Tuesday Posters

Matter-wave interferometry with charged particles

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Important achievements have been accomplished until now in neutral particle interferometry. To extend this field of research to charged matter-waves, we present the design and current status in the construction of the first stable interferometer for ions and charged molecules. It potentially combines the advantages of electron, atom and molecule interferometry: the high technical standard in the generation, detection and precise control of electron beams can be applied on ions together with the possibility of laser manipulation of ionic states or thermal rovibrational excitation in charged molecules. Such an interferometer can cover fundamental Aharonov-Bohm experiments that were up to now mainly accessible for pointlike electrons, for particles with inner structure and test gauge and decoherence theories. In our setup, a stable and coherent ion beam will be separated and recombined by a fine charged biprism wire. The longitudinal coherence is adjusted by a Wien-filter and the interference pattern is detected after a quadrupole magnification. We also discuss future applications for ion-interferometers as highly sensitive, compact sensors for rotation and acceleration.

Atom interferometry Tu-002

Limit to spin squeezing in finite temperature Bose-Einstein condensates

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Quantum correlations could be used in atomic clocks and interferometers to increase their sensitivity with respect of using uncorrelated atoms. A simple class of states useful for metrology are *spin squeezed states*. Recently such states could be obtained using interactions in condensates with two internal states [1]. A crucial question is the scaling of the spin squeezing (or metrology gain) with the atom number. We show that, at finite temperature, the maximum spin squeezing achievable using interactions in Bose-Einstein condensates has a finite limit when the atom number $N \to \infty$ at fixed density and interaction strength. We calculate the limit of the squeezing parameter for a spatially homogeneous system and show that it is bounded from above by the initial non-condensed fraction [2].

References

[1] C. Gross, T. Zibold, E. Nicklas, J. Estève, M. K. Oberthaler, *Nonlinear atom interferometer surpasses classical precision limit*, Nature **464**, 1165 (2010);
M. F. Riedel, P. Böhi, Li Yun, T. W. Hänsch, A. Sinatra, P. Treutlein, *Atom-chip-based generation of entanglement for quantum metrology*, Nature **464**, 1170 (2010).

[2] A. Sinatra, E. Witkowska, J.-C. Dornstetter, Li Yun, Y. Castin, *Limit of Spin Squeezing in Finite Temperature Bose-Einstein Condensates*, Phys. Rev. Lett. **107**, 060404 (2011);
A. Sinatra, E. Witkowska, Y. Castin, *Spin Squeezing in Finite Temperature Bose-Einstein Condensates : Scaling with the system size*, arXiv:1112.3795.

Quantum metrology with a scanning probe atom interferometer

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Interferometers using N uncorrelated (non-entangled) particles are fundamentally limited by shot-noise to an interferometric phase uncertainty of $\Delta\varphi \geq 1/\sqrt{N}$. This *standard quantum limit* (SQL) is particularly relevant in applications such as electromagnetic field imaging, where the desired high spatial resolution forces one to work with small probe size (small N). Using entangled states, $\Delta\varphi$ could be reduced significantly, towards the Heisenberg limit $\Delta\varphi \geq 1/N$.

Here we report an atom-interferometric measurement of microwave fields from an integrated circuit, with an uncertainty of 4.0 dB below the SQL [1]. Our interferometer employs $N = 1300$ entangled atoms in a spin-squeezed state and maintains performance below the SQL for Ramsey interrogation times up to 20 ms. Using an atom chip, we spatially scan the spin-squeezed atoms over 10 μm while maintaining sub-SQL operation. We perform a quantum-state tomography of our interferometer input state [2], demonstrating a spin noise reduction of up to 4.5 dB and a spin coherence of > 98%, which implies a depth of entanglement of at least 40 particles. Our technique is promising for high-resolution imaging of electromagnetic fields near solid-state microstructures [3].

References

[1] C. F. Ockeloen, M. F. Riedel, R. Schmied, and P. Treutlein, to be published (2012).
[2] R. Schmied and P. Treutlein, New J. Phys. **13**, 065019 (2011).
[3] P. Böhi, M. F. Riedel, T. W. Hänsch, and P. Treutlein, Appl. Phys. Lett. **97**, 051101 (2010).

A trapped atom interferometer for short range forces measurements

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We have demonstrated laser controlled tunneling of ^{87}Rb atoms in a vertical optical lattice using two- photon Raman transitions [1], allowing performing high resolution laser spectroscopy of Wannier Stark (WS) states. A sequence of such laser pulses is used to first split the atoms into neighboring WS states and later recombine them. This realizes a trapped atom interferometer, which, in our geometry, is sensitive to the difference in gravitational potential energies between the coupled WS states, allowing for a precise measurement of the Bloch frequency $\nu_B = mg\lambda/2h$, where m is the mass of the ^{87}Rb atom, g the gravity acceleration, and λ the lattice laser wavelength. We have reached a relative sensitivity on ν_B of 10^{-5} at 1 s. Performing this interferometer close to a reflecting surface, this sensitivity will allow performing measurements of Casimir Polder forces to better than 1% at distances of a few microns, and improving significantly tests of gravity at short range [2].

References

[1] Q. Beaufils, G. Tackmann, X. Wang, B. Pelle, S. Pélisson, P. Wolf and F. Pereira dos Santos, “Laser controlled tunneling in a vertical optical lattice”, Phys. Rev. Lett. **106**, 213002 (2011).
[2] R. Messina, S. Pelisson, M.-C. Angonin, and P. Wolf, “Atomic states in optical traps near a planar surface”, Phys. Rev. A **83**, 052111 (2011).

Long-lived coherence of an interacting Bose-Einstein condensate

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We report that atomic interactions not only lead to quantum and spatial dephasing of a trapped BEC interferometer but also produce mean-field-driven rephasing through periodic collective oscillations. We observe the coherence of an interacting two-component Bose-Einstein condensate of ^{87}Rb atoms surviving for seconds in a Ramsey interferometer. Mean-field-driven collective oscillations of two components lead to periodic dephasing and rephasing of condensate wave functions with a slow decay of the interference fringe visibility. We apply spin echo synchronous with the self-rephasing of the condensate to reduce the influence of state-dependent atom losses, significantly enhancing the visibility up to 0.75 at the evolution time of 1.5 s. Mean-field theory consistently predicts higher visibility than experimentally observed values. We quantify the effects of classical and quantum noise and infer a coherence time of 2.8 s for a trapped condensate of 5.5×10^4 interacting rubidium atoms.

Reference

[1] M. Egorov, R. P. Anderson, V. Ivannikov, B. Opanchuk, P. Drummond, B. V. Hall, and A. I. Sidorov, "Long-lived periodical revivals of coherence in an interacting Bose-Einstein condensate", Phys. Review A **84**, p. 021605(R)-4 (2011).

Entanglement and optimized interferometric phase measurement

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We derive a phase-entanglement criterion for two bosonic modes which is immune to number fluctuations. This also provides an operational definition of relative phase-measurements, via analysis of phase measurement in interferometry. We show that the new entanglement measure is directly proportional to enhanced phase-measurement sensitivity. As an example, we calculate the phase-entanglement of the ground state of a two-well, coupled Bose-Einstein condensate, similar to recent experiments[1]. We show that a new type of quantum squeezing is found, namely planar quantum squeezing [2], which squeezes two orthogonal spin directions simultaneously. This is possible owing to the fact that the SU(2) group that describes spin symmetry lives in a three-dimensional space, of higher dimension than the group for photonic quadratures. The advantage of planar spin-squeezing is that, unlike conventional spin-squeezing, it allows noise reduction over all phase-angles simultaneously.

References

[1] J. Esteve, C. Gross, A. Weller, S. Giovanazzi & M. K. Oberthaler, *Squeezing and entanglement in a Bose-Einstein condensate* Nature **455**, pp. 1216-1219 (2008).
[2] Q. Y. He, Shi-Guo Peng, P. D. Drummond, and M. D. Reid, *Planar quantum squeezing and atom interferometry*, Phys. Rev. A **84**, pp. 022107 (2011).

Gravitational output-coupling of an atom laser

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In this poster we present a novel type of output coupling of an atom-laser from a BEC. Traditional output couplers either use a weak RF field [1] or a weak Bragg beam [2] to resonantly outcouple a small fraction of the BEC. The gravitational output coupler, presented here, uses a *strong* RF field to *dress* the trapping potential of a Ioffe-Pritchard magnetic trap such, that a small hole is created in the very bottom of the trap. The gravitational output coupler is fully coherent: Whereas the outcoupled atoms of weak RF are distributed over a range of magnetic hyperfine states, the ones of the gravitational output coupler are all in the $m_F = 2$ state. This not only increases thebrightness of the atom laser by a factor of 5, but also raises the spectre of a reversible atom laser, where the beam not only exits, but also enters a BEC. We demonstrate well-collimated atom beams – both of thermal and condensed origin – and discuss their transverse coherence.

References
[1] I. Bloch, T. W. Hänsch, and T. Esslinger, *Atom Laser With a CW Output Coupler*, Phys. Rev. Lett. **82-15**, pp. 3008–3011 (1999).
[2] E. W. Hagley *et al. A Well-Collimated Quasi-Continuous Atom Laser* Science **283:5408**1706-1709 (1999).

Interferometry with chip-based atom lasers in microgravity

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We report on the implementation of a Bragg-type interferometer operated with a chip-based atom laser for Rubidium ^{87}Rb. With the chip based atom laser we can generate thermal ensembles as well as Bose-Einstein condensates (BEC)[1]. With the help of delta-kick cooling [2], implemented via the atom chip, we can further slow down the expansion of thermal and condensed atoms. In addition, the chip allows transferring atoms in the individual Zeeman states of the two hyperfine ground states, in particular into the non-magnetic state. With this toolbox we could extend the observation of a BEC of only 10^4 atoms up to two seconds. Benefiting from the extended free fall in microgravity we could combine this with an asymmetric Mach-Zehnder type interferometer over hundreds of milliseconds to study the coherence and to analyze the delta kick cooling with the help of the observed interference fringes.

References
[1] T. van Zoest *et al.*, “Bose-Einstein condensation in microgravity”, Science **328**, pp 1540 (2010).
[2] H. Amman and N. Christensen, “Delta Kick Cooling: A New Method for Cooling Atoms”, Phys. Rev. Lett., 78, pp 2088 (1997).

Measuring small energy differences by BEC interferometry on a chip

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We investigate the use of a Bose-Einstein condensate trapped on an atom chip for making interferometric measurements of small energy differences[1,2]. A nearly pure condensate is split horizontally using an RF magnetic field. A relative height difference between the clouds is introduced through adjustment of the RF field. The trap is turned off allowing the clouds to interfere in free fall. For varying height separations we measure the relative phase difference between the clouds from the observed fringes in the atomic density distribution. We measure and explain the noise in the energy difference of the condensates, which derives from the binomial distribution in the number difference. An energy difference of 2.17(32) Hz/nm ismeasured, as expected from Earth's gravity. We have considered systematic errors and are now working towards more precise control of the atoms. This will improve the accuracy that the interferometer can achieve.

References

[1] R. J. Sewell *et. al.*, *Atom chip for BEC interferometry*, J. Phys. B. **43** 051003 (2010).
[2] F. Baumgärtner *et. al.*, *Measuring energy differences by BEC interferometry on a chip*, Phys. Rev. Letts. **86**, 1195-1198 (2010).

A compact and transportable cold atom inertial sensor for space applications

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We have developped a compact, robust and transportable cold atom inertial sensor to test the Univarsility of Free-Fall (UFF) during parabolic flights. Our system uses laser pulses to measure the acceleration of a cloud of cold ^{87}Rb atoms. The laser source is based on telecom technology and can be operated in difficult environments [1]. We reject vibrations by correlating the atom sensor with an external mechanical accelerometer [2].

The next step, by adding another atomic species (^{39}K) to our system, is to perform a test of UFF. We have constructed a dual-wavelength laser system and performed simultaneous cooling of Rb and K in two species MOT. We will then use the atom interferometer to measure the differential acceleration between the two atom clouds in free-fall. This will be an important step towards a space-based test at the level 10^{-15}, such as the one planed in the frame of ESA's STE-QUEST mission [3].

References

[1] V. Ménoret *et al.*, Optics Lett. **36**, 21 (2011).
[2] R. Geiger *et al.*, Nature Communications **2**, 474 (2011).
[3] http://sci.esa.int/ste-quest-doi2011.

Matter-wave interferometry with single bright solitons

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Bright solitons [1, 2] are suitable candidates for matter-wave interferometry due to their self focusing, and non-dispersive nature. In our experiments, we use the broad Feshbach resonance of ^{7}Li in the $|1,1\rangle$ state to tune the scattering length through zero to small negative values to form a single bright matter wave soliton close to the critical number for collapse. The soliton is confined to a 1D potential formed from a single focused laser beam, which is weakly confining in the axial direction. We excite the collective dipole mode of the soliton and investigate the interaction with a thin potential barrier formed by a near-resonant, blue detuned, cylindrically focused laser beam that perpendicularly bisects the trapping beam at its focus. Through adjustment of the barrier potential, the soliton can either be split in two, transmitted or reflected. By applying a phase imprinting beam to one arm of the split soliton we study the phase dependent interactions on the subsequent barrier interaction.

References

[1] L. Khaykovich *et al.*, *Formation of a bright matter wave soliton*, Science **296**, pp. 1290-1293 (2002).
[2] K. E. Strecker *et al.*, *Formation and propagation of matter-wave soliton trains*, Nature **417**, pp. 150-153 (2002).

Tu-012 Atomic clocks

Highly-charged ions as a basis of optical atomic clockwork of superb accuracy

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State of the art clocks carry out frequency measurements at the eighteenth decimal place [1]. As the projected "end-of-the-road" fractional accuracy of such clocks is at the level of 10^{-18}, it is natural to wonder how to extend the accuracy frontier even further. While the nuclear clock [2] holds a promise of a projected accuracy at the improved 10^{-19} level, it relies on a yet unobserved optical transition in the radioactive ^{229}Th nucleus. Considering large uncertainties of nuclear models, the frequency of that transition can not be reliably computed. Here we show that the nuclear clock performances can be replicated with atomic systems, fully overcoming these challenges. We identify several highly-forbidden laser-accessibe transitions in heavy stable isotopes of highly-charged ions (HCI) that may serve as clock transitions. Similarly to the singly-charged ions of modern clocks [1], HCIs can be trapped and cooled. The key advantage of HCIs comes from their higher ionic charge. As the ionic charge increases, the electronic cloud shrinks thereby greatly reducing couplings to detrimental external perturbations. Our analysis of various systematic effects for several HCIs demonstrates the feasibility of attaining the 10^{-19} accuracy mark.

References

[1] C. W. Chou *et al.*, Phys. Rev. Lett. **104**, 70802 (2010).
[2] C. J. Campbell *et al.*, Phys. Rev. Lett. **108**, 120802 (2012).

Progress of the NPL Sr optical lattice clock

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Frequency standards based on optical atomic transitions show great promise as next generation clocks and some have already demonstrated frequency stabilities and systematic uncertainties better than the current caesium fountain microwave primary frequencystandard [1, 2]. One prime example is the Sr optical lattice clock, which has reached fractional frequency uncertainties at the level $\sim 1 \times 10^{-16}$ in several laboratories, limited by knowledge of the black-body radition (BBR) induced frequency shift [1]. At NPL, a Sr optical lattice clock apparatus is under development with the capability to directly measure the BBR-induced frequency shift. As an initial step, we have demonstrated efficient slowing and trapping of Sr with aid of a simple permanent-magnet Zeeman slower [3]. We report on recent progress, with focus on compact narrow linewidth clock laser systems, novel BBR measurement apparatus, and characterisation of the permanent-magnet Zeeman slower.

References
[1] A. D. Ludlow et al., Science **319**, 1805 (2008).
[2] C. W. Chou et al., Phys. Rev. Lett. **104**, 070802 (2010).
[3] Yu. B. Ovchinnikov, Opt. Comm., **276**, 261 (2007).

Lattice clock comparisons with 1 × 10^–17 stability at 500 s

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Optical lattice clocks based on alkaline earth atoms outperform single ion clocks [1] in measurement precision, and they have the potential to catch up with ion clocks in overall systematic uncertainty. The fractional uncertainty of our first generation strontium lattice clock has been evaluated at 1×10^{-16} [2]. To demonstrate a much smaller systematic uncertainty, we have built a second generation lattice clock based on a cavity enhanced optical lattice [3]. The large circulating power in the cavity allows us operate with a larger trap volume than a retroreflected configuration, yielding more atoms transferred into our lattice but at a lower density. Therefore, this setup both improves our signal to noise and reduces density-dependent collision shifts. Comparing our two strontium clocks, we are able to average down to the 10^{-17} level in 500 s. We report on our progress using this unprecedented stability to evaluate systematics beyond the 10^{-17} level.

References
[1] C. W. Chou *et al.*, Phys. Rev. Lett. **104**, 070802 (2010).
[2] A. D. Ludlow *et al.*, Science **319**, 1805 (2008).
[3] P. G. Westergaard *et al.*, Phys. Rev. Lett. **106**, 210801 (2011).

Generalized Ramsey excitation of an optical transition with suppressed light shift

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We investigate an optical frequency standard based on the 467 nm electric-octupole transition $^2S_{1/2} \rightarrow {}^2F_{7/2}$ in a single trapped $^{171}Yb^+$ ion. The extraordinary features of this transition result from the long natural lifetime and from the $4f^{13}6s^2$ configuration of the upper state. The coefficients for field-induced shifts of the $^2F_{7/2}$ state are smaller than for the metastable *D* states in the alkaline earth ions. Recently, we have realized the unperturbed frequency of the octupole transition with a fractional uncertainty of 7.1×10^{-17} [1]. A significant contribution to this uncertainty is caused by the light shift induced by the laser driving the octupole transition. We have thereforeimplemented the generalized Ramsey excitation scheme proposed in [2] – using two pulses that are tailored in duration, frequency and phase. We demonstrate the elimination of the light shift dependence of the frequency of the central Ramsey resonance, which largely reduces the corresponding uncertainty.

References

[1] N. Huntemann *et al.*, Phys. Rev. Lett. **108**, 090801 (2012).
[2] V. I. Yudin *et al.*, Phys. Rev. A **82**, 011804 (2010).

Testing time-variation of fundamental constants using Th and U nuclear clocks

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The low-energy (7.6 eV) transition in Th-229 could provide a reference for an optical clock of extremely high accuracy [1, 2]. Nuclear clocks would be very sensitive probes of any potential changes to the values of fundamental constants of nature [3, 4]. The 76 eV isomeric transition of U-235 has some potential advantages over the Th-229 transition, not least that its properties (energy, line width) are well known. With recent advances in high-UV frequency combs using high-harmonic generation [5] the transition may come within laser range in the foreseeable future. We present results of nuclear and atomic calculations that show a U-235 nuclear clock would have comparable accuracy to the Th-229 clock, and an absolute sensitivity to variation of fundamental constants that is larger than any other proposed laboratory reference standard.

References

[1] E. Peik and Chr. Tamm, Europhys. Lett. **61**, 181 (2003).
[2] C. J. Campbell *et al.*, Phys. Rev. Lett. **108**, 120802 (2012) (arXiv:1110.2490).
[3] V. V. Flambaum, Phys. Rev. Lett. **97**, 092502 (2006).
[4] J. C. Berengut *et al.*, Phys. Rev. Lett. **102**, 210801 (2009).
[5] A. Cingöz *et al.*, Nature **482**, 68 (2012).

Ultra-stable laser local oscillators

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Laser frequency stabilization via spectral-hole burning has the potential to extend laser coherence beyond what is possible with Fabry-Pérot cavities. Spectral holes in $Eu^{3+}:Y_2SiO_5$ crystals are less sensitive to the thermal noise that limits optical cavities [1], and for two crystals we observe differential fractional-frequency noise below 4×10^{-17}. The absolute performance is currently limited by technical noise at an Allan deviation of 2×10^{-16} with atypical drift rate of 3×10^{-17}/s. In addition, robust spherical Fabry-Pérot cavities [2] exhibit a passive acceleration sensitivity of $2(1) \times 10^{-11}$/g, which is reduced to below 10^{-12}/g by use of active feed-forward techniques [3].

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References

[1] M. J. Thorpe *et al.*, *Frequency stabilization to 6×10^{-16} via spectral-hole burning*, Nat. Photonics **5**, pp. 688-693 (2011).
[2] D. R. Leibrandt *et al.*, *Spherical reference cavities for frequency stabilization of lasers in non-laboratory environments*, Opt. Express **19**, pp. 3471-3482 (2011).
[3] M. J. Thorpe *et al.*, *Measurement and real-time cancellation of vibration-induced phase noise in a cavity-stabilized laser*, Opt. Express **18**, pp. 18744-18751 (2010).

First primary frequency standard in Tunisia

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In this poster, we describe an optically pumped cesium-beam frequency standard (JPO) under reconstruction at the National Centre for Nuclear Science and Technology (CNSTN) in Tunisia. This prototype instrument which has been develop at laboratory "SYRTE", will be the first primary frequency standard to be implanted in Tunisia. The aim of this project is the transfer of JPO clock from SYRTE to CNSTN. It will be rebuilt in Tunisia, studied and characterized. New approaches will have to be found in order to evaluate its accuracy without having an onsite reference clock, but using comparisons by satellite. The purpose of the project is also to demonstrate the feasibility of improving the performance of the optically pumped cesium beam clock.

Precision calculation of blackbody radiation shifts for optical frequency metrology

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We show that four group IIIB divalent ions, B^+, Al^+, In^+, and Tl^+ have anomalously small blackbody radiation (BBR) shifts of the $ns^2\ {}^1S_0 - nsnp\ {}^3P_0^o$ clock transitions [1, 2]. The fractional BBR shifts for these ions are at least 10 times smaller than those of any other present or proposed optical frequency standards at the same temperature. We have developed a hybrid configuration interaction + coupled-cluster method that provides accurate treatment of correlation corrections in such ions and yields a rigorous upper bound on the uncertainty of the final results. We reduce the BBR contribution to the fractional frequency uncertainty of the Al^+ clock to 4×10^{-19} at $T = 300$ K. We also reduce the uncertainties due to this effect at room temperature to 10^{-18} level for B^+ In^+, and Tl^+ to facilitate further development of these systems for metrology and quantum sensing. These uncertainties approach recent estimates of the feasible precision of currently proposed optical atomic clocks.

References

[1] M. S. Safronova, M. G. Kozlov, and Charles W. Clark, Phys. Rev. Lett **107**, 143006 (2011).
[2] Z. Zuhrianda, M. S. Safronova, and M. G. Kozlov, Phys. Rev. A **85**, 022513 (2012).

Atomic masses of calcium, strontium and ytterbium

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Currently, the second most precise value for the fine structure constant is derived from "photon-recoil" measurements of *h/M* for ^{87}Rb [1] combined with the Rydberg constant, atomic transition frequencies, and the atomic masses of the electron and of ^{87}Rb [2]. An improved photon-recoil value for alpha will enable the combination of theory and experiment for the *g*-factor of the electron (which produces the most precise value for alpha), to provide an improved test of QED. Besides the alkalis, isotopes of the alkaline-earths and ytterbium make promising candidates for precise photon-recoil measurements of *h/M(atom)*. In addition, the mass of ^{40}Ca is required for obtaining the *g*-factor of hydrogen-like calcium from measurements of electron spin-flip and cyclotron frequencies of Ca^{19+}, which can be used to test bound-state QED [3]. For these and other applications, by measuring cyclotron frequency ratios of pairs of ions in a cryogenic Penning trap, we obtain the atomic masses of ^{40}Ca, $^{86,87,88}Sr$, and $^{170,171,172,173,174,176}Yb$, to a relative precision in the region of 2×10^{-10}.

References

[1] R. Bouchendira, *et al.*, Phys. Rev. Lett. **106**, 080801 (2011).
[2] B. J. Mount, M. Redshaw and E. G. Myers, Phys. Rev. A **82** 042513 (2010).
[3] S. Sturm, *et al.*, Phys. Rev. Lett. **107**, 023002 (2011).

Progress towards measuring the electron EDM with thorium monoxide

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Measurement of a non-zero electric dipole moment (EDM) of the electron within a few orders of magnitude of the current best limit [1] of 1.05×10^{-27} e × cm would be an indication of CP violation beyond the Standard Model. The ACME Collaboration is searching for an electron EDM by performing a precision measurement of spin precession signals from the metastable $^3\Delta_1$ state of thorium monoxide (ThO) in a cold and slow beam. We discuss the design and completion of the first-generation apparatus, and the preliminary statistical and systematic uncertainties. We have achieved a one-sigma statistical uncertainty of 7×10^{-29} e × cm/$\sqrt{T}$, where T is the experimental running time in days, based on a data set acquired from 14 hours of running time over a period of two days.

Reference

[1] J. J. Hudson *et al.*, "Improved measurement of the shape of the electron." Nature **473**, 493 (2011).

Frequency metrology in quantum degenerate helium

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We have measured the absolute frequency of the 1557-nm doubly forbidden transition between the two metastable states of helium, $2\ ^3S_1$ (lifetime 8000 s) and $2\ ^1S_0$ (lifetime 20 ms), with 1 kHz precision [1].With an Einstein coefficient of 10^{-7} s^{-1} this is one of weakest optical transitions ever measured. The measurement was performed in a Bose-Einstein condensate of ^{4}He* as well as in a Degenerate Fermi Gas of ^{3}He*, trapped in a crossed dipole trap. From the isotope shift we deduced the nuclear charge radius difference between the α-particle and the helion. Our value differs by 4σ with a very recent result obtained on the $2\ ^3S \rightarrow 2\ ^3P$ transition [2].

References

[1] R. van Rooij, J. S. Borbely, J. Simonet, M. D. Hoogerland, K. S. E. Eikema, R. A. Roozendaal, W. Vassen, "Frequency metrology in quantum degenerate helium: Direct measurement of the $2\ ^3S_1 \rightarrow 2\ ^1S_0$ transition", Science **333**, pp. 196-198 (2011).
[2] P. Cancio Pastor, L. Consolino, G. Giusfredi, P. De Natale, M. Inguscio, V. A. Yerokhin, K. Pachucki, "Frequency metrology of helium around 1083 nm and determination of the nuclear charge radius", arXiv:1201.1362 (2012).

Frequency combs and precision spectroscopy in the extreme ultraviolet

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We present the first direct frequency comb spectroscopy in the extreme ultraviolet (XUV) part of the spectrum by resolving transitions in atomic argon and neon at 82 and 63 nm, respectively. The XUV frequency comb is generated by frequency up conversion of a near-infrared frequency comb via intra-cavity high-harmonic generation. It is capable of delivering > 20 μW of average power per harmonic in the 50-100 nm wavelength range. The observed argon transition linewidth of 10 MHz, limited by Doppler broadening, is unprecedented in this spectral region and provides a stringent upper limit on the linewidth of individual comb teeth. The measured transition frequency of 3,655,454,073 ± 3 MHz is limited by residual Doppler shifts and provides ~10^3 times improvement over earlier measurements. We will also discuss ongoing XUV comb coherence studies via heterodyne beat of two such combs, which will provide a new paradigm for high precision tests and spectroscopy in the XUV.

References

[1] A. Cingöz *et al.*, "Direct Frequency Comb Spectroscopy in the Extreme Ultraviolet", Nature **482**, pp. 68-71 (2012).
[2] T. K. Allison *et al.*, "Extreme Nonlinear Optics in a Femtosecond Enhancement Cavity", PRL **107**, pp. 183903-183908 (2011).

Search for an electron EDM with trapped hafnium fluoride ions

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The precision measurement of an electron electric dipole moment (eEDM) is an experiment that tests fundamental symmetries and physics beyond the Standard Model [1]. Trapped hafnium fluoride molecular ions in the $^3\Delta_1$ metastable electronic state are suitable candidates for an eEDM search due to their large effective electric fields and long electron spin coherence times [2]. To create HfF^+ in the desired quantum state, we first use two optical photons to excite a supersonic beam of neutral HfF molecules to a Rydberg state, which then autoionizes into predominantly a single rovibrational level of HfF^+ in its ground $^1\Sigma^+$ state. The autoionized HfF^+ in the ground state can then be transferred to the $^3\Delta_1$ state using transitions that have been recently identified. We report progress towards an eEDM measurement on several fronts: the mapping out of energy levels of HfF^+ up to 15000 cm^{-1} using velocity modulation spectroscopy, which leads to the identification of promising transitions to the $^3\Delta_1$ state; the loading and trapping of ions in a novel radiofrequency Paul trap optimized for collection of fluorescence photons and field uniformity; the reading out of ion states using laser-induced fluorescence in the ion trap; the search for more efficient state readout systems beyond laser-induced fluorescence. This work is funded by the National Science Foundation and the Marsico Endowed Chair.

References

[1] J. J. Hudson, D. M. Kara, I. J. Smallman, B. E. Sauer, M. R. Tarbutt, and E. A. Hinds, *Improved measurement of the shape of the electron*, Nature **473**, pp. 493-496 (2011).
[2] A. E. Leanhardt, J. L. Bohn, H. Loh, P. Maletinsky, E. R. Meyer, L. C. Sinclair, R. P. Stutz, and E. A. Cornell, *High-resolution spectroscopy on trapped molecular ions in rotating electric fields: A new approach for measuring the electron electric dipole moment*, J. Mol. Spectrosc. **270**, pp. 1-25 (2011).

A nuclear-electronic spin gyro-comagnetometer

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We are presently starting a project aiming to fully characterize a new generation of atomic gyroscope based on the detection of a nuclear spin orientation with an alkali magnetometer [1]. The key element of the device is a spherical gas cell heated at about 170°C and shielded from parasite magnetic fields. This cell is filled with an alkali gas (Rb, K…) with an electronic spin and a noble gas (^{3}He, ^{21}Ne, ^{129}Xe…) with a nuclear spin. The noble gas is polarized by Spin Exchange Optical Pumping (SEOP). In addition, the magnetic field created by the nuclear magnetization is canceled with a homogeneous magnetic field. Alkali atoms feel no magnetic field and evolve in a collisional regime (Spin Exchange Relaxation Free – SERF) allowing the realization of an ultra sensitive in situ alkali magnetometer [2] which detects the nuclear spin dynamic and then gives us a rotation measurement of the system. Our project deals with the conception, realization and characterization of this nuclear-electronic spin gyroscope very promising for applications requiring miniature sensors with a high performance.

References

[1] T. W. Kornack, R. K. Ghosh, and M. V. Romalis, "Nuclear Spin Gyroscope Based on an Atomic Comagnetoter", PRL, vol. **95**, 230801, 2005.
[2] I. K. Kominis, T. W. Kornack, J. C. Allred, and M. V. Romalis, "A subfemtotesla multichannel atomic magnetometer", Nature, vol. **422**, p. 596-599, 2003.

Accurate measurement and control of an IR laser frequency using an optical frequency comb and a remote frequency reference

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Ultra-high-resolution spectroscopy enables to test fundamental physics with molecules such as parity non conservation 0 or the stability of the electron-to-proton mass ratio 0. It is thus very challenging to develop an ultrastable frequency stabilization scheme in the mid-IR region where molecules exhibit rovibrational transitions. We have built a frequency chain which enables to measure the absolute frequency of a CO_2 laser emitting around 10 µm and stabilized onto a molecular absorption line. The set-up uses an optical frequency comb with sum-frequency generation. The frequency reference is an ultrastable 1.55 µm laser, transferred from SYRTE to LPL by an optical link [3]. We are now progressing towards the frequency stabilization of the IR laser via the frequency comb and the extension of this technique to quantum cascade lasers for a larger spectral range.

References

[1]. B. Darquié *et al.*, Chirality 22, pp. 870-884 (2010).
[2]. A. Shelkovnikov *et al.*, Phys. Rev. Lett. 100, p. 150801-150803 (2008).
[3]. O. Lopez *et al.*, Opt. Expr. 18, p. 16849-16857 (2010).

Fundamental physics tests using the LNE-SYRTE clock ensemble

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SYRTE is developing an ensemble of high performance atomic clocks comprising 3 laser-cooled atomic fountain clocks [1], 3 optical lattice clocks and ultra stable microwave and optical oscillators. Such an ensemble provides many possibilities for testing fundamental physical laws, relying on the high accuracy and stability of these devices. We report more specifically on comparisons between the ^{87}Rb and ^{133}Cs ground state hyperfine frequencies using the fountains. The measurements over 14 years set a stringent limit to a possible variation with time, and also with gravitational potential, of the Rb/Cs hyperfine frequency ratio. A notable advance in this work was the simultaneous operation with Rb and Cs in one fountain [2]. Combining with other available highly accurate clock comparisons, we provide independent constraints on today time variations and couplings to gravity of the 3 constants: fine structure constant α, scaled quark mass m_q / Λ_{QCD}, and electron-to-proton mass ratio m_e / m_p.

References

[1] J. Guéna *et al.*, *Progress on Atomic Fountains at LNE-SYRTE*, IEEE Trans. on Ultrason. Ferroelectr. and Freq. Control **59**, pp. 391-410 (2012); arXiv:1204.3621v1.
[2] J. Guéna *et al.*, *Demonstration of a Dual Alkali Rb/Cs Fountain Clock*, IEEE Trans. on Ultrason. Ferroelectr. and Freq. Control **57**, no.3, pp. 647-653 (2010).

Optical transitions in highly charged ions for atomic clocks with enhanced sensitivity to variation of fundamental constants

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Optical transitions can occur in some highly charged ions (HCIs) when the ion stage and nuclear charge are tuned such that orbitals with different principal quantum number and angular momentum are nearly degenerate [1]. In these cases thetransition energy may be within laser range even though the ionisation energy is large (of order several hundred eV). We have identified several such systems and shown that they have a number of properties that could make them suitable for atomic clocks with high accuracy. Strong E1 transitions provide options for laser cooling and trapping, while narrow transitions can be used for high-precision spectroscopy and tests of fundamental physics. In particular we found transitions that would have the highestsensitivity to variation of the fine-structure constant ever seen in atomic systems [2, 3]. HCI clocks utilising these transitions could confirm the indications of a spatial gradient in the fine-structure constant observed in quasar absorption spectra data [4, 5].

References

[1] J. C. Berengut, V. A. Dzuba, V. V. Flambaum, Phys. Rev. Lett. **105**, 120801 (2010).
[2] J. C. Berengut, V. A. Dzuba, V. V. Flambaum, A. Ong, Phys. Rev. Lett. **106**, 210802 (2011).
[3] J. C. Berengut, V. A. Dzuba, V. V. Flambaum, A. Ong, arXiv:1204.0603 (2012).
[4] J. K. Webb *et al.*, Phys. Rev. Lett. **107**, 191101 (2011).
[5] J. C. Berengut and V. V. Flambaum, Europhys. Lett. **97**, 20006 (2012).

Leggett-Garg inequalities for atom interferometry

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We construct generalisations of Leggett-Garg (LG) inequalities [1] that test realism (R) and non-invasive measurability (NIM) in multi-particle scenarios not limited to two outcomes. The inequalities provide a means to quantify the level of realism and NIM being tested – from micro, though to meso and, ultimately, macro – with the inclusion of parameters S and δ that denote the size of reality and noninvasiveness of measurement, in terms of particle number. We show how these LG inequalities are predicted to be violated by dynamical correlated systems, as might be realised using double-potential well Bose-Einstein condensates, and atom interferometers [2]. The measured output of a Mach-Zehnder interferometer can reveal violations of these inequalities, and be used to falsify classical trajectories for particle paths. We analyse three different strategies to realise the NIM: measure-and-regenerate, ideal-negative result, and weak quantum nondemolition QND number measurements [3].

References

[1] A. J. Leggett and A. Garg, *Quantum Mechanics versus Macroscopic realism: Is the flux there when nobody looks?*, Phys. Rev. Lett. **54**, pp. 857-860 (1985).

[2] C. Gross *et al.*, *Nonlinear atom interferometer surpasses classical precision limit*, Nature **464**, pp. 1165-1169 (2010).

[3] M. E. Goggin *et al.*, *Violation of the Leggett-Garg inequality with weak measurements of photons* Proc. Natl. Acad. Sci. **108**, pp. 1256-1261 (2011).

A new search for tensor currents in the weak decay of magneto-optically trapped ^{6}He

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The beta decay of ^{6}He presents a unique opportunity to search for new physics. Determining the correlation between the electron and the anti-neutrino allows searching for tensor currents predicted by extensions of the Standard Model. Because the neutrino cannot be detected with high efficiency, ^{6}He is ideal for this search because it is a light nucleus and yields a recoiling ^{6}Li ion with sufficient energy to be detected. In coincidence with the beta, measuring the ^{6}Li ion allows kinematic reconstruction of the neutrino momentum. Up to the present the precision has been limited due to either low number of ^{6}He atoms (nuclear half-life < 1 second) or interactions of the ^{6}Li ions with the environment. To overcome these limitations we have developed the most intense source of ^{6}He in the world [1] and we have set up a MOT. We have succeeded in trapping 30 atoms already. We also developed an original method, using an additional cycling transition, which allows detection of a few atoms in spite of the unavoidable light scattering from the intense trap lasers. Results will be presented.

Reference

[1] A. Knecht *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **660**, 43 (2011).

Towards packaged micro-integrated semiconductor laser modules for the deployment of cold atom based quantum sensors in space

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We report on the development of very robust, energy efficient, micro-integrated Master-Oscillator-Power-Amplifier (MOPA) and Extended Cavity Diode Laser (ECDL) modules for the deployment of cold atom based quantum sensors in space. They fit on micro optical benches not larger than 80 × 25 mm^2 and make use of either already space qualified or space qualifiable components and integration technologies. With MOPAs and ECDLs designed for Rubidium BEC and atom interferometry experiments at 780 nm we achieved an intrinsic linewidth of 190 kHz at 1 W and of 300 Hz at 35 mW, respectively. The MOPA module has been successfully vibration tested up to 8 g_{RMS} random noise, and micro-integrated modules based for 1060 nm that are based on the same integration technology have successfully passed vibration tests up to 29 g_{RMS} and 1500 g pyro-shock. Further, we outline the next steps in diode laser system micro-integration that combine the MOPA and ECDL concepts with micro-integrated fibre-coupling in a hermetic housing that allows for space deployment. These concepts can be transferred to other wavelengths.

Precision spectroscopy of the 2S-4P transition in atomic hydrogen

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The comparison between measured and calculated transition frequencies in atomic hydrogen can provide stringent tests of bound state QED. For the last decade, this comparison has been limited by the proton charge radius determined by electron-proton scattering. Recently, laser spectroscopy of muonic hydrogen provided a value, which is ten times more accurate than any previous measurement [1]. But this value differs from the CODATA 2010 value, obtained by a global adjustment of fundamental constants using data from electron-proton scattering and hydrogen experiments for the proton charge radius, by seven standard deviations [2]. The muonic hydrogen result led to a comprehensive search for the cause of this discrepancy, but no convincing argument could be found so far. Because the current CODATA value is mainly based on observations in atomic hydrogen, transition frequency measurements with improved accuracy can help to solve this puzzle or at least to rule out hydrogen experiments asa possible source for the discrepancy. Here we report on the setup which has been developed for the measurement of the one-photon $2S_{1/2}$-$4P_{1/2}$ transition frequency and discuss our preliminary results.

References

[1] Pohl *et al.*, *The size of the proton*, Nature **466** (7303), 2010.
[2] Mohr *et al.*, *CODATA 2010*, arXiv:1203.5425.

Recent measurements of 1S-2S transition frequency in atomic hydrogen

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We report on two recent precision measurements of 1S-2S transition frequency in atomic hydrogen. The first done in May 2011 against the LNE-SYRTE transportable cesium fountain clock FOM has shown a fractional uncertainty of 4.2×10^{-15} [1], 3.3 times better than for the previous result from 2003. The second measurement was performed in November 2011 using distant CSF1 fountain clock at PTB, Braunschweig. To compare frequencies we used a 900 km long actively stabilized fiber link. The link allows to measure the frequency of a transfer Er-doped cw fiber laser running at MPQ against CSF1. By comparison of two most recent results for the hydrogen 1S-2S transition frequency we can constrain the linear combination of Lorentz boost symmetry violation parameters in the SME framework.

Reference

[1] C. G. Parthey *et al.*, Phys. Rev. Lett. **107**, 203001 (2011).

Strontium atoms in optical lattices: applications to optical clocks and accurate gravimeters

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I will present the most recent precision measurements done with ultracold strontium atoms trapped in optical lattices. While fermionic ^{87}Sr atoms have been considered a good candidate for future optical clocks aiming to 10^{-17} relative accuracy or below [1], we concentrated on accurate measurements of gravity with the most abundant ^{88}Sr bosonic isotope. The long coherence time in Bloch oscillation exploited with ^{88}Sr trapped in vertical optical lattice, allow to observe more than 10^4 Bloch oscillations with a resulting resolution of 10^{-7} in gravity measurements, with no fundamental limit to reduce the resolution by another order of magnitude. Detailed study of systematic effects and a comparison with a classical FG5 gravimeter will be presented [2]. Furthermore, I will present the status of the recent developed compact and transportable version of a strontium optical lattice clock [3] and the prospect toward optical frequency comparisons with primary frequency standards in Italy.

References

[1] A. D. Ludlow *et al.*, Science **319**, 1805 (2008).
[2] N. Poli, *et al.*, Phys. Rev. Lett. **106**, 038501 (2011).
[3] M. Schioppo *et al.*, Proceedings of EFTF 2010 (2010).

Enhanced electron EDM $\mathcal{P},\mathcal{T}$-odd constant obtained from highly-correlated molecular four-component configuration interaction calculations

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The current upper limit on the electron electric dipole moment (EDM) is $|d_e| < 10.5\times10^{-28} e$ cm [1], from measurements on YbF. Due to their strong internal electric fields, polar diatomic molecules in general are interesting candidates in the search for the electron EDM, the discovery of which would significantly constrain proposed extensions to the Standard Model of particle physics [2].

We have implemented the evaluation of the electron EDM Hamiltonian operator as an expectation value over four-component molecular Dirac wavefunctions including the contributions of dynamic electron correlation. The electronic-structure programs used in this approach are the `KR-CI` module [3] of the `DIRAC10` program package. In initial applications we show the importance of dynamic electron correlation effects on the $\mathcal{P},\mathcal{T}$-odd interaction constant W_d in the IH^+ molecular ion, a possible candidate [4] in the search for the electron EDM.

References
[1] J. J. Hudson, D. M. Kara, I. J. Smallman, B. E. Sauer, M. R. Tarbutt, *et al.*, *Nature* **473** (2012) *493*.
[2] E. D. Commins, *Adv. Mol. Opt. Phys.* **40** (1999) *1*.
[3] S. Knecht, H. J. Å. Jensen, T. Fleig, *J. Chem. Phys.* **132** (2010) *014108*.
[4] T. A. Isaev, A. N. Petrov, N. S. Mosyagin, A. V. Titov, *Phys. Rev. Lett.* **95** (2005) *163004-1*.

Regularities and tendencies in atomic spectra

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Historically, the use of statistical methods for the description of complex quantum systems was primarily motivated by the failure of a line-by-line interpretation of atomic spectra. Such methods reveal regularities and tendencies in the distributions of levels and lines. Up to now, much attention was paid to the distribution of energy levels (Wigner surmise, random-matrix model...). However, information about the distribution of the lines (energy and strength) is lacking. Thirty years ago, Learner found empirically an unexpected law: the logarithm of the number of lines whose intensities lie between $2^k I_0$ and $2^{k+1} I_0$, I_0 being a reference intensity and k an integer, is a decreasing linear function of k [1, 2]. In this work, the fractal nature of such an intriguing regularity is outlined and a calculation of its fractal dimension is proposed. Other properties which remain unexplained are also presented, such as the role of quantum chaos or the fact that the distribution of line strengths follows Benford's law of anomalous numbers [3].

References
[1] R. C. M. Learner, *A simple (and unexpected) experimental law relating to the number of weak lines in a complex spectrum*, J. Phys. B **15**, pp. L891-L895 (1982).
[2] C. Bauche-Arnoult and J. Bauche, *Comparison of atomic data modeling with experimental intensities*, J. Quant. Spectrosc. Radiat. Transfer **58**, pp. 441-447 (1997).
[3] J.-C. Pain, *Benford's law and complex atomic spectra*, Phys. Rev. E , 012102 (2008).

Laser spectroscopy of the radioactive La isotopes

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We have used collinear laser spectroscopy to measure on-line nuclear moments and charge distributions of many short lived isotopes. Experiments were done at ISAC, JAEA , and Riken. Nuclei are known to have spherical, prolate, oblate and exotic octopole shapes. All of these are rotationally symmetrical. We have further evaluated our data and confirm that the neutron deficient isotopes $^{129\text{-}135}$La show a rare none rotationally symmetrical triaxial shape in their ground states. That means their masses are distributed unequally along the three axes of length, width and height. This feature is reflected in the hyperfine structure (HFS) spectrum of a suitably chosen valence electron. By measuring the nuclear moments (μ and Q) the onset and decline of this unusual shape is investigated on the chain of neutron deficient La isotopes. This work was supported in part by the Robert A. Welch Foundation (grant No. A1546).

Optically detected magnetic resonance using elliptical polarization

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We present theoretical and experimental results on optically detected magnetic resonance (ODMR) signals in the $3S_{1/2}$-$3P_{1/2}$, $D1$ transition of a hot Na atomic vapor [1], particularly focusing on the dependence of the ODMR signals on the incident light polarization. We have found that, while circular polarization gives the largest ODMR signal for the Zeeman end-resonances including ($F = 2$, $m_F = \pm 2$ levels, elliptical polarization is much more favorable for the observation of the inner Zeeman transitions. Detailed theoretical analysis based upon the rate equations including all the Zeeman sublevels is presented. Experimentally, the nuclear Zeeman splitting has been observed by using elliptical polarization. Satisfactory agreement has been obtained between theoretical simulations and experimental results.

Reference

[1] K. Motomura and M. Mitsunaga, *High-resolution spectroscopy of hyperfine Zeeman components of the sodium D_1 line by coherent population trapping*, J. Opt. Soc. Am. **B19**, pp. 2456-2460 (2002).

Velocity selective polarization spectroscopy of an atomic Rb vapor in lambda and ladder excitation schemes

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We present both theoretical and experimental results for the absorption of a linearly polarized weak probe laser beam locked to an hyperfine transition in the rubidium D_2 line while the frequency of a circularly polarized pump beam, either co- or counter-propagating with the probe beam, is scanned either across the same manifold or through the $5P \rightarrow 5D$ transition. Using balanced detection, we recorded separately variations in the intensities of the two mutually orthogonal linearly polarized components of the probe beam, which corresponds to measuring the birefringence induced on the atomic vapor by the pump beam. In both co- and counter-propagating cases we clearly obtained defined absorption and polarization atomic signals, as well as cross-over resonances. Numerical calculations based on rate equations allowed us to determine the population differences between the $5S$ and $5P$ magnetic sublevels in Rb. With these results we calculated the changes of the absorption coefficients for right and left circularly polarized light as functions of the pump light frequency and intensity obtaining excellent agreement with experimental spectra. These results were applied to the development of modulation-free laser frequency stabilization techniques.

Electromagnetically induced polarization rotation in Na ladder systems

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We have observed electromagnetically induced polarization rotation (EIPR) in the $3S_{1/2}$-$3P_{1/2}$-$4D_{3/2}$ and $3S_{1/2}$-$3P_{3/2}$-$4D_{3/2,5/2}$ three-level ladder systems in a hot Na vapor [1]. In the presence of a strong circularly-polarized coupling beam resonant to the upper ladder transition, the polarization angle of a probe beam, resonant to the lower ladder transition, was rotated by up to 18 degrees. The EIPR spectra exhibited a unique double-dispersion feature, which was related to the EIT (electromagnetically induced transparency)-circular dichroism spectra by the Kramers-Kronig relations and was more pronounced for the higher coupling powers. The optical switch experiment based on EIPR gave a fast response of less than 100 ns.

Reference

[1] N. Hayashi, A. Fujisawa, H. Kido, K. Takahashi, and M. Mitsunaga, *Interference between electromagnetically induced transparency and two-step excitation in three-level ladder systems*, J. Opt. Soc. Am. **B27**, pp. 1645-1650 (2010).

A frequency-comb-referenced OPO for sub-Doppler spectroscopy

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We present a singly-resonant, 1064-nm-pumped, cw optical parametric oscillator (OPO), emitting more than 1 W between 2.7 and 4.2 μm, specifically designed for high-resolution and precise spectroscopy in the mid-infrared region. Both pump and signal are frequency stabilized to a near-infrared optical frequency comb, referenced to the Cs primary time standard. A fractional Allan deviation of $\sim 3 \times 10^{-12}\ \tau^{-1/2}$ has been estimated between 1 and 200 s. As a test, we carried out sub-Doppler spectroscopy of rovibrational transitions of CH_3I around 3.4 μm, resolving their electronic quadrupole hyperfine structure, estimating an OPO linewidth lower than 200 kHz (FWHM), and determining absolute frequencies with a statistical uncertainty of 50 kHz [1]. The availability of such a precise and powerful source is of primary interest for spectroscopic studies of subtle effects, tests of fundamental theories, or optical manipulation of molecules.

Reference

[1] I. Ricciardi *et al.*, *A frequency-comb-referenced singly-resonant OPO for sub-Doppler spectroscopy*, Optics Express **20**, 9178–9186 (2012).

Realtime software-base frequency control for two diode lasers

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This work presents the design and implementation of a LabView based system for controlling and stabilizing the frequency of extended cavity diode lasers. The system was developed for creating a magneto-optical trap for rubidium atoms. Hence, our system automatically scans the frequency of our lasers across the D_2 line and then locks it to any of the transitions or crossovers in the manifold. A polarization spectroscopy apparatus [1] is used to generate a dispersion signal to feedback the laser after a simple PID algorithm implemented entirely within LabView. The lock bandwidth is ~ 2 MHz. Currently, we are capable of controlling two lasers simultaneously and independently. An additional advantage is that the locking point over the transition spectrum can be controlled in realtime while the laser frequency remains locked. Although the system was developed for a magneto-optic trap experiment, it can be used in a wide variety of control applications.

Reference

[1] C. P. Pearman, *Polarization spectroscopy of a closed atomic transition: applications to laser frequency locking*, J. Phys. B: At. Mol. Opt. Phys. **35**, pp. 5141-5151 (2002).

Raman tweezers spectroscopy of supercooled water droplet

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Supercooled water exhibits unique physical properties such as a negative thermal expansion and the thermodynamic singularity around -45 °C. Although it is generally accepted that hydrogen bonding between water molecules is responsible for the properties, their detailed mechanism is not well understood. We probe thermodynamic anomalies of liquid water in highly supercooled state by use of optical trapping and Raman spectroscopy. Micron-sized drops of purified water are levitated in air and cooled down to -35 °C free from contact freezing. Stokes photons are scatterred from water molecules excited by the trapping radiation. An enthalpy change due to hydrogen-bond breaking is derived from temperature dependence of the Raman spectral profile in the OH stretching band. The isobaric heat capacity calculated from the enthalpy data shows an anomalous increase as the temperatures approaches -45 °C, suggesting the existence of the second critical point [1].

Reference

[1] P. H. Poole, F. Sciortino, U. Essmann, H. E. Stanley, Nature **360**, 324 (1992).

Dielectronic recombination of low-ionized tungsten ions

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Our recent work on theoretical studies of dielectronic recombination of W ions focuses first on highly ionized [1] and now on low-ionized W ions [2]. In particular, energy levels, radiative transition probabilities, and autoionization rates for [Cd] $4f^{14}5p^{6}5l'nl$, [Cd] $4f^{14}5p^{6}6l''nl$, [Cd] $4f^{14}5p^{5}5d^{2}nl$, [Cd] $4f^{14}5p^{5}5d6l''nl$, [Cd] $4f^{13}5p^{6}5d^{2}nl$, and [Cd] $4f^{13}5p^{6}5d6l''nl$ ($l' = d, f, g$, $l'' = s, p, d$, $l = s - g$, and $n = 5 - 7$) states of Yb-like tungsten (W^{4+}) are calculated and compared using the relativistic many-body perturbation theory method (RMBPT code), the Multiconfiguration relativistic Hebrew University Lawrence Livermore Atomic Code (HULLAC code), and the Hartree-Fock-Relativistic method (COWAN code). It allows to critically evaluate recommended atomic data for their accuracy. Synthetic dielectronic satellite spectra are simulated in a broad spectral range from 200 to 1400 Å. This research was supported by DOE under OFES grant DE-FG02-08ER54951.

References

[1] U. I. Safronova, A. S. Safronova, P. Beiersdorfer *Excitation energies, radiative and autoionization rates, dielectronic satellite lines and dielectronic recombination rates for excited states of Mg-like W from Na-like W*, J. Phys. B **42**, pp. 165010 (2009).
[2] U. I. Safronova, A. S. Safronova *Dielectronic recombination of Er-like tungsten*, Phys. Rev. A **85**, 032507 (2012).

Elastic constants of hcp ^{4}He through of path integral Monte Carlo

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Through of Path Integral Monte Carlo method (PIMC) we determine the elastic constants of solid ^{4}He in its hcp phase. These elastic properties are very important in view of their apparent involvement in the phenomenon of supersolidity in solid ^{4}He. The stiffness coefficients are obtained by imposing different distortions to a periodic cell containing 180 atoms, followed by measurement of the elements of the corresponding stress tensor. For this purpose an appropriate path-integral expression for the stress tensor observable is derived and implemented into the PIMC++ package. A comparison of the results to available experimental data shows an overall good agreement of the density dependence of the elastic constants, with the single exception of C_{13}.

Reference

[1] Luis Aldemar Peña Ardila, Silvio A. Vitiello, and Maurice de Koning, " Elastic Constants of hcp ^{4}He: Path Integral Monte Carlo Vs. Experiment", Phys. Rev. B **84**, 094119 (2011) [6 pages].

Observation of topologically stable 2D skyrmions in an antiferromagnetic spinor Bose-Einstein condensate

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We observed the two-dimensional skyrmion excitations and its time-dependent phenomenon in quasi-2D polar Bose-Einstein condensate of F=1 23Na atoms, where 2D skyrmion is topologically protected. [1] Spin rotation method was used to imprint skyrmion spin textures on the condensate. The skyrmion was stable about tens of ms, but decayed to a uniform spin texture after all. The collapse of the skyrmion indicates that the polar phase inside the condensate is being broken during time evolution without topological charge density flow from the outside of the finite size condensate. We suggest the possible formation of Half-quantum vortices in the collapse process

Reference

[1] J. Choi, W. J. Kwon and Y. Shin, Physical Review Letters **108**, 035301(2012).

Vortex lattices in two-species Bose-Einstein condensates

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One of the most remarkable characteristics of a Bose–Einstein condensate is that it responds to rotation by forming quantized vortices. In this theoretical work, we investigate vortex lattices in a rotating two-component condensate in which the components have unequal atomic masses and interact attractively with each other [1]. We show that when the ratio of the atomic masses is suitable and the intercomponent attraction is sufficiently strong, the system exhibits unconventional ground-state vortex structures in a harmonic trap, such as lattices having a square geometry or consisting of two-quantum vortices. The exotic lattices can be understood in terms of the Feynman relation, which states that the vortex density is proportionalto the atomic mass, and they should be realizable with current experimental techniques.

Reference
[1] P. Kuopanportti, J. A. M. Huhtamäki, and M. Möttönen, Phys. Rev. A **85**, 043613 (2012).

Two mode at Bose-Einstein Condensate in triple well

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In this work we investigate the dynamics of a system constituted by Bose-Einsten condensate in three well in line [1, 2]. This system presents among its collectives modes, a behavior of two-mode called twin mode [3, 4].The twin modes are generated over specific initial conditions and only in this mode there are not chaos when we change the interaction parameters.

We used the semi-classical Hamiltonian form obtained by three modes through the coherent state transformation based in the su(3) algebra [5]. We analyzed a way to obtain a hamiltonian semi-classical two-mode [6] by canonical transformation from semi-classical three-mode model.

References
[1] S. Mossmann and C. J. Jung, Phys. Rev. A **74** 033601 (2006).
[2] F. Trimborn, D. Witthaut, and H. J. Korsch, Phys. Rev. A **79**, 013608 (2009).
[3] Thiago F. Viscondi, K. Furuya, and M. C. de Oliveira, Euro. Phys. Lett. **90**,10014 (2010).
[4] Thiago F. Viscondi and K. Furuya, J. Phys. A: Math. Theor. **44** 175301 (2011).
[5] Frederico Firmo de Souza Cruz, Tese: *Teorias Microscópicas para Movinentos Coletivos de Grande Amplitude*., Doutorado, Universidade de São Paulo, São Paulo, 1986.
[6] A. Smerzi, S. Fantoni, S. Giovannazi and S. R. Shenoy, Phys. Rev. Lett. A **79**, 4950 (1997).

Unlock the mystery of near-resonance Bose gases

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The properties of quantum gases beyond the usual dilute limit have been one of the most challenging topics in the field of quantum many-body physics. In this talk, I am going to report the recent results of our theoretical studies on Bose gases near resonance or at large scattering lengths. We show that 3D Bose gases near resonance are nearly fermionized, analogous to one-dimensional Tonks-Girardeau gases of hardcore bosons. Furthermore, beyond the Lee-Huang-Yang dilute limit, the chemical potential reaches a maximum when approaching the resonance from the molecule side and an onset instability sets in at a positive critical scattering length. We attribute this peculiar property to the sign change of the effective interactions due to a many-body renormalization effect. The effect of Efimov states on the chemical potential is estimated to be around a few percent.

Reference

[1] D. Borzov, M. Mashayekhi, S. Z. Zhang, J. L. Song and F. Zhou, Phys. Rev. A85, 023620 (2012).

Crystallized merons and inverted merons in the condensation of spin-1 Bose gases with spin-orbit coupling

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The non-equilibrium dynamics of a rapidly quenched spin-1 Bose gas with spin-orbit coupling [1] is studied. By solving the stochastic projected Gross-Pitaevskii equation, we show that crystallization of merons can occur in a spinor condensate of 87Rb. The stability of such a crystal structure is analyzed. Likewise, inverted merons can be created in a spin-polarized spinor condensate of 23Na. Our studies provide a chance to explore the fundamental properties of meron-like matter.

Reference

[1] Y.-J. Lin, K. Jimenez-Garcia and I. B. Spielman, *Spin-orbit-coupled Bose-Einstein condensates*, Nature **471**, pp. 83-86 (2011).

Bose-Einstein condensation of ^{85}Rb by direct evaporation in an optical dipole trap

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Bose-Einstein condensates of ^{85}Rb are produced by direct evaporation in a crossed optical dipole trap [1]. The independent control of the trap frequencies and magnetic bias field afforded by the trapping scheme permits full control of the trapped atomic sample, enabling the collision parameters to be easily manipulated to achieve efficient evaporation in the vicinity of the 155 G Feshbach resonance.

The tunable nature of the atomic interactions in ^{85}Rb makes it possible to initiate a collapse of the condensate which can, in the right trapping geometry, result in the creation of bright matter-wave solitons. These self-stabilizing wave packets arewell localized due to attractive atomic interactions and hence show great potential as surface probes for the study of short-range atom-surface interactions [2]. In light of recent theoretical interest, there is also much scope for the study of binary soliton collisions and the scattering of solitons from barriers with a view to developing interferometry schemes.

References

[1] A. L. Marchant *et al.*, *Bose-Einstein condensation of ^{85}Rb by direct evaporation in an optical dipole trap*, arXiv:1203.6598v1 (2012).
[2] S. L. Cornish *et al.*, *Quantum reflection of bright matter-wave solitons*, Physica D **238**, 1299 (2009).

Cooling by heating a superfluid

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We consider a uniform superfluid confined in two compartments connected by a superleak and initially held at equal temperatures. If one of the two compartments is heated, a fraction of the superfluid will flow through the superleak. We show that, under certain thermodynamic conditions, the atoms flow from the hotter to the colder compartment, contrary to what happens in the fountain effect observed in superfluid Helium. This flow causes quantum degeneracy to increase in the colder compartment. In superfluid Helium, this novel thermomechanical effect takes place in the phonon regime of very low temperatures. In dilute quantum gases, it occurs at all temperatures below T_c. The increase in quantum degeneracy reachable through the adiabatic displacement of the wall separating the two compartments is also discussed.

Reference

[1] D. J. Papoular, G. Ferrari, L. P. Pitaevskii, S. Stringari, *Increasing Quantum Degeneracy by Heating a Superfluid*, in preparation (2012).

Creating and characterizing vortex clusters in atomic Bose-Einstein condensates

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We extend available methods for creating vortices in 2D atomic Bose-Einstein condensates by demonstrating that a moving obstacle, in the form of an elongated paddle, can be used to stir a condensate in two quite different ways, to create clusters of like-signed vortices, or induce vortices that are dispersed. We introduce new statistical measures of clustering based on Ripley's K-function and nearest neighbor techniques which are suitable to the small size and number of vortices in atomic condensates. These measures are applied to analyze the evolution and decay of clustering. The theoretical techniques we present are accessible to experimentalists and extend the current methods of inducing 2D quantum turbulence in Bose-Einstein condensates.

Vortex core deformation in spin-1 BECs

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We have numerically minimised the free energy of a rotating, spin-1 BEC in 3 dimensions to determine the structure of the core of a singular, singly-quantised vortex. For the polar state, the vortex splits into two half-quantum vortices, each with a ferromagnetic core. In the ferromagnetic state, a hybrid spin disgyration and phase vortex forms, again with the core filled with the polar state. These results agree with studies in 2 dimensions[1, 2], though previously the nature of these core structures has not been understood. We also report on the stability of these vortices for varying spin-dependent scattering lengths, rotation frequencies, linear and quadratic Zeeman splittings in isotropic or strongly oblate harmonic traps.

References

[1] S.-K. Yip, *Internal Vortex Structure of a Trapped Spinor Bose-Einstein Condensate*, Phys. Rev. Lett. 83, 4677 (1999).
[2] T. Mizushima, K. Machida and T. Kita, *Axisymmetric versus nonaxisymmetric vortices in spinor Bose-Einstein condensates*, Phys. Rev. A 66, 053610 (2002).

Stability of ring dark solitons in toroidal Bose-Einstein condensates

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We investigate the effect of toroidal confiment on the stability of ring dark solitons, and propose a simple model to explain the main features of the snake instability [1]. We predict the number of vortex-anti-vortex pairs produced in thesnake instability and compare to numerical simulations. In our simulations toroidal confiment accelerates the onset of the snake instability compared to e.g. a cylindrical trap of similar size.

We also investigate the connection between imaginary Bogoliubov modes and the snake instability using the exact soliton-like dark ring solution of the radial Gross-Pitaevskii equation [2]. There exists only a single imaginary eigenvalue, and we show it corresponds to the snake instability.

References

[1] L. A. Toikka, K-A. Suominen *The Snake Instability of Ring Dark Solitons in Toroidally Trapped Bose-Einstein Condensates*, manuscript in preparation.
[2] L. A. Toikka, J. Hietarinta, K-A. Suominen *Exact Soliton-like Solutions of the Radial Gross-Pitaevskii Equation*, arXiv:1204.3009v1 [cond-mat.quant-gas] (2012).

Tu-056 Bose gases

A hybrid optical and magnetic ultracold atom chip system

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High resolution optical access (< 1 µm) to ultracold atoms offers new capabilities and insights into applications where single-site resolution and control of optical lattices is warranted [1, 2]. Using ColdQuanta's GlasSi™ atom chips, we have demonstrated high-resolution imaging and optical control in a vacuum system small enough to be held in one's hand. GlasSi atom chips have substrates comprised of arbitrarily defined glass and silicon regions. Using these chips, ^{87}Rb BECs were produced within 100 µm of a window in the atom chip. Using high numerical aperture (NA) optics placed *outside of the vacuum* system and within 1 mm of the atoms, we obtained resolutions of 2.5 µm, which is within a factor of 4 for the NA of 0.6 and imaging wavelength of 780 nm. Using the optics in reverse, optical potentials can be projected onto the atoms with the same high resolutions. As an example, we show images of a BEC sliced into multiple pieces by a blue-detuned laser.

References

[1] W. S. Bakr, A. Peng, M. E. Tai, R. Ma, J. Simon, J. I. Gillen, S. Fölling, L. Pollet and M. Greiner, Science **329**, 547 (2010).
[2] J. F. Sherson, C. Weitenberg, M. Endres, M. Cheneau, I. Bloch and S. Kuhr, Nature **467**, 68 (2010).

Critical rotation of an annular superfluid Bose gas

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After the pioneering work on persistent flow in helium, recent experimental success at producing circulating superfluid flow of Bose gases in annular traps has focused interest on the issue of dissipation of this macroscopic quantum state.

In this work [1], we analyze the excitation spectrum of a superfluid Bose-Einstein condensate rotating in a ring trap. We identify two important branches of the spectrum related to external and internal surface modes that lead to the instability of the superfluid. Depending on the initial circulation of the annular condensate, either the external or the internal modes become first unstable. This instability is crucially related to the superfluid nature of the rotating gas. In particular we point out the existence of a maximal circulation above which the superflow decays spontaneously, which cannot be explained by invoking the average speed of sound.

Reference

[1] R. Dubessy, T. Liennard, P. Pedri, and H. Perrin, *Critical Rotation of an Annular Superfluid Bose Gas*, arXiv:1204.6183 (2012).

High-contrast spatial interference of condensates

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We use magnetic levitation and a variable-separation dual optical plug to obtain clear spatial interference between two condensates axially separated by up to 0.25mm – the largest separation observed with this kind of interferometer. Clear planar fringes are observed using standard (i.e. non-tomographic) resonant absorption imaging. The ‘magnifying’ effect of a weak inverted parabola potential on fringe separation is observed and agrees well with theory [1]. With longer levitation we recently observed single-shot interference contrasts of 95%, close to the theoretical limit due to pixellation of the sinusoidal fringes on our CCD camera.

Reference

[1] M. E. Zawadzki, P. F. Griffin, E. Riis, and A. S. Arnold, *Spatial interference from well-separated split condensates*, Phys. Rev. A **81**, 043608 (2010).

Hanbury Brown and Twiss correlations across the Bose-Einstein condensation threshold

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The seminal experiments of Hanbury Brown and Twiss on the measurement of photon correlations have been pivotal to the advancement of quantum optics. Drawing on the analogy between photons and atoms, similar methods have recently been developed for matter waves sources. Relying on the single atom sensitivity of a novel fluorescence detection scheme, we have measured the density density correlation of Bose gases across the phase transition to Bose-Einstein condensation [1]. We are able to observe the gradual establishment of long range order while still being sensitive to the residual thermal excitations in the system. Moreover, we observe an anticorrelation at finite distances that can already been qualitatively interpreted within ideal gastheory.

Reference

[1] A. Perrin, R. Bücker, S. Manz, T. Betz, C. Koller, T. Plisson, T. Schumm and J. Schmiedmayer, *Hanbury Brown and Twiss correlations across the Bose-Einstein condensation threshold*, Nat. Phys. **8**, pp. 195-198 (2012).

Recurrence time of quantum dynamics in the interacting 1D Bose gas

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The quantum dynamics of interacting particles has recently attracted much interest associated with the question of "equilibration" and "thermalization" of isolated systems. In Ref. [1] the exact relaxation dynamics of a localized many-body state in the 1D Bose gas has been shown explicitly through the Bethe-ansatz method. Here, the localized many-body state gives a localized density profile which is the same with that of a dark soliton in the Gross-Pitaevskii equation. In our study, we calculate the dynamics of a quantum soliton exactly and observe the localized state collapsing into a flat profile in equilibrium for a large number of particles. Furthermore, we show a recurrence phenomenon for a small number of particles. In this presentation, we report the result of the dependence of the recurrence time on the number of particles and the interaction strength.

Reference

[1] J. Sato, R. Kanamoto, E. Kaminishi, and T. Deguchi, "Exact Relaxation Dynamics of a Localized Many-Body State in the 1D Bose Gas", Phys. Rev. Lett. **108**, 1140401 (2012).

Intensity correlations of Bose-Einstein-condensed light in a dye microcavity

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In recent work, we have observed Bose-Einstein condensation of a two-dimensional photon gas in an optical microcavity [1]. Here, the transversal motional degrees of freedom of the photons are thermally coupled to the cavity environment by multiple absorption-fluorescence cycles in a dye medium, with the latter serving both as a heat bath and a particle reservoir. Due to particle exchange between photon gas and molecular reservoir, grandcanonical experimental conditions are expected to be realized in this system – unlike in the presently available atomic BEC experiments. Under these conditions, a regime with strong fluctuations of the condensate number (fluctuation catastrophe) is theoretically expected [2]. I will give an update on the current status of our theoretical and experimental work.

References

[1] J. Klaers, J. Schmitt, F. Vewinger, and M. Weitz, *Bose-Einstein condensation of photons in an optical microcavity*, Nature **468**, pp. 545-548 (2010).
[2] J. Klaers, J. Schmitt, T. Damm, F. Vewinger, and M. Weitz, *Statistical Physics of Bose-Einstein-Condensed Light in a Dye Microcavity*, Phys. Rev. Lett. (in press), arXiv1201.0444 (2012).

Ab initio stochastic model for 2D Bose gas experiments: no free parameters

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Following the successful description of atom chip experiments [1], the stochastic Gross-Pitaevskii equation (SGPE) is shown to give an excellent *ab initio* description of weakly interacting, finite temperature two-dimensional Bose gases, accurately reproducing the experiment of Hung *et al.* [2]. This is achieved by addressing a common limitation of 'classical field' applications to date, associated with the appropriate momentum cut-off choice in the otherwise divergent 'classical' theory. Using a systematic approach based on the modified Popov theory [3], we show how to fix the momentum cut-off inherent in the SGPE so that it no longer corresponds to a free parameter. The excellent agreement between theory and experiment shown here at equilibrium forms an important basis for future studies of the dynamics of non-equilibrium 2D Bose gases. We acknowledge funding from EPSRC (EP/F055935/1).

References

[1] S. P. Cockburn, D. Gallucci and N. P. Proukakis, *Quantitative study of quasi-one-dimensional Bose gas experiments via the stochastic Gross-Pitaevskii equation*, Phys. Rev. A **84**, 023613 (2011).
[2] C-L. Hung, X. Zhang, N. Gemelke, C. Chin, *Observation of scale invariance and universality in two-dimensional Bose gases*, Nature **470**, pp. 236-239 (2011).
[3] U. Al Khawaja, J. O. Andersen, N. P. Proukakis, and H. T. C. Stoof, *Low dimensional Bose gases*, Phys. Rev. A **66**, 013615 (2002).

Engineering entanglement for metrology with rotating matter waves

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By rotating a collection of ultracold bosons in an asymmetric trapping potential at just the right frequency, it is possible to induce a quantum phase transition between two macroscopically distinct states. A recent theoretical study [1] has shown that for weakly interacting systems the critical frequency at which this occurs can be predicted accurately by considering only the lowest Landau level (LLL) and that the resulting state is highly entangled. We consider a more detailed calculation and show the surprising result that, although the LLL approximation predicts the frequency well, it is a very poor predictor of both the quantum Fisher information and the precise form of the entangled state. This issues a warning about relying on this approximation for certain applications. Our more detailed calculation reveals a rich system for engineering a range of interesting entangled states with potential applications to quantum metrology.

Reference

[1] D. Dagnino, N. Barberan, M. Lewenstein, and J. Dalibard, Nature Physics **5**, 431 (2009).

Quantum Kinetic Theory of Collisionless Superfluid Internal Convection

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Superfluids can transport heat independently of mass via simultaneous opposite flows of their spatially interpenetrating superfluid and thermal components. This phenomenon of internal convection is known from experiments on superfluid Helium and is usually described within Landau's phenomenological two fluid hydrodynamics. Applying quantum kinetic theory to a dilute Bose gas held between two thermal reservoirs at different temperatures, we identify the same phenomena in the collisionless Bogoliubov regime of a Bose-condensed gas [1]. The emergence of internal convection as an environmentally induced coherent effect requires a long quasi-particle lifetime within the thermal reservoirs, and its analysis needs explicit treatment of non-resonant master equation terms. Our results for the energy and particle currents suggest that internal convection should be directly observable in currently feasible experiments on trapped ultracold vapors.

Reference

[1] Lukas Gilz, James R. Anglin, *Quantum Kinetic Theory of Collisionless Superfluid Internal Convection*, Phys. Rev. Lett. **107**, 090601 (2011).

Instabilities of periodic soliton patterns with a long-ranged interaction

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We study the existence and stability of self-organized periodic soliton solutions in the quasi-one-dimensional homogeneous system, but with a long-ranged interaction. The imposed period condition induces oscillatory unstable modes when the degree of long-ranged interaction is small; while the system involves into a quasi-linear and stable one when the long-ranged interaction is large. In terms of Jacobian elliptic functions, parameter space to support stable period soliton patterns would be illustrated.

References
[1] L. D. Carr, C. W. Clark, and W. P. Reinhardt, Phys. Rev. A **62**, 063610 (2000).
[2] Y. Y. Lin, R.-K. Lee, Y.-M. Kao, and T.-F. Jiang, Phys. Rev. A **78**, 023629 (2008).
[3] T. Lahaye, C. Menotti, L. Santos, M. Lewenstein, and T. Pfau, Rep. Prog. Phys. **72**, 12640 (2009).

Towards probing quantum many-body systems with single atom resolution

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Based on our experience with single-atom detection using integrated micro-optics [1] we build a new experiment heading for a detection efficiency of > 0.95. This will enable us to study properties of single atoms as well as interatomic correlations at shot noise limit. In combination with standard imaging techniques we can compare the macroscopic properties of Bose-Einstein condensates with the coherence properties of its constituents. Using the flexibility of our atom chip in sculpturing different magnetic potentials, we will be able to study different regimes: 3D condensates and quasicondensates both in equilibrium as well as in a controlled 1D expansion, thus entering the regime of non-equilibrium dynamics.

As a second project we are going to combine magnetic chip traps with photonic structures, namely tapered nanofibers and photonic crystal fibers in order to strongly couple light to a tightly confined atomic ensemble, enabling us to study EIT, light storage and polariton gases in a quasi 1D geometry.

Reference
[1] D. Heine, W. Rohringer, D. Fischer, M. Wilzbach, T. Raub, S. Loziczky, X. Liu, S. Groth, B. Hessmo and J. Schmiedmayer, New J. Phys. **12**, 095005 (2010).

A mesoscopic gas of spin 1 bosons

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One of the most active topic in the field of ultra cold quantum gases is the study of interacting many-body systems with spin [1,2]. Atoms with arbitrary Zeeman structure can be trapped by far-detuned optical traps. In our group, we construct an all-optical setup in order to study spin 1 condensates in sodium gases. We achieved to reach Bose-Einstein condensation regime by MOT pre-cooling and two-stages evaporative cooling, with about 5000 atoms. We explore the phase diagram with magnetization and magnetic field at low temperature in equilibrium state. Two phases are found, reflecting a competition between the spin-dependent interaction and the quadratic Zeeman energy. The measurements are in quantitative agreement with mean-field theory and single mode approximation. We also notice an abnormal large fluctuation at small magnetization and low magnetic field, which opens future works for us.

References
[1] T.-L. Ho, Phys. Rev. Lett. 81, 742 (1998).
[2] T. Ohmi and T. Machida, J. Phys. Soc. Jpn 67, 1822 (1998).

Nonthermal fixed points and superfluid turbulence in an ultracold Bose gas

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Turbulence appears in situations where, e.g., an energy flux goes from large to small scales where finally the energy is dissipated. As a result the distribution of occupation numbers of excitations follows a power law with a universal critical exponent. The situation can be described as a nonthermal fixed point of the dynamical equations. Single-particle momentum spectra for a dynamically evolving Bose gas are analysed using semi-classical simulations and quantum-field theoretic methods based on effective-action techniques. These give information about possible universal scaling behaviour. The connection of this scaling with the appearance of topological excitations such as solitons and vortices is discussed. For the one-dimensional case, a random-soliton model provides analytical results for the spectra, and their relation to those found in a field-theory approach to strong wave turbulence is discussed. The results open a view on solitary wave dynamics from the point of view of critical phenomena far from thermal equilibrium and on a possibility to study non-thermal fixed points and superfluid turbulence in experiment without the necessity of detecting solitons and vortices in situ.

Reference
[1] B. Nowak *et al.*, Phys. Rev. B 84, 020506(R) (2011); B. Nowak *et al.*, arXiv:1111.6127 [cond-mat] (2011); J. Schole *et al.*, arXiv:1204.2487 [cond-mat] (2012).

Rapid formation of Rubidium Bose-Einstein Condensates in a crossed dipole trap with tunable trap aspect ratio

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We report on the rapid formation of Rubidium Bose-Einstein Condensates (BEC) in a dipole trap. The experiment comprises a simple vapor cell MOT and two single-focused Nd:YAG laser beams crossing at a small angle. The two dipole beams, each with 8 W of power, are tightly focused and are overlapped with the MOT. The laser-cooled atoms are directly loaded into the dipole trap and are forced to evaporate till the formation of BEC. Tuning the crossing angle of the two single-focused beams allows us to greatly tune the longitudinal trap frequency, as well as the effective trap volume, which play important roles for the initial loading number and subsequent efficiency of evaporation. We will report the study details and future direction of this experiment.

Reference

[1] Barrett, M. D., Sauer, J. A. & Chapman, M. S. All-optical formation of an atomic Bose-Einstein condensate. Phys. Rev. Lett. **87**, 010404 (2001).

Ultra-sensitive in situ imaging for matter-wave optics

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Quantum degenerate Fermi gases and Bose-Einstein condensates give access to a vast new class of quantum states. The resulting multi-particle correlations place extreme demands on the detection schemes. Here we introduce diffractive dark-ground imaging as a novel ultra-sensitive imaging technique [1]. Using moderate detection optics, we image clouds with less than ten atoms with near-atom shot-noise-limited signal-to-noise ratio. This is an improvement of more than one order of magnitude comparedto our standard absorption imaging. We also analyse the mechanical effects of the probe beam onto the atoms. We show that the resulting Doppler shift has to be taken into account even for moderate saturation intensities (s=0.1) and exposure times (100 μs).

Reference

[1] Pappa *et al.* New Journal of Physics 13 (2011) 115012.

Two-body anticorrelation in harmonically trapped Bose gases

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Density fluctuations in degenerate Bose gases are quantified by the second-order coherence function [1] $g^{(2)}(\mathbf{r},\mathbf{r}')$, which for ideal and weakly interacting gases typically ranges from values $g^{(2)}(\mathbf{r},\mathbf{r})\approx 2$ at zero separation, to a value of 1 at large separations $|\mathbf{r}-\mathbf{r}'|$. Here we show that nonlocal density-density *anticorrelations* $g^{(2)}(\mathbf{r},\mathbf{r}')<1$ can manifest in a harmonically confined ideal Bose gas. In the grand-canonical ensemble, this phenomenon is obscured by the "fluctuation catastrophe" of the ideal Bose gas [2], and a careful canonical-ensemble treatment of the condensate number fluctuations is required to accurately quantify the magnitude of the anticorrelation. We also discuss how interactions in elongated and quasi-one-dimensional interacting Bose gases suppress the density anticorrelations in position space, but amplify the corresponding anticorrelations in momentum space, and compare our theoretical predictions with the results of recent experiments [3].

References

[1] M. Naraschewski and R. J. Glauber, Phys. Rev. A **59**, 4595 (1999).
[2] V. V. Kocharovsky *et al.*, Adv. At. Mol. Opt. Phys. **53**, 291 (2006).
[3] A. Perrin *et al.*, Nat. Phys. **8**, 195 (2012).

Quantised decay of high charge vortices in an annular BEC

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We present work on metastability and decay of multiply-charged superflow in a ring-shaped BEC [1]. A holographically generated Laguerre-Gauss(LG) beam is used to both trap and rotate a condensate of Rb^{87} atoms. The atoms are rotated via a two-photon Raman process using the trapping LG beam with a Gaussian beam to impart a well defined amount of angular momentum in quantised units of $\hbar$. Supercurrent corresponding to a giant vortex with topological charge up to $q=15$ is phase imprinted optically and detected both interferometrically and kinematically. We observe $q=3$ superflow persisting for over a minute and clearly resolve resolve a cascade of quantised steps in the eventual decay of the supercurrent. These stochastic glitches in the superflow, associated with vortex-induced phase slips, correspond to collective jumps of atoms between discrete q values. Current work is focused on supercurrent decay of a co-rotating spinor condensate, where we find the additional degree of freedom introduced by the two components reduces the stability of superflow.

Reference

[1] S. Moulder, *Quantised superflow glithces in an annular Bose-Einstein condensate*, ArXiv preprint (2012), arXiv:1112.0334.

Interaction between cold atoms and carbon nano tubes

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We perform a theoretical study of cold atoms interacting with static and vibrating carbon nanotubes. We construct the full finite temperature Casimir-Polder interaction and explore the scattering of atoms on the tube. We find that elastic quantum reflection can typically be ignored for thermal atom clouds but is important if a Bose-Einstein condensate is used. Atom loss from the condensate is shown to be highly non-trivial, but provided atomic interaction effects and quantum pressure are included in the description , our simulations describe experiments [1] well. Finally, we study a vibrating nanotube in a condensate and show that vibration frequencies typical to nanoscaled objects do not significantly reduce the condensate's coherence, but certain low frequency oscillations dramatically heat the cloud.

Reference

[1] M. Gierling, P. Schneeweiss, G. Visanescu, P. Federsel, M. Haffner, D. P. Kern , T. E. Judd, A. Günther, and J. Fortágh, Nat. Nano. **6**, 446 (2011).

Bose gases Tu-074

Dynamic Kosterlitz-Thouless transition in 2D Bose mixtures of ultra-cold atoms

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We propose a realistic experiment to demonstrate a dynamic Kosterlitz-Thouless transition in ultra-cold atomic gases in two dimensions. With a numerical implementation of the Truncated Wigner Approximation we simulate the time evolution of several correlation functions, which can be measured via matter wave interference. We demonstrate that the relaxational dynamics is well-described by a real-time renormalization group approach, and argue that these experiments can guide the development of a theoretical framework for the understanding of critical dynamics.

This poster is based on Ref. [1].

Reference

[1] L. Mathey, Kenneth J. Günter, Jean Dalibard, and A. Polkovnikov, cond-mat/1112.1204.

Calorimetry of a Bose-Einstein condensate

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We investigate the heat capacity of a Bose-Einstein Condensate (BEC) following the suggestions by Blakie *et al.* [1]. We start with a BEC of ^{87}Rb atoms, close to zero temperature, trapped in the intersection of two focused CO_2 laser beams. The trap is turned off for times in the order of a millisecond, during which it expands ballistically and falls under gravity. The atoms are then recaptured, and the atoms are allowed to reach thermal equilibrium. Subsequently, the temperatureof the atomic ensemble is measured by time-of-flight. We present some new measurements, varying the interaction strength by the trap depth, as well as the energy transferred by the drop time.

Reference

[1] P. B. Blakie, E. Toth and M. J. Davis, *Calorimetry of Bose-Einstein condensates*, J. Phys. B: At. Mol. Opt. Phys. **40**, 3273 (2007).

Tu-076 Bose gases

Quantum and thermal density fluctuations in 1D Bose gases

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We have carried precise studies of density fluctuations in weakly repulsive 1D Bose gases held in atom chip traps, using hundreds of pictures and carefully analysing the statistics of atom number in the imaging pixels. Previously, fluctuations were used to precisely study the thermodynamics of 1D Bose gases. Fluctuations up to the third moment were measured and the transition from the ideal gas to the quasicondensate regime was mapped out in the temperature-density space [1]. Observing subpoisonian fluctuations marked the entrance into the quantum quasicondensate regime, and the regime of strong interactions was approached [2]. Here, at record low temperatures, using a non-local analysis at variable observation length, we observe a clear discrepancy with a classical field model which unambiguously proves our direct detection of quantum fluctuations, as the thermodynamic limit breaks down [3].

References

[1] J. Armijo, T. Jacqmin, K. V. Kheruntsyan, and I. Bouchoule, Phys. Rev. Lett. **105**, 230402 (2010), Phys. Rev. A , 021605 (2011).
[2] T. Jacqmin, J. Armijo, T. Berrada, K. V. Kheruntsyan and I. Bouchoule, Phys. Rev. Lett. **106**, 230405 (2011).
[3] J. Armijo, Phys. Rev. Lett. **108**, 225306 (2012).

Thermal spin fluctuations in spinor condensates

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Spinor gases present a rich physics due to the interplay between internal and external degrees of freedom. We study the finite-temperature physics of spinor condensates in two different scenarios. We first consider dynamically stable spin-1 condensates inthe Zeeman m = 0 state, and study the thermal population of m = 1 via spin-changing collisions. Interestingly, these collisions are typically characterized by a very low energy, and as a consequence, for magnetic fields close to the dynamical instability, the spinor populations may be extremely sensitive to temperature. We then analyze dynamically stable Chromium F = 3 condensates in m = 3, where magnetic dipolar interactions introduce spin relaxation, which leads not only to a very temperature-sensitive population of m = 2, but also to a non-trivial angular dependence of the activated m = 2 atoms. The discussed thermal effects may be employed for thermometry at very low temperatures.

References

[1] L. Santos and T. Pfau, *Spin-3 Chromium Bose-Einstein condensates*, Phys. Rev. Lett. **96**, 190404 (2006).
[2] T. Lahaye, C. Menotti, L. Santos, M. Lewenstein and T. Pfau, *The physics of dipolar bosonic quantum gases*, Rep. Prog. Phys. **72**, 126401 (2009).

Confinement-induced collapse of a dipolar Bose-Einstein condensate

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We experimentally investigate the instability and collapse dynamics of a dipolar Bose-Einstein condensate (dBEC) in a 1D optical lattice. In contrast to the usual method relying on a change in the interaction strength, the instability is here initiated by a modification of the external confinement potential, while keeping the interaction strength constant. Only a dBEC offers this possibility, since its stability depends on the lattice depth due to the anisotropic dipole-dipole interaction [1]. We consider a ^{52}Cr BEC with reduced scattering length, initially confined in a trap created by a shallow optical lattice superimposed to a crossed optical dipole trap. We show that its instability can be induced in-trap by decreasing the lattice depth below a critical value. We also show that a dBEC initially stabilized by the lattice may become unstable and collapse during the time-of-flight dynamics upon release, which is a unique feature of dipolar systems in optical lattices.

Reference

[1] S. Müller *et al.*, "Stability of a dipolar Bose-Einstein condensate in a one-dimensional lattice", Phys. Rev. A **84**, 053601 (2011).

Observation of Feshbach resonances in ultracold Er gases

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We report on the first measurements of Feshbach resonances in ultracold gases of submerged-shell atoms. Our experiments focus on ^{168}Er, which is a highly magnetic atom of the lanthanide series. Because of its large magnetic moment of 7 μ_B, with μ_B the Bohr magneton, and a non-S electronic ground state, Er features very strong anisotropic interactions, which are not accessible with alkali atoms. It has recently been predicted that Feshbach resonances in lanthanide atoms, as Er and Dy, are induced by the strong anisotropy of the dispersion interaction and magnetic dipole-dipole interaction [1]. Our measurements show a rich Feshbach spectrum in the low magnetic field region below 50 G and thus give first insights into the scattering physics of lanthanide atoms.

Reference

[1] A. Petrov, E. Tiesinga and S. Kotochigova, arXiv:1203.4172, 2012.

Towards stable groundstate NaK molecules

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Ultracold quantum gases can serve as bench mark systems for strongly interacting manybody physics [1]. Conventional alkali atomic systems at ultra low temperatures exhibit interaction potentials that have essentially zero range. If long range interaction can be introduced, many intriguing effects and new quantum phases will be accessible. Examples are real space long range (crystalline) order for bulk systems, supersolids and fractional Mott insulators in optical lattices. Two promising candidates for ultra cold particles with tunable long range interaction are Rydberg atoms and ground state polar molecules. We are setting up an experiment to create ultracold NaK molecules. In this system instability due to inelastic two body collisions known from pioneering experiments [2] is absent and chances are good to reach far into the interesting parameter space.

References

[1] I. Bloch, J. Dalibard and W. Zwerger, *Many-body physics with ultracold gases*, Rev. Mod. Phys. **80**, 885 (2008).
[2] K. K. Ni *et al.*, *A high phase-space-density gas of polar molecules*, Sience, **322**, 231 (2008).

Dipolar gases

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Dipolar quantum gas systems at ultralow temperatures are expected to exhibit novel many-body quantum phases as a result of the long-range and anisotropic dipole-dipole interaction. The present work focuses on the creation of ultracold samples of polar ground-state RbCs molecules. We first produce two spatially separated Bose-Einstein condensates (BEC) of Rb and Cs atoms [1]. After overlapping the BECs we produce weakly bound RbCs molecules [2] using the Feshbach-association technique. We transfer the molecules into the rovibrational ground state[3] with 90% efficiency by employing the STIRAP (Stimulated Raman Adiabatic Passage) method. Our next goal is to improve the production efficiency for the RbCs molecules by performing the Feshbach association and STIRAP transfer in the presence of an optical lattice.

References

[1] A. Lercher *et al.*, “Production of a dual-species Bose-Einstein condensate of Rb and Cs atoms”, EUR PHYS J D **65**, pp. 3 (2011).
[2] T. Takekoshi *et al.*, “[…] Feshbach resonances, weakly bound states, and the coupled-channel model”, PRA **5**, pp. 032506 (2012).
[3] M. Debatin *et al.*, “Molecular spectroscopy for ground-state transfer of ultracold RbCs molecules”, PCCP **13**, pp. 18926 (2011).

Evaporative cooling of polar molecules

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Ultracold polar molecules in the quantum degenerate regime open the possibility of realizing strongly correlated quantum systems with long-range and spatially anisotropic interactions. Although KRb is observed to undergo bi-molecular chemical reactions at ultralow temperatures [1], the anisotropy of the dipole-dipole interaction can be exploited to suppress these chemical reactions by trapping the molecules in a one-dimensional optical lattice [2]. In this reduced 2D geometry, the repulsive dipole-dipole interaction further enhances the p-wave barrier between two indistinguishable fermionic molecules, drastically reducing the chemical reaction rate. We now demonstrate evaporative cooling of KRb in this reduced geometry. Although s-wave scattering is forbidden by quantum statistics and the rethermalization rate from p-wave collisions is negligible, the molecules rethermalize via long range dipole-dipole interactions. The observed increase in phase space density is an important step towards the exploration of collective quantum effects in an ultracold gas of molecules.

References

[1] S. Ospelkaus *et al.*, “Quantum-State Controlled Chemical Reactions of Ultracold Potassium-Rubidium Molecules”, Science **327**, pp. 853 (2010).
[2] M. H. G. de Miranda *et al.*, “Controlling the Quantum Stereodynamics of Ultracold Bimolecular Reactions”, Nature Physics **7**, pp. 502 (2011).

Ultracold dipolar Bose-Einstein condenstates in an optical lattice

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Most researches on quantum degenerate gases in optical lattices so far have considered only short-ranged, isotropic, and Van der Waals type interactions of alkali atoms. However, recent experimental realizations [1, 2] of almost pure dipolar gases of dysprosium-161 and erbium-168 offer fascinating opportunities to study how long-ranged, anisotropic, and dipole-dipole interactions modify the properties of trapped quantum gases of bosons and fermions. We have investigated collective excitation of dipolar bosons trapped in a 2D optical lattice using numerical simulations for different trap geometries. It is found that anisotropic trap has great impact on the collective mode shift. As the number of atoms decreases, our result demonstratesdisagreement with the one predicted in the Thomas-Fermi limit.

References

[1] M. Lu, N. Q. Burdick, and B. L. Lev, *Quantum Degenerate Dipolar Fermi Gas*, Phys. Rev. Lett. **108**, 210301 (2012).
[2] K. Aikawa, A. Frisch, M. Mark, S. Baier, A. Rietzler, R. Grimm, and F. Ferlaino, *Bose-Einstein Condensation of Erbium*, Phys. Rev. Lett. **108**, 210401 (2012).

Coherent multi-flavor spin dynamics in a fermionic quantum gas

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Multi-component fermion systems give rise to many intriguing physical phenomena, such as baryon formation and SU(N) symmetric magnetism. We report on the realization of a spin-9/2 fermionic quantum gas of ^{40}K atoms in an optical lattice and study its fundamental spin-exchange processes [1]. At low magnetic fields, interactions allow for dynamical exchange of the internal spin, while at high fields the spins are stable. The spin dynamics is initialized by a quench of the magnetic field between these regimes. For isolated atom pairs, long-lived coherent oscillations of the spin populations are observed and a spin resonance as a function of the magnetic field is identified. The results are in very good agreement with numerical calculations including all scattering channels. Allowing for tunneling in one direction, we observe a damping of the coherent oscillations. We attribute this to a melting of the initial band insulator, induced by spin-changing collisions which open additional spin channels.

Reference

[1] J. S. Krauser, *et al.*, “Coherent Multi-Flavor Spin Dynamics in a Fermionic Quantum Gas“, arXiv, 1203.0948v1 (2012).

Feynman diagrams versus Fermi-gas Feynman emulator

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Precise understanding of strongly interacting fermions, from electrons in modern materials to nuclear matter, presents a major goal in modern physics. For the first time, we sum the series of Feynman diagrams for such a many-body problem to essentially infinite order. This is made possible by a new theoretical approach, Bold Diagrammatic Monte Carlo (BDMC), combining a Monte Carlo process capable of sampling billions of diagrams, bold lines representing fully dressed propagators, and divergent-series resummation techniques. Specifically, we compute the equation of state of the unitary gas in the normal unpolarised phase. We cross-validate the results with new precision experiments on ultra-cold ^{6}Li atoms at the broad Feshbach resonance. Excellent agreement demonstrates that a series of Feynman diagrams can be controllably resummed in a non-perturbative regime using BDMC. This opens the door to the solution of challenging problems across many areas of physics.

Topological superfluid in a trapped two-dimensional polarized Fermi gas with spin-orbit coupling

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We study the stability region of the topological superfluid phase in a trapped two-dimensional polarized Fermi gas with spin-orbit coupling and across a BCS-BEC crossover. Due to the competition between polarization, pairing interaction, and spin-orbit coupling, the Fermi gas typically phase-separates in the trap. Employing a mean-field approach that guarantees the ground-state solution, we systematically study the structure of the phase separation and investigate in detail the optimal parameter region for the preparation of the topologically nontrivial superfluid phase. We then calculate the momentum space density distribution of the topological superfluid state and demonstrate that the existence of the phase leaves a unique signature in the trap integrated momentum space density distribution which can survive the time-of-flight imaging process [1].

Reference

[1] J. Zhou, W. Zhang and Y. Wei, Phys. Rev. A **84**, 063603 (2011).

Dynamic spin response of a strongly interacting Fermi gas

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Two-component Fermi gases near Feshbach resonances exhibit universal properties and provide a well controlled setting to explore many-body phenomena in highly correlated quantum systems. Probing dynamic response functions, such as the dynamic spin susceptibility, can reveal new universal aspects in the dynamics of these systems. Here we present the first measurement of the dynamic spin response of a strongly interacting ^{6}Li Fermi gas in the two ground states using Bragg spectroscopy. By appropriate choice of the Bragg laser detuning either the spin or the density response can be measured independently. This allows full characterisation of the spin-parallel and spin-antiparallel components of the dynamic $S(k, \omega)$ and static $S(k)$ structure factors. At high momentum transfer k, the spin response is suppressed at low energies due to pairing and displays a universal high frequency tail, decaying as $\omega^{-5/2}$, where $\hbar\omega$ is the probe energy [1,2].

References
[1] H. Hu and Xia-Ji Liu, *Universal dynamic structure factor of a strongly correlated Fermi gas*, Phys. Ref. A **85**, 023612 (2012).
[2] S. Hoinka *et al.*, *Dynamic spin response of a strongly interacting Fermi gas*, arXiv:1203.4657 [cond-mat.quant-gas] (2012).

Low temperature properties of the fermionic mixtures with mass imbalance in optical lattice

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Mass imbalanced system has attracted current interest since the successful realization of the superfluid (SF) state in the Fermi-Fermi mixtures with distinct ions, ^{40}K and ^{6}Li [1,2]. One of the interesting problems in such a mass imbalanced system is how the SF state is realized in the optical lattice. It is known that in the lattice model, a density wave (DW) state is stabilized since less mobile fermions tend to crystallize. Therefore, it is necessary to clarify how the SF state coexists or competes with the DW state at low temperatures. Here, we studyf the infinite-dimensional attractive Hubbard model with different masses [3], combining dynamical mean-field theory with the continuous time quantum Monte Carlo simulations. It is clarified that the coexisting (supersolid) state is indeed realized in the mass imbalanced system [4]. The low-temperature phase diagram is then determined.

References
[1] M. Taglieber, *et al.*, Phys. Rev. Lett. **100**, 010401 (2008).
[2] E. Wille, *et al.*, Phys. Rev. Lett. **100**, 053201 (2008).
[3] T. Dao, A. Georges, and M. Capone, Phys. Rev. B **76**, 104517 (2007).
[4] N. Takemori and A. Koga, arXiv:1204.1783.

Conduction properties of ultracold fermions

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We experimentally study the conduction properties of ultracold fermionic atoms flowing through a quasi two-dimensional channel connecting macroscopic, incoherent reservoirs. An atomic current is induced by creating an imbalance in the particle number of the two reservoirs. Combining the measurement of the current with the high-resolution in-situ measurement of the density in the channel, we observe the drop of chemical potential due to the contact resistance which develops at the contacts between the ballistic channel and the reservoirs [1].

Analogous to a field-effect transistor, we use an additional beam to independently tune the atomic density in the channel region and study the current as a function of the chemical potential. For a strongly interacting Fermi gas we observe a striking increase of the current which we attribute to the onset of superfluidity. We also study the effect of disorder for weakly and strongly interacting Fermi gases.

Reference

[1] J. Brantut, J. Meineke, D. Stadler, S. Krinner, and T. Esslinger. *Conduction of Ultracold Fermions Through a Mesoscopic Channel*. arXiv:1203.1927 (2012).

Attractive and repulsive Fermi polarons in two dimensions

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The dynamics of a single impurity in an environment is a fundamental question in many-body physics. A spin-up impurity dressed by a bath of spin-down particles, constitutes the Fermi polaron problem. This is the extreme, but conceptually simple, limit oftwo important quantum many-body problems: the BEC-BCS crossover with spin-imbalance for attractive interactions and Stoners itinerant ferromagnetism for repulsive interactions. We create and investigate Fermi polarons in two dimensions and measure their spectral function using momentum-resolved photoemission spectroscopy [1]. For attractive interactions we find evidence for the disputed pairing transition between polarons and tightly bound dimers, which provides insight into the elementary pairing mechanism of imbalanced, strongly-coupled two-dimensional Fermi gases. Additionally, for repulsive interactions we study novel quasiparticles, repulsive polarons, whose lifetime determine the possibility of stabilizing repulsively interacting Fermi systems [2].

References

[1] M. Feld, B. Fröhlich, E. Vogt, M. Koschorreck & M. Köhl, Nature **480**, 75-78 (2011).
[2] M. Koschorreck, D. Pertot, E. Vogt, B. Fröhlich, M. Feld & M. Köhl, submitted to Nature.

Possibility of gapless superfluid states of Fermi atoms in triangular optical lattices

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Fermi superfluids in optical lattices have attracted much attention due to the possibility of simulating superconducting systems with strong correlations. Recently, triangular optical lattices have been realized in order to simulate geometrically frustrated systems [1]. In this poster, we study Fermi superfluids in triangular lattices to investigate the effects of frustration on the superfluid states. Using the attractive Hubbard model, we calculate the superfluid order parameter in the presence of superflow within the BCS-Leggett mean-field theory. We find that finite order parameter solution exists even when the negative energy Bogoliubov quasiparticle states are occupied. This indicates the possibility of gapless superfluid state in contrast to the square lattice case [2]. We discuss the stability of the gapless superfluid states. We calculate the energy spectrum of superfluid collective modes to map out the stability phase diagram.

References
[1] C. Becker *et al.*, ”Ultracold quantum gases in triangular optical lattices”, New J. Phys. **10**, 045014 (2010).
[2] R. Ganesh *et al.*, ”Collective modes and superflow instabilities of strongly correlated Fermi superfluids”, Phys. Rev. A **74**, 031604(2009).

Virial expansion with Feynman diagrams

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Experiments performed on ultracold ^{6}Li atoms have measured the equation of state with great accuraccy [1]. From the high temperature behavior, virial coefficients b_3 and b_4 have been extracted. In this work, we have calculated, using diagramatic techniques, the third virial coefficient b_3 in the whole BEC-BCS crossover. Our approach is analytic, and we get closed expressions for b_3 in terms of the 3 – body T-matrix. We recover in this way the experimental result of Ref.[1] in the unitary limit. Our results for b_3 are also in excellent agreement in the whole BEC-BCS crossover with a previous theoretical work [3] using a totally different approach.

References
[1] S. Nascimbène, N. Navon, K. J. Jiang, F. Chevy, and C. Salomon, Nature **463**, 1057 (2010).
[2] X. Leyronas, Phys. Rev. A **84**, 053633 (2011).
[3] X.-J. Liu, H. Hu, and P. D. Drummond, Phys. Rev. Lett. **102**, 160401 (2009).

Spin-depairing transition in one-dimensional two-component Fermi gases

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We investigate one-dimensional two-component Fermi gases with a time-dependent gauge field on the spin sector. It is known that the ground state of two-component attractive Fermi gases is filled with bound states of up-spin and down-spin particles and the spin excitation has a gap, which is attributed to the appearance of fermionic superfluidity. By combining the methods of the Bethe ansatz with complex twists and Landau-Dykhne, we show that a spin-depairing transition occurs, which may represent a nonequilibrium transition from fermionic superfluids to normal states with spin currents. We analyze cases of Fermi-Hubbard and Yang-Gaudin models, and show how filling (density) affects the transition probability.

Reference

[1] S. Uchino and N. Kawakami, Phys. Rev. A **85**, 013610 (2012).

General properties of universal Fermi gases in arbitrary dimensions

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We consider spin-1/2 Fermi gases in arbitrary, integer or non-integer spatial dimensions, interacting via a Dirac delta potential. We first generalize the method of Tan's distributions that implement short-range boundary conditions to arbitrary dimension and then use it to obtain a set of universal relations for the Fermi gas, which serve as dimensional interpolation/extrapolation formulae in between integer dimensions. Using these universal properties we are then able to show that, under very general conditions, effective reduced-dimensional scattering lengths due to transversal confinement depend on the original three-dimensional scattering length in a universal way. As a direct consequence, we find that confinement-induced resonances occur in all dimensions different than two without any need to solve the associated multichannel scattering problem. Finally, we show that reduced-dimensional contacts — related to the tails of the momentum distributions — are related to the actual three-dimensional contact through a correction factor of purely geometric origin.

Strongly interacting mixtures of bosonic ^{23}Na and fermionic ^{40}K

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Mixtures of bosonic and fermionic quantum gases can form ideal model systems to study intriguing quantum phenomena. Polaron and molecule physics as well as exotic many-body quantum phases become accessible when appropriate Feshbach resonances are available to freely tune the interactions between bosons and fermions. We have created a new quantum degenerate Bose-Fermi mixture of bosonic ^{23}Na and fermionic ^{40}K. We demonstrated that this mixture offers widely tunable interactions via broad interspecies Feshbach resonances [1]. Over thirty resonances were identified, the broadest of which being located at about 138 G and being 30 G wide. Radiofrequency spectroscopy in the vicinity of that resonance has allowed us to create ultracold fermionic Feshbach molecules with lifetimes of up to100 ms. Our work opens up the prospect to create chemically stable, fermionic ground state molecules of ^{23}Na-^{40}K. Due to a large permanent electric dipole moment of 2.72 Debye long-range dipolar interactions will be strong and set the dominant energy scale in many-body systems of fermionic ^{23}Na-^{40}K ground state molecules.

Reference

[1] J. W. Park *et al.*, *Quantum degenerate Bose-Fermi mixture of chemically different atomic species with widely tunable interactions*, Phys. Rev. A **85**, 051602(R) (2012).

Unconventional superfluidity in higher bands of an optical lattice

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Atoms trapped in optical lattices have been used successfully to study many-body phenomena. However, the shape that bosonic ground-state wavefunctions can take is limited, apparently compromising the usefulness of this approach. Such limitations, however,do not apply to excited states of bosons. The study of atomic superfluids realized in higher Bloch bands, where orbital degrees of freedom are essential, can bring the world of optical lattices closer to relevant condensed matter systems. We discuss our observations of extremely long coherence times, chiral superfluid order and topological features in higher bands in a square optical lattice.

References

[1] G. Wirth *et al.*, *Evidence for orbital superfluidity in the P-band of a bipartite optical square lattice*, Nature Physics **7** , pp. 147–153 (2011).
[2] M. Ölschläger *et al.*, *Unconventional Superfluid Order in the F Band of a Bipartite Optical Square Lattice*, Phys. Rev. Lett. **106** , 015302 (2011).
[3] M. Ölschläger *et al.*, *Topologically Induced Avoided Band Crossing in an Optical Checkerboard Lattice*, Phys. Rev. Lett. **108**, 075302 (2012).

Matter wave scattering on a time-dependent optical lattice

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We experimentally study the scattering of guided matter waves on a time-dependent amplitude optical lattice. We observe different types of frequency-dependent dips in the asymptotic output density distribution. Their positions are compared quantitativelywith numerical simulations. A semiclassical model that combines *local* Floquet-Bloch bands analysis and Landau-Zener transition provides a simple picture of the observed phenomena in terms of elementary absorption-emission Floquet photon processes and Bragg reflections. Finally, we propose and demonstrate the use of this technique with a bichromatic amplitude modulation to design a tunable sub-recoil velocity filter.

Reference

[1] C. M. Fabre, P. Cheiney, G. L. Gattobigio, F. Vermersch, S. Faure, R. Mathevet, T. Lahaye, and D. Guéry-Odelin, Phys. Rev. Lett. **107**, 230401 (2011).

Optical lattices Tu-098

Magnetic lattices for ultracold atoms

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Magnetic lattices based on periodic arrays of permanent magnetic microstructures [1] provide a promising complementary tool to optical lattices and have certain distinguishing features including the potential to tailor geometries of arbitrary shape, to perform in-situ RF evaporative cooling and RF spectroscopy, and to produce highly stable potentials. Here, we report on the trapping and cooling of ^{87}Rb F=1 atoms in a 1D 10 µm-period magnetic lattice. Typically 3×10^5 atoms are loaded into the magnetic lattice with trap lifetimes of ~ 10 s and evaporatively cooled to 1-2 mK, which is close to the BEC transition temperature. Using *in situ* absorption imaging the clouds of ultracold atoms can be optically resolved in the individual magnetic lattice sites. Potential applications of micron-period magnetic lattices with honeycomb or triangular lattices to simulate condensed matter systems will be presented.

Reference

[1] A. Sidorov and P. Hannaford, "From magnetic mirrors to atom chips", In *Atom Chips*, Eds. J. Reichel and V. Vuletic, Wiley-VCH Verlag, Weinheim, Ch 1, pp 3-31 (2011).

Dual Mott insulator in a spin-dependent optical lattice

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A major goal of the field of ultracold atoms is to realize novel many-body states, and in particular magnetic states. It has been suggested that a spin-dependent optical lattice can provide the tunability necessary to realize the Heisenberg Hamiltonian which can give rise to ferromagnetic and antiferromagnetic states [1]. Such a spin-dependent optical lattice can be realized by tuning the laser wavelength close to the D1 and D2 lines of the alkali atoms [2]. We have implemented such a lattice to realize the ability to control the interspin interaction energy for a mixture of two hyperfine states of bosonic ^{87}Rb in a three-dimensional optical lattice. In particular, we have studied the system in a dual Mott insulator state where the two hyperfine states are both Mott insulators and tuned the interspin interaction energy with the spin-dependent optical lattice.

References
[1] L.-M. Duan, E. Demler and M. D. Lukin, *Controlling Spin Exchange Interactions of Ultracold Atoms in Optical Lattices*, Phys. Rev. Lett. **91**, 090402 (2003).
[2] O. Mandel, M. Greiner, A. Widera, T. Rom, T. W. Hänsch and I. Bloch, *Coherent Transport of Neutral Atoms in Spin-Dependent Optical Lattice Potentials*, Phys. Rev. Lett. **91**, 010407 (2003).

Interplay between interaction and localization in 1D quasiperiodic systems

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Stimulated by recent experiments with ultracold in bichromatic lattices [1], we investigate the evolution of initially localized wave packets in two quasiperiodic models, namely a discrete nonlinear Schrödinger equation and a quartic Klein Gordon lattice. In the regime where, in the absence of nonlinearity, all eigenstates are exponentially localized, we show that the inclusion of a nonlinear term induces a destruction of localization resulting in a subdiffusive spreading. We interpret this delocalization on the basis of mode-mode resonances. Two spreading regimes of weak and strong chaos can be identified by comparing the strength of the nonlinearity with the energy scales of the underlying linear system. For large enough nonlinearity, a wave packet undergoes self-trapping, as in purely random systems. In the quasiperiodic case, however, we find that a partial self-trapping of the expanding wave packet can also occur at weaker nonlinearity due to the existence mini-gaps in the spectrum.

Reference
[1] E. Lucioni, B. Deissler, L. Tanzi, G. Roati, M. Zaccanti, M. Modugno, M. Larcher, F. Dalfovo, M. Inguscio, and G. Modugno, Phys. Rev. Lett. **106**, 230403 (2011).

Engineering Dirac points with ultracold fermions in a tunable optical lattice

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We report on the creation of Dirac points with adjustable properties in a tunable honeycomb optical lattice. Using momentum-resolved interband transitions, we observe a minimum band gap inside the Brillouin zone at the position of the Dirac points. We exploit the unique tunability of our lattice potential to adjust the effective mass of the Dirac fermions by breaking the inversion symmetry of the lattice. Changing the lattice anisotropy allows us to move the position of the Dirac points inside the Brillouin zone. When increasing the anisotropy beyond a critical limit, the two Dirac points merge and annihilate each other. We map out this topological transition and find excellent agreement with ab initio calculations. Our results not only pave the way for using cold atoms to model materials where the topology of the band structure plays a crucial role, but also provide the possibility to explore many-body phases resulting from the interplay of complex lattice geometries with interactions.

Rydberg atoms in optical lattices

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We investigate highly excited Rydberg atoms in optical-lattice traps. The potential experienced by a Rydberg atom in an optical lattice is given by the spatial average of the free-electron ponderomotive energy due to the laser field, weighted by the Rydberg electron's probability distribution. Here, we study the dependence of the potential on the angular portion of the atomic wavefunction. Experimentally, the angular dependence of the potential is demonstrated using various (j, m_j) levels of ^{85}Rb Rydberg nD states ($50 \leq n \leq 65$) in both an optical lattice (wavelength 1064 nm) and transverse electric field. We present measurements of the lattice depths for various (j, m_j) levels and compare them to theoretical results. The tunability of Rydberg-atom trapping potentials using the angular degrees of freedom will be important for applications of Rydberg-atom optical lattices.

Numerical investigation of electromagnetically induced grating for tripod scheme

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The tripod scheme implies that the coupling and probe resonant beams are applied in a two-dimensional geometry [4]. This geometry is particularly appealing as it allows us to study the effect of the phase difference between two standing waves on the diffraction pattern. In this contribution we study the electromagnetically induced phase and amplitude gratings in the tripod configuration scheme. The medium is optically thick and assumed to be homogeneously-broadened. We analyze the four-level scheme driven by the three fields using a density matrix formalism. Thus, our model is based on solving Liouville equations self-consistently with Maxwell equations. Wave equations for the fields are written in the approximation of slowly varying phases and amplitudes. We demonstrate how one can totally suppress diffraction in a desirable diffraction order, or oppositely, amplify a given diffraction order. As for the efficiency of the diffraction in the first diffraction order, it depends on the level of phase modulation, as expected.

References

[1] H. Y. Ling, Y. Q. Li and M. Xiao// Phys. Rev. A **57**, 1338-1344 (1998).
[2] M. Mitsunaga and N. Imoto// Phys. Rev. A **59**, 4773-4776 (1999).
[3] E. Paspalakis and P. L. Knight // J. Opt. B: Quantum Semiclass. Opt, **4**, S372-S375, (2002).
[4] V. Ivanov and Yu. Rozhdestvensky// Phys. Rev. A **81**, 033809 (1998).

Bose-fermi mixtures in one-dimensional incommensurate lattices

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Disordered Bose systems with strong correlation, described by Bose Hubbard models with disorder, have been one of the targets of theoretical and experimental investigation. Current interest is also directed towards disordered systems of ultracold atoms generated by using laser speckle patterns or additional incommensurate optical lattice potentials. Fallani *et al.* [1] observed a localization transition of strongly interacting ^{87}Rb bosons in incommensurate lattices, which suggested the formation of a Bose glass.

We numerically studied the localization property of Bose-Fermi mixture systems on one-dimensional incommensurate optical lattices and parabolic confining potentials. We focus on the interaction region where bosons and fermions are in different phases, especially when fermions are localized and bosons are delocalized. Using quantum monte carlo simulation we found new localized or delocalized phases which are formed by bose-fermi interactions and are dependent of the ratio of the density of bosons to that of fermions. We propose a mechanism of these phenomena, showing the visibility of momentum space, the density distributions and the tructure factors.

Reference

[1] L. Fallani *et al.*, Phys. Rev. Lett. **98**, 130404 (2007).

Transport and excitations in lattice-trapped bosonic mixtures

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Atomic quantum gases in optical lattices allow for fundamental studies of strongly-correlated many-body systems. We have recently studied transport and excitation effects in 1D atomic mixtures (derived from a BEC) in component-specific lattices. One experiment [1] addressed the effects of uncorrelated disorder, formed by localized impurities, on a lattice-modulated 1D Bose gas. Near the superfluid-to-insulator transition, we observed a shift of the critical lattice depth for the breakdown of transport, in contrast to the case of quasi-disorder from an incommensurate optical lattice, where no such shift is seen. In a second experiment [2] we explored the scattering of atomic de Broglie waves to detect spatial structure in a lattice-modulated 1D Bose gas, as well as the suppression of inelastic scattering in the band structure. Matter-wave Bragg diffraction is a powerful technique to non-destructively probe long-range order, such as in spin mixtures, and its tunability precludes limitations on spatial resolution.

References

[1] B. Gadway, *et al.*, *Glassy Behavior in a Binary Atomic Mixture*, PRL **107**, 145306 (2011).
[2] B. Gadway, *et al.*, *Probing an Ultracold-Atom Crystal with Matter Waves*, arXiv:1104.2564v2 (2/20/2012).

Schwinger-Keldysh approach to a quantum quench in the Bose Hubbard model

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We use the Schwinger-Keldysh technique to study the real-time dynamics of the Bose-Hubbard model, allowing for a finite-temperature initial state. We find the real-time strong coupling action for the problem at both zero and finite temperature. This action allows for the description of both the superfluid and Mott-insulating phases. We use this action to obtain dynamical equations for the superfluid order parameter as hopping is tuned in real time so that the system crosses the superfluid phase boundary. We find that under a quench in the hopping, the system generically enters a metastable state in which the superfluid order parameter has an oscillatory time dependence with a finite magnitude, but with vanishes under time-averaging. We relate our results to recent out of equilibrium experiments involving cold atoms in traps and point out that equilibration is impeded when the average number of atoms per site differs in the superfluid and Mott insulating phases.

Reference

[1] M. P. Kennett and D. Dalidovich, *Schwinger-Keldysh approach to out-of-equilibrium dynamics of the Bose-Hubbard model with time-varying hopping*, Phys. Rev. A **84**, 033620 (2011).

Resolution assessment of a fluorescence microscope for observing single ytterbium atoms trapped in two-dimensional optical lattice

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^{171}Yb atom behaves as an ideal qubit, since its 1/2 nuclear spin has long coherence time. Complicated tasks of quantum information processing will be thus implemented with a 2D quantum gas microscope [1] using the ^{171}Yb atoms. Using a solid immersion lens (SIL), both the resolution and the magnification can be improved by factor of n which is the refractive index of the SIL. The brightness of the microscope can also be improved by factor of n^2. Here we constructed a high-resolution microscope consisting of both a glass-corrected objective lens (N.A.=0.42) and the SIL, and evaluated its resolution using a fluorescence particle with its diameter of 200nm. Obtained resolution was 680nm at 590nm which is center of transmission wavelength of the optical filter (we are planning to detect 556nm of fluorescence from Yb atoms). The chromatic aberration was within 5μm between 399nm and 556nm. Note that we make a deep potential using 399nm laser light at the stage of the fluorescence detection.

Reference
[1] W. S. Bakr, J. I. Gillen, A. Peng, S. Fölling and M. Greiner, *A quantum gas microscope for detecting single atoms in a Hubbard-regime optical lattice*, Nature **462**, pp. 74-78 (2009).

High-resolution optical spectra of bosonic ytterbium atoms in an optical lattice: comparison between numerical calculations and experiments

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We investigate laser spectra of bosonic ^{174}Yb atoms in a three dimensional optical lattice both theoretically and experimentally. With the aid of a ultra-narrow optical transition of the Yb atoms [1], high-resolution spectra are systematically measured by varying the lattice depth. We also perform the following numerical simulations; first, determine parameters of the bosonic Hubbard model with the *ab initio* manner; then, analyze this model based on the Gutzwiller approximation considering finite temperature effects; finally, calculate the excitation spectra described by the Lehman representation. Here we consider modifications of the model parameters due to the formation of two-body bound states induced by confinement of the lattice potential [2]. The numerical simulations clarify how the spectra change depending on both temperatures and lattice depths. By comparing the numerical results with the measured spectra, we discuss phase transitions of the present system at finite temperatures.

References
[1] S. Kato, *et al.*, accepted in Appl. Phys. B: Lasers and Optics (2012).
[2] H. P. Büchler, Phys. Rev. Lett. **104**, pp. 090402 (2010).

Single-particle excitation spectrum and correlation effects in a Bose-Fermi mixture

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Realizations of the Bose-Fermi Hubbard model in an optical lattice have been demonstrated by S. Sugawa, *et al.* [1]. Encouraged by these experiments, we have investigated correlation effects in a mixture of interacting bosons and polarized fermions [2]. We show that novel correlation effects inherent in the mixture system appear in the presence of the boson superfluidity. We demonstrate that the correlation effects form a peak structure in the single-particle excitation spectrum for the fermions in metal, insulator, and supersolid phases. We also address how the effects appear in a mixture of bosons and two-component fermions.

References

[1] S. Sugawa, K. Inaba, S. Taie, R. Yamazaki, M. Yamashita, and Y. Takahashi, *Interaction and filling-induced quantum phases of dual Mott insulators of bosons and fermions*, Nat. Phys. **7**, 642 (2011).
[2] K. Noda, R. Peters, N. Kawakami, and Th. Pruschke, *Many-body effects in a Bose-Fermi mixture* Phys. Rev. A **85**, 043628 (2012).

Towards Russian optical clock with cold strontium atoms, present status and performance

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Neutral strontium is an interesting candidate for the realization of an optical clock using a magic-wavelength optical lattice to store the atoms. I this poster, we will report on our work towards the development of an optical lattice clock using Sr atoms in the VNIIFTRI. As the first step for the realization of proposed optical clock, we have efficiently cooled and trapped atoms in a blue magneto-optical trap (MOT) employing a Zeeman slower. The first stage MOT is operated on the $^1S_0$- $^1P_1$ transition at 461 nm. It was demonstrated, that the number of strontium atoms were substantially increased using the 679 nm and 496 nm repamping diode lasers. The Sr –MOT is operative and the first observation of cold atoms is reported. The experimental set-up with ULE –cavity and error signals are discussed.

Reference

[1] S. Slusarev *et al.*, Proc. of joint Conference of the IEEE International Control Symposium & European Frequency and Time Forum, May 1-5, San Francisco, California, pp. 736-738 (2011).

Lattices of atom microtraps on magnetic-film atom chips

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We discuss the latest progress of our experiments with atomic microclouds on a magnetic-film atom chip [1]. So far we have demonstrated a shift register, atom number squeezing close to quantum degeneracy [2], and spatially resolved, coherent excitation of Rydberg atoms [3]. A recently installed next-generation chip facilitates the continuation of our experiments at trap separations of 10 µm. Also our improved imaging setup is presented. We aim to measure Rydberg-Rydberg Interactions between different microclouds to make quantum gates. Scaling down even further, we propose to aim for mesoscopic ensemble qubits in a 5 µm lattice, and for direct quantum simulators using sub-optical lattices of 100 nm period [4].

References

[1] Whitlock *et al.*, New J. Phys. **11**, 023021 (2009).
[2] Whitlock *et al.*, PRL **104**, 120402 (2010).
[3] Tauschinsky *et al.*, PRL **81**, 063411 (2010).
[4] Leung *et al.*, Quantum Inf. Process. **10**, 955 (2011).

Controlled emission and absorption of single photons by a single ion

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We study emission and absorption of single photons by a single atom as the fundamental processes in quantum information technology. We observe the absorption of single resonant photons from an 854 nm SPDC photon pair source by a single Ca^+ ion, heralded by the detection of the partner photon. Photon absorption induces a quantum jump in the ion in coincidence with the arrival of the partner photon [1]. Moreover, we prepare the ion as a polarization-selective absorber with adjustable basis, and show that the heralded absorption reveals the entanglement of the photon pairs; this is a prerequisite of photon-to-atom entanglement transfer [2]. We also generate resonant single 854 nm photons by controlled emission from a single ion into a single optical mode at ~ 3000 s^{-1} rate. We currently investigate the transmission of these photons and their resonant absorption in a second ion at 1 m distance, enabling distant entanglement between the ions [3].

References

[1] N. Piro *et al.*, “Heralded single-photon absorption by a single atom”, DOI:10.1038/nphys1805.
[2] J. Huwer *et al.*, arXiv: 1111.1085.
[3] S. Ritter *et al.*, arXiv: 1202:5955.

Amelioration of BB84 Quantum transmission protocol based on Blind detection method

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We report on the development of a Quantum Cryptographic Networks for an approach to more secure communications, including a BB84 protocol and Blind detection method. Information is encoded in quantum bits (qubits), intrinsic physical properties, such as polarization of a photon. Quantum physics allows encoding information using the correlation between two or more particles. Quantum Key Distribution (QKD) is one of the innovative methods of information processing that emerged from the properties of «superposition of states» and «entanglement». QKD is used before classical information is transmitted over conventional non-secure communication channels like phone lines and optical fiber networks. Since quantum physics laws state that a single particle like a photon cannot be split or cloned, it certifies the absolute security of communication. In fact, quantum links are combined with fiber counterparts could extend secure communication between points on earth to a global level. Our proposed paper presents a blind detection algorithm for linear mixtures of sources and therefore can be applied to systems of mobile communications. However, in our study it is used for coding and decoding quantum transmissions. The essential aim of our implementation is to present an example of application for single secure optical communication using BB84. We expect future applications of this method in quantum communications such as quantum transmission satellite to each other or satellite to ground station. Our work is a part of approach study and idea to product Quantum Error Correction Algorithm Control in LEO satellite quantum communications that is ongoing under the different Space Agency in the world.

Einstein-Podolsky-Rosen entanglement and quantum steering for a BEC

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We analyse how to generate multi-particle Einstein-Podolsky-Rosen (EPR) entanglement [1] between groups of atoms in a double-well Bose-Einstein condensate. We consider both the statistics of the ground state and that of dynamical evolution, with two internal modes at each well, so that the entanglement can be detected as a reduction in the variances of the sums of local Schwinger EPR spin observables [2]. The local nonlinear S-wave scattering interaction creates a spin squeezing at each well, while the tunneling introduces an interference that results in an inter-well entanglement. The entanglement increases with atom number, and becomes sufficiently strong at higher numbers that the EPR paradox and steering nonlocality [3] can be realised. Our predictions are based on a full quantum solution and, for larger numbers, a truncated Wigner function simulation using a multi-mode model. We explain how the strategy can be extended to generate genuine tripartite entanglement among three wells.

References

[1] A. Einstein, B. Podolsky, and N. Rosen, *Can Quantum-Mechanical description of physical reality be considered complete?*, Phys. Rev. **47**, 777 (1935).
[2] Q. Y. He *et al.*, *Einstein-Podolsky-Rosen Entanglement Strategies in Two-Well Bose-Einstein Condensates*, Phys. Rev. Lett. **106**, 120405 (2011).
[3] D. H. Smith *et al.*, *Conclusive quantum steering with superconducting transition-edge sensors* Nat. Commun. **3**, 625 (2012).

Four-partite cluster states and their application for quantum teleportation

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There are two ways to generating multipartite entangled states: in gaseous and in condensed matter. In the latter, generation of entangled photon states is based on optical parametric down-conversion. Other way of creating the multipartite entanglement is the atom-field one. We study quantum properties of cluster four-partite state for continuous variables. The cluster state under consideration can be generated both in gas [1] and in aperiodical nonlinear photonic crystals [2]. They are described by the identical interaction Hamiltonian. We also study teleportation of two-mode entangled CV state using the cluster state; the teleportation fidelity is computed.

References

[1] X. Liang, X. Hu, C. He "Creating multimode squeezed states and GXZ entangled states using atomic coherence effects" Phys. Rev. A **85,** 032329 (8pp) (2012).
[2] O. V. Belyaeva, A. S. Chirkin "Statistical properties of four-mode quantum states in coupled optical parametric down-conversions" J. Russian Laser Research, **30**, 499-507 (2009).

Heralded noiseless linear amplifier in continuous variable QKD

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Quantum key distribution (QKD) consists of distributing a secret key to two distant parties in an untrusted environment controlled by an adversary. Among QKD protocols, those encoding information in the amplitude and phase of coherent states provide interesting performances and implementation [1]. However, due to losses or noise of the quantum channel, there exist a maximum transmission distance for which the secret key rate drops to zero. In this work [2], we consider the use of a linear noiseless amplifier [3], which has the interesting property of amplifying the signal without amplifying the noise, in order to increase the performances of the QKD. We show that the maximum distance of transmission can be increased using thisdevice, as well as the maximum tolerable noise.

References

[1] F. Grosshans *et al.*, Nature **421**, 238Ð241 (2003).
[2] R. Blandino *et al.*, arXiv:1205.0959 (2012).
[3] F. Ferreyrol *et al.* , Phys. Rev. Lett. **104**, 123603 (2010).

Observation of quantum superposition state without wave function collapse

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We present a paradox that coherence transfer to macroscopic quantum pure state allows amplification of the coherence, and which may violate the no-cloning theorem. It is also shown that the wave function collapse during observation can be explained with decoherence while pure states shift to mixed states through interaction with macroscopic body in mixed states.

Reference

[1] Quantum Measurement, Vladimir B. Braginsky and Farid Ya. Khalili, "Quantum measurement" (Cambridge university press 1992).

Neutral atom qubits in a planar lattice of magic ground-Rydberg traps

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We have loaded single Cs atoms into a planar array of blue detuned optical traps. The array is created using a novel optical beam arrangement that creates an intrinsically 2D array, is phase stable, and suitable for magic trapping of ground and Rydberg states [1]. We demonstrate single qubit gates in the array, and show that Rydberg excited atoms can be trapped. The array forms the basis for experiments with several atomic qubits and Rydberg gates. Work supported by IARPA, ARO, and DARPA.

Reference

[1] S. Zhang, F. Robicheaux, and M. Saffman, *Magic-wavelength optical traps for Rydberg atoms*, Phys. Rev. A **84**, 043408 (2011).

Long-lived ion qubits in a microfabricated surface trap

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A chain of trapped ion qubits together with Coulomb mediated two-qubit gates is a promising way to construct a modest-size quantum register. Quantum logic gates can also be performed between two remote ions using photon-mediated entanglement [1], which leads to the possibility of connecting two remote chains together to form a larger quantum information processor. These two physical mechanisms can be used to realize a quantum computer architecture where multiple ion chains are interconnected through a recon?gurable all-optical network [2].

Silicon microfabrication technology can be used to design and fabricate scalable surface trap structures. Here, we trap a single ytterbium-171 ion in a surface trap made by Sandia National Laboratories [3]. We use an off-resonant picosecond pulsed laser with stabilized repetition rate to drive Raman transitions between the hyperfine qubit states. Ramsey interferometry demonstrates a coherence time of more than 1.5s.

References

[1] P. Maunz et al., Phys. Rev. Lett. **102**, 250502 (2009).
[2] J. Kim and C. Kim, Quant Inf. Comput. **9**, 0181 (2009).
[3] D. T. C. Allcock et al., Applied Physics B 10.1007/s00340-011-4788-5 (2011).

Nonclassicality indicators for entangled number states

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Recently a nonclassicality indicator is introduced which is based on the interference of quantum states in phase space quantum mechanics [1]. It is applied for some real distribution functions. Kenfack and Życzkowski[2] had also defined a non classicality indicator based on the amount of negativity in Wigner function. Here, we applied these nonccassicality indicators for entangled state of two eigenstate of Harmonic oscillator in the Wigner, Husimi and Rivier representations. The maximum of nonclassicality indicator is happen for pseudo bell states and the behavior of nonclassicality indicators are compared with the entanglement of formation.

References

[1] P. Sadeghi, S. Khademi and S. Nasiri; "Nonclassicality Indicator for the Real Phase-space Distribution Functions"; Phys. Rev. A, **82**, pp 012102 (2010).
[2] A. Kenfak and. K. Zyczkowski; "Negativity of the Wigner function as an indicator of nonclassicality"; *J. Opt. B: Quantum Semiclass. Opt.* **6**, pp 396-404 (2004).

Remote entanglement between a single atom and a BEC

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Entanglement between stationary systems at remote locations is a key resource for quantum networks. We report on the experimental generation of remote entanglement between a single atom inside an optical cavity and a Bose-Einstein condensate (BEC) [1]. To produce this, a single photon is created in the atom-cavity system, thereby generating atom-photon entanglement. The photon is transported to the BEC and converted into a collective excitation in the BEC, thus establishing matter-matter entanglement. After a variable delay, this entanglement is converted into photon-photon entanglement. The matter-matter entanglement lifetime of 100 µs exceeds the photon duration by two orders of magnitude. The total fidelity of all concatenated operations is 95 %. This hybrid system opens up promising perspectives in the field of quantum information. The performance of the system is limited by the atom-cavity system. The BEC as a quantum memory is characterized in [2].

References

[1] M. Lettner, M. Mücke, S. Riedl, C. Vo, C. Hahn, S. Baur, J. Bochmann, S. Ritter, S. Dürr, and G. Rempe, *Remote entanglement between a single atom and a Bose-Einstein condensate*, Phys. Rev. Lett. **106**, 210503 (2011).

[2] S. Riedl, M. Lettner, C. Vo, S. Baur, G. Rempe, and S. Dürr, *Bose-Einstein condensate as a quantum memory for a photonic polarization qubit*, Phys. Rev. A **85**, 022318 (2012).

Spatial entanglement in two-electron atomic systems

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Recently, there have been considerable interests to investigate quantum entanglement in two-electron model atoms ([1-3] and references therein). Here we investigate quantum entanglement for the ground and excited states of two-electron atomic systems using correlated wave functions. We study the spatial entanglement of such systems, concentrating on the particle-particle entanglement coming from the continuous spatial degrees of freedom. We use two-electron wave functions constructed by employing *B*-spline basis to calculate the linear entropy of the reduced density matrix $L = 1 - Tr_A(\rho_A^2)$. Here $\rho_A = Tr_B(|\varphi\rangle_{AB\ AB}\langle\varphi|)$ is the one-electron reduced density matrix obtained after tracing the two-electron density matrix over the degrees of freedom of the other electron. For the helium atom (Z = 2), we have calculated the linear entropy for the ground state and the $1sns\ ^1S^e$ (n = 2 – 10) excited states. Results are compared with other calculations in the literature [1-3].

References

[1] J. P. Coe and I. D'Amico, *J. Phys.: Conf. Ser.* **254**, 012010 (2010).
[2] D. Manzano *et. al.*, *J. Phys. A: Math. Theor.* **43**, 275301 (2010).
[3] J. S. Dehesa *et. al.*, *J. Phys. B* **45**, 015504 (2012).
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Nonlinear interferometer and multipartite entanglement using two four wave mixing amplifiers

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Optical interferometer is the basis for precision measurement. We report on an experiment in which we construct a nonlinear interferometer with four wave mixing amplifiers acting as beam splitters to split and recombine an incoming optical field. The interferometer can in principle have 100% visibility. Since amplification is actively involved in the interferometer, the phase sensing field inside the interferometer is amplified from the input field and so is the output field exhibiting the interference fringe. Thus, the sensitivity can be greatly enhanced as compared to the traditional linear interferometer [1, 2]. The quantum correlation between multiple beams is very important for constructing a real quantum network and precision measurement [3]. Thus, we also explored the several possibilities for achieving quantum correlation among multiple beams in such system.

References
[1] B. Yurke, S. L. McCall, and J. R. Klauder, “SU(2) and SU(1,1) interferometers,” Phys. Rev. A33, 4033 (1986).
[2] Jietai Jing, Cunjin Liu, Zhifan Zhou, Z. Y. Ou, and Weiping Zhang, “Realization of a nonlinear interferometer with parametric amplifiers,” Appl. Phys. Lett. 99, 011110 (2011).
[3] P. van Loock and S. L. Braunstein, Phys. Rev. Lett. “Multipartite Entanglement for Continuous Variables: A Quantum Teleportation Network” 84, 3482(2000).

On a systematic degenerate adiabatic perturbation theory

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We present a degenerate adiabatic perturbation theory (DAPT) for quantum systems whose Hamiltoninans possess degenerate eigenvalues [1]. Its goal is to solve the time dependent Schrödinger equation, with the zeroth order being the quantum adiabatic approximation, in terms of a power series expansion built on a small parameter that is related to the inverse of the time it takes to drive the system’s Hamiltonian from its initial to its final form. As an application, DAPT leads to the derivation of rigorous conditions for the validity of the adiabatic theorem of quantum mechanics for degenerate systems [2]. The same formalism can be used to find non-adiabatic corrections to the non-Abelian Wilczek-Zee geometric phase [1]. These corrections are relevant to assess the validity of the practical implementation of the concept of fractional exchange statistics. We illustrate the formalism by exactly solving a time-dependent problem and comparing its solution to the perturbative one and also by studying several problems numerically solved.

References
[1] G. Rigolin and G. Ortiz, *Adiabatic Perturbation Theory and Geometric Phases for Degenerate Systems*, Phys. Rev. Lett. **104**, 170406 (2010).
[2] G. Rigolin and G. Ortiz, *The Adiabatic Theorem for Quantum Systems with Spectral Degeneracy*, eprint arXiv:1111.5333v1 [quant-ph].

Efficient atomic excitation by multi-photon pulses propagating along two spatial modes for quantum information processing

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Efficient coupling between a single atom and light lies at the heart of scalable quantum networks, where the photon as "flying qubit" transfers the information to the "stationary qubit" - the atom. We investigate the dynamics of a single two-level atom, which interacts with pulses propagating in two spatial-modes (odd and even) and frequency-continuum, a setup particularly relevant for applications in integrated quantum optical devices. We discuss the single and multi-photon pulse properties maximizing the atomic excitation. We show that the maximum atomic excitation probability with multi-photon pulses in the even-mode is a monotonic function of the average photon number for coherent state, but not for Fock states. Furthermore, we demonstrate that the atomic dynamics can be controlled by the relative phase between the two counter-propagating coherent state pulses incident on the atom.

Reference

[1] Y. Wang, J. Minář and V. Scarani, "State-dependent atomic excitation by multi-photon pulses propagating along two spatial modes", arXiv:1204.5265 (2012).

Topological protection in photonic systems

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Topological properties of physical systems can lead to natural protection against perturbations. In electronic systems, this robustness is exemplified by quantized conductance and edge state transport in the quantum Hall effects. Here we demonstrate how various quantum spin Hall Hamiltonians can be simulated with linear optical elements using a two dimensional network of coupled optical resonators. Key features of quantum Hall systems, including the characteristic Hofstadter butterfly and robust edge state transport, can be obtained in such systems. We experimentally investigate the implementation of such ideas in silicon-on-insulator technology and their application as an optical delay line. Such systems allow the presence of photonic edge states, which are insensitive to disorder, caused by fabrication errors. Furthermore, the addition of an optical non-linearity to our proposed system leads to the possibility of implementing a fractional quantum Hall state of photons, where phenomenon such as fractional statistics may be observable.

Exploring cavity-mediated long-range interactions in a dilute quantum gas

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We report on the observation of a characteristic change in the excitation spectrum of a Bose-Einstein condensate and increased density fluctuations due to cavity-mediated long-range interactions. Increasing the strength of the interaction leads to a softening of an excitation mode at a finite momentum, preceding a superfluid to supersolid phase transition. The observed behavior is reminiscent of a roton minimum, as predicted for quantum gases with long-range interactions [1]. We create long-range interactions in the BEC using a non-resonant transverse pump beam which induces virtual photon exchange via the vacuum field of an optical cavity. The mode softening is spectroscopically studied across the phase transition using a variant of Bragg spectroscopy. At the phase transition a diverging density response is observed which is linked to increased density fluctuations. Using the openness of the cavity we monitor these fluctuations in-situ and identify the influence of the quantum measurement backaction.

Reference

[1] Mottl *et al.*, arXiv: 1203.1322.

Non-Markovian waiting time distribution

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Simulation methods based on stochastic realizations of state vector evolutions are commonly used tools to solve open quantum system dynamics, both in the Markovian and non-Markovian regime. Here, we address the question of waiting time distribution (WTD) of quantum jumps for non-Markovian systems. We generalize Markovian quantum trajectory methods in the sense of deriving an exact analytical WTD for non-Markovian quantum dynamics and show explicitly how to construct this distribution for certain commonly used quantum optical systems [1].

Reference

[1] K. Luoma, K. Härkönen, S. Maniscalco, K.-A. Suominen and J. Piilo *Non-Markovian waiting time distribution*, to be submitted.

Line shapes in electromagnetically induced transparency for $5S_{1/2}$ –$5P_{3/2}$–$5D_{5/2}$ transitions of ^{87}Rb atoms

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We present an accurate calculation and discrimination of the electromagnetically induced transparency for the $5S_{1/2}$–$5P_{3/2}$–$5D_{5/2}$ transition of ^{87}Rb atoms. Considering all possible transitions, time–dependent density matrix equations were set up for six polarization configurations of the lasers, and solved numerically. The solved density matrix elements were then averaged over the Maxwell-Boltzmann velocity distribution and various transit times. In particular, we could discriminate the contribution of one-photon and two-photon resonance effects in the calculated spectra. We found that the signals for the $5D_{5/2}(F'' = 2,3)$ states were mostly composed of the mixed term, whereas the signal for the $5D_{5/2}(F'' = 4)$ state was originated from both the pure two-photon resonance term and the mixed term [1].

Reference

[1] H. R. Noh and H. S. Moon, *Transmittance signal in real ladder-type atoms*, Phys. Rev. A **85**, 033817 (2012).

Long lived polaritons confined in a tunable Fabry-Perot microcavity

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Semiconductor microcavity polaritons offer new opportunities to study the properties of interacting bosons in the quantum degenerate regime. Here, we present a novel experimental platform to produce trapped polaritons with potentially long lifetimes. Ourcavity is a fiber Fabry–Perot cavity [1] formed between a concave mirror at the tip of a fiber and a planar semiconductor Bragg mirror located below the quantum well. With a single quantum well, we observe strong coupling to the cavity as witnessed by an avoided level crossing as a function of cavity detuning. For multiple quantum wells, the system exhibits signatures of polariton lasing observed through pump-power dependence, blue-shift and linewidth narrowing at threshold. One particular feature of our setup is the possibility to realize high Q values (> 70000). In principle, this should allow for the realization of tightly confined polaritonic Bose-Einstein condensates with a decay time much longer than the polariton thermalization rate.

Reference

[1] D. Hunger, T. Steinmetz, Y. Colombe, C. Deutsch, T. W. Hänsch, and J. Reichel, *A fiber Fabry–Perot cavity with high finesse*, New J. Phys. **12**, p. 065038 (2010).

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

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We report the scalable generation of W-states (Dicke states of first order) encoded in the hyperfine structure of neutral ^{87}Rb-atoms in a high-finesse fiber Fabry-Perot cavity. We prepare an ensemble of atoms in the hyperfine state $|F=1\rangle$ and apply a weak microwave pulse resonant to the transition $|F=1\rangle \rightarrow |F=2\rangle$, which leads to the transfer of a single atom to $|F=2\rangle$ with a probability p=0.2. We then detect if there is an atom in $|F=2\rangle$ by probing the cavity and repeat the sequence if it was not succesful. The use of the cavity allows detection with high fidelity and negligible spontaneous emission [1], thus preventing the destruction of the entangled state. To quantify the entanglement, we havedeveloped a new tomography method that also makes use of the cavity detection and allows to measure the Husimi-Q distribution, from which we reconstruct the density matrix of the prepared state. W-states consisting of 6, 11, 25 and 42 atoms were created with a fidelity of approx. 30%.

Reference
[1] J. Volz, R. Gehr, J. Estève and J. Reichel, *Measurement of the internal state of a single atom without energy exchange*, Nature **475**, pp. 210-213 (2011).

Generating non-classical light using Rydberg interactions

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We study, both theoretically and experimentally, the possibility to use an ensemble of cold Rydberg atoms as a strongly non-linear optical medium which could enable strong photon-photon interactions and the deterministic generation non classical states of light. The quantum state of a light beam can be stored in an ensemble of cold atoms as a polarisation wave involving two long-lived atomic states. If one of these atomic states is a Rydberg state, this polariton will evolve due to long-range atomic interactions. As a result, a coherent pulse of light stored in the atomic medium should turn into a non-classical polaritonic state which could be retrieved as a pulse of non-classical light. We have theoretically shown that the Rydberg gas should act as "quantum scissors" on the stored quantum state, and the retrieved optical pulse should become a coherent superposition of zero and one photons presenting a non-classical, negative Wigner function [1]. We have also found realistic experimental parameters to retrieve this pulse with a high efficiency in a well-defined spatial and temporal mode, which should make the non-classical properties of the state observable in a homodyne measurement [2]. As a first step in this direction, we are experimentally investigating the non-linear optical susceptibility of a Rydberg cloud in a classical regime.

References
[1] J. Stanojevic, V. Parigi, E. Bimbard, A. Ourjoumtsev, P. Pillet, P. Grangier, arXiv:1203.6764v1.
[2] J. Stanojevic, V. Parigi, E. Bimbard, R. Tualle-Brouri, A. Ourjoumtsev, P. Grangier, Phys. Rev. A **84**, 053830 (2011).

Quantum noise for Faraday light-matter interfaces

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In light matter interfaces based on the Faraday effect quite a number of quantum information protocols have been successfully demonstrated. In order to further increase the performance and fidelities achieved in these protocols a deeper understanding of the relevant noise and decoherence processes needs to be gained. In this work [1] we provide for the first time a complete description of the decoherence from spontaneous emission. We derive from first principles the effects of photons being spontaneously emitted into unobserved modes. Our results relate the resulting decay and noise terms in effective equations of motion for collective atomic spins and the forward propagating light modes to the full atomic level structure. We illustrate and apply our results to the case of a quantum memory protocol. Our results can be applied to any Alkali atoms, and the general approach taken in this article can be applied to light matter interfaces and quantum memories based on different mechanisms.

Reference

[1] arXiv:1112.5394v2 (it is about to appear in special issue of Journal of Physics B: Atomic, Molecular & Optical Physics).

Interaction of light-quantized pulse with atomic system

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We explore the interaction between an atom and a quantized pulse in the arbitrary coupling strength regim. Two complementary situations are studied both theoretically and numerically. In the first a propagating one-photon wave packet interacts with an atom located in a one-dimensional waveguide, and in the second situation an atom pass through a single mode detuned micromaser cavity. In the former case we show that the one photon wave packet experienced a temporal reshaping leading its algebraic area to vanish. A Schrödinger approach is used and an interpretation in the spectral domain is given. In the latter case we highlight the importance of non-adiabatic coupling, that depends on the mode shape, and their interplay with the (quantized) atomic motion. We show that the transfer of population can be modulated by varying the atomic velocity. An analogy with a Michelson interferometer is exhibited.

References

[1] J. Gillot and M. A. Bouchene, *Complete population transfer induced by transient nonadiabatic effects in a strongly detuned micromaser*, JOSA B, **28**, pp. 1324-1327 (2011).
[2] S. Derouault and M. A. Bouchene, *Pulse area theorem for one photon wavepacket interacting with a two-level atom in a waveguide*, submitted to Phys. Rev. A (2012).

Strong coupling of single atoms to a whispering-gallery-mode bottle microresonator

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We describe our recent results demonstrating strong coupling between single rubidium atoms and a high-Q whispering-gallery-mode bottle microresonator (Q = 50 million)[1]. We observe clear signals of individual atoms passing through the resonator mode with interaction times of several microseconds. Given this brief interaction time, we have implemented a real-time atom detection/probing scheme to enable experiments on this timescale. We investigate the light transmission and reflection characteristics of the atom-resonator system. Our experimental results show a strong interaction between the atom and the resonator, which is observed by the large change in light transmission through the coupling fibers.

As an application of this system, we describe our progress towards the realization of a four-port device capable of routing photons between two optical nanofibers coupled to the resonator mode. Financial support by the DFG, the Volkswagen Foundation, and the ESF is gratefully acknowledged.

Reference

[1] D. O'Shea, C. Junge, M. Pöllinger, A. Vogler, and A. Rauschenbeutel, *All-optical switching and strong coupling using tunable whispering-gallery-mode microresonators*, Appl. Phys. B, **105**, 1, 129 (2011).

Excitation of a single atom with a temporaly shaped light pulses

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We investigate the interaction between a single ^{87}Rb atom and optical pulses with a controlled temporal envelope [1]. We prepare optical pulses with rising exponential and rectangular temporal profiles and couple them to an atom with high NA lens. We have found that an atom is excited faster by using less photons in a driving pulse with a rising exponential shape. Although a rectangular shape eventually leads to higher excitation probability it takes more photons to excite the atom. We also observe that the atomic transition can be saturated with approximately 100 photons in a pulse. This suggests that one expects to see a nonlinear interaction between atom and light for such low photon number. Indeed, by increasing photon number to ≈ 1000 we observe Rabi oscillations with ≈ 100 MHz. This result show a possibility of optical switching for low photon numbers without cavity assistance.

Reference

[1] Y. Wang et. al., *Efficient excitation of a two level atom by a single photon in a propagating mode*, Phys. Rev. A. **79**, 011402(R) (2011).

Mechanical resonance imaging and optomechanical coupling of atoms in a intracavity trichromatic lattice

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Complex designer potentials for ultracold atoms can be created by combining optical lattices, and have great utility for simulations of condensed matter systems. Here, using optomechanical interactions, we spectrally resolve atoms at individual sites of asuperlattice with site dependent mechanical resonance frequencies. This allows us to make a "mechanical resonance image", mapping the atomic distribution and lattice geometry. Further, the optomechanical coupling creates infinite-range interactions between motion of atoms at spatially disparate sites. This systems acts as a coupled array of quantum mechanical resonators with implementable entanglement and state-transfer operations.

Local fields and renormalization of characteristic frequencies for light emitters in a dielectric

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The macroscopic and microscopic quantum theories are known to give corrections to the rate of spontaneous emission in a dielectric. At the same time, there are only few works that provide Maxwell-Bloch-type equations for embedded particles derived using ab initio techniques. Another problem is that competing theories often give conflicting results while experiments tend to aggravate the confusion. We study how a continuous dielectric medium that fills the space between quantum light emitters may influence their interaction with external laser fields and modify their radiative properties. A generalized master equation is derived for two-level emitters, which form an ensemble of optical centers in a dielectric. The equation contains the effective values of the acting pump field and the radiation relaxation rate of the optical center. The formalism represents a fully microscopic approach and is based on a BBGKY hierarchy for reduced density matrices and correlation operators of material particles and field modes. The method allows one to avoid phenomenological procedures when taking into account the effects of individual and collective behavior of the emitters associated with the presence of intermediate environment. The analytical expressions for the excitation lifetime of an optical center are shown to be in agreement with several experiments. The similarities and differences with the other existing theories are discussed.

Dynamics of atom-atom correlations in the Fermi model

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In this work we study the dynamics of several types of atom-atom correlations in the famous two-atom Fermi problem [1]. Although any causality issue regarding quantum mechanical probabilities in such a model was recently solved in [2], the influence of micro-causality on correlations behavior is still an open subject of investigaition.

References
[1] E. Fermi, Rev. Mod. Phys. **4**, 87 (1932).
[2] C. Sabín, M. del Rey, J. J. García-Ripoll, and J. León, Phys. Rev. Lett **107**, 150402 (2011).

Tu-140 Quantum optics…

Coupling color centers in diamond to fiber-based Fabry-Pérot microcavities

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Optical fibers with machined and coated end facets can serve as high reflectivity mirrors to build low loss optical resonators with free space access [1, 2]. These microcavities feature a very small mode volume on the order of a few tens of cubic wavelengths and a very large Finesse of up to 105, corresponding to quality factors of several millions. Thus, the Purcell factor being proportional to the ratio of quality factor and mode volume can be as high as 104, which can dramatically increase the emission rate of an emitter inside the cavity.

We use the microcavities to couple solid state based emitters such as color centers in diamond to the cavity. First results from spectra of ensembles of nitrogen-vacancy centers coupled to the cavity show a strongly increased emission efficiency into the cavity mode. The emission behavior can be modeled with a modified Purcell factor accounting for the dephasing.

References
[1] D. Hunger, New Journal of Physics **12**, 065038 (2010).
[2] D. Hunger, AIP Advances **2**, 012119 (2012).

Size effects on thermal radiation of a dielectric microparticle

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Although Planck's law of blackbody radiation well describes spectral profiles of thermal radiation from macroscopic objects, it remains an open question if Planck's formula applies to particles of size comparable to optical wavelengths. We experimentally demonstrate that thermal radiation from a micron-sized dielectric particle depends sensitively on its morphology and optical properties. Our laser trapping technique levitates a high-temperature microsphere of aluminum oxide and enables emission spectroscopy of the single particle [1]. As the particle becomes smaller, a blackbody-like spectrum turns into a spectrum dominated by multiple peaks resonant with whispering gallery modes of the spherical resonator. Analysis of the particle size dependence of the emission power reveals that the emissivity of a microparticle strongly depends on the extinction coefficient and the liquid-solid phase transition occurred in the optical trap.

Reference

[1] H. Odashima, M. Tachikawa, and K. Takehiro, "Mode-selective thermal radiation from a microparticle", Phys. Rev. A **80**, 041806(R) (2009).

Coherently pumped cavity-QED microlaser

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The cavity-QED micromaser/laser is the maser/laser system based on coherent interaction between a small number of two-level atoms and a high finesse cavity field. So far incoherently pumped micromaser/lasers have been experimentally realized and studied. For the micromaser/laser coherently pumped by injecting atoms in a coherent superposition state, there are many interesting predictions such as symmetry breaking in the cavity field and generation of a mesoscopic cat state yet to be confirmed. Here, we present our experimental progress toward realization of the coherently pumped microlaser. In our experiment both atomic position control and superposition state pumping are made possible by employing an atomic beam aperture with an array of nanoholes with a period matching the resonance wavelength(791 nm of barium $^1S_0$-$^3P_1$ transition). The cavity mirrors are specially shaped so that the nanohole aperture can be brought to the cavity mode within 300 μm for preventing atomic position spread. Preliminary data on coherent pumping will be presented and discussed.

Reference

[1] Krause, J. and Scully, M. O. and Walther, H "Quantum theory of the micromaser-Symmetry breaking via off-diagonal atomic injection", Phys, Rev. A **34**, 2032-2037 (1986).

Quantum correlated pulses from a synchronously pumped optical parametric oscillator

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Optical frequency comb with non-classical properties can be produced via parametric down-conversion of a pumping comb in a degenerate synchronously pumped optical parametric oscillator. In the time domain we developed a quantum theory of the oscillator that describes its operation both below and above oscillation threshold and gives clear insight into the character of quantum properties of an output signal comb being a train of pulses. Now we are thinking about application of a frequency comb and its non-classical counterpart for ultra-precise position sensing, particularly, in gravitational wave detectors. Here the fundamental limit on an accuracy of position determination (standard quantum limit) appears as interplay between time-arrival uncertainty of pulses and light back-action on a mechanical sub-system.

Direct observation of coherent backscattering of ultracold atoms

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Phase coherence has dramatic effects on the transport properties of waves in random media. Interferences between certain scattering events may act against diffusion, and eventually lead to a complete halt of the wave (Anderson localization). In momentum space, such interference effects manifest themselves as the well-known coherent back scattering (CBS) peak, i.e. an enhanced scattering in the backward direction. A remarkable tool to probe phase coherence in mesoscopic systems, CBS has been widely studiedwith various kinds of waves, from light to electronic waves [1]. Here we report the direct observation of CBS of ultracold atoms in presence of disorder. Following the landmark experiments that have demonstrated Anderson localization, it constitutes a smoking gun of phase coherence in ultracold disordered gases. This opens new prospects to investigate phase coherence properties, and especially the emergence of Anderson transition in 3D.

Reference

[1] E. Akkermans and G. Montambaux, *Mesoscopic Physics of Electrons and Photons*, Cambridge University Press, London, 2007).

Towards single-atom-resolved detection and manipulation of strongly correlated fermions in an optical lattice

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Motivated by the recent achievement of single-site-resolved imaging and manipulation of strongly correlated bosonic systems in an optical lattice, we illustrate our progress and future plans in our attempts to realize a fermionic quantum simulator. Detecting and manipulating strongly correlated fermionic systems at the level of a single atom will further exploit the potential of ultracold atoms as a quantum simulator for, e.g., the Fermi-Hubbard model, which is a key model in condensed matter physics.

Atoms from a two-stage magneto-optical trap of ^{87}Rb and ^{40}K are loaded into a magnetic trap, before evaporative cooling and transport in an optical trap delivers a quantum degenerate gas to a 3-dimensional optical lattice. By selective removal of atoms from all lattice planes but the one at the focal plane of a NA = 0.68 microscope objective, we will resolve the distribution and evolution of atoms across individual sites of the 2D lattice using fluorescence imaging. We plan to use this novel detection method to characterize, e.g., temperature, spin-structure, or entropy distribution of quantum phases such as fermionic Mott insulators, Band insulators, metallic phases or Néel antiferromagnets. Single-site manipulation will be possible by means of an addressing beam focused by the imaging microscope, which will allow us to investigate the effect of local perturbations on the system.

Quantum simulators… Tu-146

Collective oscillation of a Spin-Orbit coupled Bose-Einstein condensate

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We experimentally produce a Spin-Orbit coupled Bose-Einstein condensate with the technique of Raman coupling and systematically study the dynamical properties of such a condensate. We present an experimental study of the collective dipole oscillation of a spin-orbit (SO) coupled Bose-Einstein condensate in a harmonic trap. A number of interesting properties is observed. The frequency of the center-of-mass dipole oscillation deviatesfrom the harmonic trap frequency and depends on the oscillation amplitude, as a manifestation of the change of single-particle dispersion. A magnetization oscillation induced by the dipole oscillation is also observed, revealing the coupling of the spin to the momentum of an atom and the absence of Galilean invariance of this system. These experimental results are then compared to theoretical calculations based on variational wave function approximation.

Reference

[1] Shuai Chen et.al., *Revealing Unconventional Properties of a Spin-Orbit Coupled Bose-Einstein Condensate from Collective Dipole Oscillation*, arXiv: 1201.6018.

Simulation of electric dipole moment of neutral relativistic particles

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The electric dipole moments of various neutral elementary particles, such as neutron, neutrinos, certain hypothetical dark matter particles and others, are predicted to exist by the standard model of high energy physics and various extensions of it. However, the predicted values are beyond the present experimental capabilities. We propose to simulate and emulate the electric dipole moment of neutral relativistic particles and the ensuing effects in the presence of electrostatic field by simulation of an extended Dirac equation in ion traps.

Strongly correlated bosons on frustrated optical lattices

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Artificial gauge fields open the route to the realization of unconventional bosonic phases in optical lattices, including condensate phases in which the bosons create an array of persistent currents whose "handedness" (chirality) corresponds to an emergent, discrete degree of freedom; and novel bosonic insulators, which are the particle analog of exotic spin liquid phases for quantum spins, among others. Here we will present a variety of theoretical results concerning strongly interacting bosons on a frustrated lattice, as recently realized in a seminal experiment [1]. We will address the separation between the onset of condensation and of chiral order (detected in time-of-flight measurements by the unequal height of the diffraction peaks), and the possibility of measuring it for the first time in experiments on frustrated triangular and square lattices; moreover we will illustrate the possibility of observing spin liquid phases for the same lattice geometries in the limit of half filling.

Reference

[1] J. Struck *et al.*, Science **333**, 996 (2011).

Observation of phonon hopping in radial vibrational modes of trapped ions

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Trapped and laser cooled ions are the promising candidates for realizations of quantum information processors and simulators. Recently, many experiments related to quantum simulation with trapped ions are reported and quantum phase transition of Ising spin model are observed.

Our goal is to simulate Bose-Hubbard model (BHM) by using ions. The radial vibrational phonons act as bosons in BHM and the coulomb coupling between ions induces phonon hopping [1]. Here we report observation of phonon hopping dynamics of two trapped $^{40}Ca^{+}$ and the measured hopping rate is a few kHz [2]. Moreover, we succeeded in controlling the hopping rates by changing the inter-ion distance and this work is the essential step for physical implementation of BHM simulator with trapped ions.

References

[1] D. Porras and J. I. Cirac, Phys. Rev. Lett. **93**, 263602 (2004).
[2] S. Haze, Y. Tateishi, A. Noguchi, K. Toyoda, and S. Urabe, Phys. Rev. A, **85**, 031401(R) (2012).

Relativistic and multipole effects on the polarization of Lyman line emission following radiative recombination of bare ions

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We calculated the polarization degree of the Ly-α_1 and Ly-β_1 lines emitted by highly charged H-like ions after radiative recombination (RR) of bare nuclei with unidirectional electrons. These calculations were performed for several ions with atomic numbers $10 \leq Z \leq 92$ and various incident electron kinetic energies from 0.01 to 10 times the 1*s* ionization potential, and have included RR into states with principal quantum number up to n=6 followed by cascades. Three sets of the RR cross sections to magnetic sublevels were computed: the first two in the electric-dipole approximation with the non-relativistic and relativistic electron wavefunctions and the third in the exact relativistic method including all multipoles of the radiation field [1]. The results of our polarization calculations using these three sets of cross-section data were compared with each other in order to reveal the importance of the relativistic and multipole effects as Z and the electron energy increase.

Reference

[1] L. Bettadj, M. K. Inal, A. Surzhykov and S. Fritzsche, ‘‘Effects of the radiative recombination on the intensity and polarization of the Ly-a emission of hydrogen-like ions’’, Nucl. Instr. Meth. B **268**, pp. 3509-3516 (2010).

Inelastic collisions of Al and Sb atoms with helium in homogeneous magnetic fields

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We present an experimental and theoretical study of Al and Sb colliding with helium at 800 mK. Zeeman relaxation in atom–He collisions can serve as a probe of their interaction potentials. We observe Zeeman relaxation by measuring dynamics of the magnetic sublevel distribution in different Zeeman states in homogeneous magnetic fields. Both Al and Sb show rather rapid relaxation; however, the relaxation mechanisms are different. In the case of Al, the anisotropic $^2P_{3/2}$ excited state is mixed with the isotropic $^2P_{1/2}$ ground state during a collision to cause relaxation. We investigate both m_J- and J-changing collisions as a function of magnetic field to further confirm the theoretical model previously developed for In and Ga. In the case of Sb, spin-orbit coupling mixes $L \neq 0$ states into the ground state($^4S_{3/2}$), and hence introduces electronic anisotropy into its interaction with He. This work constrains the Sb-He potentials and extends our understanding of cold collisions in pnictogens.

Dielectronic Recombination rates for Ar^{6+} and Kr^{24+}

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In thermal plasma, the ion- atom collisions proceed most probably though resonance processes. One of the important processes is resonate transfer excitation (RTE) followed by emission X-ray (RTEX). It causes a self cooling for plasma. In addition, it is identical to the dielectronic recombination (DR) in electron-ion collisions. The present wok deals with the calculation of DR rate coefficients (α^{DR}′s) and DR cross sections (σ^{DR}′s) as well as RTEX cross sections (σ^{RTEX}′s) for Mg-like ions [Ar^{6+} and K^{24+}] with L- shell and K-shell excitation for $\Delta n = 0$ and $\Delta n \neq 0$. Specifically, RTEX cross sections are calculated for the collusion of Ar^{6+} and Kr^{24+} ions with He and H_2 targets. The calculations are carried out using the adapted angular momentum average (AMA) scheme in the isolated resonance approximation (IRA). The results are compared with other results [1] for the same ions.

Reference

[1] Takeshi Kai, Rajesh Srivastave, and Shinobu Nakazaki, Phys. Rev. **A 70**, pp. 062705 (2004).

Macroscopic quantum self-trapping in dynamical tunnelling

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It is well-known that increasing the nonlinearity due to repulsive atomic interactions in a double-well Bose-Einstein condensate suppresses quantum tunnelling between the two sites. Here we find analogous behaviour in the dynamical tunnelling of a Bose-Einstein condensate between period-one resonances in a single driven potential well.

For small nonlinearities we find unhindered tunnelling between the resonances, but with an increasing period as compared to the non-interacting system. For nonlinearities above a critical value we generally observe that the tunnelling shuts down. However,for certain regimes of modulation parameters we find that dynamical tunnelling re-emerges for large enough nonlinearities, an effect not present in spatial double-well tunnelling. We develop a two-mode model in good agreement with full numerical simulations over a wide range of parameters, which allows the suppression of tunnelling to be attributed to macroscopic quantum self-trapping.

Reference

[1] S. Wüster, B. J. Dąbrowska and M. J. Davis, *Macroscopic Quantum Self-Trapping in Dynamical Tunnelling*, http://arxiv.org/abs/1112.2086.

Long-range Rydberg-Rydberg interactions in two-electron atoms

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We present perturbative calculations of dipole-dipole and quadrupole-quadrupole long-range interactions between calcium, strontium and ytterbium Rydberg atoms based on the Coulomb approximation and degenerate perturbation theory. Expressions are given forthe leading order dispersion coefficients, C_5 (first-order quadrupole-quadrupole) and C_6 (second-order dipole-dipole), in terms of radial matrix elements and angular factors [1,2].

The Coulomb approximation enables the use of analytic expressions for the radial matrix elements [3] requiring only the orbital angular momentum and binding energies of the electronic states. The latter are obtained by extrapolation from quantum defect fits to experimental data.

Examination of the results reveals large variations between the different series. Two Förster resonances are found in the range examined, both in triplet states of strontium. Particular attention is paid to the isotropic S states of strontium and ytterbium, where attractive interactions are found for strontium and comparatively weak repulsive interactions in ytterbium.

References

[1] Vaillant C. L., Jones M. P. A. and Potvliege R. M. 2012, arXiv:1203.3736.
[2] Singer K., Stanojevic J., Weidemüller M. and Côté R. 2005 *J. Phys.* B **38** S295.
[3] Oumarou B., Picart J., Tran Minh N. and Chapelle J. 1988 *Phys. Rev.* A **37**, 1885.

Towards photon blockade using Rydberg superatoms

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Rydberg blockade limits the number of excitations in an atomic ensemble to one, creating a powerful platform for quantum information processing using neutral atoms [1]. It is possible to map the Rydberg blockade process into a photon blockade, producing a large optical non-linearity [2]. In our experiments we aim to isolate a single blockaded ensemble, or superatom, and exploit the photon blockade process to produce non-classical states of light. We tightly confine an ultra-cold cloud of rubidium atoms in a strongly focused dipole trap. Electromagnetically induced transparency is used to map the non-linear response of the medium onto the probe laser field.

In recent experiments we have focused on the writing and reading of Rydberg polaritons in the ensemble providing information on the dephasing of the superatom.

References

[1] M. D. Lukin *et al.*, *Dipole Blockade and Quantum Information Processing in Mesoscopic Atomic Ensembles*, Phys. Rev. Lett. **87**, 037901 (2001).
[2] J. D. Pritchard *et al.*, *Cooperative Atom-Light Interaction in a Blockaded Rydberg Ensemble*, Phys. Rev. Lett. **105**, 193603 (2010).

Non-gaussian distribution of photoassociated cold atom

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The momentum distribution of cold atom with photoassociation was studied using laser -cooled and trapped ^{85}Rb. Due to the energy conservation, a pair of atoms can only be associated, if its internal kinetic energy is equal to the detuning of the excitation laser. In our photoassociation trap loss experiment, the atoms with a certain velocity was “kicked” out of trap by controlling the laser frequency. The momentum distribution was then manipulated and observed using time-of-flight. A non-gaussianvelocity distribution was resulted.

High resolution spectroscopy of interacting Rydberg gases

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The giant size and large polarizibility of Rydberg-atoms, resulting in strong long-range Rydberg-Rydberg interactions, make them ideal to study many-body effects in ultracold atomic gases. We use an interferometric technique based on an optical Ramsey sequence to study such resonances in the $44d_{5/2}$ Rydberg state of ultracold ^{87}Rb atoms. With this phase sensitive method we show that we can switch and tune the inter-atomic interaction [1]. Extending the scheme using different electric pulse sequences we can additionally probe the coherent coupling of the involved pair states [2]. The coherent nature of the Förster induced interaction is crucial for many of its applications. Furthermore the system presented here could be used to model Förster induced energy transfer processes which play an important role in biophysics.

References
[1] J. Nipper, J. B. Balewski, A. T. Krupp, B. Butscher, R. Löw, and T. Pfau, "Highly Resolved Measurements of Stark-Tuned Förster Resonances between Rydberg Atoms", Phys. Rev. Lett. **108** 113001 (2012).
[2] J. Nipper, J. B. Balewski, A. T. Krupp, S. Hofferberth, R. Löw, T. Pfau, "Förster interaction induced phase shift in a pair state interferometer", accepted in Phys. Rev. X, arXiv:1203.1851.

Intensity correlations in electromagnetically induced absorption

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Recently, the intensity-intensity correlations between probe and coupling lasers in electromagnetically induced transparency (EIT) have been reported [1, 2]. However, we first observed intensity correlations between the coupling and probe lasers interacted with Rb atoms under condition of electromagnetically induced absorption (EIA). The intensity correlations between two counter-circular polarized coupling and probe laser in the Hanle configuration were investigated as a function of the applied magnetic field. When the condition of EIA medium was changed from on-resonance to off-resonance as a function of the magnetic field strength, the second order correlation function $G^{(2)}(0)$ was transformed from 0.3 (correlation) to −0.9 (anti-correlation). Also, $G^{(2)}(0)$ of EIA medium was measured as functions of the incident laser power and the temperature of the Rb atomic vapor cell. We could illuminate the intensity correlation and anti-correlations of EIA using the N-type four-level atomic model.

References
[1] V. A. Sautenkov, Y. V. Rostovtsev, and M. O. Scully, "Switching between photon-photon correlations and Raman anticorrelations in a coherently prepared Rb vapor", Phys. Rev. A **72**, 065801 (2005).
[2] G. O. Ariunbold, Y. V. Rostovtsev, V. A. Sautenkov, and M. O. Scully " Intensity correlation and anti-correlations in coherently driven atom vapor," J. Mod. Opt. **57**, 1417-1427 (2010).

Avalanche ionization dynamics of a strongly blockaded Rydberg gas

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The production of strongly coupled plasmas, where the Coulomb interaction between neighbouring particles dominates their kinetic energy, would allow for better understanding of dense astrophysical plasmas and for preparing bright, correlated ion and electron sources [1]. The strongly coupled regime is however hardly reached so far by ionising ultra-cold atomic or molecular gases, due in part to a fast re-equilibration of the ion spatial distribution. This phenomenon, called disorder-inducedheating, could be prevented by starting from a pre-organised sample [2]. To do so, we release a dense ^{87}Rb cloud from an optical dipole trap, and continuously couple the atoms to the $|55S\rangle$ Rydberg state. Using combined opticaland ion detection, we observe a sudden ionisation avalanche, triggered despite repulsive Rydberg interactions. Prior to its onset, we observe that strong spatial correlations have already built up between Rydberg atoms, which should be preserved in the avalanche to form a strongly correlated plasma.

References
[1] T. C. Killian, T. Pattard, T. Pohl, and J. M. Rost, *Ultracold Neutral Plasmas*, Phys. Rep. **449**, pp. 77-130 (2007).
[2] M. S. Murillo, *Using Fermi Statistics to Create Strongly Coupled Ion Plasmas in Atom Traps*, Phys. Rev. Lett. **87**, pp. 115003 (2001).

Impact of collisions with neutral Hydrogen on spectral lines' polarization of a multilevel atomic model

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In order to interpret the spectrum of the linear polarization which is produced by scattering processes observed close to the solar limb, we need to evaluate the impact of collisions with neutral Hydrogen atoms on polarization's signals of some neutral and ionized atoms.

We present preliminary results concerning the calculation of emergent fractional linear polarization amplitudes produced by scattering processes by radiation field, these calculations involve collisional rate calculations.

Vortices in the final-state continuum of a positron-atom ionization collision

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We employ a continuum distorted wave (CDW) approximation with the correct kinematics to calculate the probability flux of the final-state continuum in the ionization of atoms by positron impact. Different structures are unveiled and investigated, among them a vortex, akin to a deep minimum recently uncovered in the triple differential cross section for electron-atom ionization collision [1]. We also explore how this structure develops in the multidimensional continuum of the impinging positron, the emitted electron and the recoiling ion. Finally, we discuss this finding in the framework of Madelung's hydrodinamical and de Broglie - Bohm formulations of Quantum Mechanics.

Reference

[1] J. H. Macek, J. B. Sternberg, S. Y. Ovchinnikov and J. S. Briggs, "Theory of Deep Minima in (e,2e) Measurements of Triply Differential Cross Sections", Phys. Rev. Lett. **104**, 033201 (2010).

Feshbach resonances in cesium at ultra-low static magnetic fields

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We have observed Feshbach resonances for ^{133}Cs atoms in two different hyperfine states at ultra–low static magnetic fields by using an atomic fountain clock. The extreme sensitivity of our setup allows for high signal–to–noise–ratio observations at densities of only 2×10^7 cm^{-3}. We have reproduced these resonances using coupled–channels calculations which are in excellent agreement with our measurements. We justify that these are *S*–wave resonances involving weakly–bound states of the triplet molecular Hamiltonian, identify the resonant closed channels, and explain the observed multi–peak structure. We also describe a model which precisely accounts for the collisional processes in the fountain and which explains the asymmetric shape of the observed Feshbach resonances in the regime where the kinetic energy dominates over the coupling strength.

Reference

[1] D. J. Papoular, S. Bize, A. Clairon, H. Marion, S. J. Kokkelmans, and G. V. Shlyapnikov, *Feshbach Resonances in Cesium at Ultra–Low Static Magnetic Fields*, arXiv:1205.2553.

Studying two-photon cooperative absorption on cold atoms

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The phenomenon of two-photon cooperative absorption is common in solid-state physics [1]. In a sample of trapped cold atoms, that effect may open up new possibilities for the study of nonlinear effects. In this work, we demonstrate the occurrence of a two-photon cooperative absorption in a pair of colliding cold Na atoms kept in a magneto-optical trap. In our experiment, we start with two colliding Na atoms in the S hyperfine ground state. The pair absorbs two photons, resulting in: a $P_{1/2}$ and a $P_{3/2}$ atom. The result of this excitation is observed by ionization using an external light source. A model that considers only dipole-dipole interactions between the atoms allows us to understand the basic features observed in the experimental results. Both the pair of generated atoms and the photons originating from their decay are correlated and may have interesting applications that remain to be explored.

Reference

[1] J. R. Rios Leite *et al.*, Chem. Phys. Lett. 73, 71 (1980).

Ultracold polar molecule collisions in quasi-1D geometries

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We study collisions of polar molecules confined in quasi-1D optical lattices. Molecules are treated as fixed dipoles and the short-range dynamics is modeled by the complex boundary condition introduced in [1]. We solve the scattering equations using a spectral element discretization approach that ideally exploits the sparse nature of the potential coupling matrix and guarantees high accuracy. Elastic, inelastic, and reactive rates are calculated as a function of the applied electric field and collision energy. When the field is perpendicular to the trap axial direction, depending on the experimental parameters the reaction rates can be strongly suppressed, stabilizing the gas versus reactive processes. The difference between bosonic and fermionic symmetry cases is discussed. The numerical results are interpreted on the basis of simple energy barrier considerations and of reduced adiabatic models.

Reference

[1] Z. Idziaszek and P. S. Julienne, *Universal Rate Constants for Reactive Collisions of Ultracold Molecules*, Phys. Rev. Lett. **104**, 113202-1-4 (2010).

Geometric phase in electron exchange excitation of a single atom

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A geometrical (Berry) phase of 180^o has been observed in the electron spin exchange excitation of zinc atoms from the ground $(3d^{10}4s^2)^1S_0$ state (M_S=0) to the $(3d^{10}4s5s)^3S_1$ (M_S=0) state. The Stokes parameter P_2 (aligned linear polarization) of the light emitted in the optical 468.1, 472.3, and 481.1 nm decays to the $(3d^{10}4s4p)^3P_{0,1,2}$ states reveals an aligned angular momentum. The excitation from a ^1S to a ^3S state was expected to be a pure exchange process but the Fermi statistics and Pauli exclusion principle establish the phase change of 180^o. The Pauli sign is a geometric phase factor of topological origin such that the electron spin is "parallel transported" around a closed path and acquires a fixed phase which is not changed by the kinematics of the excitation exchange process.

Reference

[1] J. F. Williams, L. Pravica, and S. N. Samarin, "Topological angular momentum in electron exchange excitation of a single atom." Phys Rev A 85 022701 (1012).

Controlling chemical reactions of a single particle

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The full control over all quantum mechanical degrees of freedom in binary collisions allows for the identification of fundamental interaction processes and for steering chemical reactions. Focussing on the best-controlled experimental conditions, such as using state-selected single particles and low temperatures, is crucial for the investigation of chemical processes at the most elementary level.

The hybrid system of trapped atoms and ions offers key advantages in this undertaking: ion traps have a large potential well depth in order to trap the reaction products, while the absence of a Coulomb-barrier allows the particles to collide at short internuclear distance.

Here, we report on the experimental tuning of the exchange reaction rates of a single trapped ion with ultracold neutral atoms by exerting control over both their quantum states. We observe the influence of the hyperfine state on chemical reaction rates and branching ratios and monitor the kinematics of the reaction products. These investigations advance chemistry with single trapped particles towards achieving quantum-limited control of chemical reactions and pave the way to the study of the coherence properties of a single trapped ion in an ultracold buffer gas.

Elastic scattering of positronium using the confined variational method

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We demonstrate that the phase shift in elastic S-wave positronium (Ps)-atom scattering can be precisely determined by the confined variational method, in spite of the fact that the Hamiltonian includes an unphysical confining potential acting on the center-of-mass of the positron and one of the atomic electrons. The calculated phase shifts are precise mainly because the unphysical effect of the potential can be eliminated by adjusting the confining potential. Using the stochastic variational method, explicitly correlated Guassian-type basis functions are optimized and the energies of confined Ps-atom systems are determined. Then the discrete energies are taken as a reference for tuning auxiliary one-dimensional potentials. The phase shifts calculated for the one-dimensional potential scattering are the same as the phase shifts of the Ps-atom scattering. For the Ps-hydrogen scattering, the present calculations are in very good agreement with the Kohn variational calculations. Therefore, the 2% ~ 4% discrepancy between the Kohn variational and R-matrix calculations is resolved. For Ps-helium scattering, our calculations achieve a higher precision than reported in any previous publication.

A high-flux polar molecular radical source for the ThO eEDM experiment

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A bright, stable beam of cold thorium monoxide is an essential component of an ongoing experiment to measure the electron's electric dipole moment [1]. The source presents interesting technical challenges since ThO is reactive, while its production precursors, thorium metal and thorium dioxide, are highly refractory. We have realized a ThO source that produces 10^{13} molecules sr^{-1} s^{-1} in a single ro-vibrational level [2]. A ThO_2 ceramic in a cryogenic buffergas cell is laser ablated to produce pulses of gas-phase ThO, which is cooled by the buffer gas before exiting the cell in a beam. We are also developing a continuous source of ThO via a high-temperature reaction between Th and ThO_2 that promises increased peak and time-averaged yields. We discuss ongoing work and recent results.

References

[1] A. C. Vutha *et al.*, *Search for the electric dipole moment of the electron with thorium monoxide*, J. Phys. B **43**, p. 074007 (2010).
[2] N. R. Hutzler *et al.*, *A cryogenic beam of refractory, chemically reactive molecules with expansion cooling*, Phys. Chem. Chem. Phys. **13**, pp. 18976-18985 (2011).

Towards a quantum gas of polar YbCs molecules

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The potentials of ultracold polar molecules have been discussed with respect to quantum information processing and quantum simulation [1]. This experiment focuses on the production of quantum degenerate YbCs molecules. We propose to magneto-associate the atoms over a Feshbach resonance [2] and transfer them to the ground state using Stimulated Raman Adiabatic Passage (STIRAP) [3]. Ground state YbCs will, due to its singe valence electron, exhibit an electric as well as a magnetic dipole moment. It should therefore exhibit spin dependent interactions in addition to long-range dipole-dipole interactions [1]. Here we outline the theoretical and experimental progress on creating a dual species Magneto-Optical Trap (MOT) of Yb and Cs.

References

[1] A. Micheli, G. K. Brennen and P. Zoller, "A toolbox for lattice-spin models with polar molecules", Nature Physics **2**, pp. 341-347 (2006).
[2] T. Köhler, K. Goral, P. S. Julienne, "Production of cold molecules via magnetically tunable Feshbach resonances", Rev. Mod. Phys. **78**, pp. 1311-1361 (2006).
[3] K. Bergmann, H. Theuer and B. W. Shore, "Coherent population transfer among quantum states of atoms and molecules", Rev. Mod. Phys. **70**, pp. 1003-1025 (1998).

Making a magneto-optical trap for polar molecules

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The development of laser cooling and trapping for a diverse set of atomic species revolutionized atomic and quantum physics. Expanding the techniques of laser cooling and trapping to molecules would provide new systems with complex, rich interactions. Theadditional structure that arises from the rotational and vibrational degrees of freedom in diatomic molecules makes difficult the adaptation of a traditional atomic magneto-optical trap (MOT) for use with molecules, but it is a challenge that we can overcome. In order to maintain a closed rotational manifold for the optical cycling transition, one typically excites from an $N'' \rightarrow N' = N'' - 1$ rotational sublevel. This excitation scheme corresponds to a type II MOT [1]. We will present the latest results on the development of a MOT for laser cooled yttrium monoxide molecules based on a resonant LC-baseball coil geometry for a time-varying magnetic quadrupole field.

Reference

[1] A. M. L. Oien, *et. al*, Phys. Rev. A **55**, pp. 4621-4624, (1997).

Toward laser cooling of photoassociated KRb molecules

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Recently, laser cooling of molecular beam was realized for SrF molecule by a group in Yale university[1]. The key issue for the laser cooling of molecules was to form an almost closed cycling transition by using a transition with diagonal Franck-Condon factors. Laser cooling technique of molecules could be a breakthrough for many experiments of ultracold molecules.

In our experiment, we are making ultracold KRb molecules by an indirect method, where K and Rb atoms are cooled by MOT and weekly bound molecules are formed with photoassociation from these atoms, and then the molecules are transferred into the rovibrational ground state ($X^1\Sigma^+$, v=0, N=0) by STIRAP[2]. From ab-initio calculations of molecular potentials, we found that $X^1\Sigma^+$-$b^3\Pi_0$ transition may have a narrow natural linewidth and diagonal Franck-Condon factors. Recently, we have succeeded in observing this transition. And we have experimentally determined its natural linewidth and Franck-Condon factors for (v-v′)=(0-0), (1-0) and (2-0) transitions, which are (2π) x 4.9(4) kHz, 0.948(2), 0.051(2) and 0.0013(1), respectively. Since the temperature of photoassociated molecules is as low as 135 uK, we expect that three-dimensional laser cooling of photoassociated molecules can be realized by using this transition.

References

[1] E. S. Shuman *et al.*, Nature **467**, 820 (2010).
[2] K. Aikawa *et al.*, PRL **105**, 203001 (2010).

Systematic analysis of long-range interactions between polar bialkali molecules

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The determination of the long-range anisotropic interaction between polar bialkali molecules is of crucial importance for the achievement of a quantum gas of ultracold polar molecules. In particular, the coefficient C_6 of the multipolar interaction depends on the dynamic polarisability of the molecule evaluated at imaginary frequencies, expressed as a sum over all possible radiative transitions of electronic dipole moments. Using a mixture of up-to-date spectroscopic data and accurate ab initio data for potential energy curves, and permanent and transition dipole moments, we have obtained the values of the coefficients between identical polar molecules (LiNa, LiK, LiRb, LiCs, NaK, NaRb, NaCs, KRb, KCs, RbCs) in an arbitrary vibrational level of their electronic ground state. For the lowest vibrational levels the C_6 parameter varies from about 10^3 atomic units for LiNa up to 10^7 atomic units for NaCs, which will lead to different collisional regimes at ultracold temperatures.

Enhancing photoassociation rates by non-resonant light control of a shape resonance

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We suggest to employ non-resonant field control of shape resonances to enhance photoassociation rates in trapped ultracold gases. Non-resonant light with intensities of the order of 10^9 W/cm^2 modifies the thermal cloud of atoms, i.e., the initial state for photoassociation. By using non resonant laser fields the energy of a shape resonance is adiabatically moved close to k_B times the trap temperature, thus enhancing its thermal weight [1]. The quasi-bound nature of the resonance wavefunction results in larger free-to-bound transition matrix elements and subsequently enhances the photoassociation rates by several orders of magnitude [2]. Results for the photoassociation rates of the Cs_2 and Sr_2 molecules will be presented as the laser intensity is varied.

References
[1] R. Aganoglu, *et al.*, *Controlling a diatomic shape resonance with non-resonant light*, arXiv:1105.0761v1, (2011).
[2] R. González-Férez and C. P. Koch, *Enhancing photoassociation rates by non-resonant light control of a shape resonance*, preprint (2012).

Production of ultracold Sr_2 molecules in the electronic ground state

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The creation of ultracold state controlled molecules is a promising field motivated by fundamental insights and important applications, such as precision measurements of fundamental constants, study of dipolar physic, and quantum computation. We hereby demonstrate the efficient production of ultracold molecules in the electronic ground state, without relying on a magnetic Feshbach resonance. We implement instead a STIRAP sequence, using laser frequencies near the weak $^1S_0$-$^3P_1$ intercombination line, and operating on ultracold Bose condensed ^{84}Sr atoms [1] loaded into a 3D optical lattice. For this purpose, we first perform one- and two-color photoassociation spectroscopy on the last bound vibrational levels of the excited state 0_u, 1_u and the ground state $^1\Sigma_g^+$ potentials. We then produce samples of 4×10^4 molecules, with a STIRAP efficiency of 30%. Such Sr_2 molecules are good candidates [2] for the model independent measurement of time variations of the proton-to-electron mass ratio.

References
[1] S. Stellmer *et al.*, *Bose-Einstein Condensation of Strontium*, PRL **103**, 200401 (2009).
[2] T. Zelevinsky *et al.*, *Precision Test of Mass-Ratio Variations with Lattice-Confined Ultracold Molecules*, PRL **100**, 043201 (2008).

A path integral study on a CO molecule trapped by *para*-hydrogen clusters

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Understanding the dynamics of larger clusters CO-$(H_2)_n$ can serve as a model for molecules trapped in solid *para*-hydrogen (pH_2), which is useful for a range of low-temperature physics applications. Recently, we have built *ab initio* three-body potential energy surfaces for the cluster whose configuration space are sampled with coupled-cluster calculations and the three-body contributions to the nine-dimensional potential energy surface in the van der Waals well are fitted with a neural-network based method [1]. On the other hand, pH_2 clusters are predicted to exhibit a superfluid behaviour, however the direct observation of this phenomenon has been elusive. In experimental studies, a probe molecule is used and the increase of its effective rotational constant implies superfluidity of the system. In order to verify the validity of this criterion, it is necessary to study the behavior of molecules in the pH_2 cluster that is not in the superfluid state. In this study, the CO molecule is chosen as a trapped molecule and its rotational motion is traced using a path integral hybrid Monte Carlo (PIHMC) method. A cluster size dependence of the effective rotational constant is presented. It is found that the increase in rotational constants is also seen in the pH_2 cluster that is not in the superfluid state. This is due to the microscopic structure of the pH_2 cluster around the CO molecule.

Reference

[1] S. Manzhos, K. Nakai, K. Yamashita, "Three-body interactions in clusters CO-$(pH_2)_n$", Chem. Phys. Lett. **493**, 229-233 (2010).

2-photon photoassociation spectroscopy in a mixture of Yb and Rb

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Due to its paramagnetic ground state YbRb is an interesting candidate for the realization of dipolar molecules with additional degrees of freedom. Here we report on the first spectroscopic investigation of vibrational levels in the electronic ground stateof YbRb which is an important step towards the realization of YbRb ground state moelcules [1]. Using two-photon photoassociation spectroscopy in laser-cooled mixtures of ^{87}Rb and various Yb isotopes we are able to determine the binding energies of weakly-bound vibrational levels and the positions of possible magnetic Feshbach resonances. Recent theoretical work suggests that also in mixtures of alkali and spin-singlett atoms magnetic Feshbach resonances could be experimentally accessible [2]. From additional investigations by means of Autler-Townes spectroscopy we obtain information on the transition rates between vibrational levels of different electronic molecular states.

References

[1] F. Münchow, C. Bruni, M. Madalinski, and A. Görlitz. Two-photon photoassociation spectroscopy of heteronuclear YbRb. *PCCP*, 13(42):18734–18737, 2011.
[2] Piotr S. Zuchowski, J. Aldegunde, and Jeremy M. Hutson. Ultracold rbsr molecules can be formed by magnetoassociation. *Phys. Rev. Lett.*, 105(15):153201, Oct 2010.

Simple 2D permanent magnetic lattices for ultracold atoms

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Arrays of permanent magnetic slabs for producing 2D arrays of microtraps for trapping and controlling ultracold atoms have been introduced [1]. We propose a 2D array of square magnetic slabs which has been previously used to obtain analytical expressions for a class of permanent magnetic lattices [2]. We also, propose a more feasible magnetic lattice, consisting of the first configuration of square slabs plus a permanent magnetic substrate which holds the slabs together. In both configurations, we consider a bias magnetic field. To create Ioffe-Pritchard microtraps, the two non-zero components of the bias field in the magnetic film plane must have different values. Our analytical expressions and numerical results for different atoms are in very good agreement. The second pattern of the array of the square magnets may be fabricated using laser carving on a permanent magnetic film.

References

[1] S. Ghanbari, T. D. Kieu, A. Sidorov and P. Hannaford, *Permanent magnetic lattices for ultracold atoms and quantum degenrate gases*, J. Phys. B: At. Mol. Opt. Phys. **39**, pp. 847-860 (2006).
[2] S. Ghanbari, T. D. Kieu, and P. Hannaford, *A class of permanent magnetic lattices for ultracold atoms*, J. Phys. B: At. Mol. Opt. Phys. **40**, pp. 1283-1294 (2007).

Realization of a ^{85}Rb-^{87}Rb hetero-nuclear single atom array

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We report a realization of determinately trapping individual isotopic ^{85}Rb and ^{87}Rb atoms in a ring shaped optical far-off resonant trap (FORT) array. The sites of the array and the species trapped in sites are fully manipulated by using a blue-detuned Laguerre-Gaussian (LG) beam[1]. The LG beam has a repulsive potential and prevents the trap already having an atom from loading a second type of atom and from light assisted atom-atom collision. Using this atomic valve, a pair of two hetero-nuclear atoms in a two-site ring lattice has been prepared with an efficiency of 90%. While we demonstrate trapping ^{85}Rb-^{87}Rb dual-species, an extension to other dual-species is straightforward. Combined with our ability to efficiently transfer the two hetero-nuclear atoms into a single FORT by using the spatial light modulator [2], this work would be a key step toward the study of ^{85}Rb-^{87}Rb collision and formation of a single hetero-nuclear dipolar molecule.

References

[1] X. D. He *et al.*, "Combining red and blue-detuned optical potentials to form a Lamb-Dicke trap for a single neutral atom", Opt. Exp., **20**, pp.3711- 3724 (2012).
[2] X. D. He *et al.*, "High efficient loading of two atoms into a microscopic optical trap by dynamically reshaping the trap with a spatial light modulator", Opt. Exp. **18**, pp.13586-13592 (2010).

Temperature measurement of cold atoms using transient absorption from an optical nanofibre

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Optical nanofibres are effective tools for probing cold atoms in magneto-optical traps. The evanescent field arising from the light guided through the fibre interacts with atoms close to the fibre surface. Recently, the optical nanofibre has been used to measure sub-Doppler temperatures of a cold atom cloud by using forced trap oscillations [1]. Here, we study transient absorption [2] of a probe beam passing though an optical nanofibre during free expansion of a cold cloud of Rubidium-85 atoms. Using this method, the temperature of cold atoms near the surface of the fibre can be measured. The study is useful for characterizing the effect which surface interactions have on cold atoms.

References
[1] L. Russell, K. Deasy, M. Daly, M. J. Morrissey and S. Nic Chormaic, "Sub-Doppler temperature measurements of laser-cooled atoms using optical nanofibres", Meas. Sci. Tech. **23**, 015201(2012).
[2] R. R. Silva, K. M. F. Magalhães, E. A. L. Henn, L. G. Marcassa and V. S. Bagnato, "Temperature determination for magneto optical trapped atoms using a single parameter transient absorption", Opt. Commun. **265**, 526 (2006).

Beam-laser spectroscopy and optical pumping on iron atoms

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An original beam-laser spectroscopy set-up has been built at University of Liège. This setup allows us to produce atomic beams from samples heated in a high temperature oven. With help of laser beams crossing the atomic beam at given angles and a specific observation chamber equipped with a PM tube, a high-resolution sub-Doppler spectroscopy is obtained. We get similar resolutions to those inherent of usual laser saturation spectroscopy setups, while being able to access atomic levels otherwise unaccessible with saturation spectroscopy. Preliminary results on previously totally unknown hyperfine structure and isotopic effects for a non-resonance Iron atomic line will be presented. Our line intensities will be confronted to theoretical predictions to monitor the exact flux of atoms interacting with the laser beam. Our setup also allows for colinear optical pumping to enhance the laser absorption signals. These effects will be discussed as well, along with future prospects of our experiments.

Laser cooling of thulium atoms with Blue-Ray diodes

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We have set up a laser system based on laser diodes from Blue-Ray devices operating at 410.6 nm [1]. This system consists of a master oscillator and a slave laser. The master is a Blue-Ray chip with extended resonator; output power is 20 mW and the spectral width is of 1.2 MHz. The slave laser is injection locked to the master. The system delivers 120 mW of blue light in single frequency regime. With the help of this system we demonstrate laser cooling and magneto-optical trapping of 30000 Tm atoms. Previously, laser cooling of Tm was demonstrated by a bulky frequency doubled Ti:Sapphire laser [2].

References

[1] M. Mehlhorn, Bachelor thesis, Ludwig-Maximilians-Universitaet Muenchen (2011).
[2] D. Sukachev , et. al., “Magneto-optical trap for thulium atoms”, Phys. Rev. A **82**, 011405 (2010).

Simulation of the motion of ions in Paul trap

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Linear Paul traps are devices that allow the confinement of charged particles using a combination of static and radio-frequency electric fields. Their elongated configurations allow for the trapping of many ions along an axis and consequently provide a suitable environment to study quantum information processing and quantum computing. We develop simulation of the classical and quantum motion of a single trapped ion in a linear Paul trap. In particular we make use of Floquet theory to reduce the problem to an effective time-independent one, based on the time periodicity of the trapping field. In addition, we derive a model for the simulation of a trapped diatomic molecular ion, where all degrees of freedom are treated quantum mechanically.

Simultaneous magneto-optical trapping of Rb and Sr

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In recent years, there has been increasing interest in ultracold polar molecules. In particular, a molecule consisting of alkali and alkali-earth atoms has an electron spin, offering variety of research such as quantum simulators of lattice spin models. Recently, the electric dipole moment of the RbSr molecule has been predicted to be 1.36 Debye in the rovibrational ground state [1], which is advantageous to explore new quantum phases such as a crystalline phase.

We constructed an apparatus for laser cooling of Rb and Sr. For laser cooling of Sr, a 461-nm cooling beam was derived from a SHG cavity using a $KNbO_3$ crystal [2], whereas a 497-nm repumping beam was derived from a PPLN waveguide. We succeeded in simultaneous magneto-optical trapping of Rb and Sr.

References

[1] P. S. Żuchowski, J. Aldegunde, and J. M. Hutson, “Ultracold RbSr Molecules Can Be Formed by Magnetoassociation”, Phys. Rev. Lett. **105**, 153201(2010).
[2] T. Aoki, K. Umezawa, Y. Yamanaka, N. Takemura, Y. Sakemi, and Y. Torii, “A 461nm Laser System and Hollow-Cathode Lamp Spectroscopy for Magneto-Optical Trapping of Sr Atoms”, J. Phys. Soc. Jpn. **81** (2012) 034401.

Large Sr^+ Coulomb crystals: isotopic enrichment and single-pass absorption

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We present the realization of large Coulomb crystals containing up to 5×10^6 strontium ions. This kind of sample has potential applications in different fields such as quantum information [1] and cold-molecule spectroscopy [2]. Our experiment is based on a linear Paul trap loaded by photo-ionization of a strontium atomic vapor using ultrafast pulses allowing for the formation of large multi-isotope Sr+ Coulomb crystals. We also present a method for controlling the ratio between the various strontium isotopes in the ion crystals. For example we realized pure crystals (of $^{88}Sr^+$, $^{86}Sr^+$, and $^{84}Sr^+$ which has a natural abundance of 0.6%) as well as two-isotope crystals (e.g. $^{86}Sr^+ + ^{84}Sr^+$). Coulomb crystals containing two spatially segregated isotopes have applications in quantum information experiments in which one isotope sympathetically cools a second isotope fully available for quantum manipulation. We also present preliminary measurements of single-pass absorption realized in such atomic samples.

References

[1] T. Coudreau, F. Grosshans, S. Guibal, L. Guidoni, *Feasibility of a quantum memory for continuous variables based on trapped ions: from generic criteria to practical implementation*, J. Phys. B: At. Mol. Opt. Phys. **40**, 413 (2007).
[2] X. Tong, A. H. Winney, and S. Willitsch, *Sympathetic Cooling of Molecular Ions in Selected Rotational and Vibrational States Produced by Threshold Photoionization*, Phys. Rev. Lett. **105**, 143001 (2010).

Towards ground state electron guiding on a surface electrode microwave chip

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We investigate the guiding of electrons in a miniaturized planar ac-quadrupole guide (linear Paul trap) [1]. Electrons propagating freely along electrodes on a micro-fabricated chip experience a tight transverse harmonic confinement. For our guiding parameters the dimensions of the quantum mechanical ground state of the guiding potential is still resolvable by electron optics. This encourages experiments to prepare electrons in the transverse motional ground state by matching the wavefunction of an incident electron with the ground state of the microwave guide. Here we report on our ongoing experimental efforts. We use a single-atom tip electron emitter, a point source for electrons producing an exceptionally bright and fully coherent electron beam, for injection into the guide. Efficient ground state coupling requires a spot size of ~ 100 nm and an angular spread of ~ 1 mrad of the incoming electron wavefunction. For collimation of the electron wavepacket right after emission we are fabricating a sub-micron electrostatic lens. We present the current status of the experiment as well as numerical simulations on quantum mechanical electron wavefunction propagation. In this context electron guiding represents an ideal starting point for guided matter-wave interferometry and controlled electron-electron or electron-surface interactions where the quantum mechanical states of the guide serves as carrier of quantum information.

Reference

[1] J. Hoffrogge, R. Fröhlich, M. Kasevich and P. Hommelhoff, *Phys. Rev. Lett.* **106**, 193001 (2011).

Sympathetic cooling of ions by ultracold Na atoms in a hybrid trap

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Laser cooling atoms to ultracold temperatures has opened a new fruitful regime for atomic physics. Closed shell atomic ions, such as Na^+, and nearly all molecular ions lack the optical transitions that are required for laser cooling, precluding their use in a variety of experiments, including near zero-K reaction studies and applications such as quantum gates. We have created a hybrid atom-ion trap system to cool atomic or molecular ions which cannot be laser cooled [1]. It consists of a magneto-optic trap (MOT) for Na, concentric with a linear Paul r.f. ion trap [2,3]. Recent simulations we have carried out using SIMION 7 show that cold MOT atoms may be used to sympathetically cool hot ions to sub-Kelvin temperatures. We have found experimental evidence of this: trapped Na+ ions exposed to the MOT have extended lifetimes in the Paul trap. We have studied secular frequency quenching of unwanted ions (e.g. Na_2+) from the Paul trap, without disturbing the trapped Na^+ ions.

References

[1] W. Smith, E. Babenko, R. Cote' and H. Michels, in Coherence and Quantum Optics, VIII, N. Bigelow, *et al.*, eds., Kluwer Academic Publ., NY 2003, pp. 623-624.
[2] W. Smith, *et al.*, J. Modern Optics 52, pp. 2253-2260 (2005).
[3] E. R. Hudson, Phys. Rev. A 79, 032716 (2009) and references therein to related work.

Effects of a non-Gaussian profile intensity beam in a magneto-optical trap

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The magneto-optical traps allow cooling and trapping of atoms. Some of the possible applications for the cold atoms are: spectroscopy of ultra-high resolution, atomic clocks and the achievement of Bose-Einstein condensate [1]The purpose of our research is to study the behaviour of the movement of atoms by varying some parameters of the trap, such as gradient magnetic field, the intensity of laser beams, the detuning and the intensity profile of the beams. Simulations were conducted to describe the behaviour of the trajectory of an atom under the influence of the forces present in a magneto-optical trap in the case of using beams with non-Gaussinan profile, it was also necessary to deduce the force equation taking into account a new general intensity profile, calculated as follows:

$$I = I_0\left(1-\left(\frac{y}{a}\right)^n\right)$$

It is possible to obtain clouds of the atoms in a ring, by using a beam intensity profile different from the Gaussian. Moreover, it is clear that the cloud of atoms in this new configuration becomes smaller.

Reference
[1] S. Bize, et. al. J. of Phys. B , 449(2005); M. H. Anderson et. al., Science **269**, 198 (1995).

Generation of a decoherence-free entangled state using a radio-frequency dressed state

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A noisy environment induces unwanted disturbances to quantum states and leads to decoherence. From this point of view, a decoherence-free subspace (DFS) is well known to prolong the coherence time. In particular, a DFS using a dressed state [1] ("dressed DFS") has the advantage that quantum states are protected even in the presence of a stray magnetic field gradient, which often limits the coherence time in a traditional DFS [1]. If qubits are globally exposed to an external field (dressing field), a Dicke ladder is constructed. States on the Dicke ladder whose projections of total angular momentum are zero can be used to construct the dressed DFS.

We demonstrate dressed decoherence-free entangled state [2] i.e. a logical qubit in dressed DFS using a combination of a dressed state of rf qubits and an Mølmer-Sørensen interaction. The coherence time of this entangled state is increased by about 2 orders of magnitude with the protection of rf dressing field.

References
[1] N. Timoney, et. al., *Quantum gates and memory using microwave-dressed states.* Nature **476**, 185 (2011).
[2] A. Noguchi, et. al., *Generation of a Decoherence-Free Entangled State Using a Radio-Frequency Dressed State* Phys. Rev. Lett. **108**, 060503 (2012).

Towards ultracold mixtures on an atom chip

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Ultracold mixtures hold the promise of understanding new phases of matter and collisions at very low energies. By combining the capabilities of the atom chip with optical dipole trapping, it will be possible to trap these mixtures in low dimensions and tune their scattering lengths via Feshbach resonances. In this way it will also be possible to realise experiments with additional magnetic potentials, position dependent interactions or impurity dynamics. Here we present the current status of our Lithium and Cesium experiment. We detail the cooling schemes for both atom species and include the recent development of implementing an optical dipole trap. We discuss ideas for future measurements with separately addressable Bose-Fermi mixtures in optical dipoletraps, such as transport and impurity studies in low dimensions, close to a chip surface.

A versatile collider for ultracold atoms

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We report on the progress on a laser based accelerator for studying cold collisions between ultracold atoms. Such miniature colliders may for example open up routes to study Efimov physics via the collision energy dependence of three-body scattering observables [1] and to implement “hard probes” for strongly interacting gases. Having demonstrated and characterized the working principle of the optical collider [3] using ^{87}Rb atoms in the $|F=2, m_F=2\rangle$ ground state, we are presently extending the scheme to multiple internal quantum states and to collisions between different atomic species. With a scheme based on laser confinement and acceleration an external magnetic field can be exploited to tune atomic interactionsand scattering experiments can be conducted at fixed collision energies into the millikelvin (measured in units of the Boltzmann constant) regime with nanokelvin samples.

References

[1] Y. Wang, J. P. D’Incao, H.-C. Nägerl, and B. D. Esry, *Colliding Bose-Einstein Condensates to Observe Efimov Physics*, Phys. Rev. Lett. **104**, 113201 (2010).
[2] Y. Nishida, *“Hard probes” of strongly-interacting atomic gases*, arXiv:1110.5926 (2011).
[3] A. Rakonjac, A. B. Deb, S. Hoinka, D. Hudson, B. J. Sawyer, and N. Kjærgaard, *Laser based accelerator for ultracold atoms*, Opt. Lett. **37**, 1085 (2012).

Fundamental atomtronic circuit elements

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Recent experiments have demonstrated steps toward creating neutral atom analogs to superconducting circuits[1]. The goals of these experiments are to create complex systems like Josephson junctions. For these devices to function, an understandingof the more fundamental atomtronic elements is also needed. We describe the first experimental realization of these fundamental elements. We have created an atom analog to a capacitor that we discharged through a resistor and inductor. We derive theoretical values for the capacitance, resistance and inductance, showing them to be analogous to the quantum capacitance[2], Sharvin resistance[3] and kinetic inductance[4] found in condensed matter. This atomtronic circuit is implemented in a thermal sample of laser cooled rubidium atoms. The atoms are confined using free-space atom chips, a novel optical dipole trap produced using a generalized phase-contrast imaging technique. We also discuss current progress in extending this work to a sodium BEC.

References

[1] A. Ramanathan *et al.*, *Superflow in a Toroidal Bose-Einstein Condensate: An Atom Circuit with a Tunable Weak Link*, Phys. Rev. Lett. **106**, pp. 130401 (2011).
[2] S. Luryi, *Quantum capacitance devices*, Appl. Phys. Lett. **6**, pp. 501 (1988).
[3] A. G. M. Jansen *et al.*, *Point-contact spectroscopy in metals*, J. Phys. C: Solid State Phys. **13**, pp. 6073-6118 (1980).
[4] A. M. Kadin, *Introduction to Superconducting Circuits*, New York: John Wiley and Sons (1999).

Doppler cooling of multilevel-level systems by the coherent pulse trains

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Direct application of the conventional Doppler cooling to multilevel atoms and molecules is challenging: most atoms and all molecules have transitions that can radiatively branch out to a multitude of other states. Exciting population from all these lower-energy states requires a large number of lasers which makes the conventional scheme impractical. Here we explore an alternative scheme: cooling with trains of ultrashort laser pulses. Frequency comb (FC) spectrum generated by the pulse train can drive many transitions simultaneously. Positions and intensities of individual FC teeth can be manipulated by pulse shaping techniques. Recently we demonstrated that the ensembles of two- and three-level systems can be effectively cooled by such trains [1]. As a result of cooling, atomic velocity distribution gravitates towards "velocity comb": a series of narrow groups of atomic velocities separated by λ_c / T, where λ_c is the carrier wave length and T is the pulse repetition period. Here we report our theoretical results on Doppler cooling multilevel systems with coherent trains of shaped laser pulses.

Reference

[1] E. Ilinova, A. Derevianko, *Doppler cooling of three-level Λ-systems by coherent pulse trains*, http://arxiv.org/abs/1203.1963 (2012).

Excited state spatial distributions in a cold strontium gas

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Long-range interactions between Rydberg atoms in cold atom ensembles lead to spatial correlations that are not present in the ground state distribution [1, 2]. We aim to study these correlations using a scanning autoionising microscopy technique. We excite a cloud of Sr atoms cooled to 5mK to a Rydberg state via a resonant two-photon transition using narrowband CW lasers. Working with strontium means there is a second valence electron with a transition at an accessible optical wavelength. Excitation of this electron leads to autoionisation of the atom. Previously we have used the fact that the autoionisation spectrum is dependent upon the atomic state of the Rydberg atom to study the population transfer mechanics caused by the onset of plasma formation [3]. By translating a tightly focused autoionisation laser across the ensemble we have extended the technique to measure the spatial distribution of the Rydberg atoms. We present preliminary measurements of the 2D Rydberg state spatial distribution.

References

[1] M. Lukin *et al.*, *Dipole blockade and quantum information processing in mesoscopic atomic ensembles*, Phys. Rev. Lett. **84**, 037901 (2001).
[2] T. Pohl, E. Demler, and M. D. Lukin, *Dynamical Crystallization in the Dipole Blockade of Ultracold Atoms*, Phys. Rev. Lett. **104**, 043002 (2010).
[3] J. Millen, G. Lochead and M. P. A. Jones, *Two-electron excitation of an interacting cold Rydberg gas*, Phys. Rev. Lett. **105**, 213004 (2010).

Rf spectroscopy of the Efimov energy level

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We develop an experimental technique for rf association of Efimov trimers from a three-atom continuum. We apply it to probe the lowest accessible Efimov energy level in bosonic lithium in the region where strong deviations from the universal behavior are expected, and provide a quantitative study of this effect. Our measurements indicate a shifted position of the Efimov resonance at the atom-dimer threshold as compared to the universal theory prediction. The result of a different experimental technique concurs with the rf association measurements. This technique explores secondary collisions of the dimer, formed in a three-body recombination, which cross-sections are expected to increase in the vicinity of the Efimov resonance. We developed a model that counts the number of elastic and inelastic collisions of a dimer with trapped atoms based on the available analytical expressions for the cross-sections of these events. We show shift in the position of the secondary collisions' enhancement for large collisional opacities.

References

[1] O. Machtey, Z. Shotan, N. Gross, and L. Khaykovich, "Association of Efimov trimers from a three-atom continuum", arXiv:1201.2396.
[2] O. Machtey, D. A. Kessler, and L. Khaykovich, "Universal Dimer in a Collisionally Opaque Medium: Experimental Observables and Efimov", Phys. Rev. Lett. **108**, 130403 (2012).

Observation of ferromagnetic spin correlations in a 1D Fermi system

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One of the simplest models used to explain ferromagnetism of delocalized spin 1/2 fermions is the Stoner model, which predicts a transition to a ferromagnetic state when the strength of the repulsive interaction exceeds the Pauli repulsion between identical fermions. Here we report on our studies of a quasi one-dimensional system of ultracold fermionic ^{6}Li atoms in two different hyperfine states. For such a 1D system it has been shown that the Stoner transition to ferromagnetism does not occur for a finite strengthof the repulsive interaction. We start from ground-state systems of three to five particles and tune the interaction strength across $\pm\infty$ using a Feshbach resonance. This allows us to create long-lived metastable states in which the energy of theinteracting spin $|\uparrow\downarrow\rangle$ system is larger than energy of the corresponding spin-polarized system. We probe the spin-spin correlations in the system by letting a fraction of the particles escape from the trap and measuring the total spin of the remaining ensemble. For the metastable branch across the resonance we find a strong enhancement in the number of spin polarized systems created by the spilling process, which signals the appearance of ferromagnetic correlations.

Universality and the three-body parameter of helium-4 trimers

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We consider a system of three helium-4 atoms, which is so far the simplest realistic three-body system exhibiting the Efimov effect [1], in order to analyse deviations from the universal Efimov three-body spectrum. We first calculate the bound states using a realistic two-body potential, and then analyse how they can be reproduced by simple effective models beyond Efimov's universal theory.

We find that the non-universal variations of the first two states can be well reproduced by models parametrized with only three quantities: the scattering length and effective range of the original potential, and the strength of a small three-body force. Furthermore, the three-body parameter which fixes the origin of the infinite set of three-body levels is found to be consistent with recent experimental observations in other atomic species.

Reference
[1] F. Ferlaino, R. Grimm, Physics 3 (2010) 9.

Exploration into ultra cold chemistry: few-body calculation in Bose-Fermi mixture

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This project investigates the properties of fermionic molecules $^{87}Rb^{40}K$, including (i) its formation from a mixed gas of bosonic ^{87}Rb and fermionic ^{40}K through magnetic field ramping and (ii) its scattering properties after formation, which sheds light on both the formation and decay processes of the fermionic molecules. We mainly approach this from a few-body perspective: the spectrum of two bosons (^{87}Rb) and two fermions (^{40}K) is first calculated in a harmonic trap using a standard correlated-Gaussian basis throughout the range of a broad Fano-Feshbach resonance. We also perform hypherspherical correlated-Gaussian calculation of the adiabatic hyperspherical potential curve describing the bose-fermi mixture system at various scattering lengths. The single channel calculation and multi-channel calculation provide effective dimer-atom scattering lengths and trimer-atom scattering lengths as well as the dimer-dimer scattering phase shift.The avoided crossings in the hyperspherical potential curves of the few-body system enables an interpretation of the scattering dynamics of the bose-fermi mixture system. This single- and multi-channel scattering calculation shows agreement with the zero-range potential calculation in a harmonic trap [1, 2].

References

[1] B. Bogdan and D. Blume and Chris H. Greene, New J. Phy. **5**, 1 (2003), 111.
[2] T. Busch, B. Englert, K. Rzazewski and M. Wilkens, **28**, 4 (1998), 549-559.

Investigating magnetic field near a superconducting atom chip with cold atoms

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Magnetic field near a superconducting atom chip and an interaction between cold atoms and the cryogenic surface of a superconductor have yet to be observed. In this paper an experimental study is made of the magnetic field near a superconducting Nb disc with cold Rb atoms. When a superconducting disc in a pure state is exposed to a perpendicular magnetic field, a funnel-form potential with a field minimum at the center of the disc surface appears and atoms released in the potential are temporally accumulated near the surface. When the disc temperature is set lower than the dendritic instability temperature the magnetic flux penetration is observed with inhomogeneously distributed atomic clouds near the surface. A change in the magnetic flux distribution is triggered depending on the disc temperature at which a magnetic field is applied.

Reference

[1] Tetsuya Mukai, *Investigating magnetic field near a superconducting disc with cold atoms*, in preparation.

Conversion of bright magneto-optical resonances into dark by changing temperature at fixed laser frequency for D_2 excitation of atomic rubidium

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We present experimental results and theoretical predictions of magneto-optical resonances changing from bright to dark resonances as a result of temperature changes when excited by circularly polarized light at the D_2 transition of rubidium in natural mixture [1]. As the temperature was increased, the contrast of the bright resonance decreased until the bright resonance disappeared at around 40^0C. At this temperature, the optical depth traversed by the laser beam in the 25-mm-long cell was ~ 0.39. At higher temperatures, a dark resonance was observed, and its contrast grew with increasing temperature. The change from bright to dark resonance around an optical depth of 0.66 is probably related to reabsorption. With each reabsorption cycle, information about the original coherent atomic state is lost. At linearly polarized excitation substantial changes in the resonance profile also were observed, although the resonance remained dark over the entire range of accessible temperatures.

Reference

[1] M. Auzinsh *et al.* "Conversion of bright magneto-optical resonances into dark resonances at fixed laser frequency for D_2 excitation of atomic rubidium", PHYSICAL REVIEW A 85, 033418 (2012).

Effects of dark state formation in the hyperfine excitation spectra of Na atoms

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We consider the formation of dark states upon interaction of hyperfine level systems with strong laser fields [1]. Sodium $3S_{1/2}, F'' = 1{,}2$ $3S_{1/2}, F'' = 1{,}2$ and $3P_{1/2}, F' = 1{,}2$ levels are coupled by a strong S-laser field with Rabi frequency Ω_S forming the laser-dressed states. The latter are monitored by scanning a weak probe field across the $3P_{1/2}, F = 1{,}2 \rightarrow 7D_{3/2}$ transition. The excitation spectrum of the $7D_{3/2}$ state shows the presence of an intense main peak with side peaks of much smaller intensities. The increase of Ω_S shifts the the side-peaks further apart, while the position of the main peak is hardly affected. These observations are explained in the dressed-state formalism; depending on the S-field detuning either $F'' = 1$ or $F'' = 2$ component of the ground state is coupled to the two $F' = 1{,}2$ levels of $3P_{1/2}$. We show that the such system exhibits a visible "gray" state whose eigenvalue is weakly affected by the magnitude of Ω_S. This gray state evolves into a dark state at high Ω_S.

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Reference

[1] J. S. Morris and B. W. Shore, *Reduction of degenerate two-level excitation to independent two states system*, Phys. Rev. A **27**, pp. 906-912 (1983).

Suppression of excitation channels by composite pulse sequences

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We present a method for suppression of unwanted excitation channels in specific multistate quantum systems by the application of composite pulse sequences. By making suitable choices for the phases of the constituent pulses, we suppress excitation channels even when the couplings between the corresponding states are different from zero. Compensation with respect to deviations in polarization, pulse area, and detuning are demonstrated. The accuracy of the proposed technique, its experimental feasibility, and its robustness make it suitable for various physical applications in quantum information processing and quantum optics.

Optimal control of a few atoms in a bipartite superlattice

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For a single particle held in a bipartite superlattice with two different separations and under a external driving of arbitrary shape, we construct analytical solutions in the nearest-neighbour tight binding approximation, through a discrete Fourier transformation. By optimally designing the driving shapes, the analytical solutions are adopted to quantitatively describe and control transport characterizations of the particle. Take the biperiodic driving, Rosen-Zener pulse and Gaussian pulse as examples, the selective coherent destruction of tunneling (SCDT) and dynamic localization are found, which are applied to coherent manipulations of the directed motion and Rabi oscillation. The results could be extended to few-particle case and are useful for transporting quantum information carried by the particles in a bipartite superlattice material or a bipartite optical lattice.

References

[1] L. Guidoni and P. Verkerk, “Direct observation of atomic localization in optical superlattices”, Phys. Rev. A57, R1501 (1998).
[2] C. E. Creffield, “Quantum Control and Entanglement using Periodic Driving Fields”, Phys. Rev. Lett. 99, 110501 (2007).
[3] Kuo Hai, Wenhua Hai, and Qiong Chen, “Controlling transport and entanglement of two particles in a bipartite lattice”, Phys. Rev. A82, 053412 (2010).
[4] Kuo Hai, Qiong Chen, and Wenhua hai, “Instability inducing directed tunneling of a single particle in a bipartite lattice”, J. Phys. B44, 035507(2011).

Optical repumping of triplet-P states enhances magneto-optical trapping of ytterbium atoms

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Radiative decay from the excited $^1P_1$ state to metastable $^3P_2$ and $^3P_0$ states is expected to limit the attainable trapped atomic population in a magneto-optic trap of ytterbium (Yb) atoms. In experiments we have carried out with optical repumping of $^3P_{0,2}$ states to $^3P_1$, we observe an enhanced yield of trapped atoms in the excited $^1P_1$ state. The individual decay rate to each metastable state is measured and the results show excellent agreement with the theoretical values.

References
[1] T. Loftus, J. R. Bochinski, R. Shivitz, and T. W. Mossberg, Phys. Rev. A 61, 051401(R) (2000).
[2] S. G. Porsev, Y. G. Rakhlina, and M. G. Kozlov, Phys. Rev. A 60, 2781 (1999).
[3] K. Honda, Y. Takahashi, T. Kuwamoto, M. Fujimoto, K. Toyoda, K. Ishikawa, and T. Yabuzaki, Phys. Rev. A 59, R934 (1999).

Development of perturbed relativistic coupled-cluster theory for the calculation of electric dipole polarizability of closed-shell systems

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The coupled-cluster theory is one of the most reliable quantum many-body theory [1]. In the present work, we have developed perturbed relativistic coupled-cluster (PRCC) theory [2] to incorporate the effect of external electric field as a perturbation in the atomic many-body calculations. For this, the coupled-cluster equations of the singles and doubles cluster operators are derived and the contributing diagrams are examined. These diagrams are further evaluated using angular momentum algebra. The PRCC operators, obtained by solving the coupled non-linear equations, are then used for the dipole polarizability calculation of closed-shell systems. In this poster, we will present results of electric dipole polarizability of noble gas atoms using the PRCC theory.

References
[1] F. Coester, *Bound states of a many-particle system*, Nucl. Phys. **7**, 421 (1958).
[2] B. K. Mani and D. Angom, *Relativistic coupled-cluster theory of nuclear spin-dependent parity non-conservation*, arXiv:1105.3447v2 (2011)

Hyperfine frequency shift and Zeeman relaxation in alkali vapor cells with anti-relaxation alkene coating

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A recently identified alkene based anti-relaxation coating exhibit Zeeman relaxation times in excess of 60 s in alkali vapor cells (two orders of magnitude longer than in paraffin coated cells) [1]. The long relaxation times, motivate revisiting the long-standing question of what is the mechanism underlying wall-collision induced relaxation and renew interest in applications of alkali vapor cells to secondary frequency standards. We measure the Zeeman relaxation time, and the width and frequency shift of the clock resonance, in ^{85}Rb and ^{87}Rb vapor cells with alkene anti-relaxation coating. in paraffin coated cells. We find that the frequency shift is slightly larger than for paraffin coated cells. However we observe that the Zeeman relaxation rate appears to be a linear function of the hyperfine frequency shift, whereas a linear dependence was not observed in paraffin coated cells. To shed light on this result we propose a model describing different Zeeman relaxation mechanisms of alkene and alkane cell-wall coatings.

Reference

[1] M. V. Balabas, T. Karaulanov, M. P. Ledbetter, and D. Budker. *Polarized Alkali-Metal Vapor with Minute-Long Transverse Spin-Relaxation Time*, Phys. Rev. Lett.**105**, pp. 7 (2010).

Programmable trap geometries with Superconducting atom chips

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The use of superconductors in atom chips is a recent development, presenting new opportunities for atom optics [1, 2]. One demonstrated advantage of superconductors over conventional conductors is the significant reduction of near-field noise in current-carrying structures, leading to low atomic heating rates and enhanced spin-flip lifetimes [3]. We demonstrate the trapping of ultracold atoms in the magnetic field formed entirely by persistent supercurrents induced in a thin film type-II superconducting square. The supercurrents are carried by vortices induced in the 2D structure by applying two magnetic field pulses of varying amplitude perpendicular to its surface. This results in a selfsufficient trap which does not require any externally applied fields. To demonstrate possible applications of these types of supercurrent traps we show how a central quadrupole trap can be split into four traps by use of a bias field.

References

[1] T. Müller, B. Zhang, R. Fermani, K. S. Chan, Z. W. Wang, C. B. Zhang, M. J. Lim and R. Dumke, *Trapping of ultra-cold atoms with the magnetic field of vortices in a thin-film superconducting micro-structure*, New Journal of Physics **12**, 043016 (2010).
[2] T. Müller, B. Zhang, R. Fermani, K. S. Chan, M. J. Lim and R. Dumke, *Trapping of ultra-cold atoms with the magnetic field of vortices in a thin-film superconducting micro-structure*, Phys. Rev. A **81**, 053624 (2010).
[3] R. Fermani, T. Müller, B. Zhang, M. J. Lim, and R. Dumke *Heating rate and spin flip lifetime due to near-field noise in layered superconducting atom chips*, J. Phys. B **43**, 095002 (2010).

Hybrid atom-membrane optomechanics

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In optomechanics, laser light is used for cooling and control of the vibrations of micromechanical oscillators, with many similarities to the cooling and trapping of atoms. It has been proposed that laser light could also be used to couple the motion of atoms in a trap to the vibrations of a mechanical oscillator [1]. In the resulting hybrid optomechanical system the atoms could be used to read out the oscillator, to engineer its dissipation, and ultimately to perform quantum information tasks.

We have realized a hybrid optomechanical system by coupling ultracold atoms to a micromechanical membrane [2]. The atoms are trapped in an optical lattice, formed by retro-reflection of a laser beam from the membrane surface, resulting in optomechanical coupling as proposed in [1]. We observe both the effect of the membrane vibrations onto the atoms as well as the backaction of the atomic motion onto the membrane. By coupling the membrane to laser-cooled atoms, we engineer the dissipation rate of the membrane. This mechanism can be used to sympathetically cool the membrane with the atoms.

References

[1] K. Hammerer, K. Stannigel, C. Genes, P. Zoller, P. Treutlein, S. Camerer, D. Hunger, and T. W. Hänsch, Phys. Rev. A **82**, 021803 (2010).
[2] S. Camerer, M. Korppi, A. Jöckel, D. Hunger, T. W. Hänsch, and P. Treutlein, Phys. Rev. Lett. **107**, 223001 (2011).

Cavity optomechanics with micromirrors and nanomembranes

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Reaching the quantum ground state of a macroscopic mechanical object is a major experimental challenge in physics, at the origin of the rapid emergence of cavity optomechanics. We developed a new generation of optomechanical devices, either based on microgram 1-mm long quartz micropillar with very high mechanical quality factor (10^6) [1], or on 100-pg photonic crystal suspended nanomembranes [2]. Both are used as end mirror in a Fabry-Perot cavity with a high optical finesse(up to 50 000) leading to ultra-sensitive interferometric measurement of the resonator displacement. We expect to reach the ground state of such optomechanical resonators combining cryogenic cooling with a dilution fridge at 30 mK and radiation-pressure cooling [3]. We already carried out a quantum-limited measurement of the micropillar thermal noise at low temperature, and the cold damping of the nanomembrane.

References

[1] A. G. Kuhn *et al.*, *A micropillar for cavity optomechanics*, App. Phys. Lett. **99**, 121103 (2011).
[2] T. Antoni *et al.*, *Deformable two-dimensional photonic crystal slab for cavity optomechanics*, Opt. Letters **36**, 3434 (2011).
[3] O. Arcizet *et al.*, *Radiation-pressure cooling and optomechanical instability of a micromirror*, Nature **444**, 71 (2006).

Long-range gravitational-like interaction in a neutral cold gas

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The equilibrium characteristic of gravitational systems is theoretically well established. For example it has been shown that particular phase transition occurs in the presence of non-additive long range interaction. In this context microcanonical and canonical ensembles are not anymore equivalent. This situation is in striking contrast with the experimental side of the subject where there is, so far, no controllable experimental system. We have recently show some experimental evidences of a gravitational-like interaction on an one-dimensional test system consisting in a cold gas of neutral Strontium atoms. For that purpose, two counter-propagating laser beams are tuned on the narrow intercombination line. In particular, we found that the density profile follows the expected $1/\cosh^2$ law and the relaxation dynamic of the cold gas is modified by the long range interaction.

Towards room-temperature electron spin detection in biological systems

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We report on recent progress of room-temperature electron spin sensing for biological applications using nitrogen-vacancy (NV) centers in diamond. Room-temperature detection of a small number of electron spins, situated outside the measurement substrate, has yet to be accomplished. Such an advance could lead to a number of applications, including measurement of concentrations of radicals in living cells, detection of magnetic resonance signals from individual electron or nuclear spins of complex biological molecules, and monitoring the ion channel function across cell membranes (important for exploring drug delivery mechanisms). Thus, the ability to measure magnetic fields with sensitivity allowing detection of a small number of electron spins with sub-micrometer resolution would be of major importance to the biological sciences.

In situ tomography of femtosecond optical beams with a holographic knife-edge

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We present an in situ beam characterization technique to analyze femtosecond optical beams in a folded version of a 2f-2f setup [1]. This technique makes use of a two-dimensional spatial light modulator (SLM) to holographically redirect radiation between different diffraction orders. This manipulation of light between diffraction orders is carried out locally within the beam. Because SLMs can withstand intensities of up to $I \sim 10^{11}$ W/cm^2, this makes them suitable for amplified femtosecond radiation. The flexibility of the SLM was demonstrated by producing a diverse assortment of "soft apertures" that are mechanically difficult or impossible to reproduce. We test our method by holographically knife-edging and tomographically reconstructing both continuous wave and broadband radiation in transverse optical modes. This work was supported by the Robert A. Welch Foundation (grant No. A1546) and the National Science Foundation (grant No. 0722800).

Reference

[1] J. Strohaber, et. al., "In situ tomography of femtosecond optical beams with a holographic knife-edge," Optics Express **19,** 14321-14334 (2011).

Intensity-resolved above threshold ionization yields obtained with femtosecond laser pulses

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Photoelectron yields from the ionization of xenon with linearly polarized, unchirped 50 fs laser pulses were measured for a set of laser intensities using an above threshold ionization (ATI) [1] apparatus. All laser parameters other than the radiation intensity were held constant over the set of intensity measurements. A recently developed deconvolution algorithm was used to retrieve the photoelectron ionization probability from spatially averaged data in three dimension. Finally, an error analysis was performed to determine the stability and accuracy of the algorithm as well as the quality of the data. It was found that the algorithm produced greater contrast for peaks in the ATI spectra where atom specific resonant behavior is observed. Additionally, the total yield probability showed that double ionization was observed in the ionization yields. The error analysis revealed that the algorithm was stable under the experimental conditions for a range of intensities. This work was supported by the Robert A. Welch Foundation (grant No. A1546) and the National Science Foundation (grant No. 0722800) and the U.S. Army Research Office (W911NF-07-1-0475).

Reference

[1] G. G. Paulus, W. Nicklich, Huale Xu, P. Lambropoulos, and H. Walther, "Plateau in above threshold ionization spectra", Phys. Rev. Lett. 72, 2851–2854 (1994).

Time evolution method in rigged QED: formulation and simulation

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Simulations of time evolution of the quantum system involving light and matter are so far performed using the time-dependent Schrödinger or Dirac equation with classical electromagnetic fields or using a quantized photon field with the very much simplified matter part. We consider, however, it is of great importance to develop a simulation method based on QED (Quantum Electrodynamics) in the form of quantum field theory, and without recourse to the perturbative approach. We believe such a theoretical technique opens up a way to study and predict new phenomena. Rigged QED [1] is a theory which has been proposed to treat dynamics of charged particles and photons in atomic and molecular systems in a quantum field theoretic way. We discusses a method to follow the step-by-step time evolution of the quantum system employing Rigged QED. We found “electron-positron oscillations” in the charge density, the fluctuations originated from virtual electron-positron pair creations/annihilations [2].

References
[1] A. Tachibana, J. Chem. Phys. **115**, 3497 (2001); J. Mol. Struct. (THEOCHEM), **943**, 138 (2010).
[2] K. Ichikawa, M. Fukuda and A. Tachibana, International Journal of Quantum Chemistry, published online. [DOI: 10.1002/qua.24087].

Strong-field above-threshold ionization in laser-irradiated C_{60}: the signature of orbital symmetry and intramolecular interference

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The strong-field process of multiphoton *above-threshold ionization* (ATI) in laser-irradiated carbon molecule of fullerene C_{60} is addressed theoretically within the *velocity-gauge* (VG) formulation of molecular *strong-field approximation* (SFA) [1]. Our VG-SFA results demonstrate a high suppression of ATI peaks in two different (viz., in low-energy and high-energy) domains of calculated molecular photoelectron spectrum and two respective pronounced interference minima both arising due to destructive *intramolecular* (multislit) quantum interference. The applied approach also suggests quite a clear and transparent interpretation for the physical mechanism underlying the phenomenon of high suppression in C_{60} strong-field ionization earlier observed in relevant experiment [2].

References
[1] Vladimir I. Usachenko, Pavel E. Pyak and Vyacheslav V. Kim. “Comparative study of strong-field ionization in laser-irradiated F_2 and other diatomic molecules: Density-functional-theory-based molecular strong-field approximation”, Phys. Rev. A **79**, p. 023415 (2009).
[2] M. Tchaplyguine *et al.* “Ionization and fragmentation of C_{60} with sub-50 fs laser pulses“, J. Chem. Phys. **112**, pp. 2781-2789 (2000).

Generation of a pilot phase pulse during propagation of slow elliptically polarized optical pulses in a medium under coherent population trapping

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Propagation of elliptically polarized light pulses under the coherent population trapping (CPT) in a medium of two-level atoms with degenerate energy levels is studied. Theoretical analysis is based on the density matrix formalism and the reduced Maxwell's equation. It is shown that the pulses of ellipticity and orientation angle of the polarization ellipse travel with delay. We derive the analytical expression for a group velocity for all possible "dark" transitions $J_g = J \rightarrow J_e = J$ (J is integer), where J_g and J_e are the total angular momentum of atomic ground and excited states. In addition, the new interesting effect is revealed. The sense of the effect consists in stimulated phase modulation due to variation of the polarization ellipse spatial orientation. This phase modulation includes two light pulses: a pilot pulse that passes through the medium with velocity of light in vacuum and a slow pulse, propagating in sync with the pulse of the orientation angle.

Tu-216 Other

Numerical study on the spin coherence in a non-ideal atom cloud

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The robustness of cohenrent nuclear spin superposition was to be tested experimentally under electromagnetically-induced transparency scheme [1] using a Λ-system consisted of Sr^{87} atoms in $|^1S_0,F=9/2,m_F=5/2\rangle$, $|^1S_0,F=9/2,m_F=9/2\rangle$, $|^3P_1,F=7/2,m_F=7/2\rangle$ states. The storage time of light in a coherent spin superposition was planned to be measured in the experiment. A numerical semi-classical approach to solve the distribution of atoms [2] under the previous set-up was performed so as to provide an insight to the situation where a minority of 'impurity' Sr^{87} atoms in different spin states existed, resulting in low temperature collisions in the cloud. Such impact in spin coherence of the atom cloud was to be investigated through the simulation.

References

[1] D. F. Phillips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, "Storage of light in atomic vapor," Phys. Rev. Lett., vol. 86, p. 783, 2001.
[2] T. Lepers, D. Davesne, S. Chiaccheira, and M. Urban, "Numerical solution of the Boltzmann equation for the collective modes of trapped Fermi gases," Phys. Rev. A., vol. 82, p. 023609, 2010.

Dynamical decoherence control of atomic spin ensemble

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Decoherence of central spin S in a bath made of sufficiently close I spins leads to loss quantum property of central spin. The coupling between different central spins S and intrabath coupling is neglected. We apply spin flip σ_i at time t_i and $\mathcal{G} = \{\sigma_i\}$. We use controlled randomness in dynamical decoupling for switching off unwanted evolution in interacting quantum systems by proposing a random decoupling setting that uses a random decoupler to encode a logical frame related to physical of and then to spin flip the system randomly over time by following a random control path.

Reference

[1] V. V. Dobrovitski, A. E. Feiguin, D. D. Awschalom, and R. Hanson, *Decoherence Dynamics of single spin versus spin ensemble*, Phys. Rev. B **77**, 245212 (2008).

Quantum particles around near-black hole objects: resonant particle capture, spectrum collapse, and the smooth transition to black hole absorption

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We investigate quantum properties of particles in the gravitational fields of "near black-hole objects": bodi es with radius R that slightly exceeds the Schwarzschild radius r_s. We find that massless quantum particles scattered by the gravitational field of such an object possess a dense spectrum of narrow resonances: a set of long lived metastable states whose lifetimes and density tend to infinity in the black-hole limit $R \to r_s$. The cross-section of particle capture into these resonances at low energy is equal to the absorption cross-section for a Schwarzschild black hole; thus, a non-singular static metric acquires black-hole properties before the actual formation of a black hole [1]. Massive particles also have bound states in the field of these near black-hole objects. In the limit $R \to r_s$ all bound states tend to zero energy and the energy spectrum becomes quasi-continuous. However until there is a singularity in the metric, there are no zero-energy states, and hence no pair production occurs in these systems.

References

[1] V. V. Flambaum, G. H. Gossel, and G. F. Gribakin, accepted to Phys. Rev. D (2012), arXiv:1012.2134.
[2] G. H. Gossel, J. C. Berengut, and V. V. Flambaum, Gen. Rel. Gravit., **43**, 2673 (2011).

Adiabatic evolution of light in parallel curved optical waveguide array

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Adiabatic evolution of light in parallel curved optical waveguide array is theoretically investigated. For two waveguides it has been demonstrated in [1]. This problem is shown to bear a close connection with coherent population transfer in a “bow-tie” model for atoms and molecules. For the presented models complete light transfer between the outer waveguides is achieved, and the respective conditions of validity are given. These conditions impose certain restrictions on the geometry of the waveguides and on the optical properties of the system. The case of three waveguides is analysed using the solutions of the well known bow-tie model. For the case of more than three waveguides the system can be reduced to a number of three-level waveguide sub-systems. The latter is illustrated on the specific example of an array of four waveguides. Analytic results supported by numerics are derived for complete light transfer.

Reference

[1] F. Dreisow, A. Szameit, M. Heinrich, S. Nolte, A. Tünnermann, M. Ornigotti and S. Longhi, *Direct observation of Landau-Zener tunnelling in a curved optical waveguide coupler*, Phys. Rev. A **79**, 055802 (2009).

Circularly polarized emission from ensembles of InGaAs/GaAs quantum rings

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The magnetic-field dependence of the circular polarization evidences the exciton fine structure and helps to determine the anisotropic part of the exciton exchange splitting. This splitting increases from 110 to 160 μeV with increasing the detection energy. This behavior is explained by the fact that the splitting is essentially due to the anisotropic shape in this quantum ring [1]. Symmetry of the QR structures as well as its breaking cause characteristic features in the optical spectra, which are determined by the electron –hole exchange and the Zeeman interaction of the carriers. The symmetry breaking is either inherent to the dot due to geometry asymmetries, or it can be obtained by applying a magnetic field with an orientation different from the ring axis.

Reference

[1] G., Bester *et al.*, Phys. Rev. B 67, 161306(R) (2003).