 (2002).
2. V.I. Korobov, Phys. Rev. A **67**, 026501 (2003); Y. Kino *et al.*, Nucl. Instr. Methods B **214**, 84 (2004).

*Spokesperson, asacusa collaboration at cern antiproton decelerator (ad)

3. M. Hori *et al.*, Phys. Rev. Lett. **91** 123401 (2003).
4. S. Eidelman *et al.*,. Phys. Lett. B **592**, 1 (2004).

BLOCH OSCILLATIONS OF ULTRACOLD ATOMS: A TOOL FOR A H/M_{RB} MEASUREMENT

P. CLADÉ, M. CADORET, E. DE MIRANDES, S. GUELLATI-KHÉLIFA*, C. SCHWOB, F. NEZ, L. JULIEN AND F. BIRABEN

Laboratoire Kastler Brossel, École Normale Supérieure, CNRS, UPMC, 4 place Jussieu, 75252 Paris Cedex 05, France

∗ also Institut National de Métrologie, CNAM, 292 rue Saint Martin, 75141 Paris Cedex 03, France

We use Bloch oscillations in vertical moving standing wave to accelerate coherently ^{87}Rb atoms. Recently we have transferred about 2000 photon recoils to the atoms with an efficiency of 99.9% per cycle. The recoil velocity is determined with a relative uncertainty of 0.1 ppm in half hours of data collection.

Atom manipulation using laser light allows us now to precisely measure the recoil velocity v_r of the atom absorbing or emitting a single photon ($v_r = \hbar k/m$, where k is the wave vector of the photon absorbed by the atom of mass m). Such a measurement yields to a determination of h/m which can be used to infer a value of the fine structure constant α

$$\alpha^2 = \frac{2R_\infty}{c}\frac{M}{M_e}\frac{h}{m} \qquad (1)$$

where M and m are respectively, the mass of the test particle in atomic and SI units. As in this expression the other terms are known with a very small uncertainty, the determination of α using this formula is now limited by the uncertainty in the ratio h/m. The fine structure constant can be deduced from experiments related to different branches of physics (QED, solid state physics,...). Many of these measurements lead to determinations of α with a relative uncertainty close to 10^{-9} but their total dispersion remains significant (CODATA 02 [1]). A new accurate determination of α is highly recommended to test the validity of these measurements.

The experimental sequence for measuring the recoil velocity of ultracold rubidium atoms involves three steps: first a narrow subrecoil velocity class with a well defined mean initial velocity is selected using a Raman

velocity-selective π-pulse. Next, $2N$ photon recoils are transferred by a coherent acceleration using N Bloch oscillations. Finally, the final velocity is measured using an other velocity selective Raman π-pulse.

The recent measurements are taken using a moving vertical standing wave. To reduce systematic errors, we perform an alternate and symmetric recoil transfer in both opposite directions. A differential measurement of the center of the two final velocity distributions gives a typical total transfer of 1780 recoils velocity (see Figure 1). A relative precision in the photon recoil measurement of 0.1 ppm is obtained in half hours of data collection.

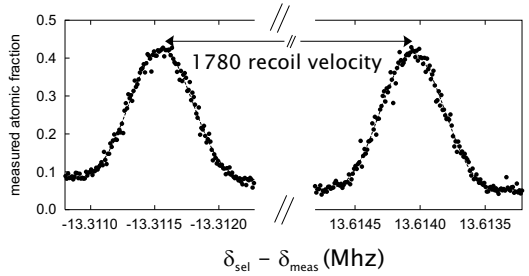

Figure 1. The final distribution velocity of atoms in both vertical opposite directions.

The Bloch oscillations in a pure vertical standing are also studied. In this experimental scheme, the center-of-mass of the atomic wavepacket oscillates on a very small amplitude with frequency $mg\lambda/2h$ (where λ is a wavelength of light used to create the optical potential, m the atomic mass and g the local acceleration of gravity). The measurement of the Bloch period leads to a preliminary determination of g with a relative uncertainty of 1.1×10^{-6} as the h/m ratio [1] and the wavelength are known with better accuracies.

References

1. P. Mohr and B. Taylor, *Rev. Mod. Phys.* **77**, 1 (2005).

ULTRACOLD MOLECULAR IONS: TOWARDS PRECISION SPECTROSCOPY OF HD^+. *

P. BLYTHE, B. ROTH, U. FRÖHLICH, H. WENZ, S. SCHILLER

Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany

We report the generation of translationally cold ($\sim$ 20 mK) diatomic and triatomic isotopomers of molecular hydrogen ions (H_2^+, H_3^+, HD^+, H_2, D^+, HD_2^+, D_2^+, and D_3^+), in a linear ion trap. Coulomb crystals containing over 3000 sympathetically cooled particles have been generated by sympathetic cooling of the molecular ions with laser-cooled Be^+ ions. We have studied the structural properties of the generated ion crystals and have developed methods to identify and distinguish between different sympathetically cooled particle species. Our experimental results show good agreement with results from molecular dynamics simulations. The availability of cold hydrogen molecular ions is an important step toward precision laser spectroscopy of simple molecules.

Ultracold molecular ions represent a new frontier in the field of quantum optics and are excellent systems for high-precision measurements. One of the most promising applications of trapped and cooled molecular ions with translational temperatures in the mK-range is high-precision spectroscopic measurements, for example of fundamental constants (particle mass ratios)[1], nuclear properties, QED effects, parity violation and Lorentz invariance[2].

Charged particles can be efficienty cooled sympathetically by laser-cooled atomic ions. In order to cool the hydrogen molecular ions, we have chosen a light atomic ion, Be^+. We previously used this ion species to demonstrate efficient cooling of $^3He^+$ and $^4He^+$,[3] and here extend this to ions having mass 2.

We use a linear quadrupole trap to simultaneously store both Be^+ and molecular ions. After loading the trap with a laser-cooled Be^+ Coulomb crystal neutral molecular gas is leaked into the chamber and ionised by an

*This work was supported by the Humboldt-Stiftung, the DFG and the EU-network "Ultracold Molecules".

electron beam with an energy of 200 eV. The charged molecules partially react with the background molecular gas to form triatomic hydrogen. In the resulting mixed-species ion crystals, the ions with a higher charge-to-mass ratio (in this case the molecular ions) are more tightly confined, and thus tend to form a dark (non-fluorescing) core to the crystal. The spatial distribution is also influenced by the radiation pressure exerted by the cooling laser on the Be^+ ions, but not on the sympathetically cooled species.

To identify trapped species, we excite the ions' motion in the time- averaged total potential using an additional ac electrode. The frequency of the excitation is scanned, and the Be^+ fluorescence recorded. When the applied frequency is resonant with a motional frequency of a crystal component, that motion is excited, the ions are heated, and the fluorescence of the beryllium ions in the crystal is affected. For small cores, the resonance frequencies give direct information about the charge-to-mass-ratio of the trapped particles. For larger cores, the particle interactions lead to frequency shifts, which also depend on the relative concentration of species in the core. Nevertheless, by comparing molecular dynamics simulations with the experimental data, the mass spectra can be interpreted.

Pending optical spectroscopy of the molecular species, we determine the temperature from the observed crystal structures. The thermal motion of the ions leads to blurring of our acquired images over their exposure time. This blurring can be compared with simulated images, and the temperature of the simulated ions adjusted until the calculated image is consistent with the observed crystal. Values in the range 10 mK to 30 mK are typically found.

Work is in progress to perform vibrational overtone spectroscopy on trapped HD^+ molecules at 1.4 μm.

References

1. S. Schiller and V. Korobov, Phys. Rev. A **71**, 032505 (2005)
2. H. Müller et al., Phys. Rev. D, **70**, 076004 (2004)
3. B. Roth et al, Phys. Rev. Lett. **94**, 053001 (2005)

ASTROPHYSICAL LASER SPECTROSCOPY

S. JOHANSSON[a], V.S. LETOKHOV[a,b]

[a] *Lund Observatory, Lund University, P.O. Box 43, S-22100 Lund, Sweden*

[b] *Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow region, 142190, Russia*

Stimulated emission concepts proved very useful and productive in astrophysics. This fact was convincingly verified in the microwave region of the spectrum (the discovery of astrophysical masers operative on a number of simple molecules [1–3]). We extend this trend to the visible region along two lines.

First, we present the results of our investigations that have, in our opinion, lead to the discovery of optically pumped astrophysical lasers [4] active in the quantum transitions of the Fe II ion [5, 6] and OI atom [7] in the range 0.8–1 μm in the vicinity of Eta Carinae – the most luminous and massive star of our Galaxy. The resonance optical pumping of high-lying states in Fe II and OI owes to the accidental coincidence between their absorption lines and the intense HI Ly_α and Ly_β emission lines, respectively.

Secondly, we consider the possibility of measuring the true (sub-Doppler) width of the narrow astrophysical laser lines by means of the Brown-Twiss-Townes heterodyne correlation interferometry and spectroscopy using spatially-separated telescopes and a diode laser as a local heterodyne coupled by an optical fiber to the telescopes [8]. This can simultaneously ensure a spectral resolution at the level of 1 MHz and an angular resolution at the level of 0.001–0.1 arcsec.

References

1. H. Weaver, D.R.W. Williams, N.H. Dieter and W.E. Lum, *Nature*, **208**, 29 (1965).
2. A.C. Cheung, D.M. Rank, C.H. Townes, O.D. Thornton and W.J. Wehl, *Nature*, **221** (1969).
3. M. Elitzur, *Astronomical Masers* (Dordrecht: Kluwer, 1992).
4. S. Johansson and V.S. Letokhov, *Publ. of Ast. Soc. of Pacific*, **115**, 1375 (2003).
5. S. Johansson and V.S. Letokhov, *Phys. Rev. Lett.*, **90**, 011101 (2003).

6. S. Johansson and V.S. Letokhov, *Astronomy and Astrophysics*, **428**, 497 (2004).
7. S. Johansson and V.S. Letokhov, (submitted).
8. S. Johansson and V.S. Letokhov, *New Astronomy* (in press)

BEC- THE FIRST 10 YEARS

CARL WIEMAN

JILA and Dept of Physics, University of Colorado
Boulder, CO, USA

The first observation of BEC in a gas was obtained almost exactly ten years before the date of this conference and was first presented in public by Eric Cornell at ICOLS 1995. Since that time, BEC has blossomed into a major subfield of research and has even spawned a vibrant off-spring in the study of degenerate Fermi gases. I will provide a necessarily highly condensed and incomplete retrospective of how gaseous BEC research has developed and evolved over the past ten years.

ULTRACOLD CHROMIUM: A DIPOLAR QUANTUM GAS*

T. PFAU, J. STUHLER, A. GRIESMAIER, M. FATTORI, T. KOCH

5th Institute of Physics, University of Stuttgart, Germany

We have Bose-Einstein condensed ^{52}Cr-atoms that interact by their large magnetic dipole moment and experimentally observed how the long-range and anisotropic magnetic interaction modifies the condensate expansion depending on the orientation of the magnetic moments.

1. Summary

The essential properties of a Bose-Einstein condensate (BEC) depend on strength, sign and symmetry of the interactions present. In BECs realized so far, the dominant interaction between the atoms stems from the short-range, isotropic contact potential. A BEC of ^{52}Cr atoms offers for the first time the possibility to experimentally explore dipolar interactions in degenerate quantum gases. Due to the high magnetic moment of chromium atoms, the magnetic dipole-dipole interaction in ^{52}Cr is 36 times stronger than in the alkalis and becomes comparable to the contact interaction. In addition, it is expected that the character of the interaction can be varied from mainly contact to purely dipolar utilizing one of the recently observed Feshbach resonances in ^{52}Cr-collisions [1] to tune the strength of the contact interaction.

We have produced Bose-Einstein condensates with up to 100,000 condensed ^{52}Cr-atoms [2]. The preparation of the chromium condensate requires novel cooling strategies that are adapted to its special electronic and magnetic properties. The final step to reach quantum degeneracy is forced evaporative cooling within a crossed optical dipole trap. We observe Bose-Einstein condensation by the appearance of a two-component velocity distribution at a critical temperature of $T_c \approx 700$ nK.

The influence of the magnetic dipole-dipole interaction becomes visible when carefully looking at the expansion of the condensate after release from an anisotropic trap [3]. Fig. 2 shows the aspect ratio (vertical size r_y / horizontal size r_z) of the expanding BEC for two different orientations of the magnetic moments. The data agree well with the theoretical prediction (black and gray

* This work is supported by the priority programme SPP1116 of the German Research foundation (DFG).

lines), which are obtained by numerically solving the collisionless hydrodynamic equation (without any free parameter) for dipolar superfluids.

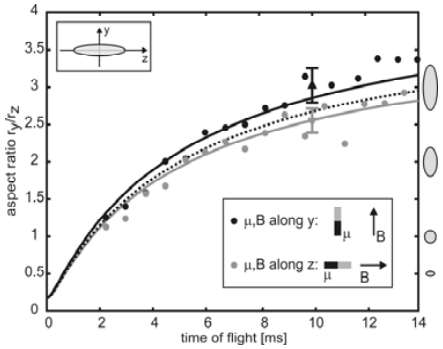

Fig. 2: Aspect ratio r_y/r_z of the expanding Cr-BEC after release from an anisotropic trap for two different orientations of the atomic magnetic dipoles (μ). Black: experimental data and theoretical prediction without adjustable parameter (solid line) for y-polarization. Gray: like black but now for z-polarization. Dashed line: theory curve without magnetic dipole-dipole interaction. The inset in the upper left corner sketches the orientation of the in-trap BEC and the coordinate system..

In summary, we have for the first time Bose-Einstein condensed a transition metal – chromium. The large magnetic moment of chromium enables studies of anisotropic and long-range dipolar interactions in degenerate quantum gases. As a first manifestation of the magnetic dipole-dipole interaction, we have observed a modification of the condensate expansion that depends on the orientation of the magnetic moments with respect to the trap axis.

References

1. A. Griesmaier, J. Werner, S. Hensler, J. Stuhler, and T. Pfau, *Phys. Rev. Lett. in press (cond-mat/0503044)*
2. J. Werner, A. Griesmaier, S. Hensler, J. Stuhler and T. Pfau "Observation of Feshbach resonances in an ultracold gas of ^{52}Cr" *Phys. Rev. Lett. in press (cond-mat/0412049)*
3. J. Stuhler, A. Griesmaier, T. Pfau, S. Giovanazzi, P. Pedri, L. Santos, *in preparation*

EXPERIMENTS WITH A QUANTUM DEGENERATE BOSE GAS IN ONE DIMENSION*

W. D. PHILLIPS, C. D. FERTIG, J. H. HUCKANS, B. LAURTHE TOLRA, K. M. O'HARA, J. V. PORTO, AND S. L. ROLSTON

Atomic Physics Division, National Institute of Standards and Technology
Gaithersburg, Maryland, USA 20899-8424

Using a two-dimensional optical lattice comprised of two intersecting standing waves, we create a cluster of one-dimensional tubes into which we load a Bose-Einstein condensate of ^{87}Rb atoms. In contrast to the case in 3D, the 1D system is strongly correlated at low density and we see a "fermionization" of the bosons: They tend to avoid each other, producing, for example, a substantial reduction in 3-body recombination collisions [1]. Applying an optical lattice along the 1D axis, we see features suggestive of a Mott insulator transition and we see a dramatic and unexpectedly large damping of dipole oscillations, oscillations that are completely undamped in the 3-D case [2]. The damping can be understood in terms of the fermionization of the bosons.

References

1. B. Laburthe Tolra, K. M. O'Hara, J. H. Huckans, W. D. Phillips, S. L. Rolston, and J. V. Porto , Phys. Rev. Lett. **92**, 190401 (2004).
2. C. D. Fertig, K. M. O'Hara, J. H. Huckans, S. L. Rolston, W. D. Phillips, and J. V. Porto, Phys. Rev. Lett. **94**, 120403 (2005).

* This work was supported in part by ARDA/NSA, ONR, and NASA.

NONLINEAR ATOM OPTICS OF BOSE-EINSTEIN CONDENSATES IN OPTICAL LATTICES

ELENA A. OSTROVSKAYA

Nonlinear Physics Centre and Australian Centre for Quantum-Atom Optics [*],
Research School of Physical Sciences and Engineering,
The Australian National University, Canberra, ACT 0200, Australia
E-mail: ost124@rsphysse.anu.edu.au

We review the effects that occur due to the interplay of the inherent nonlinearity of atomic matter waves and the periodicity of optical lattice potentials. Nonlinear localization of weakly interacting Bose-Einstein condensates in the form of gap solitons and lattice vortices will be described and parallels drawn with the effects observed in the nonlinear optics of coherent light waves in periodic photonic structures. Generation and detection methods of nonlinear localized states of the condensate will be discussed.

Due to the nonlinearity of the coherent matter waves and the band-gap structure of the matter-wave spectrum imposed by a periodic potential, the behavior of weakly interacting Bose-Einstein condensates in optical lattices finds its analog in nonlinear optics of periodic photonic structures. In particular, the effects of dispersion management and nonlinear localization of coherent waves in in the form of bright solitons is possible for both coherent light and matter waves in 1D, 2D, and 3D periodic potentials [1,2]. It was predicted [3] and demonstrated experimentally [4] that even condensates with repulsive interatomic interactions can form high-density localized states - matter wave gap solitons - supported by the anomalous diffraction at the edges of spectral bands and confined to the gaps of the matter-wave band-gap spectrum.

In two and three dimensions, localization of nontrivial phase states - gap vortices - is also possible [5,6]. The existence of vortices in a lattice is not obvious due to the lack of rotational symmety and non-conservation of angular momentum. However, a lattice vortex can exist as a structure with

[*]Australian Centre for Quantum-Atom Optics is an Australian Research Council Centre of Excellence.

persisting circular particle flow and a density that is strongly modulated by the lattice.

Observation of the localized states of Bose-Einstein condensates in an optical lattice proved to be difficult due to necessity to move the initial BEC wavepacket to the edge of the Brillouin zone, and the limited atom number in the initial state [4]. Theoretical study of the generation of lattice vortices [5] has shown their formation is a thresholod effect that depends not only on the total number of atoms but also on the peak density of the initial state. Above threshold, gap vortices of different symmetry types can be generated from a general initial state at the band-gap edge, with an imprinted vortex phase. The two symmetry types are those of the on-site (centered on a minimum of the lattice potential) and off-site (centered on the lattice maximum) states.

The release dynamics of the gap vortices shows that although the spatial structure of the localized state is lost in the expansion process, the phase retains its characteristic winding structure. This feature can enable homodyne interferometric detection [7] of the gap vortex after its release from the lattice, based on the Bragg splitting of the condensate into two different momentum states.

Finally, a non-adiabatic loading of the 3D condensate prepared in a magnetic trap with a single vortex into a 2D optical lattice leads to localization of broad high-density vortex states. The spatial structure of these states links them to the recently observed self-trapped nonlinear states in 1D optical lattices, and makes them likely candidates for experimental observation.

References

1. H. Pu *et al.*, Phys. Rev. A **67**, 043605 (2003); B. B. Baizakov *et al.*, Europhys. Lett., **63**, 642 (2003); E.A. Ostrovskaya and Yu.S. Kivshar, Phys. Rev. Lett. **90**, 160407 (2003); E.A. Ostrovskaya and Yu.S. Kivshar, Opt. Express **12**, 19 (2004); V. Ahufinger et al., Phys. Rev. A **69**, 53604 (2004).
2. B. Eiermann *et al.*, Phys. Rev. Lett. **91**, 060402 (2003); L. Fallani *et al.*, Phys. Rev. Lett. **91**, 240405 (2003).
3. O. Zobay *et al.*, Phys. Rev. A **59**, 643 (1999); P.J. Louis *et al.*, Phys. Rev. A **67**, 013602 (2003).
4. B. Eiermann *et al.*, Phys. Rev. Lett. **92**, 230401 (2004).
5. E. A. Ostrovskaya and Yu. S. Kivshar, Phys. Rev. Lett., **93**, 160405 (2004).
6. T.J. Alexander *et al.*, arXiv:cond-mat/0501590.
7. J. Tempere and J.T. Devreese, Solid State Comm. **108**, 993 (1998); L. Dobrek et al., Phys. Rev. A **60**, R3381 (1999).
8. Th. Anker *et al.*, Phys. Rev. Lett. **94**, 020403 (2005).

COLD GASES IN INHOMOGENEOUS AND RANDOM OPTICAL LATTICES

ANNA SANPERA*

Grup de Física Teòrica, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain
E-mail: sanpera@ifae.es

Since the discovery of quantum localisation phenomenon by P.W. Anderson in 1958[1], disorder and frustrated systems have played a central role in condense matter and are related to some of the most challenging open questions concerning many-body physics. Quenched disorder determines physical effects ranging from transport and conductivity, through localisation effects, spin glasses, neural networks, percolation to high Tc-superconductivity or quantum chaos. Disorder and frustrated systems are extremely hard to describe or simulated because one needs to average over the particular realisations of the disorder. After the almost perfect realisation of various Hubbard Hamiltonian models by transferring ultracold gases to optical lattices[2,3], we might question if ultracold gases can help to improve our understanding of disorder systems. Introducing disorder and/or frustration in lattice gases in a controlled way is possible using available experimental techniques. In this contribution I will concentrate in the physics of Bose-Fermi(BF) mixtures in disorder lattices to revisit some of most challenging condense matter open questions under a cold gases perspective.[4,5]

References

1. W.P. Anderson *Phys. Rev.* **109**, 5 (1958).
2. D. Jaksch, C. Bruder, J.I. Cirac, C.W. Gardiner and P. Zoller *Phys. Rev. Let.* **81**, 3108 (1998).
3. M. Greiner, O. Mandel, T. Esslinger, T.W. Hänsch and I. Bloch *Nature* **415**, 39 (2002).
4. J.E. Lye, L. Fallani, M. Modugno, D. Weirsma, C. Fort, and M. Inguscio *cond-matt/0412167*.
5. A. Sanpera, A. Kantian, L. Sanchez-Palencia, J. Zakrzewski and M. Lewenstein *Phys. Rev. Lett.* **93**, 040401 (2004).

*also at ICREA; institució catalana de Recerca i Estudis avançats.

CORRELATIONS AND COLLECTIVE MODES IN FERMIONS ON LATTICES

P. D. DRUMMOND, J. F. CORNEY, X.-J. LIU, H. HU
Australian Centre for Quantum-Atom Optics
University of Queensland
AUSTRALIA
E-mail: drummond@physics.uq.edu.au

Con ning ultracold fermions in an optical lattice gives us an outstanding opportunity for implementing the famous Hubbard model. We present an exact Gaussian phase-space method for fermion systems, which is used to calculate nite temperature atomic correlations. Luttinger liquid theory and the local density approximation let us calculate collective mode frequencies at the metal-insulator transition.

1. Introduction

Recent experiments with ultra-cold atomic fermions in optical lattices are paving the way to explore quantum phase transitions like the Mott metal-insulator transition (MMIT), which is a fundamental concept in strongly correlated many-body systems. Calculating the quantum many-body physics of such interacting Fermi systems is one of the great challenges in modern theoretical physics. These issues appear in physical problems at all energy scales, from ultra-cold atomic physics to high-energy lattice QCD. In even the simplest cases, first-principles calculations are inhibited by the complexity of the fermionic wavefunction, manifest notoriously in the Fermi sign problem. Motivated by this opportunity to compare fundamental predictions with experiment, we address the problems of how to:

- calculate observable correlation functions at finite temperatures
- detect the emergence of fermionic Mott-insulator phases

2. Gaussian representations

To calculate correlations, we need a representation of the density matrix, which we expand as a probability distribution over Gaussian forms $\widehat{\Lambda}_f$:

$$\widehat{\Lambda}_f \propto :\exp\left[\widehat{\underline{a}}^\dagger \left(\underline{\underline{I}} \quad \underline{\underline{\sigma}}^{-1}/2\right)\widehat{\underline{a}}\right]: , \tag{1}$$

Here $\widehat{\underline{a}} = (\widehat{\mathbf{a}}, \widehat{\mathbf{a}}^\dagger)$is a vector composed of fermionic annihilation and creation operators, so these Gaussian forms include thermal states and BCS states. This positive operator representation is able to represent arbitrary physical states of fermions. We obtain and present identities for calculating quantum correlations, both dynamical (real time evolution) and canonical (imaginary time evolution). Interacting systems with quartic terms in the Hamiltonian generate stochastic equations which can be readily simulated numerically. Unlike density functional methods, this is a first principles method. Unlike quantum Monte Carlo, there is neither a sign problem nor computationally intensive determinant calculations.

We present results for one and two-dimensional Hubbard models, corresponding to two-component interacting Fermi gases in an optical lattice. More details are given elsewhere at this conference.

3. Collective modes

Another useful probe of many-body systems is the occurrence of collective modes, which are many-body excited states. In optical lattices, a harmonic potential is necessary to prevent the atoms from escaping, so that the collective modes must be calculated in an environment where the Mott-insulator phase is restricted to an insulator domain at the center of the trap, and coexists with two compressible metallic wings. This problem can be treated using the exactly known one-dimensional solutions, together with the Luttinger liquid Hamiltonian that describes long-wavelength excitations.

Here, we present a phase diagram for 1D confined fermions in an optical lattice. We show that the behavior of the frequencies of collective density modes is distinct in each phase. The phase transition can be detected unambiguously by measuring a dip in the frequency of the density oscillations. This provides a useful signature for locating the quantum phase transition from the metallic phase to the Mott-insulator phase. We expect that a similar sensitivity of the mode frequencies with respect to the thermodynamic phase will arise in higher dimensions as well.

References

1. J. F. Corney and P. D. Drummond, PRL **93**, 260401 (2004).
2. X-J. Liu, P. D. Drummond, and H. Hu, PRL **94**, 136406 (2005).

INDIVIDUAL ATOMS AND PHOTONS UNDER CONTROL

GERHARD REMPE

Max-Planck Institute for Quantum Optics,
Hans-Kopfermann-Str. 1, D-85748 Garching, Germany

Cavity Quantum Electrodynamics provides an ideal setting for many investigations ranging from single-atom physics to quantum information science. For example, the strong atom-photon coupling achievable in a high-finesse cavity allows one to observe individual atoms in real time, build novel interfaces between classical and quantum fields of light or – most recently – cool a trapped and continuously observed atom to low temperatures. The long trapping times achieved in combination with the ability to precisely control the position of the atom inside the cavity paves the way towards new applications, e.g. the realization of a distributed network of individually addressable quantum systems.

CONTROLLING STRINGS OF SINGLE TRAPPED ATOMS

A. RAUSCHENBEUTEL, W. ALT, I. DOTSENKO, L. FÖRSTER, M. KHUDAVERDYAN, Y. MIROSHNYCHENKO, D. SCHRADER, AND D. MESCHEDE

Institute for Applied Physics,
Wegelerstraße 8,
D-53115 Bonn, Germany
E-mail: Arno.Rauschenbeutel@iap.uni-bonn.de

We control and manipulate strings of neutral atoms trapped inside a standing wave dipole trap. We show that such a string realizes a quantum register, where coherent information is encoded in the atomic hyperfine states using microwave radiation. Furthermore, using high resolution imaging optics, we measure the absolute and relative positions of the atoms with a sub-optical wavelength resolution. The overall position of the string is then actively controlled with an optical conveyor belt. Finally, by extracting and reinserting atoms at predetermined positions with a second, perpendicular dipole trap, we control the interatomic distances, prepare equidistant strings, and rearrange their order.

Neutral atoms trapped in light induced potentials are a promising candidate for storing and processing quantum information. Recently, we have demonstrated that a string of optically resolved single trapped cesium atoms can serve as a quantum register. Using microwave radiation and resonant laser pulses, we have initialized, selectively addressed, coherently manipulated, and state-selectively detected the hyperfine states of individual atoms within the string.[1,2] The spatial resolution of our scheme relies on a position dependent Zeeman shift of the 9.2 GHz qubit transition through a magnetic field gradient.

Several schemes have been proposed to process the information stored in such a quantum register. In neutral atom cavity QED the atomic qubits interact through photon exchange inside an ultrahigh Q optical resonator,[3] while in cold collision schemes the necessary atom–atom interaction is achieved by state-selectively confining them inside one potential well using spin-dependent potentials.[4] Both schemes require a high degree of control over the absolute and relative positions of the atoms within the string.

We have realized such a position control with a sub-optical wavelength precision. We record the atomic fluorescence using high resolution imaging optics in combination with an intensified CCD camera. After 1 s exposure time, the resulting fluorescence image allows us to determine the absolute atomic positions with a precision of 143 nm rms.[5] The distance between the atoms has been measured with an even higher precision of 36 nm rms. We thus resolve the discrete distribution of the interatomic distances due to the 532 nm spatial period of the standing wave potential and infer the the exact number of trapping potential wells separating the atoms. The overall position of the string is then manipulated using an optical conveyor belt, while we use a second, perpendicular standing wave optical dipole trap to extract atoms out of the string and to reinsert them at predetermined positions. This second dipole trap, which is operated as optical tweezers, thereby allows us to control the interatomic distances, to prepare equidistant strings of atoms, and to rearrange their order.[6]

References

1. D. Schrader et al., *Phys. Rev. Lett.* **93**, 150501 (2004).
2. M. Khudaverdyan et al., *Phys. Rev. A* **71**, 031404(R) (2005).
3. L. You, X. X. Yi, and X. H. Su, *Phys. Rev. A* **67**, 032308 (2003).
4. O. Mandel et al., *Nature (London)* **425**, 937 (2003).
5. I. Dotsenko et al., *e-print* quant-ph/0411062.
6. Y. Miroshnychenko et al., *in preparation* (2005).

ATOM CHIPS: COHERENCE AND SINGLE ATOMS

JAKOB REICHEL

Laboratoire Kastler Brossel de l'E.N.S., Paris and
Max-Planck-Institut für Quantenoptik, Garching/München
E-mail: jakob.reichel@ens.fr

Microchip traps for cold atoms ("atom chips") have enabled drastically simplified Bose-Einstein condensation experiments. Atomic BECs are created in close proximity to the chip surface, and coherence between internal atomic states maintained for seconds despite the fact that the surface is at room temperature. Additional elements, such as resonators, can be integrated on this surface with the goal of making them interact with the trapped BEC. I will present two projects involving two very different types of resonators. In the first experiment, for which I will present first results, a trapped BEC or cold atom cloud is transported into a miniature, optical fiber-based Fabry-Perot resonator on the chip. The resonator has an exceptionally small mode volume, and can be used as a detector with single-atom detectivity. It seems likely that strong coupling between the cavity mode and a single trapped atom can be reached with a realistic improvement of the mirror quality. In the second project, the resonator is a nanomecanical device, which couples to the atoms magnetically, via a submicron-sized ferromagnetic island applied on the resonator. One goal of such a hybrid solid-state – atomic-BEC system is to realize a single-phonon detector.

BOSE-EINSTEIN CONDENSATES STUDIED WITH A LINEAR ACCELERATOR*

CH. BUGGLE, J. LEONARD†, W. VON KLITZING‡, AND J. T. M. WALRAVEN

FOM Institute for Atomic and Molecular Physics, Kruislaan 407, 1098 SJ Amsterdam, The Netherlands
and
Van der Waals-Zeeman Institute of the University of Amsterdam, Valckenierstraat 65/67, 1018 XE The Netherlands
E-mail: walraven@science.uva.nl

We present a stand-alone interference method for the accurate determination of the s- and d-wave scattering amplitudes in a quantum gas. Colliding two ultracold atomic clouds we observe the scattering halo in the rest frame of the collisional center of mass by absorption imaging. The clouds are accelerated up to energies at which the scattering pattern shows the interference between the s- and d- partial waves (see Fig. 1).

With computerized tomography we transform the images to obtain an angular distribution directly proportional to the differential cross section. This allows us to measure the asymptotic phase shifts $\eta_l(k)$ (with k the relative momentum) of the s-wave ($l = 0$) and d-wave ($l = 2$) scattering channels. Using these $\eta_l(k)$ as boundary conditions, we integrate the radial Schrödinger equation inwards over the $-C_6/r^6$ tail of the potential and compute the accumulated phase of the wavefunction at radius $20\,a_0$ (with a_0 the Bohr radius).

All data of $\eta_l(k)$ are used to obtain a single optimized accumulated phase from which we can infer all the low-energy scattering properties, by integrating again the Schrödinger equation outwards over the same potential. Note that this procedure does not require knowledge of the density of the colliding and scattered clouds, unlike the stimulated raman detection approach.[1]

Tthis work is part of the research program on cold atoms of the stichting voor fundamenteel onderzoek der materie (fom), which is financially supported by the nederlandse organisatie voor wetenschappelijk onderzoek (nwo).
†present address: universit de strasbourg, institut de physique et chimie des materiaux
‡present address: iesl - forth, p.o. box 1527, 711 10 heraklion, greece.

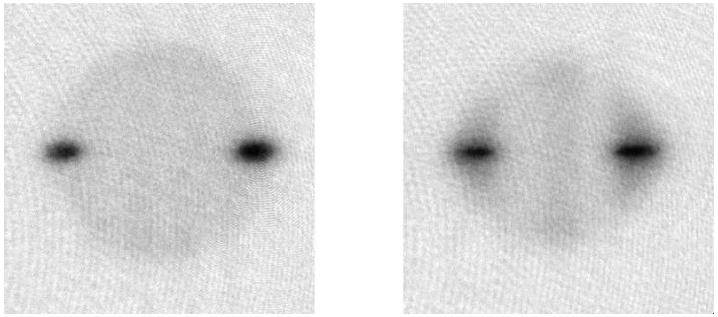

Figure 1. Left: Scattering halo of two ^{87}Rb condensates for collision energy $E/k_B = 138(4)\,\mu$K (mostly s-wave scattering), measured 2.4 ms after the collision; Right: idem but measured 0.5 ms after a collision at 1230(40) μK (mostly d-wave scattering). The field of view of the images is $\sim 0.7 \times 0.7\text{mm}^2$.

We demonstrate this method with ^{87}Rb atoms interacting through the ground-state triplet potential. We took data with both condensates and thermal clouds. Here we report on the condensates, as they allow to observe the largest range of scattering angles, $25° < \theta < 90°$. Up to 80% of the atoms are scattered without destroying the interference pattern. With our method, we obtain $a = +102(6)\,a_0$ for the scattering length. The d-wave resonance is found at the energy $E_{res} = 300(70)$ μK. These results coincide within experimental error with the precision determinations ($a = 98.99(2)\,a_0$ and $E_{res} = 270$ μK), obtained by combining the results of several experiments as input for state-of-the-art theory.[2]

We point to the close relation between our results[3] and other work.[4,5]

References

1. R. Legere and K. Gibble, Phys. Rev. Lett. **81**, 5780 (1998).
2. E.G.M. van Kempen, S.J.J.M.F. Kokkelmans, D.J. Heinzen, and B.J. Verhaar, Phys. Rev. Lett. **88**, 93201 (2002); A. Marte *et al.*, Phys. Rev. Lett., **89**, 283202 (2002).
3. Ch. Buggle *et al.*, Phys. Rev. Lett. **93** 173202 (2004)
4. N. R. Thomas, N. Kjærgaard, P. S. Julienne, and A. C. Wilson, Phys. Rev. Lett. **93** 173201 (2004).
5. T. Voltz, S.Durr, N. Syassen, G. Rempe, E. van Kempen, S. Kokkelmans, cond-mat/0410083.

ELECTRIC-FIELD SPECTROSCOPY OF WEAKLY-BOUND MOLECULAR DIMERS *

J. L. BOHN

JILA, NIST and Department of Physics,
University of Colorado,
UCB 440, Boulder, CO 80305 USA
E-mail: bohn@murphy.colorado.edu

Traditional spectroscopy of atoms and molecules takes the energy levels as given, and interrogates them using an energy-dependent probe (e.g., a photon or a charged or neutral material particle). The achievement of ultracold environments for atoms and molecules has reversed this picture. Now, collisions are a non-tunable and essentially monochromatic probe, with energy resolution set by the milliKelvin or microKelvin temperature of the gas. On the other hand, resonant states of the collision complex can be shifted in energy by the application of external fields. The most prominent example of this so far is the magnetically-engineered Fano-Feshbach resonance, by means of which careful placement of a scattering resonance can alter the collision dynamics and mean-field properties of an ultracold gas. This kind of experiment has also afforded by far the most accurate determination of the interaction between weakly-bound constituents.

In this talk I will expand this idea to include resonances between heteronuclear polar molecules, where resonances can be shifted in energy by the application of dc electric fields. There emerge in this context a large number of resonant states, owing to the comparatively large strength of the dipole-dipole interaction. Some of these resonances are also of Fano-Feshbach type, but many occur instead because an electric field warps the intermolecular potential energy surface itself. Analysis of these resonances should yield insight into cold collision dynamics, weakly-bound clusters, chemical transition states, and techniques for tuning the properties of anisotropic quantum degenerate gases.

*This work is supported by the National Science Foundation

OPTICAL PRODUCTION OF ULTRACOLD POLAR MOLECULES

D. DEMILLE, J. SAGE, AND S. SAINIS

Physics Department, Yale University, P.O. Box 208120, New Haven, CT 06520
E-mail: david.demille@yale.edu

T. BERGEMAN

Department of Physics and Astronomy, SUNY, Stony Brook, NY 11794-3800

Samples of ultracold, polar molecules (UPMs) can provide access to new regimes in many phenomena. Ultracold temperatures allow trapping, and polarity can be used to engineer large, anisotropic, and tunable interactions between molecules. These features make UPMs attractive as qubits for quantum computation,[1] as building blocks for novel many-body systems,[2] and for the study of chemistry in the ultracold regime.[3] UPMs also could be used as uniquely sensitive probes of phenomena beyond the Standard Model of particle physics.[4]

Methods such as buffer-gas cooling, Stark-slowing, billiard-like collisions, and velocity filtering have produced samples of polar molecules at temperatures of $\sim 10-100$ mK.[5] Formation of heteronuclear molecules from pre-cooled atoms via photoassociation[6,7] or Feshbach resonance[8] techniques promises access to much lower temperatures. However, these processes leave molecules in highly excited vibrational levels, which have vanishingly small polarity[9] and are unstable to collisions.

Here we report the production of UPMs with an all-optical technique. RbCs molecules are first "assembled" by photoassociation of laser-cooled Rb and Cs atoms; the resulting electronically-excited molecular states rapidly decay, with substantial probability, to vibrationally-excited levels of the electronic ground state. Next, one of these metastable levels is transferred to a lower vibrational state, using a two-color stimulated emission pumping process. This sequence of steps yields RbCs molecules in their absolute vibronic ground state $X^1\Sigma^+(v = 0)$. The molecular formation and state transfer process are monitored with state- and mass-selective

photoionization techniques. Unambiguous evidence for UPM formation is obtained from spectral signatures in the ion signals.

The resulting polar molecules (calculated electric dipole moment[10] $\mu \approx 1.3$ D) have a translational temperature of ~ 100 μK. The distribution of rotational states is also quite narrow, so the resulting sample of $X^1\Sigma^+(v = 0)$ state molecules is cold in all degrees of freedom. We demonstrate an efficiency for the stimulated emission pumping process of $\approx 6\%$, which is clearly limited by the spectral properties of our pulsed lasers. With optimized lasers, near unit efficiency should be possible.

The method described here can be used to produce substantial samples of trapped UPMs. Far-detuned optical dipole traps can trap atoms, vibrationally-excited molecules, and $X(v = 0)$ molecules. Excited molecules formed in such a trap could be transferred to their absolute rovibrational ground state as described here, with optimized efficiencies resulting in large numbers of UPMs. Translational temperatures limited only by atomic cooling methods should be achievable, and with available technology population of a single rovibronic state with high purity should be possible. The work described here thus opens a clear route to the study and manipulation of polar molecules in the ultracold regime.

References

1. D. DeMille, *Phys. Rev. Lett.* **88**, 067901 (2002).
2. M. A. Baranov *et al., Phys. Rev. A* **66**, 013606 (2002); K. Goral, L. Santos, and M. Lewenstein, *Phys. Rev. Lett.* **88**, 170406 (2002).
3. E. Bodo, F. A. Gianturco, and A. Dalgarno, *J. Chem. Phys.* **116**, 9222 (2002).
4. M. Kozlov and L. Labzowsky, *J. Phys. B* **28**, 1933 (1995); J. J. Hudson *et al., Phys. Rev. Lett.* **89**, 023003 (2002); D. DeMille, *Bull. Am. Phys. Soc.* **49**, 97 (2004).
5. For a review, see: J. Doyle, B. Friedrich, R.V. Krems and F. Masnou-Seeuws, *Eur. Phys. J. D* **32**, 149-164 (2004).
6. A. J. Kerman *et al., Phys. Rev. Lett.* **92**, 153001 (2004); *ibid.*, 033004 (2004).
7. M. W. Mancini *et al., Phys. Rev. Lett.* **92**, 133203 (2004); C. Haimberger *et al., Phys. Rev. A.* **70**, 021402(R) (2004); D. Wang *et al., Phys. Rev. Lett.* **93**, 243005 (2004).
8. S. Inouye *et al., Phys. Rev. Lett.* **93**, 183201 (2004); C. A. Stan *et al., Phys. Rev. Lett.* **93**, 143001 (2004).
9. S. Kotochigova, P. S. Julienne, and E. Tiesinga, *Phys. Rev. A* **68**, 022501 (2003).
10. G. Igel-Mann *et al., J. Chem. Phys.* **84**, 5007 (1986).

MOLECULES AND CORRELATED PAIRS IN ULTRACOLD GASES*

M. H. SZYMANSKA, K. GORAL, T. KOEHLER AND K. BURNETT

Department of Physics,
University of Oxford,
Clarendon Laboratory,
Parks Road,
Oxford OX1 3PU,
E-mail: k.burnett1@physics.ox.ac.uk

In this talk we shall discuss recent theoretical work on the description of strongly interacting atoms in degenerate gases. This field has seen truly exciting developments in recent years with the production of molecular condensates from atomic ones. We have also seen the production of Fermionic condensates, i.e. BCS-like pairing, in degenerate Fermi gases. These striking achievements have been made possible through the use of Feshbach resonances to tune the interaction between ultracold atoms. We shall give a brief review of the theoretical methods needed to describe these systems and outline the predictions for the physical nature of the pair correlations. We will then explain why these developments have opened up new avenues of atomic physics based research that should have implications for the study of strong correlations in a wide range of physical systems.

*This work is supported by the EU, the EPSRC, the Royal Society and the Wolfson Foundation.

EXPERIMENTS ON THE BEC-BCS CROSSOVER IN AN ULTRACOLD FERMI GAS OF ^{6}LI ATOMS

M. BARTENSTEIN, A. ALTMEYER, S. RIEDL, R. GEURSEN, S. JOCHIM, J. HECKER DENSCHLAG, R. GRIMM

Institute of Experimental Physics, Univ. of Innsbruck, 6020 Innsbruck, Austria, and Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Innsbruck, Austria
www.ultracold.at

C. CHIN

Department of Physics and James Franck Institute, University of Chicago, Chicago, IL 60637, USA

Experiments with ultracold fermionic quantum gases have entered regimes, where phenomena related to pairing and superfluidity can be experimentally studied at densities typically a billion times below the ones in usual condensed-matter systems. The tunability through Feshbach resonances is the experimental key to explore a wide range of different interaction regimes in the crossover from a molecular Bose-Einstein condensate (BEC)[1] to a Bardeen-Cooper-Schrieffer (BCS) superfluid.

We will discuss our recent experiments[2] on fermionic pairing in an ultracold two-component gas of ^{6}Li atoms. By radio-frequency spectroscopy we observed an *energy gap* in the excitation spectra. With precise control of the two-body interactions through a broad Feshbach resonance[3] we demonstrate the dependence of the pairing gap on coupling strength, temperature, and Fermi energy. The appearance of an energy gap with moderate evaporative cooling suggests that our full evaporation brings the strongly interacting system deep into a superfluid state.

References

1. S. Jochim *et al.*, Science **302**, 2101 (2003); M. Greiner *et al.*, Nature **426**, 537 (2003); M. W. Zwierlein *et al.*, Phys. Rev. Lett. **91**, 250401 (2003).
2. C. Chin *et al.*, Science **305**, 1128 (2004).
3. M. Bartenstein *et al.*, Phys. Rev. Lett. **94**, 103201 (2005).

THERMODYNAMICAL AND MECHANICAL PROPERTIES OF A STRONGLY-INTERACTING FERMI GAS

J. E. THOMAS

Physics Department, Duke University
Durham, NC 27708-0305, USA

Strongly-interacting Fermi gases provide a paradigm for exotic systems in nature, ranging from high temperature superconductors to neutron stars. Using precision energy input methods and empirical thermometry, we measure the properties of a 50-50 mixture of spin-up and spin-down fermionic ^{6}Li atoms, cofined in an optical trap. The gas is magnetically tuned near the center of a broad Feshbach scattering resonance, where the scattering length far exceeds the interparticle spacing, producing scale-invariant, universal strong interactions. The cloud exhibits nearly perfect hydrodynamics, providing links to recent string theory predictions and to observations of elliptic flow in a quark-gluon plasma. Our measurements of both the heat capacity and the damping rate reveal transitions in behavior at 30% of the Fermi temperature, indicating the onset of high temperature superfluidity.

INERTIAL NAVIGATION SENSORS BASED ON ATOM INTERFEROMETRY

MARK KASEVICH

Physics and Applied Physics, Stanford University, Stanford, CA 94305

Recent advances in the field of atom interferometry have opened the possibility of a new class of precise and accurate inertial force sensors. We have built laboratory prototypes of accelerometers, gravity gradiometers and gyroscopes based on atom interference principles which now perform at levels which compare favorably with other state-of-the-art sensors. These instruments, and their applications in science and technology, will be presented. Applications range from new measurements of G and tests of General Relativity to the development of next generation inertial navigation systems. We will assess the possible impact of Bose-Einstein condensed atomic sources and cavity-assisted spin squeezing on these sensors.

A STRONTIUM ION OPTICAL FREQUENCY STANDARD WITH HZ-LEVEL UNCERTAINTY *

H. S. MARGOLIS, G. P. BARWOOD, G. HUANG, H. A. KLEIN, S. N. LEA, K. SZYMANIEC AND P. GILL

National Physical Laboratory, Teddington, Middlesex TW11 0LW, UK
E-mail: helen.margolis@npl.co.uk

The $5s\,^2S_{1/2}$–$4d\,^2D_{5/2}$ electric quadrupole transition at 674 nm in $^{88}Sr^+$ is an excellent choice for an optical frequency standard because of its narrow natural linewidth of 0.4 Hz. In the NPL strontium ion standard, a single strontium ion is trapped in an endcap trap with an electrode separation of ~ 0.6 mm. The ion is laser-cooled to a temperature of a few mK on the $5s\,^2S_{1/2}$–$5p\,^2P_{1/2}$ transition at 422 nm, with an additional laser at 1092 nm to prevent optical pumping into the metastable $4d\,^2D_{3/2}$ state. The optical clock transition at 674 nm is probed using an extended-cavity diode laser stabilized to a high-finesse ultra-low-expansion (ULE) cavity. The centre frequency of the $5s\,^2S_{1/2}$–$4d\,^2D_{5/2}$ Zeeman structure is determined by using a four-point servo scheme to probe a pair of Zeeman components which are symmetrically placed around line centre.

The largest source of systematic frequency uncertainty for the $^{88}Sr^+$ optical frequency standard arises from the electric quadrupole shift of the reference transition. This is due to the interaction between the electric quadrupole moment of the $^2D_{5/2}$ state and any residual electric field gradient present at the position of the trapped ion, and can easily be several Hz or more. By deliberately applying and varying an electric field gradient to the trap, we have made an accurate measurement of the quadrupole moment of the the $^2D_{5/2}$ level, yielding a result of $2.6(3)ea_0^2$ [1].

The residual dc electric field gradient in the trap can be determined from measurements of the trap secular frequencies and minimized by adjusting the dc voltages applied to the outer electrodes of the endcap trap. In this

*Work supported by the UK Department of Trade and Industry under the National Measurement System Length programme, contract no. LE02/A01.

way we have reduced the quadrupole shift to the level of a few Hz. However, by using one of two different techniques to null the quadrupole shift, the uncertainty in this shift can be reduced to a substantially lower level.

Absolute frequency measurements of the $5s\,^2S_{1/2}$–$4d\,^2D_{5/2}$ transition in $^{88}Sr^+$ were carried out on 11 separate days in 2004, using a femtosecond optical frequency comb referenced to the NPL caesium fountain primary frequency standard. On the first six days the quadrupole shift was nulled by selecting a particular pair of Zeeman components and carrying out frequency measurements for three mutually orthogonal orientations of the applied dc magnetic field. The average quadrupole shift for these three measurements is zero [2]. On the remaining five days, an alternative technique was used to null the quadrupole shift. This involved making frequency measurements for three different pairs of Zeeman components corresponding to transitions with $|m_j| = 1/2$, $3/2$ and $5/2$, where m_j is the magnetic quantum number of the $4d\,^2D_{5/2}$ level. The average quadrupole shift is again zero, independent of the magnetic field direction [3]. The mean frequency values for the 674 nm clock transition obtained by each method and corrected for systematic frequency shifts differ by only 0.5 Hz with 1σ uncertainties of 1.9 Hz and 1.6 Hz respectively. Combining these mean values gives a value of 444 779 044 095 484.6 (1.5) Hz for the frequency of the clock transition, with a fractional uncertainty of 3.4×10^{-15} [4].

Apart from the uncertainty arising from the caesium standard, the dominant sources of uncertainty in this measurement are an ac Stark shift arising from the cooling laser radiation and servo errors in the lock of the 674 nm probe laser to the clock transition frequency. Improvements to the extinction ratio of the cooling laser radiation during the probe laser periods and reductions in the probe laser linewidth and ULE cavity drift rate will reduce these sources of uncertainty. A second endcap trap has also been developed to enable a more detailed investigation of systematic errors by means of two-trap comparisons. With these improvements, we anticipate a frequency measurement that is limited by accuracy of the caesium fountain. Progress towards this goal will be reported at the conference.

References

1. G. P. Barwood *et al.*, *Phys. Rev. Lett.* **93**, 133001 (2004).
2. W. M. Itano, *J. Res. Natl. Inst. Stand. Technol.* **105**, 829 (2000).
3. P. Dubé *et al.*, presentation at the 2004 Conference on Precision Electromagnetic Measurements, London, 27th June–2nd July 2004.
4. H. S. Margolis *et al.*, *Science* **306**, 1355 (2004).

OPTICAL LATTICE CLOCK

HIDETOSHI KATORI[1], MASAO TAKAMOTO[1], RYOICHI HIGASHI[1] AND FENG-LEI HONG[2]

[1] *Department of Applied Physics, Graduate School of Engineering, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan,*

[2] *National Metrology Institute of Japan / National Institute of Advanced Industrial Science and Technology (NMIJ/AIST), Tsukuba, Ibaraki 305-8563, Japan*

E-mail: katori@amo.t.u-tokyo.ac.jp

Careful elimination of perturbations on electronic states and of motional effects has been considered as a prerequisite for realizing atom frequency standards. A single ion trapped in an RF quadrupole field is one of the ideal systems that satisfy these requirements, as the trap prepares a quantum absorber completely at rest in free space for an extended time and its electric field vanishes at the center of the trap[1]. Employing this scheme, quantum projection noise (QPN) limited spectroscopy has been performed[2] with a projected accuracy of 10^{-18}, whereas the stability of the single-ion based optical clock is severely limited by QPN and long averaging time is required to meet its ultimate accuracy. One may think of increasing the number of quantum absorbers N as employed in neutral atom based optical standards. In this case, however, the atom-laser interaction time sets upper bounds for the effective transition line Q-factor[3], which is two orders of magnitude smaller than that for ion clocks[2], since an atom cloud in free space expands with finite velocity and is strongly accelerated by the gravity during the measurement. Furthermore, the residual Doppler shifts arising from imperfect wavefronts of the probe beams and atom-atom collisions during the measurement may affect its ultimate accuracy[4].

In this presentation, we discuss the feasibility of an "optical lattice clock[5]," which utilizes millions of neutral atoms prepared in an optical lattice. Sub-wavelength localization of atoms in each lattice site suppresses the first order Doppler shift as well as the collisional frequency shifts; therefore the scheme simulates millions of single-ion clocks operated simultaneously.

In striking contrast with conventional approaches toward frequency standards, this lattice clock scheme interrogates atoms while they are strongly perturbed by an external field. We have shown that this perturbation can be cancelled out to below 10^{-17} precision level[5] by designing the light shift trap so as to adjust dipole polarizabilities for the probed electronic states. By applying the scheme to the $5s^2\,{}^1S_0(F=9/2)-5s5p\,{}^3P_0(F=9/2)$ clock transition of ^{87}Sr atoms[5,6], our recent experiment resolved the clock transition with a linewidth of 27 Hz, which is one order of magnitude narrower than that observed for atomic clocks in free fall[3,4], and the clock stability is estimated to be comparable to that of single ion clocks[2]. The transition frequency for the Sr lattice clock is measured to be 429,228,004,229,952(15) Hz by an optical frequency comb referenced to the SI second.

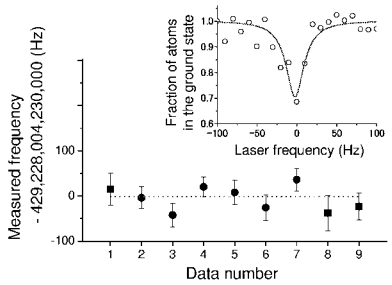

Figure 1. Absolute frequency measurement of the ${}^1S_0 - {}^3P_0$ transition of ^{87}Sr atoms trapped in an 1D optical lattice. The inset shows the typical clock transition resolving a Fourier limited linewidth of 27 Hz. The resonance frequency was measured by an optical frequency comb generator referenced to a commercial Cs clock. A systematic correction of -45.7 Hz was applied to the data shown in the figure to obtain the final result.

References

1. H. Dehmelt, *IEEE Trans. Instrum. Meas.* **31**, 83 (1982).
2. R. J. Rafac *et al.*, *Phys. Rev. Lett.* **85**, 2462 (2000); E. Peik *et al.*, *Phys. Rev. Lett.* **93**, 170801 (2004); H. S. Margolis, *et al.*, Science **306**, 1355 (2004).
3. F. Ruschewitz *et al.*, *Phys. Rev. Lett.* **80**, 3173 (1998).
4. G. Wilpers *et al.*, *Phys. Rev. Lett.* **89**, 230801 (2002).
5. H. Katori, *Proceedings of the 6th Symposium Frequency Standards and Metrology*, edited by P. Gill (World Scientific, Singapore, 2002) p 323; H. Katori, M. Takamoto, V. G. Pal'chikov, and V. D. Ovsiannikov, *Phys. Rev. Lett.* **91**, 173005 (2003).
6. M. Takamoto and H. Katori, *Phys. Rev. Lett.* **91**, 223001 (2003).

MICROFABRICATED ATOMIC CLOCKS AND MAGNETOMETERS

S. KNAPPE[1], P.D.D. SCHWINDT, V. GERGINOV[2], V. SHAH[1], H.G. ROBINSON, L. HOLLBERG, AND J. KITCHING

Time and Frequency Division, National Institute of Standards and Technology
Boulder, CO 80305, USA

The possibility of using micro electro-mechanical systems (MEMS) techniques for instruments based on atomic spectroscopy has led to a new generation of atomic clocks and atomic magnetometers. These methods not only allow for smaller sizes and more robust setups, but at the same time open the possibility of lower power consumptions, making the devices attractive for portable applications. Furthermore, wafer-level fabrication and integration could substantially reduce fabrication costs. At the same time, scaling devices to smaller sizes does not necessarily degrade their performance substantially.

Recently, the first physics packages for chip-scale atomic clocks [1,2] and magnetometers [3] have been demonstrated (see Fig. 1). These physics packages consist of a vertical-cavity surface-emitting laser (VCSEL), a micro-optics assembly, a vapor cell that contains the alkali atoms [4], and a photodetector. Coherent population trapping (CPT) resonances were excited by the laser light resonant with one of the optical D-line transitions, and frequency modulated at half the ground-state hyperfine splitting frequency. The modulation frequency was then locked to the atomic ground state splitting using the signal from the light transmitted through the vapor cell.

The chip-scale atomic clocks were probing the $m_F = 0$ ground-state Zeeman components, which are magnetically insensitive to first order. Such a chip-scale physics package based on the D1 transition in ^{87}Rb reached fractional frequency instabilities below $4 \times 10^{-11}/\tau^{1/2}$ [5]. The same physics package has been run as a chip-scale magnetometer probing the magnetically sensitive transitions coupling the $m_F = -1$ ground-state Zeeman components [3].

We anticipate that a chip-scale atomic clock physics package will be integrated with a miniature local oscillator and miniature control electronics into a package

[1] Also with: University of Colorado, Boulder, CO 80309
[2] Also with: University of Notre Dame, Notre Dame, IN 46556

of volume less than 10 cm^3, in the near future. Further miniaturization to packages of 1 cm^3 with power consumptions below 50 mW seems feasible.

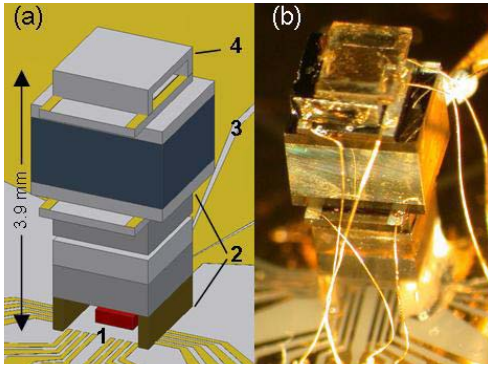

Figure 1. (a) Schematic (a) and photograph of the chip-scale physics package. The components are: 1-VCSEL, 2-micro-optics, 3-^{87}Rb vapor cell, 4-photodiode. It can be run as a frequency reference as well as a magnetometer.

First experiments using advanced atomic spectroscopy methods based on optical pumping and multiple beams [6-8] in small vapor cells indicate substantial improvements of the chip-scale atomic clocks and magnetometers, when integrated into miniature setups.

1. S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, J. Kitching, L. A. Liew and J. Moreland, *Appl. Phys. Lett.* **85**, 1460 (2004).
2. R. Lutwak, J. Deng, W. Riley, M. Varghese, J. Leblanc, G. Tepolt, M. Mescher, D. K. Serkland, K. M. Geib, and G. M. Peake, *Proc. 36th Ann. PTTI Meet.* (2004).
3. P. D. D. Schwindt,, S. Knappe, V. Shah, L. Hollberg, J. Kitching, L. A. Liew and J. Moreland, *Appl. Phys. Lett.* **85,** 6409 (2004).
4. L. Liew, S. Knappe, J. Moreland, H. Robinson, L. Hollberg, and J. Kitching, Appl. Phys. Lett. **48**, 2694 (2004).
5. S. Knappe, P. Schwindt, V. Shah, L. Hollberg, J. Kitching, L. Liew and J. Moreland, *Opt. Expr.* **14,** 1249 (2005).
6. Y. Y. Jau, E. Miron, A. B. Post, N. N. Kuzma, and W. Happer, *Phys. Rev. Lett.* **93**, 160802 (2004).
7. N. Cyr, M. Tetu, and M. Breton, *IEEE Trans. Instrum. Meas.* **42**, 640 (1993).
8. D. Budker, D. F. Kimball, V. V. Yashchuk, and M. Zolotorev, *Phys. Rev. A* **65,** 055403 (2002).

ATTOSECOND PHYSICS: CONTROLLING AND TRACKING ELECTRON DYNAMICS ON AN ATTOSECOND TIME SCALE

F. KRAUSZ

Max-Planck-Institut für Quantenoptik and
Ludwig-Maximilians-Universität München
85748 Garching, Germany
E-mail: ferenc.krausz@mpq.mpg.de

The fundamental processes in chemistry, biology and materials science are triggered or mediated by the motion of electrons inside or between atoms. Electronic dynamics on atomic length scales occur on a time scale of attoseconds (1 attosecond [as] = 10^{-18} s). Recent breakthroughs in laser science are now opening the door to watching and controlling these hitherto inaccessible microscopic dynamics. The new attosecond probes and techniques enable us to study the way in which electronic processes affect phenomena as fundamental as the photosynthesis, vision, or radiation damage in bioimaging and to pave the way towards molecular electronics by steering molecular currents and towards hyperfast optical computing and communication by exploring novel ultrafast nonlinear optical effects.

The key to accessing the attosecond time domain is the control of the electric field of (visible) light, which varies its strength and direction within less than a femtosecond (1 femtosecond = 1000 attoseconds). Atoms exposed to a few oscillations cycles of intense laser light are able to emit a single X-ray burst lasting less than one femtosecond.[1,2] Full control of the evolution of the electromagnetic field in laser pulses comprising a few wave cycles[3] have recently allowed the reproducible generation and measurement of 250-attosecond soft-X-ray bursts.[4] These X-ray bursts constitute the shortest man-made events to date. Along with the intense, waveform-controlled few-cycle laser pulses used for their generation they offer an attosecond-resolution chronoscope ("time microscope") for both

characterizing the X-ray burst[4] and the light wave[5] and capturing the motion of electrons in atoms and molecules for the first time.[6]

References

1. M. Hentschel et al., *Nature* **414**, 509 (2001).
2. R. Kienberger et al., *Science* **291**, 1923 (2002).
3. A. Baltuska et al., *Nature* **421**, 611 (2003).
4. R. Kienberger et al., *Nature* **427**, 817 (2004).
5. E. Goulielmakis, *Science* **305**, 1267 (2004).
6. M. Drescher, *Nature* **419**, 803 (2002).

QUANTUM CONTROL

P. H. BUCKSBAUM, B.J. PEARSON, AND J.L. WHITE

FOCUS Center, Physics Department, University of Michgian
Ann Arbor, MI 48109-1120

New techniques in optical coherent control have driven recent advances in laser technology, particularly for ultrafast lasers. Carrier-envelope stabilization, single-cycle optical pulses, petawatt lasers, high harmonics generation, and attosecond pulses are examples. This same exquisite control of laser frequency, phase, wave-front and intensity can also induce new quantum dynamics, and several examples of this now exist. I will review recent results and discuss the prospects for progress in this new field known as "Quantum Control."

1. What is Quantum Control?

Quantum control research employs amplified and programmably shaped ultrafast (femtosecond-scale) and/or high field (up to several volts per Angstrom) coherent radiation pulses to control quantum dynamics in matter. The tools of quantum control include large bandwidth coherent light sources of all types, and methods for altering the shape of the pulses. The objective is to produce a desired reaction or achieve a desired quantum state of the material system. This new state or process could be a chemical change, a phase transition, a special kind of light, or a coherent excitation with special properties, such as a wave packet.

2. Learning Control

A special technique employed in quantum control research is the learning feedback algorithm, a protocol for designing control fields. In learning feedback control, the quantum system under study actually runs the experiment itself! The apparatus interrogates the atom or molecule, which provides direct feedback to the laser pulse control knobs[1]. The laser system and the quantum system work together through an evolutionary trial-and-error approach search for the laser pulse that can produce the desired dynamics. A typical search could contain more than ten thousand different trial pulses. This approach has found non-intuitive pulse shapes that can enhance normally suppressed molecular processes such as selective photo-induced isomerization, leading to new insights

in molecular dynamics. Learning control holds promise for several coherent control applications, from new methods for quantum information science, to more effective ways to produce and control x-rays.

Learning feedback control experiments contain much information about the connection between different physical attributes of the laser pulse and the molecular dynamics. New data analysis techniques have been developed recently to use the search process to understand better the forces controlling quantum dynamics in atomic and chemical physics. One example is "Principal Control Analysis" (PCA), which uses measured correlations in the learning control search path to gain information about the control of quantum processes[2]. For example we can use PCA to determine the number and nature of independent degrees of freedom in the control Hamiltonian.

3. Quantum Control in Molecular Systems

Molecular systems often exhibit rapid decoherence, either through intramolecular couplings of the different modes of the system, or collisions between molecules. The ultrafast time scales employed in quantum control experiments can be faster than decoherence times, so that quantum control becomes possible even in the presence of decoherence. Strong fields from lasers can also overwhelm thermally induced forces, so that control is possible even in room temperature liquids. We have studied quantum control in room temperature molecular systems using learning control and PCA. Our current experiments concentrate on two types of systems: control of C-H vibrational excitation in alcohols[3]; and photoexcitation and photo-isomerization in simple organic molecules. These molecules have a level of complexity that is beyond our ability to predict control solutions, but they are simple enough for learning control techniques to reveal the main features of the dynamics under study.

References

1. B. J. Pearson, J. L. White, T. C. Weinacht, and P. H. Bucksbaum, Phys. Rev. A **63,** 063412 (2001); T.C. Weinacht and P.H. Bucksbaum, Jour. of Optics B, **4**, R35-R52 (2002).
2. J.L. White, B.J. Pearson, P.H. Bucksbaum, Journal of Physics B: Atomic, Molecular and Optical Physics **37**, L399-L405 (2004).
3. B.J. Pearson and P.H. Bucksbaum, Physical Review Letters **92,** 243003 (2004).

PHOTONIC ENGINEERING FOR QUANTUM INFORMATION PROCESSING

IAN A. WALMSLEY, LIJIAN ZHANG, ALFRED B. U'REN,*CHRISTINE SILBERHORN,†KONRAD BANASZEK ‡

Department of Physics, University of Oxford
Clarendon Laboratory, Parks Rd.
Oxford, OX1 3PU
E-mail: walmsley@physics.ox.ac.uk

Quantum technologies based on optics often rely on photon bunching and measurement with feedforward to achieve an effective nonlinear interaction between otherwise mutually transparent particles. The efficacy of this strategy for implementing nonlinear interactions relies upon pure state single photon wave packets with a reasonable modal structure. These, however, are not so easy to come by, since individual photons have a rich structure associated with their continuous degrees of freedom. Recent work by several groups on the preparation of pure states suggests that the concatenation of sources of conditionally prepared single photons is feasible.

1. Summary

The process of parametric downconversion (PDC) enables the preparation of single photons by heralding; the detection of one photon from the random generation of a pair of photons. [1,2,3]. In contrast, on-demand sources generate photons deterministically, but imperfect matching of emission to detection modes results in a random selection of collected photons. Heralded *single photons* from PDC are generally in mixed states, [7] because of quantum correlations present in the *photon pairs*.[4]

The conditional preparation of pure-state single photons therefore requires the ability to engineer two-photon states so as to eliminate signal-idler correlations in all degrees of freedom. In waveguided PDC[1], the spatial correlations between signal and idler **k**-vectors are suppressed with the result that the attainable single photon purity is limited only by spectral correlations. Thus, the combination of waveguiding technology with the engineering of spectrally uncorrelated states is expected to lead to nearly ideal conditional single photon sources.

The generation of broadband, spectrally uncorrelated PDC photon pairs necessitates the use of a pulsed pump. In this case, the spectral correlations of PDC photon pairs is determined by crystal dispersion, in particular by group velocity mismatch between the pump pulse and the signal and idler photons[5,6]. A number of methods have been put forward for controlling group velocity mismatch for the suppression of spectral correlations. We have shown that a viable direct method is the examination of available $\chi^{(2)}$ materials and spectral ranges locating regimes where group velocity matching occurs naturally.

In view of the restrictive nature of naturally-occurring group velocity matching, it is desirable to develop alternate tools to attain spectral uncorrelation at arbitrary wavelengths while employing materials exhibiting large $\chi^{(2)}$ nonlinearities. One possibility is the use of a segmented crystal approach, where a sequence of $\chi^{(2)}$ thin crystal segments is interspersed with linear birefringent compensators for group velocity mismatch control[7,8], leading to an additional superlattice-like contribution to the phase matching function.

The ability to control the entanglement present in the continuous variable degrees of freedom of single photons is indeed an important enabling step in the continued progress of quantum information processing in the photonic realm.

*present address: department of optics, centro de investigacion cientifica y educacion superior de ensenada, cicese, baja california, 22860, mexico
†present address: max-planck-forschungsgruppe für optik, information und photonik, günther-scharowsky str.1 / bau 24, 91058 erlangen, germany
‡present address: institute of physics, nicolaus copernicus university, ul. grudziadzka 5,pl-87-100 torun, poland

References

1. A.B. U'Ren, Ch. Silberhorn, K. Banaszek, I.A. Walmsley, *Phys. Rev. Lett.* **93**, 093601 (2004)
2. O. Alibart, S. Tanzilli, D. B. Ostrowsky, P. Baldi, *quant-ph/0405075* (2004)
3. T.B. Pittman, B.C Jacobs, J.D. Franson, *Opt. Comm.*, **246** 545 (2005)
4. A.B. U'Ren, K. Banaszek and I.A. Walmsley, *Quant. Inf. and Comp.* **3**, 480 (2003)
5. T.E. Keller and M.H. Rubin, *Phys. Rev. A*, **56** 1534 (1997)
6. W.P. Grice, A.B. U'Ren and I.A. Walmsley, *Phys. Rev. A* **64**, 063815 (2001)
7. A.B. U'Ren, Ch. Silberhorn,, K. Banaszek, I..A. Walmsley, R. Erdmann, W.P. Grice and M.G. Raymer, *Laser Physics*, **15** 1 (2005)
8. A.B. U'Ren, R.K. Erdmann and I.A. Walmsley, to appear *J. Mod. Opt.* (2005)

GIANT ATOMS FOR EXPLORATIONS OF THE MESOSCOPIC WORLD

J.M.RAIMOND

Laboratoire Kastler Brossel, Département de Physique, ENS
24 rue Lhomond, F-75005, Paris, France

Circular Rydberg atoms are almost perfect tools for the exploration of fundamental matter-radiation coupling effects. We present the progresses made at ENS in two complementary directions. On the one hand, circular atoms are used to manipulate mesoscopic fields in superconducting cavities, for fundamental decoherence studies. On the other hand, we have proposed a coherence-preserving trap for circular atoms, realizing a scalable architecture for quantum information processing.

1. Circular Rydberg atoms and superconducting cavities

The long lifetimes of circular Rydberg atoms and their strong coupling to millimetre-wave fields make it possible to manipulate at will mesoscopic coherent states stored in high quality superconducting cavities.

The resonant interaction of a single atom with a few tens of photons results in the efficient preparation of a mesoscopic quantum state superposition, involving two coherent components with different classical phases. We have monitored the gradual splitting of the field's phase distribution [1] and checked the overall coherence of the process by inducing `revivals' of the Rabi oscillation [2]. This generation of a large `Schrödinger cat state', at the border between the classical and quantum worlds, opens the way to detailed studies of the decoherence process, using, for instance, a direct measurement of the cavity field Wigner function with circular `probe' atoms [3].

The non-resonant, dispersive atom-field interaction also produces a field phase shift. The field phase gets entangled with the atomic state. This situation leads also to the production of cat states. On the other hand, the atom-field interaction results in an `amplification' of the atomic state, which is coded onto the phase of a many photons field. We have used this process to realize a quantum non-demolition high-efficiency detection of the circular states [4].

Finally, we have theoretically investigated an interesting situation involving two mesoscopic fields stored in two separate cavities [5]. A single atom prepares a state superposition presenting the non-local character of an EPR pair. The violation of a Bell-type inequality could be evidenced by a single probe atom measuring the joint Wigner function of the two fields. Studying the gradual blurring of the non-local properties under the action of decoherence is a fascinating perspective.

2. A superconducting atom chip for circular atoms

We have proposed a coherence-preserving trap architecture for Rydberg atoms, using superconducting atom chips [6]. Based on Stark effect, the deep and flexible trap provides spontaneous emission inhibition. In principle, Rydberg states could be stored and manipulated in this trap for time intervals in the minute range. Atomic guides or conveyor belts can be realized by elaborating on the same principle. A proper microwave dressing of the atoms equalizes the Stark polarisability of two adjacent circular states. A qubit coded as a superposition of these levels is then made insensitive to the trapping field and could be preserved for many seconds. Entanglement between atoms could be generated by direct atom-atom interaction of by the common coupling of two atoms to a strip-line resonator on the chip itself. This trapping mechanism thus realizes a scalable architecture for quantum information processing with Rydberg atoms. Moreover, it opens promising perspectives for the detailed study of atom/surface interactions or for the coupling of Rydberg atoms with mesoscopic superconducting circuits.

Acknowledgments

Laboratoire Kastler Brossel is a laboratory of Université Pierre et Marie Curie and ENS, associated to CNRS (UMR 8552). We acknowledge support of the European Community, of the Japan Science and Technology Corporation.

References

1. A. Auffeves et al. *Phys. Rev. Lett.* **91,** 230405 (2003)
2. T. Meunier *et al.*, *Phys. Rev. Lett*. **94**, 010401 (2005)
3. P. Bertet *et al.*, *Phys. Rev. Lett.* **89**, 200402 (2002)
4. P. Maioli *et al., Phys. Rev. Lett.* In press (2005)
5. P. Milman *et al. Eur. Phys. J. D* **32**, 233 (2005)
6. P. Hyafil *et al. Phys. Rev. Lett*. **93,** 103001 (2004)

QUANTUM INFORMATION AND CAVITY QED WITH TRAPPED IONS

CHRISTOPH BECHER[1,*]
J. BENHELM[1], D. CHEK-AL-KAR[1], M. CHWALLA[1], H. HÄFFNER[1,2], W. HÄNSEL[1], T. KÖRBER[1], A. KREUTER[1], G.P.T. LANCASTER[1], T. MONZ[1], E.S. PHILLIPS[1], U.D. RAPOL[1], M. RIEBE[1], C. ROOS[1,2], C. RUSSO[1], F. SCHMIDT-KALER[1,†], & R. BLATT[1,2]

[1]*Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria*

[2]*Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Otto-Hittmair-Platz 1, A-6020 Innsbruck, Austria*

Single Ca^+ ions and crystals of Ca^+ ions are confined in a linear Paul trap and are investigated for quantum information processing. We here report on recent experimental advancements towards realizing basic building blocks for quantum information processing with such a system..

Laser-cooled trapped ions are ideally suited systems for the investigation and implementation of quantum information processing as one can gain almost complete control over their internal and external degrees of freedom. The combination of a Paul type ion trap with laser cooling leads to unique properties of trapped cold ions, such as control of the motional state down to the zero-point of the trapping potential, a high degree of isolation from the environment and thus a very long time available for manipulations and interactions at the quantum level. The very same properties make single trapped atoms and ions well suited for storing quantum information in long-lived internal states.

Recently we have achieved the implementation of simple algorithms with up to 3 qubits on an ion-trap quantum computer. We will report on methods to implement single qubit rotations, the realization of a two-qubit universal quantum gate (Cirac-Zoller CNOT-gate) [1], the deterministic generation of two-ion entangled states (Bell states) [2] and three-ion entangled states (GHZ-

* Present address: Naturwissenschaftlich-Technische Fakultät II, Universität des Saarlandes, D-66041 Saarbrücken, Germany; *e-mail: christoph.becher@uibk.ac.at*

† Present address: Abteilung Quanten-Informationsverarbeitung, Universität Ulm, Albert Einstein Allee 11, D-89069 Ulm, Germany

and W-states) [3], the realization of a quantum register, the full tomographic reconstruction of the density matrix of such entangled states, the realization of deterministic quantum teleportation [4], quantum process tomography of this teleportation protocol and the encoding of quantum information in decoherence-free subspaces with decoherence times on a ten-second-timescale.

The transport of quantum information over large distances via photons requires an interface between atoms and photons. Such an interface is based on the deterministic coupling of a single atom or ion to a high finesse optical cavity [5]. As a step towards realizing an atom-photon interface we investigated the interaction of a single Ca^+ ion and a cavity vacuum field by measuring the modification of the spontaneous emission rate (Purcell effect) from the metastable $D_{5/2}$ level at various positions in the cavity-enhanced vacuum field [6]. The next experimental step will be the deterministic generation of single photons in a well-defined spatial and spectral mode of the radiation field. Here, we plan to combine the advantages of stimulated Raman emission schemes and laser-cooled trapped ions, stationary coupled to the mode of a high finesse optical cavity [7].

Acknowledgments

We gratefully acknowledge support by the European Commission (CONQUEST and QGATES networks), by the ARO, and by the Austrian Science Fund (FWF). H.H. acknowledges funding by the Marie-Curie-program of the European Union. T.K. acknowledges funding by the Lise-Meitner program of the FWF. C.R. acknowledges support by Fundação para a Ciência e a Tecnologia (Portugal).

References

1. F. Schmidt-Kaler et al., Nature **422**, 408 (2003).
2. C.F. Roos et al., Phys. Rev. Lett. **92**, 220402 (2004).
3. C.F. Roos et al., Science **304**, 1478 (2004).
4. M. Riebe et al, Nature **429**, 734 (2004).
5. A.B. Mundt et al., Phys. Rev. Lett. **89**, 103001 (2002).
6. A. Kreuter et al., Phys. Rev. Lett. **92**, 203002 (2004).
7. C. Maurer et al., New J. Phys. **6**, 94 (2004).

QUANTUM CONTROL, QUANTUM INFORMATION PROCESSING, AND QUANTUM-LIMITED METROLOGY WITH TRAPPED IONS*

D. J. WINELAND, D. LEIBFRIED, M. D. BARRETT†, J. C. BERGQUIST, R. B. BLAKESTAD, J. J. BOLLINGER, J. BRITTON, J. CHIAVERINI, D. HUME, W. M. ITANO, M. JENSEN, J. D. JOST, E. KNILL, J. KOELEMEIJ, C. LANGER, W. OSKAY, R. OZERI, R. REICHLE, T. ROSENBAND, T. SCHAETZ‡, P. SCHMIDT§, AND S. SEIDELIN

National Institute of Standards and Technology (NIST)
Boulder, Colorado
E-mail: djw@boulder.nist.gov

The system of trapped atomic ions, incorporating methods of coherent quantum control, has demonstrated the elements of quantum information processing. The basic requirements for a quantum computer have been demonstrated separately and ion trappers as a group can now also contemplate how a large-scale processor might be constructed. As with any possible physical implementation of a quantum computer, difficult technical problems must be solved, which will take many years. In the meantime, the ideas of quantum information processing can already help in metrology, for example, to improve spectroscopy and the performance of atomic clocks.

*Supported by ARDA/NSA, ONR, AND NIST.
†present address: Physics Department, University of Otago, New Zealand
‡present address: Max Planck Inst. for Quantum Optics, Garching, Germany
§present address: Inst. for Experimental Physics, University of Innsbruck, Austria