Leibniz Universität Hannover

Quantum Metrology and Physics beyond the Standard Model

June 12th -14th, 2019
Herrenhausen Palace

Program

VolkswagenStiftung

Program

<table>
<tr><th>Time</th><th>Wednesday,
12 June 2019</th><th>Thursday,
13 June 2019</th><th>Friday,
14 June 2019</th></tr>
<tr><td>09:00</td><td>M. Kasevich</td><td>J. Thompson</td><td>H. Müller</td></tr>
<tr><td>09:40</td><td>W. Schleich</td><td>M. Zych</td><td>K. Jungmann</td></tr>
<tr><td>10:20</td><td>BREAK</td><td>BREAK</td><td>BREAK</td></tr>
<tr><td>10:50</td><td>T. Zelevinsky</td><td>P. Treutlein</td><td>D. Leibrandt</td></tr>
<tr><td>11:30</td><td>M. Mitchell</td><td>D. Budker</td><td>M. Schleier-Smith</td></tr>
<tr><td>12:10</td><td>N. Huntemann</td><td>S. Gleyzes</td><td>S. Schiller</td></tr>
<tr><td>12:50</td><td>LUNCH</td><td>LUNCH</td><td>LUNCH</td></tr>
<tr><td>14:00</td><td>J. Eby</td><td>P. Kunkel</td><td>H. Winter</td></tr>
<tr><td>14:20</td><td>P. Feldmann</td><td>L. Morel</td><td>A. Aloy</td></tr>
<tr><td>14:40</td><td>M. Barrett</td><td>I. Fuentes</td><td>V. Flambaum</td></tr>
<tr><td>15:20</td><td>C. Champenois</td><td>P. Bouyer</td><td>B. Sauer</td></tr>
<tr><td>16:00</td><td>BREAK</td><td>BREAK</td><td>BREAK</td></tr>
<tr><td>16:30</td><td rowspan="2">W. Ubachs</td><td>K. Chabuda</td><td>E. Giese</td></tr>
<tr><td>16:50</td><td rowspan="2">S. Ulmer</td><td rowspan="2">M. Bonneau</td></tr>
<tr><td>17:10</td><td rowspan="2">E. Witkowska</td></tr>
<tr><td>17:30</td><td>J. Crespo López</td><td>S. Abend</td></tr>
<tr><td>17:50</td><td>P. Bushev</td><td></td><td>DEPARTURE</td></tr>
<tr><td>18:10</td><td rowspan="2">DINNER</td><td rowspan="2">DINNER</td><td rowspan="3"></td></tr>
<tr><td>19:00</td></tr>
<tr><td>20:00 –
22:00</td><td>Poster Session I</td><td>Poster Session II</td></tr>
</table>

Talks

Poster Session I (Wednesday)

Poster Session II (Thursday)

Twin-lattice interferometry with thousands of photon recoils

S. Abend[*,1], M. Gebbe[2], M. Gersemann[1], J.-N. Siemss[3], S. Herrmann[2], N. Gaaloul[1], C. Schubert[1], K. Hammerer[3], C. Lämmerzahl[2], W. Ertmer[1] and E. M. Rasel[1]

[*]abend@iqo.uni-hannover.de [1]Institut für Quantenoptik, Leibniz Universität Hannover
[2]Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation, Universität Bremen
[3]Institut für Theoretische Physik, Leibniz Universität Hannover

We investigate a novel interferometer scheme for infrasound gravitational wave detection with atoms. This geometry is based on recent developments in symmetric beam splitters with scalable momentum transfer, relaunching techniques for suspending the atoms against gravity, and delta-kick collimation techniques to generate very slowly expanding atomic ensembles. Today's generation of atomic inertial sensors typically operates with laser cooled atoms released or launched from an optical molasses. The finite temperature and size of these sources limit the efficiency of employed beam splitters and the analysis of systematic uncertainties. These limits can be overcome using high-flux ultracold sources such as a delta-kick collimated Bose-Einstein condensate (BEC) with an extremely narrow velocity distribution [1,2].

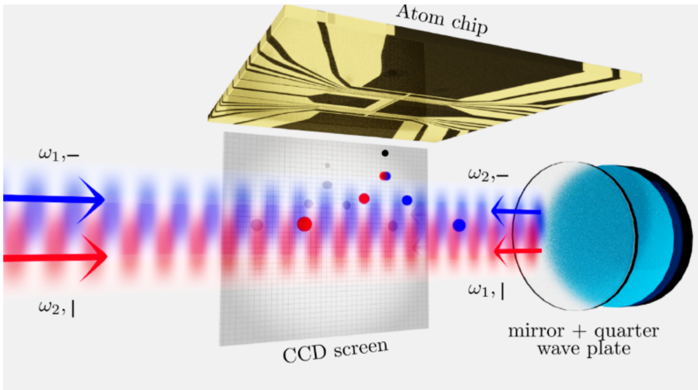


Figure 1. Scheme of the twin lattice generated by a light field of two frequency components retro-reflected of a mirror surface to drive symmetric double Bragg diffraction and Bloch oscillations.

Using condensed atoms from these sources in atom interferometry opens the possibility to implement new methods of coherent manipulation at high fidelity. With the help of Bloch oscillations in an optical lattice combined with a double Bragg diffraction pulse [3,4] we developed a novel coherent relaunch technique in a twin-lattice, a lattice of two frequencies retroreflected at a mirror (fig. 1). This technique allowed for the implementation of a relaunch technique where the atomic ensemble is coherently relaunched on a parabolic trajectory in a single laser beam [5]. Based on symmetric and scalable momentum transfer in the twin-lattice, interferometry with a momentum separation of up to 408 photon momenta is demonstrated, which is to our best knowledge the largest separation in an interferometer reported to date. Achieving these large momentum splittings is one of the cornerstones to reach the necessary sensitivities for gravitational wave detection.

[1] Hauke Müntinga et al., *Interferometry with Bose Einstein Condensates in Microgravity*, Phys. Rev. Lett. **110**, 093602, (2013).
[2] Jan Rudolph et al., *A high-flux BEC source for mobile atom interferometers*, New J. Phys. **17**, 079601, (2015).
[3] Enno Giese et al., *Double Bragg diffraction: A tool for atom optics*, Phys. Rev. A **88**, 053608, (2013).
[4] Holger Ahlers et al., *Double Bragg Interferometry*, Phys. Rev. Lett. **116**, 173601, (2016).
[5] Sven Abend et al., *Atom-Chip Fountain Gravimeter*, Phys. Rev. Lett. **117**, 203003, (2016).

Device-independent entanglement depth witness from two-body correlators

A. Aloy[1], J. Tura[2], F. Baccari[1], A. Acín[1,3], M. Lewenstein[1,3], R. Augusiak[4]
[1]ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain
[2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany
[3]ICREA. Pg. Lluis Companys 23, 08010 Barcelona, Spain
[4]Center for Theoretical Physics, Polish Academy of Sciences, Aleja Lotników 32/46, 02-668 Warsaw, Poland

Some subset of entanglement present correlations which are strong enough as to violate a Bell inequality, which manifests non-local correlations. We consider the characterization of many-body systems by making use of such non-local correlations. In general, multipartite Bell inequalities are hard to treat from both computational and experimental points of view. However, in [1] researchers presented Bell inequalities involving only one- and two-body correlation functions and constrained by symmetry. Such Bell inequalities have been proven to be experimentally feasible resulting in the detection of Bell correlations in a Bose-Einstein condensate of 480 particles reported in [2].
Furthermore, we have recently shown in [3,4] that the non-local correlations detected by such Bell inequalities can be used to characterize the amount of entanglement present on a many-body system. In particular we use them to construct a Device-Independent Witness of Entanglement Depth (DIWED). That is, a witness that certifies how many particles are genuinely entangled without relying on assumptions on the system nor on the measurements performed. As illustrated in (fig. 1), one ends up with a hierarchy of bounds whose violation provides certification of the depth of entanglement.
Finally, in recent unpublished advances, we are using the presented toolset in order to look at the role of non-local correlations near quantum critical points and how non-local correlations can be used to characterize such situations.

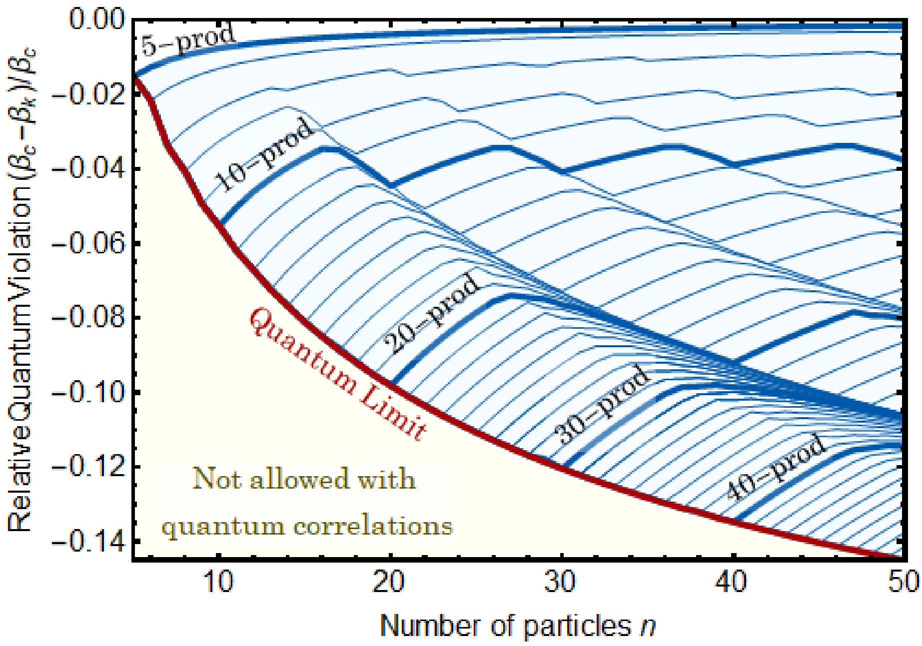


Figure 1. Example of DIWED bounds that can be achieved out of a 2-body Permutation Invariant Bell inequality. Each line represents a *k*-producible bound, the violation of which assures that at least *k*+1 particles are entangled.

[1] J. Tura, R. Augusiak, A. Acín, M. Lewenstein, *Detecting nonlocality in many-body quantum states,* Science, **344**, 1256 (2014).
[2] R. Schmied, J-D. Bancal, B. Allard, M. Fadel, V. Scarani, P. Treutlein and N. Sangouard, *Bell correlations in a Bose-Einstein condensate,* Science, **352**, 6284 (2016).
[3] A. Aloy, J. Tura, F. Baccari, A. Acín, M. Lewenstein and R. Augusiak, *Device-independent witness of entanglement depth from two-body correlators,* arXiv, 1807.06027 (2018).
[4] J. Tura, A. Aloy, F. Baccari, A. Acín, M. Lewenstein and R. Augusiak, *Optimization of device-independent witnesses of entanglement depth from two-body correlators,* arXiv, 1903.09533 (2019).

Controlling inhomogeneous broadening in a multi-ion optical clock

K. J. Arnold[1], R. Kaewuam[1], R. C. Sapam[1], T. R. Tan[1,2], Z. Zhiqiang, M. D. Barrett[1,2]

[1]Center for Quantum Technology, National University of Singapore, 3 Science Drive 2, Singapore 117543.

[2]Department of Physics, National University of Singapore, 2 Science Drive 3, Singapore 117551.

Abstract: we report a first series of experiments demonstrating the measurement and control of inhomogeneous broadening in a multi-ion optical clock using singly ionized lutetium ($^{176}Lu^+$). Lutetium is a unique clock candidate supporting a total of three clock transitions: a highly forbidden M1 transition at 848nm ($^1S_0$-$^3D_1$), a spin-forbidden E2 transition at 804nm ($^1S_0$-$^3D_2$), and an E2 transition at 577nm ($^1S_0$-$^1D_2$), [1,2,3]. A technique of hyperfine averaging eliminates shifts arising from the electronic angular momentum [1], which realizes an effective J=0 to J=0 transition in each case. For each clock transition the remaining systematics compare favorably to other leading clock candidates [4]. However, within the context of a multi-ion implementation, clock shifts eliminated by hyperfine averaging are a source of inhomogeneous broadening. Such broadening can diminish the effectiveness of the averaging and result in a shift of the clock transition. The main sources of broadening result from magnetic field inhomogeneity and the quadrupole shifts induced from neighboring ions. Using microwave spectroscopy within the $^3D_1$ manifold we demonstrate that the inhomogeneity can be measured and heavily suppressed. The low magnetic sensitivity of $^3D_1$ m=0 clocks states permit microwave Ramsey spectroscopy with interrogation times of several seconds. This allows high-resolution measurement of relative quadrupole shifts between ions and precise alignment of the magnetic field relative to the crystal axis to null this inhomogeneity. Additionally, microwave correlation spectroscopy on magnetic-field-sensitive states provides a high-resolution measurement of magnetic field gradients. Using these techniques we demonstrate suppression of inhomogeneity at the mHz level, limited only by the Ramsey time used. In addition, we use correlation spectroscopy on the optical transition to demonstrate atomic coherence out to ~10s within a three-ion crystal. This work demonstrates the feasibility of a multi-ion clock with $^{176}Lu^+$.

[1] M. D. Barrett, New J. Phys., **17** (5), 053024, (2015).
[2] Eduardo Paez, et al. Phys. Rev. A, **93** (4), 042112, (2016).
[3] R. Kaewuam, A. Roy, T. R. Tan, K. J. Arnold, and M. D. Barrett, J. Mod. Opt., **65** (5-6), 592, (2017).
[4] K. J. Arnold, R. Kaewuam, A. Roy, T. R. Tan, and M. D. Barrett, Nat. Comm., **9**, 1650, (2018).

Emitting atom pairs in strongly correlated momentum states

M. Bonneau[1], F. Borselli[1], M. Maiwöger[1], P. Haslinger[1], T. Zhang[1], J. Schmiedmayer[1]
[1]Atominstitut, TU Wien, Stadionallee 2, 1020 Wien, Austria.
Vienna Center for Quantum Science and Technology.

We are developing in Vienna a source of momentum-entangled twin atoms. Twin atoms are the atomic analog of the twin photons generated through parametric down-conversion, which are widely used in optical quantum technologies.
Twin atoms are emitted from a source Bose-Einstein condensate (BEC) through an atomic four-wave mixing process, where the non-linearity is provided by the interatomic interactions. The geometry of the experiment sets the phase-matching conditions and therefore defines the signal and idler modes populated by the atoms. Over the past years it was experimentally demonstrated that twin atoms share some properties with twin photons: their relative intensity is squeezed and they exhibit momentum correlations [1]. We report here the emission of twin atom beams in a double-well trapping potential, a geometry where the twin beams are expected to be Bell-entangled (see fig. 1).
We trap and manipulate the atoms with an atom chip, which consists of a surface with micro-fabricated structures generating magnetic fields. It permits implementing fast and accurate deformations of the magnetic potential. With the atom chip we perform high-fidelity quantum optimal control of the BEC's motional state [2]. We thus initialize the twin-atom source. We then characterize the correlation properties of the emitted twin atoms.

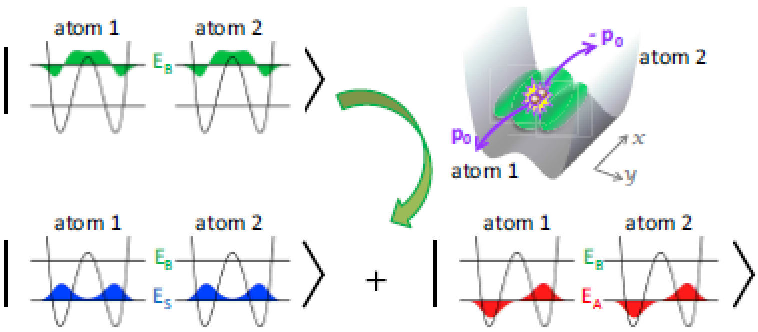


Figure 1. When a BEC is prepared in the second excited state of the double-well potential (in green), four-wave mixing occurs. The outputs modes have opposite momenta $\pm p_0$ along the weakly trapping x axis, and, due to conservation of the spatial wave-function parity, can only be either both in the ground state (in blue) or both in the first excited state (in red) of the double-well potential [3].

[1] R. Bücker et al., *Twin-atom beams*, Nat. Phys. **7**, 608–611 (2011).
[3] S. Van Frank et al., *Optimal control of complex atomic quantum systems*, Sci. Rep. **6**, 34187 (2016)
[2] M. Bonneau et al., *Characterizing twin-particle entanglement in double-well potentials*, Phys. Rev. A **98**, 033608 (2018)

Airborne and underground matter-wave interferometers: geodesy, navigation and general relativity

P. Bouyer[1]

[1]*LP2N, IOA, Rue François Mitterrand, F-33400, Talence*

The remarkable success of atom coherent manipulation techniques has motivated competitive research and development in precision metrology. Matter-wave inertial sensors – accelerometers, gyrometers, gravimeters – based on these techniques are all at the forefront of their respective measurement classes. Atom inertial sensors provide nowadays about the best accelerometers and gravimeters and allow, for instance, to make the most precise monitoring of gravity or to device precise tests of the weak equivalence principle (WEP). I present here some recent advances in these fields:

The outstanding developments of laser-cooling techniques and related technologies allowed the demonstration of an airborne matter-wave interferometers, which operated in the micro-gravity environment created during the parabolic flights of the Novespace Zero-g aircraft. Using two atomic species (for instance ^{39}K and ^{87}Rb) allows to verify that two massive bodies will undergo the same gravitational acceleration regardless of their mass or composition, allowing a test of the Weak Equivalence Principle (WEP).

New concepts of matter-wave interferometry can be used to study sub Hertz variations of the strain tensor of space-time and gravitation. For instance, the MIGA instrument, which is currently built in France, will allow the monitoring of the evolution of the gravitational field at unprecedented sensitivity, which will be exploited both for geophysical studies and for Gravitational Waves (GWs) detection.

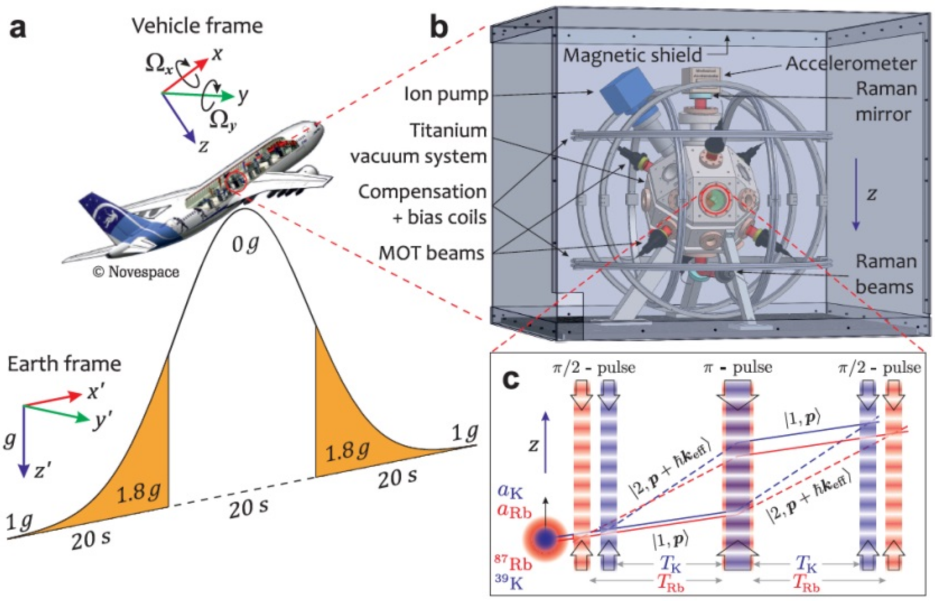


Figure 1. Test of the equivalence principle with 2 atomic species in the weighlessness environement of the 0-g AIRBUS

Magnetometry and light on dark

D. Budker[1,2]
[1]Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany
[2]Department of Physics, University of California, Berkeley, USA

I will provide an overview of the recent activities of our group and collaborators [1,2] on magnetic sensing, including applications to detection of zero- and ultralow-field nuclear magnetic resonance (ZULF NMR) and searching for ultralight bosonic dark matter.

[1] https://budker.uni-mainz.de/
[2] http://budker.berkeley.edu/

Testing of Quantum Gravity with ~kg scale acoustic resonators

A.P. Bushev[1], J. Bourhill[2], M. Goryachev[2], E.Ivanov[2], N. Kukharchyk[1],
B.S. Galliou[3], M. Tobar[2] and S. Danilishin[4]
[1]Experimental physics, Saarland University, 66123 Saarbrücken, Germany.
[2]ARC Centre of Excellence EQuS, University of Western Australia, 6609 Crawley, Australia.
[3]FEMTO-ST Institute, Universite of Bourgogne Franche-Comte, 25000 Besancon, France.
[4]Albert-Einstein Institute, Hannover University, 30167 Hannover, Germany.

Historically, the development of quantum mechanics was driven largely by key experimental observations such as blackbody radiation, the photoelectric effect, and atomic spectra, that were at complete odds with predictions made by the (classical) theoretical understanding of the time. At present, one of the grandest challenges of physics is to unite its two most successful theories — quantum mechanics (QM) and general relativity (GR) — into a single unified mathematical framework. Attempting this unification has challenged theorists and mathematicians for several decades and numerous works have highlighted the seeming incompatibility between QM and GR. It was generally supposed that this requires energies at the Planck scale and so beyond the reach of current laboratory technology. However, in the relatively recent publication, I. Pikovsky et al. [1] proposed a new way of testing a set of quantum gravity (QG) theories by using witty interferometric measurement of an optomechanical system. The prediction of most of the QG theories (such as, string theory) and the physics of black holes lead to the existence of the minimum measurable length set by the Plank length. This results in the modification of the Heisenberg uncertainty principle and as consequence leads also to the modification of the fundamental commutator for harmonic oscillator [2]. The latter is equivalent to the non-linear modification of the Hamiltonian and results in the dependence of the oscillator resonance frequency on its energy [3]. The dynamics of the system can be described by a well-known Duffing oscillator model for which an amplitude dependence of the resonance frequency, i.e. so-called amplitude-frequency effect, is one of its distinctive features.

By implementing of this new method, we measure amplitude frequency effect for 0.3 kg ultra-high-Q sapphire split-bar mechanical resonator and for mg scale quartz bulk acoustic wave resonator. Our experiments with sapphire resonator have established the upper limit on quantum gravity correction constant of $\beta_0 < 5 \times 10^6$, which is factor of 6 better than previously measured [4]. The reasonable estimates of β_0 from experiments with quartz resonators yields even more stringent limit of $\beta_0 < 4 \times 10^4$. The heavier oscillators and more precise measurements will allow for the better determination of the correction strength. Therefore, the remarkable high-Q and frequency stability of state of the art quartz BAW resonators and SB sapphire resonator in conjunction with low acoustic non-linearities have a great potential for its further applications in precise tests of minimal length scale scenarios for the quantum gravity theories in the regime $\beta_0 \lesssim 1$.

[1] I. Pikovsky et al.,*Probing Planck-scale physics with quantum optics*, Nat. Phys. **8**, 393 (2012).
[2] S. Hossenfelder, *Experimental search for Quantum Gravity* (Springer, Cham 2018)
[3] M. Bawaj et al., *Probing deformed commutators with macroscopic harmonic oscillators,* Nat. Comm. **6**, 7503 (2015).
[4] P. Bushev et al., Testing of Quantum gravity with sub-kilogram acoustic oscillators, arXiv:1903.03346 (2019).

Tensor Networks for Quantum Metrology

K. Chabuda[1], J. Dziarmaga[2], T. J. Osborne[3], R. Demkowicz-Dobrzański[1]
[1]Faculty of Physics, University of Warsaw, ul. Pasteura 5, PL-02-093 Warszawa, Poland.
[2]Institute of Physics, Jagiellonian University, Łojasiewicza 11, PL-30348 Kraków, Poland.
[3]Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstr. 2, 30167 Hannover, Germany.

Abstract: we provide a comprehensive framework exploiting matrix product operators (MPO) type tensor networks for quantum metrological problems. The MPO formalism allows for spatial and temporal noise correlations, in particular, one may determine the maximal achievable estimation precision in such models, as well as the optimal probe states in previously inaccessible regimes. Moreover, the application of infinite MPO (iMPO) techniques allows for a direct and efficient determination of the asymptotic precision of optimal protocols in the limit of infinite particle numbers. We illustrate the potential of our framework in terms of an atomic clock stabilization (temporal noise correlation) example as well as for magnetic field sensing in the presence of locally correlated magnetic field fluctuations (spatial noise correlations). As a byproduct, the developed methods for calculating the quantum Fisher information via MPOs may be used to calculate the fidelity susceptibility - a parameter widely used in many-body physics to study phase transitions.

Experimental Demonstration of a Terahertz Frequency Reference based on CPT in a Trapped Ion Cloud

M. Collombon, C. Chatou, G. Hagel, J. Pedregosa-Gutierrez, M. Houssin, M. Knoop and C. Champenois

Aix Marseille Univ, CNRS, PIIM, Marseille, France

The quantum interferences responsible for coherent population trapping (CPT) are an example of a quantum effect which is ressource for high precision measurement. Two-photon CPT has proven its relevance for spectroscopy of the GHz transition between hyperfine sublevels. We propose to use a three-photon CPT to reach spectroscopy in the THz domain, which is so far associated to rotation transitions in light molecules. The existence of a highly resolved dark line referenced to a magnetic dipole transition at 1.82~THz is observed in the laser induced fluorescence of a cloud of calcium ions, like proposed in [1]. This dark resonance results from CPT involving three optical photons at 397, 729 and 866 nm [2]. When fulfilled, the three-photon resonance condition implies a relation between the three laser frequencies and the frequency of the 1.82 THz magnetic dipole transition between the two fine-structure terms of the 3D level, which appears as the atomic reference for the dark line.

Basing a THz reference on three optical photons allows the cancellation of the first order Doppler effect by a phase matching condition involving the three laser wavevectors. We now observe a dark line with a resolved Zeeman structure, a maximum contrast of 21 % and a minimum line-width of 45~kHz in the fluorescence of a cloud made of few hundreds laser-cooled ions. The line-width is so far dominated by residual Doppler effect and fluctuations of the local magnetic field. Such a large contrast and narrow line require to maintain a phase coherence between the three lasers. This phase coherence is transferred to the 866 and 397 nm lasers from a home-made ultra-stable Ti:Sa laser emitting at 729 nm, through an offset-free optical frequency comb (OFC), phase-locked on this ultra- stable laser [3]. Very similar to 2-photon CPT, the interrogation protocole depends on numerous parameters that we have started to explore to reach sub-kHz line-width [4]. Even with a kHz line- width, the large signal to noise ratio offered by hundreds of laser-cooled ions allows the resolution to reach the 10-11 range by averaging data over seconds.

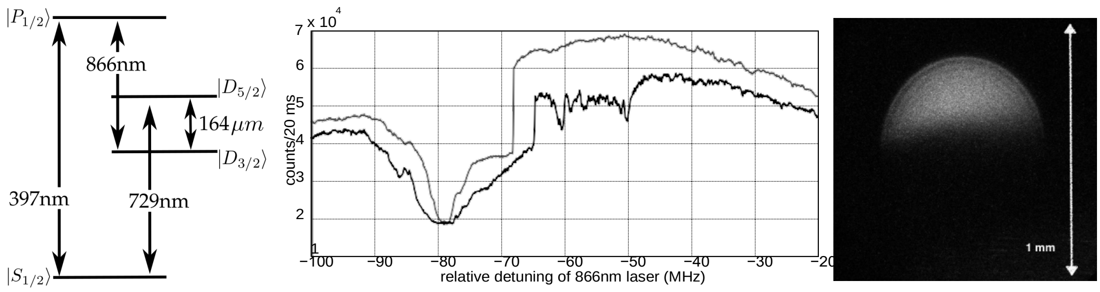


Figure 1. level scheme relevant for a three-photon CPT in Ca+, fluorescence collected from a cloud made of 630 ions, without (grey curve) and with (black curve) the 729 nm laser, picture of the cloud, showing that the sympathetic cooling is maintaining the cloud in the liquid phase, despite the radiation pressure which tends to separate the dark and bright ions.

[1] C. Champenois, G. Morigi and J. Eschner, Physical Review A 74 053404 (2006)

[2] C. Champenois *et. al*, *Terahertz Frequency Standard Based on Three-Photon Coherent Population Trapping*, Phys. Rev. Lett. 99, 013001 (2007).

[3] M. Collombon et. al, *Phase transfer between three visible lasers for coherent population trapping*, Optics Letters Vol. 44, No. 4 , 15 February 2019

[4] M. Collombon, et. al, *Experimental Demonstration of a Terahertz Frequency Reference based on Coherent Population Trapping*, arXiv:1903.05386 [quant-ph]

Possibilities for spectroscopic BSM physics tests with highly charged ions in the VUV region

J. R. Crespo López-Urrutia[1], J. Nauta[1], J. Oelmann[1], C. Warnecke[1], S. Bogen[1], J. Stark[1], P. O. Schmidt[2], T. Pfeifer[1]

[1]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany.

[2]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany.

Electronic states of highly charged ions (HCI) show enormously magnified fine-structure, Lamb shift and hyperfine effects making them exceptionally sensitive probes of bound-state quantum electrodynamics and nuclear physics. Being also impervious to external perturbations renders them ideal candidates for precision spectroscopy, and they can serve as frequency references in accurate clocks that could test physics beyond the Standard Model [1]. A variety of ion species and transitions can optimally be tailored to target such applications and handle them in the laboratory. With the demonstration of sympathetic cooling of HCI [2], such experiments have recently become possible. Moreover, extensions of current experiments into the vacuum-ultraviolet (VUV) region are interesting [3], since HCI with- stand single and multi-photon photoionization, and possess forbidden transitions at those energies. We are developing a VUV frequency comb and a superconducting RF linear trap for such studies (fig. 1).

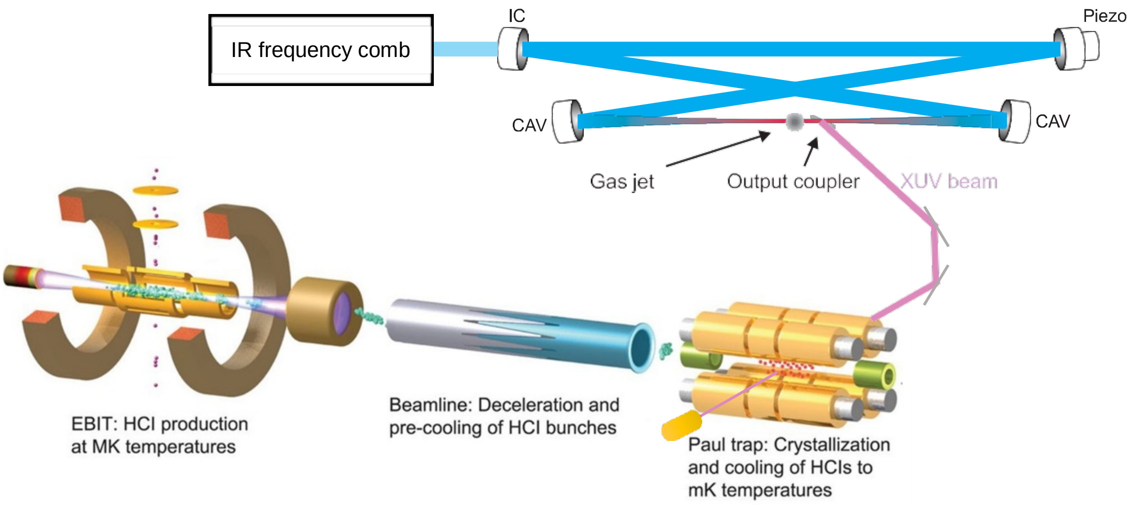


Figure 1. Scheme of an experiment combining a VUV frequency comb based on high-harmonic generation within an enhancement cavity with a RF trap for highly charged ions.

[1] M. G. Kozlov *et al.*, *Highly charged ions: Optical clocks and applications in fundamental physics*, Reviews of Modern Physics **90**, 045005 (2018).
[2] L. Schmöger *et al.*, *Coulomb crystallization of highly charged ions*, Science **347**, 1233 (2015).
[3] J. Nauta *et al.*, *Towards precision measurements on highly charged ions using a high harmonic generation frequency comb*, Nucl. Instrum. Meth. Phys. Res. B **408** 285 (2017).

Relaxion Dark Matter Detection via Atomic Physics

A. Banerjee[1] , D. Budker[2,3] , J. Eby[1], H. Kim[1] , G. Perez[1]

[1] Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 761001, Israel

[2] Helmholtz Institute Mainz, Johannes Gutenberg University, Mainz 55099 Germany

[3] Department of Physics, University of California, California 947207300, USA

The cosmological relaxion particle can address simultaneously two important problems in particle physics: the hierarchy problem related to the Higgs mass, and the dark matter problem. Due to its scalar couplings to matter, the coherent oscillations of the relaxion induce variation of the fundamental constants of nature, and can be probed using table-top atomic physics experiments. In our work [1], we postulate that relaxions can form compact objects in the galaxy, which enhance the local density of dark matter and enhance detection prospects. I will describe the current and near-future reach of such experimental tests of relaxion dark matter. Atomic physics experiments can already probe solutions to fundamental particle physics and astrophysics problems at present, and will do so with much higher sensitivity in the near future.

[1] A. Banerjee, D. Budker, J. Eby, H. Kim, and G. Perez, *Relaxion Stars and their detection via Atomic Physics*. arXiv: 1902.08212

Entanglement, interferometric sensitivity, and macroscopic superposition states by scanning through quantum phase transitions in spinor Bose-Einstein condensates

P. Feldmann[1], L. Pezzè[2], M. Gessner[3], M. Gabbrielli[2,4],
C. Klempt[5], L. Santos[1], A. Smerzi[2]
[1]Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany
[2]QSTAR, INO-CNR, and LENS, Largo Enrico Fermi 2, 50125 Firenze, Italy
[3]Laboratoire Kastler Brossel, École Normale Supérieure, 24 Rue Lhomond, 75005 Paris, France
[4]Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze,
via Sansone 1, 50019 Sesto Fiorentino, Italy
[5]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

Spinor Bose Einstein condensates (BECs) exhibit different ground state phases, when a tunable magnetic field or microwave dressing is applied as a control parameter. Some of them are experimentally well accessible. Others, in contrast, feature strong multipartite entanglement. Thus, driving the system from the former to the latter is a promising approach to the preparation of exciting, highly entangled many-body states. That this can be put into practice, though the gap between the ground state and the first excited state closes at the critical points, has been recently demonstrated in [1,2].

Encouraged by these results, which have been obtained within the F=1 manifold of ^{87}Rb, we have elaborated on the opportunities offered by the quasi-adiabatic crossing of quantum phase transitions (QPTs) in a ferromagnetic spin-1 BEC. For separable states the sensitivity of atom interferometers is fundamentally limited by the standard quantum limit (SQL), which scales as $N^{-1/2}$ with the particle number N. Employing multipartite entanglement allows to shift this bound towards the Heisenberg limit $\sim N^{-1}$. Entanglement that facilitates to surpass the SQL is unambiguously witnessed by the quantum Fisher information (QFI, F_Q). An evaluation of the QFI across all three ground state phases of a ferromagnetic spin-1 BEC unveils an intriguing regime, the state in the center of the broken axisymmetry phase (CBA state), which provides Heisenberg scaling of the QFI and is separated from the initial experimental state by only one QPT. We identify the optimal way of phase imprinting and the optimal measurement prescription to maximize the interferometric sensitivity as experimentally well accessible operations.

Investigating why the CBA state is so particularly sensitive leads up to an unexpected connection to macroscopic superposition (MS) states. A spin-1 system accommodates three magnetic modes, labeled by m_F in {1, 0, -1}. By a change of basis achievable by collective radio-frequency and microwave manipulations, $m_F = 1$ and $m_F = -1$ can be transformed into their (anti)symmetric combinations tagged by g (h). As illustrated in fig. 1, projecting the CBA state onto the particle number in one of these modes, say N_h, mostly yields highly entangled two-mode states resembling NOON states. The large contribution of suitable N_h to the CBA state allows for a probabilistic preparation of MS states being heralded by N_h.

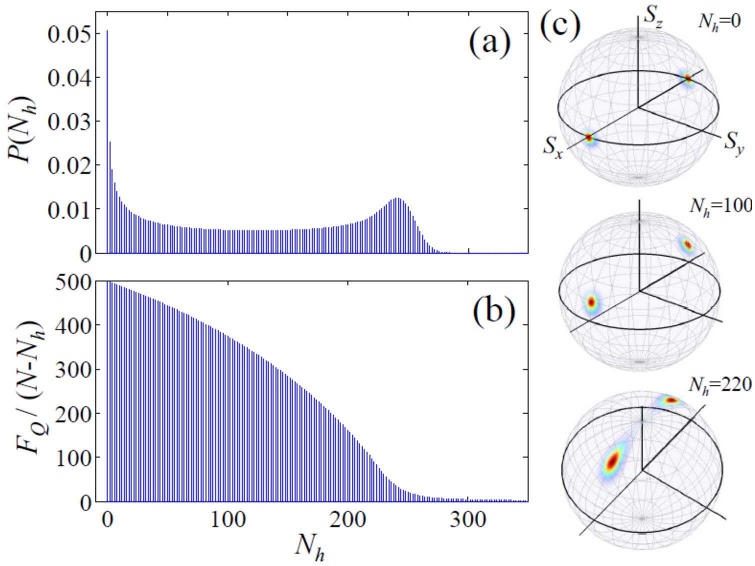


Figure 1. Macroscopic superposition states accommodated by the CBA state of a spin-1 BEC. N_h is the particle number in the antisymmetric mode. (a) With high probability P a measurement of N_h results in a state with (b) large quantum Fisher information F_Q. (c) The Husimi distribution of the projected two-mode states resembles NOON states. Here N=500.

A crucial question regarding the preparation of MSs is its stability. For N=100 particles, we include particle losses during a quasi-adiabatic driving at finite speed as well as a finite precision of the N_h measurement into our analysis. We show that both a large FI and the MS features are well preserved under realistic conditions. Sub-SQL interferometry with the CBA state has by now been demonstrated in [2]. This further emphasizes that the preparation of MS states in spin-1 BECs is brought into reach of current technology by the high stability of the enclosing CBA state.

[1] Xin-Yu Luo, Yi-Quan Zou, Ling-Na Wu, Qi Liu, Ming-Fei Han, Meng Khoon Tey, and Li You, *Deterministic entanglement generation from driving through quantum phase transitions, Science* **355**, 620-623 (2017)

[2] Yi-Quan Zou, Ling-Na Wu, Qi Liu, Xin-Yu Luo, Shuai-Feng Guo, Jia-Hao Cao, Meng Khoon Tey, and Li You, *Beating the classical precision limit with spin-1 Dicke states of more than 10,000 atoms,* PNAS **115** (25), 6381-6385 (2018)

[3] P. Feldmann, M. Gessner, M. Gabbrielli, C. Klempt, L. Santos, L. Pezzè, and A. Smerzi, *Interferometric sensitivity and entanglement by scanning through quantum phase transitions in spinor Bose-Einstein condensates,* Phys. Rev. A **97**, 032339 (2018)

[4] **L. Pezzè, M. Gessner, P. Feldmann, C. Klempt, L. Santos, and A. Smerzi,** *Heralded Generation of Macroscopic Superposition States in a Spinor Bose-Einstein Condensate,* arXiv: 1712.03864 **(2017)**

Effects of dark matter, variation of the fundamental constants and violation of the fundamental symmetries in nuclei, atoms and molecules

V.V. Flambaum[1,2]
[1]School of Physics, University of New South Wales, Sydney 2052
[1]Helmholtz Institute, J. Gutenberg University, 55099, Mainz, Germany

Low-mass boson dark matter particles form classical field and produce effects linear in the interaction strength. This may give an enormous advantage since in a traditional experiments effects are of the fourth or second power. Interaction with dark matter produces cosmological evolution and oscillating variation of the fundamental constants (fine structure constant, electron, proton and qurk masses) and oscillating effects of apparent violation of symmetries (parity, time reversal, Lorentz invariance, Einstein equivalence principle). Atomic spectroscopy measurements, the primordial helium abundance data and electric dipole moment (EDM) measurements allowed us to improve limits on the interaction of dark matter with photon, gluon, electron, quarks, Z, W and Higgs bosons up to 15 orders of magnitude [1-3]. The effects are strongly enhanced in nuclear [4,5] and highly charged ion clocks [6].

Using ^{21}Ne spectroscopy we improved limits on the anisotropy of the speed of light by 7 orders of magnitude [7]. Thousand times enhanced effects of parity and time reversal invariance (EDM) in ^{229}Th-containing molecules have been suggested [8]. New theorem about dynamical screening of the external oscillating field on atomic nucleus has been derived and effects of such field as well as new effects of oscillating dark matter field in atoms, molecules and nuclei have been considered [9-11].

[1] Y. V. Stadnik, V. V. Flambaum. Phys. Rev. Lett. **115**, 201301 (2015)
[2] Y. V. Stadnik, V. V. Flambaum, Phys. Rev. **A 94**, 022111, (2016).
[3]. G. Abel et al. Phys. Rev. X, 7, 041034 (2017)
[4]. V.V. Flambaum. Phys. Rev. Lett. **97**, 092502 (2006).
[5] V.V. Flambaum. Phys. Rev. Lett. **117**, 072501 (2016).
[6] J. C. Berengut, V. A. Dzuba, V. V. Flambaum, Phys. Rev. Lett. **105**, 120801 (2010)
[7] V.V. Flambaum, M.V. Romalis, Phys. Rev. Lett. **118**, 142501 (2017).
[8] V.V. Flambaum. Phys. Rev. C 99, 035501 (2019)
[9] V.V. Flambaum. Phys. Rev. A98, 99, 043408 (2018)
[10] V.V. Flambaum, I. B. Samsonov, Phys. Rev. A98, 053437 (2018).
[11] H. B. Tran Tan, V. V. Flambaum, I. B. Samsonov, Phys. Rev. A99, 013430 (2019).

Collective excitations as quantum sensors for fundamental physics

I. Fuentes
School of Mathematical Sciences, University of Nottingham, University Park NG72QD, UK.

Quantum sensors that are used to measure gravitational fields and detect dark energy typically use single particle interferometric techniques that are limited by the time of flight in the interferometer arm. In this talk I will present a new detection method that uses quantum resonances and the sensitivity of collective excitations (phonons) to gravitational fields. When phonons in a Bose-Einstein condensate are initially prepared in a squeezed state, spacetime distortions can create additional excitations through parametric amplification. This effect can be used to detect gravitational waves at high frequencies. We have also developed a phonon based scheme to estimate spacetime parameters, miniaturize devices to measure gravitational fields and gradients and set further constrains on dark energy models.

Twin paradox in atom interferometers

E. Giese[1], S. Loriani[1], A. Friedrich[1] and the Hannover-Ulm team[1,2]
[1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ^{ST}),
Universität Ulm, Albert-Einstein-Allee 11, D-89069 Ulm, Germany.
[1]Institut für Quantenoptik, Leibniz Universität Hannover,
Welfengarten 1, D-30167 Hannover, Germany.

Atom interferometry has become an excellent tool for high-precision quantum metrology as well as a testbed for the interface of relativity and quantum mechanics. On the other hand, quantum systems in the form of atomic clocks are routinely employed in tests of special and general relativity. The combination of atom interferometry and atomic clocks in terms of quantum-clock interferometry [1, 2] is a promising candidate for the investigation of special and general relativistic effects with and on quantum objects.
Proper time determines the phase of matter waves, such that atom interferometers are in principle susceptible to special-relativistic and gravitational time dilation. Hence, it is conceivable that light-pulse atom interferometers measure general-relativistic time-dilation effects. However, the kinetic symmetry of the interferometer determines whether proper time differences have an impact on the measured interference pattern. We show which type of light-pulse atom interferometers, performed with a single internal atomic state, are sensitive to time dilation. Only geometries that entail the special-relativistic twin paradox display it, whereas gravitational effects do not contribute in lowest order. In such a configuration, recoil measurements that can be used for the determination of the fine structure constant are sensitive to proper-time differences [3, 4, 5].
When each of the two quantum twins in such a setup carries a superposition of two internal states which constitute a clock, the visibility of the signal is modulated, which can be interpreted as a beating of the interferometers associated with each state. We propose a specific geometry for a quantum clock experiment that displays a genuine implementation of the twin paradox in light-pulse atom interferometry and isolates the effect.

[1] M. Zych, F. Costa, I. Pikovski, and Č. Brukner, *Quantum interferometric visibility as a witness of general relativistic proper time*, Nat. Commun. **2**, 505 (2011).
[2] A. Roura, arXiv 1810.06744, *Gravitational redshift in quantum-clock interferometry,* (2018)
[3] R. Bouchendira, P. Cladé, S. Guellati-Khélifa, F. Nez, and F. Biraben, *New Determination of the Fine Structure Constant and Test of the Quantum Electrodynamics*, Phys. Rev. Lett. **106**, 080801 (2011).
[4] S.-Y. Lan, P.-C. Kuan, B. Estey, D. English, J. M. Brown, M. A. Hohensee, and H. Müller, *A Clock Directly Linking Time to a Particle's Mass,* Science **339**, 554–557 (2013).
[5] R. H. Parker, C. Yu, W. Zhong, B. Estey, and H. Müller, *Measurement of the fine-structure constant as a test of the Standard Model*, Science **360**, 191–195 (2018).

Quantum metrology with Rydberg atoms

S. Gleyzes[1], A. Larrouy[1], S. Patsch[2], R. Richaud[1],
J.M. Raimond[1], M. Brune[1], and C. Koch[2]
[1]Laboratoire Kastler Brossel, College de France, CNRS, ENS-Universite PSL, Sorbonne Universite, 11 Place Marcelin Berthelot, 75005 Paris, France
[2]Theoretical Physics, University of Kassel, Heinrich-Plett-Straße 40, 34132 Kassel, Germany

Rydberg atoms are extremely sensitive to their electromagnetic field environment, which make them a very promising tools for metrology [1,2]. Rydberg atoms can be described by the model of the hydrogen atom. By applying a small static electric field, it is possible to partially lift the degeneracy between same *n* levels. The new sublevels form a regular structure. It is possible to manipulate the state of the atom using an rf field with a well-defined polarization to prepare states with large electric or magnetic dipole. In our experiment, we generate Schrödinger cat states of the Rydberg atom of rubidium by preparing quantum superposition of two trajectories with very different classical property. The relative phase of the superposition is very sensitive to the variations of the probe environment, which allows us to measure electric or magnetic field with a very good sensitivity. However, the preparation fidelity is limited by the actual energy structure of rubidium, which is much more anharmonic than that of hydrogen. I will show how implementing RF pulse shape that have been optimized by the University of Kassel using Optimal Control Theory allowed us to drastically improve the efficiency of our pulses.

[1] A. Facon, E. K. Dietsche, D. Grosso, S. Haroche, J.-M. Raimond, M. Brune et S. Gleyzes, *A sensitive electrometer based on a Rydberg atom in a Schrödinger cat state*, Nature, **532**, 262 (2016)
[2] E.K. Dietsche, A. Larrouy, S. Haroche, J.M. Raimond, S. Gleyzes, *High-sensitivity magnetometry with a single atom in a superposition of two circular Rydberg states*, Nature Physics, (doi 0.1038/s41567-018-0405-4) (2019)

Optical Clock Comparisons searching for Physics beyond the Standard Model

N. Huntemann, M. A. Hafiz, A. Al-Masoudi, E. Benkler, S. Dörscher, R. Lange, T. Legero, B. Lipphardt, C. Lisdat, E. Peik, J. Rahm, C. Sanner, R. Schwarz, H. Shao, U. Sterr, C. Tamm, S. Weyers

Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany.

We report on direct frequency comparisons of optical clocks based on different reference transitions. At PTB, we realize the $^2S_{1/2}$ – $^2D_{3/2}$ electric quadrupole (E2) and $^2S_{1/2}$ – $^2F_{7/2}$ electric octupole (E3) transition frequency using a single $^{171}Yb^+$ ion. For the E3 transition frequency systematic uncertainties as low as 3×10^{-18} have been achieved [1]. These ion-based clocks have been compared to Sr lattice clocks that use the $^1S_0$ – $^3P_0$ transition of ^{87}Sr atoms confined in an optical lattice near the magic wavelength as the reference [2]. Besides the comparison between optical clocks, their frequencies were also measured using caesium fountain clocks [3].

Data acquired over the last years permit not only a validation of clock uncertainties, but also allow for searches for so-called "new physics", because of the very different sensitivity of the reference transitions on the fine structure constant α. Furthermore, the optical to microwave comparison enables tests for possible temporal variations in the proton-to-electron mass ratio μ.

We will give an overview of the acquired data and show how they can be used to improve existing limits on a potential temporal linear drift in α and μ. Focusing on a possible oscillatory behavior in the data, we can substantially improve previous work on a possible α mediated coupling to dark matter.

[1] C. Sanner, *et al.*, *Optical clock comparison for Lorentz symmetry testing*, Nature **567**, 204 (2019).
[2] C. Grebing, *et al.*, *Realization of a timescale with an accurate optical lattice clock,* Optica **3**, 563 (2016).
[3] S. Weyers, *et al.*, *Advances in the accuracy, stability, and reliability of the PTB primary fountain clocks,* Metrologia **55**, 789 (2018).

Search for Parity and Time Reversal Violation in Atoms and Molecules

K. P. Jungmann
Van Swinderen Institute, University of Groningen, Groningen, The Netherlands

Precise measurements of discrete symmetry violations in atomic and molecular systems enable stringent tests of the Standard Model in Particle Physics. Possible extensions to it, which were proposed in order to provide explanations for reliably observed, yet fully unexplained facts, such as the nature of discrete symmetry violations or the number forces and number of particle generations. We will discuss progress in a project aiming to obtain a most precise value for the Weinberg angle ($\sin^2 \theta_W$) from precise spectroscopy on single trapped Ba^+ ions. This will include auxiliary measurements such as precise atomic lifetime and precision frequency determinations in order to scrutinize atomic theory, the reliability of which is pivotal for the success of the approach to limit beyond the Standard Model physics. Searches for permanent Electric Dipole Moments on Nuclei and on the electron in systems like the ^{129}Xe atom and the BaF molecule enable with a rather different approach to set limits on speculative theories. Two such experiments will be discussed in the framework of ongoing EDM searches on various systems.

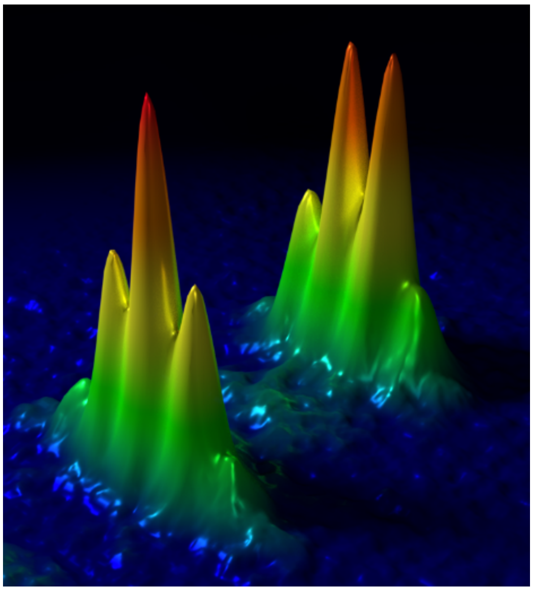
Tests of quantum mechanics and gravitation with atom interferometry

P. Asenbaum, J. Martinez, B. Pichler, Y. Wu, T. Kovachy, J. Hogan and M. Kasevich

Dept. of Physics and Applied Physics, Stanford University, Stanford CA

Recent de Broglie wave interference experiments with atoms have achieved wavepacket separations as large as 54 cm over time intervals of 2 sec [1, 2]. These experiments, and their impact on gravitational and quantum physics, will be discussed.

[1] Kovachy, T. *et al.* Quantum superposition at the half-metre scale. *Nature* **528,** 530–533 (2015).
[2] Asenbaum, P. *et al.* Phase Shift in an Atom Interferometer due to Spacetime Curvature across its Wave Function. *Physical Review Letters* **118,** (2017).



Simultaneous readout of noncommuting collective spin observables beyond the standard quantum limit

P. Kunkel[1], M. Prüfer[1], S. Lannig[1], R. Rosa-Medina[1],
A. Bonnin[1], M. Gärttner[1], H. Strobel[1], M. K. Oberthaler[1]
[1]Kirchhoff-Institut für Physik, Universität Heidelberg, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany.

We augment the information extractable from a single absorption image of a spinor Bose-Einstein condensate by coupling to initially empty auxiliary hyperfine states. Performing unitary transformations in both, the original and auxiliary hyperfine manifold, enables the simultaneous measurement of multiple spin-1 observables. In this talk, I show how we apply this scheme to an elongated atomic cloud of ^{87}Rb to simultaneously read out three orthogonal spin directions and with that access the spatial spin structure (fig. 1). In the context of spin mixing our readout scheme enables the direct visualization of the corresponding many-body dynamics in the spin nematic phase space without state reconstruction. By detecting spin nematic squeezing we demonstrate that this readout even allows the extraction of quantum correlations without state tomography.

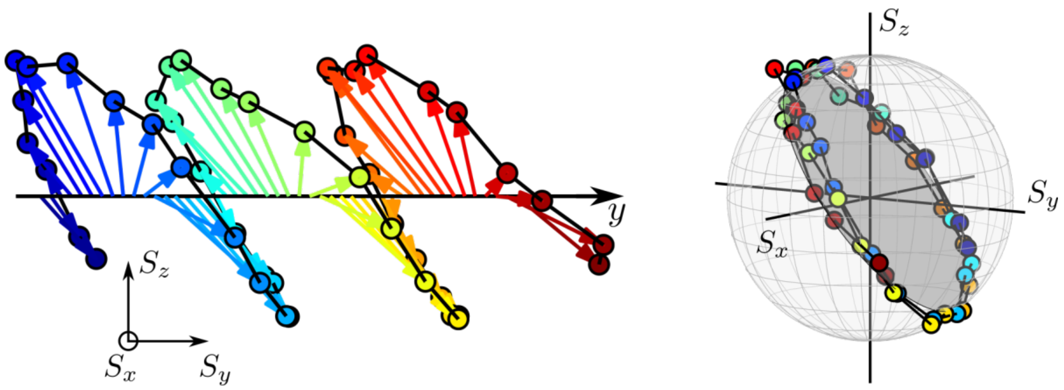


Figure 1. Reconstructed spin vector in space from a single experimental realization and its distribution on a spin sphere.

Quantum logic and precision measurements with atomic and molecular ions

D. R. Leibrandt
Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO 80305, USA
Department of Physics, University of Colorado, Boulder, CO 80309, USA

The tools of trapped-ion quantum logic can be used to enable and enhance precision measurements with applications in the search for physics beyond the standard model. In this talk, I will present two experiments at this fertile intersection of fields. I will begin with a brief review of optical atomic clocks based on Al^+, which use quantum logic with a co-trapped second ion species for preparation and readout of the Al^+ state [1]. Recent progress, including an improved ion trap design and sympathetic laser cooling to the 3D ground state, has enabled total fractional systematic uncertainty below 10^{-18} [2]. We have performed frequency ratio measurements between Al^+ [2], Sr [3], and Yb [4] clocks with uncertainty below 10^{-17}, which can be used to place constraints on models of ultralight dark matter [5]. Next, I will describe an experiment in which quantum-logic readout is used to prepare pure rotational and hyperfine states of a single CaH^+ ion in a probabilistic but heralded fashion [6]. By directly driving coherent Raman transitions with a frequency comb [7,8], we characterize the THz frequencies of rotational transitions with sub-100-Hz resolution and generate entanglement between Ca^+ electronic states and CaH^+ rotational states. Our methods can be extended to study rotational and vibrational transitions of a large class of diatomic and polyatomic molecular ions that are useful in the search for new physics [9].

[1] P. O. Schmidt *et al.*, *Spectroscopy using quantum logic*, Science **309**, 749 (2005).
[2] S. M. Brewer *et al.*, *An $^{27}Al^+$ quantum-logic clock with systematic uncertainty below 10^{-18}*, arXiv:1902.07694 (2019).
[3] T. L. Nicholson *et al.*, *Systematic evaluation of an atomic clock at $2x10^{-18}$ total uncertainty*, Nature Commun. **6**, 6896 (2015).
[4] W. F. McGrew *et al.*, *Atomic clock performance enabling geodesy below the centimetere level*, Nature **564**, 87 (2018).
[5] K. Van Tilburg *et al.*, *Search for ultralight scalar dark matter with atomic spectroscopy*, Phys. Rev. Lett. **115**, 011802 (2015).
[6] C. W. Chou *et al.*, *Preparation and coherent manipulation of pure quantum states of a single molecular ion*, Nature **545**, 203 (2017).
[7] D. Leibfried, *Quantum state preparation and control of single molecular ions*, New J. Phys. **14**, 023029 (2012).
[8] S. Ding and D. N. Matsukevich, *Quantum logic for the control and manipulation of molecular ions using a frequency comb*, New J. Phys. **14**, 023028 (2012).
[9] M. S. Safronova *et al.*, *Search for new physics with atoms and molecules*, Rev. Mod. Phys. **90**, 025008 (2018).

Quantum sensing limits from energy, space and time

M. W. Mitchell[1, 2]

[1] ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain.

[2]ICREA -- Institució Catalana de Recerca i Estudis Avançats, 08010 Barcelona, Spain.

We describe a class of quantum sensing limits that – unlike the standard quantum limit and Heisenberg limit – make no reference to particle number [1]. Rather, these "energy resolution limits" constrain E_R, the *energy resolution per bandwidth*, a figure of merit that combines the measurement noise, duration or bandwidth, and size of the sensed region. Technology-specific energy resolution limits have been derived for a number of important sensing modalities [2] and seem to converge near a limiting value of $E_R = \hbar$. We review the state of knowledge about such limits, and consider the possibility that a more general, technology-spanning limit constrains energy resolution. Possible sources include the Margolus-Levitin bound on the speed of quantum evolution and the Bremermann-Beckenstein bound on the entropy of a space-time region of given energy and volume.

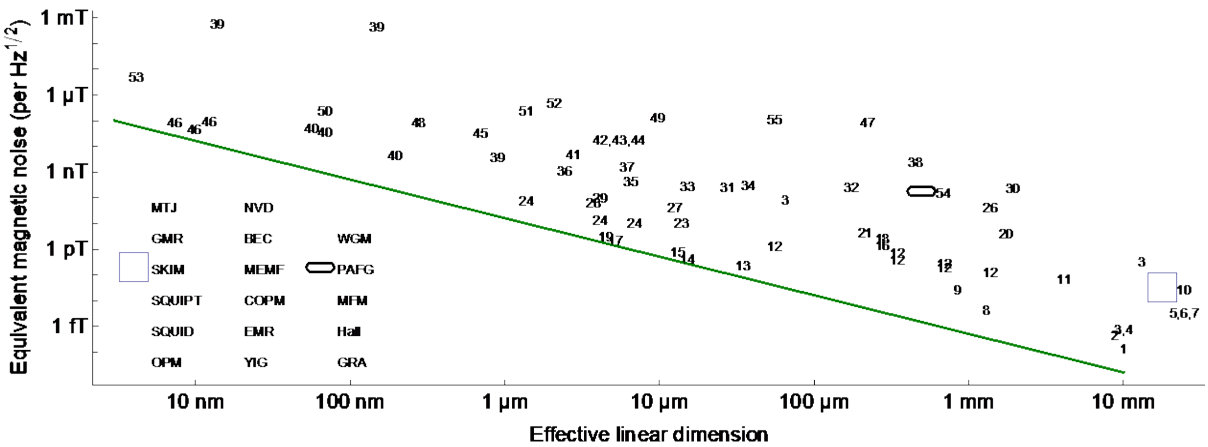


Figure 1. Reported low-frequency magnetic sensitivity versus size of the sensed region for several high-performance magnetic sensor types. MTJ - magnetic tunnel junction; GMR - giant magneto-resistance; SKIM - superconducting kinetic impedance magnetometer; SQUIPT - superconducting quantum interference proximity transistor; SQUID superconducting quantum interference device; OPM optically-pumped magnetometer; NVD - nitrogen-vacancy center in diamond (including RF sensors below 10 um); BEC Bose-Einstein condensate; MEMF - magnetoelectric multiferroic; COPM - cold-atom OPM; EMR extraordinary magneto-resistance; YIG yttrium-aluminum-garnet; GRA - graphene, MFM - magnetic force microscope, PAFG - parallel gating fluxgate, WGM - whispering-gallery mode magnetostrictive. Green line shows an energy resolution per bandwidth of $\hbar$.

[1] M. W. Mitchell, "Number-Unconstrained Quantum Sensing" Quantum Science and Technology 2, 044005 (2017).

[2] M. W. Mitchell, "Sensor self-interaction, scale-invariant spin dynamics, and the $\hbar$ limit of magnetic field sensing" arXiv:1904.01528 (2019).

Measurement of the Fine Structure Constant with a statistical uncertainty below 10^{-10}

L. Morel[1], Z. Yao[1], P. Cladé[1], S. Guellati-Khelifa[1,2]

[1]Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-PSL University, Collège de France, 4 place Jussieu, 75005 Paris, France.

[2]Conservatoire National des Arts et Métiers, 292 rue Saint Martin, 75003 Paris, France.

The comparison between determinations of the Fine Structure Constant α based on atomic interferometry and that derived from the measurement of the electron's gyromagnetic anomaly a_e provides a stringent test of the standard model.

On Fig. 1, left, we have plotted the most precise determinations of α. The value $\alpha(a_e)$ is obtained by combining the measurement of a_e made by the group of Gabrielse at Harvard university[1] with the last quantum electrodynamics calculations performed by Riken group[2]. Concerning the values deduced from the measurement of atomic recoil by atom interferometry, the group of H. Müller at Berkeley published recently a new value of α with an uncertainty of 2.0×10^{-10} (systematics: 1.2×10^{-10}, statistics: 1.6×10^{-10})[3]. This value is consistent with our previous measurement (with an uncertainty of 6.6×10^{-10})[4] and shows a discrepancy of 2.5σ with the value $\alpha(a_e)$. This discrepancy needs to be confirmed by other independent measurements with similar or better accuracy.

Last year we have exerted an intense experimental work on our new experimental setup, which now reaches a statistical uncertainty of 6×10^{-11} per 24 hours of integration (see Fig 1, right). This sensitivity allows us to investigate experimentally many systematic effects. In particular, we have been able to tackle a previously undetected effect: velocity dependent phase shift with Raman transitions, which we have used to perform a reduction of the systematic effect induced by light shifts. We are currently finalizing the error budget. In my presentation, I will present the latest results of our experiment.

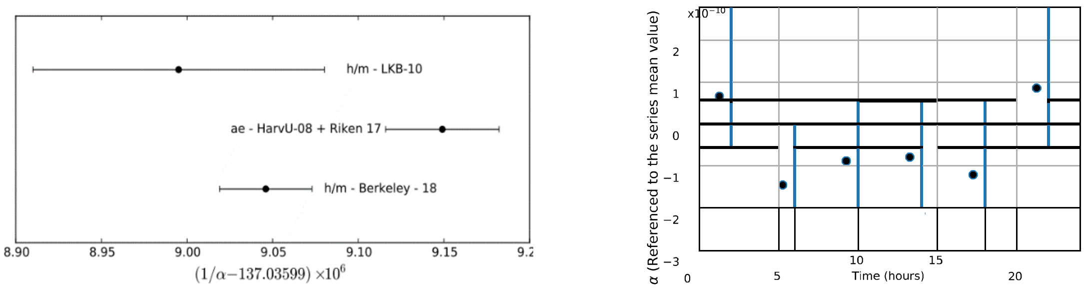


Figure 1: Left: most recent values of α. Right: typical set of data taken continuously during 24 hours. Each point corresponds to 4 hours of integration. The series statistical uncertainty is $5.6\ 10^{-11}$.

[1] D. Hanneke, S. Fogwell, G. Gabrielse, *New Measurement of the Electron Magnetic Moment and the Fine Structure Constant*, Phys. Rev. Lett. **100**, 120801 (2008)

[2] T. Aoyama, M. Hayakawa, T. Kinoshita, M. Nio, *Tenth-order electron anomalous magnetic moment: Contribution of diagrams without closed lepton loops*, Phys. Rev. D **96**, 019901 (2017).

[3] R. H. Parker, C. Yu, W. Zhong, B. Estey, and H. Müller, *Measurement of the Fine-Structure Constant as a Test of the Standard Model*, Science **360**, 6385 191-95 (2018)

[4] R. Bouchendira, P. Cladé, S. Guellati-Khélifa, F. Nez, F. Biraben, *New Determination of the Fine Structure Constant and Test of the Quantum Electrodynamics*, Phys. Rev. Lett. **106**, 080801 (2011)

Measuring the fine-structure constant by kicking atoms

R. H. Parker, C. Yu, W. Zhong, B. Estey, and H. Müller[1]
[1]Department of Physics, 366 Le Conte Hall MC 7300, University of California, Berkeley, CA 94720, USA.

Measurements of the fine-structure constant are powerful tests of the consistency of theory and experiment across physics. We have used the recoil frequency of cesium-133 atoms in an atom interferometer to measure h/M, the ratio of the Planck constant and the mass of the atom, from which we derive the most accurate measurement of the fine-structure constant to date [1]: $\alpha = 1/137.035999046(27)$. To reach this accuracy, we have used multiphoton interactions (Bragg diffraction and Bloch oscillations) to increase the phase shift in the interferometer, and to control systematic effects.

The measurement is sensitive to interesting physics, both within the Standard Model and beyond. By combining it with Standard-Model theory [2], we can predict the anomaly of the magnetic moment of the electron. Comparison between theory and experiment confronts a number of Standard-Model predictions with experiment, some of them for the first time. These include the fifth-order influence of QED, the influence of virtual muons, as well as hadronic effects. The measurement also enables a search for physics beyond the standard model, including scalar particles and vector bosons.

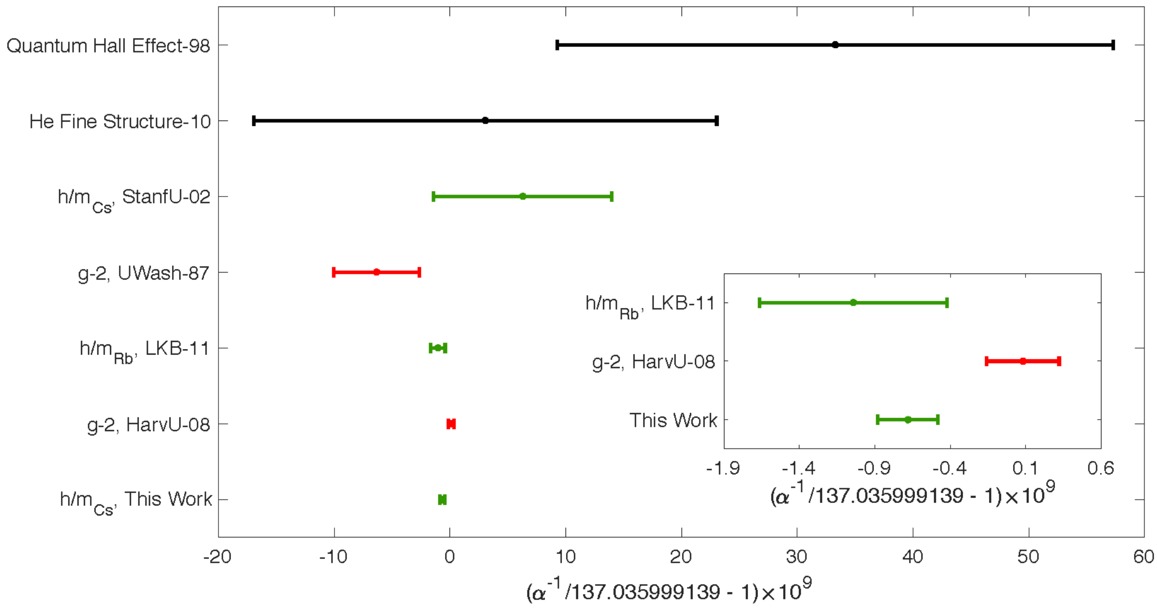


Figure 1. Our recent result alongside previous measurements of α based on quantum Hall effect, He fine structure, h/m_{Cs}, h/m_{Rb}, and electron g-2. Zero on the x-axis is the CODATA 2014 recommended value. Green points indicate photon recoil experiments; red ones, electron g-2 measurements.

[1] Parker, Richard H., Chenghui Yu, Weicheng Zhong, Brian Estey, and Holger Müller. 2018. "*Measurement of the Fine-Structure Constant as a Test of the Standard Model*." Science 360 (6385): 191–95.
[2] Aoyama, Tatsumi, Toichiro Kinoshita, and Makiko Nio. 2018. "*Revised and Improved Value of the QED Tenth-Order Electron Anomalous Magnetic Moment*." Physical Review D 97 (3): 036001.

Measuring the electron electric dipole moment with laser-cooled YbF

B. E. Sauer

Centre for Cold Matter, Blackett Laboratory, Imperial College Londos, London, SW7 2AZ UK

Measurements of the electron's electric dipole moment (eEDM) using molecules tightly constrain the parameters of theories that extend the Standard Model. Certainly polar molecules act as amplifiers for the eEDM, with the current best limit on its size coming from a recent experiment using ThO [1]. I will present our plans to make a new measurement of the eEDM using YbF. I will discuss the design and construction progress of a molecular beam apparatus which will incorporate transverse cooling of a slow YbF beam [2]. I will also discuss our implementation of cycling transitions in state preparation and detection of the molecules. These improvements promise several orders of magnitude improvement in the sensitivity of the eEDM measurement using YbF [3].

[1] *Improved limit on the electric dipole moment of the electron*, ACME Collaboration. Nature **562**, 355-360 (2018).
[2] *Laser Cooled YbF Molecules for Measuring the Electron's Electric Dipole Moment*, J. Lim et al., Phys. Rev. Lett. **120** 123201 (2018).
[3] *Improved measurement of the shape of the electron*, J. J. Hudson et al., Nature, **473** 493 (2011).

Spectroscopy of the molecular ion HD^+ in the Lamb-Dicke regime: towards determination of fundamental constants at the 10^{-10} level

S. Alighanbari[1], F. L. Constantin[1,2], G. S. Giri[1], V. Korobov[3], S. Schiller[1]

[1]Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany
[2]Laboratoire PhLAM CNRS UMR 8523,University Lille 1, Villeneuve d'Ascq, France
[3]Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Russia

Precision measurements with cold atoms and molecules allow testing the predictions of quantum electrodynamics, determining fundamental constants, probing their possible time variation, and searching for new fundamental interactions. The effective control of atoms' and molecules' external and internal degrees of freedom paves the way to increased accuracy. Molecular hydrogen ions (MHIs) are three-body quantum systems for which comparison of *ab initio* theory and experiment can provide an independent determination of the Rydberg constant, of the mass ratios of electron to proton and electron to deuteron, and ultimately also of the proton's and deuteron's charge radius. This program is enabled by recent strong advance in *ab initio* theory [1, 2], which has reached ≈ 1×10^{-11} inaccuracy.

On the experimental side, the spectroscopy of MHI has so far been limited by Doppler broadening even at the low temperatures (10 mK) achieved using sympathetic cooling, leading to line resolution not better than 5×10^{-7} [3, 4]. Recently, we have for the first time achieved Doppler-free spectroscopy of the fundamental rotational transition of HD^+ at 1.3 THz, enabled by the transverse confinement of the MHI clusters in the Lamb-Dicke regime [2]. Line resolution of 1×10^{-9} was achieved.

In this contribution we present an up to 300-fold further decrease in linewidth, to the 3×10^{-12} level (Fig. 1, arrow). This line resolution is now better than the theoretical inaccuracy of the *ab initio* prediction. This excellent resolution allows us to probe systematic shifts very sensitively. For example, we determined an upper limit of 1×10^{-11} for the light shift induced by 266 nm radiation on the rotational transition, and also resolved the ultra-small pure rotational Zeeman shift (0.55 kHz/G). To date, we measured 6 hyperfine transitions, including a number of Zeeman components (Fig. 1). Our resolution of the hyperfine structure improves on the best previous measurements of any MHI by a factor of 10 [5].

With the data obtained we are able to test the recently improved theory of the spin structure of the molecular ion [6] at the 0.1 kHz uncertainty level. We are also currently analysing the data towards determining the fundamental constant $R_{\infty}m_e(m_p^{-1}+m_d^{-1})$ with a goal uncertainty on the low-10^{-10} level. Our value can then be compared with the combined results from atomic hydrogen spectroscopy and mass spectrometry in Penning traps [7, 8]. The results of the analysis will be presented at the conference.

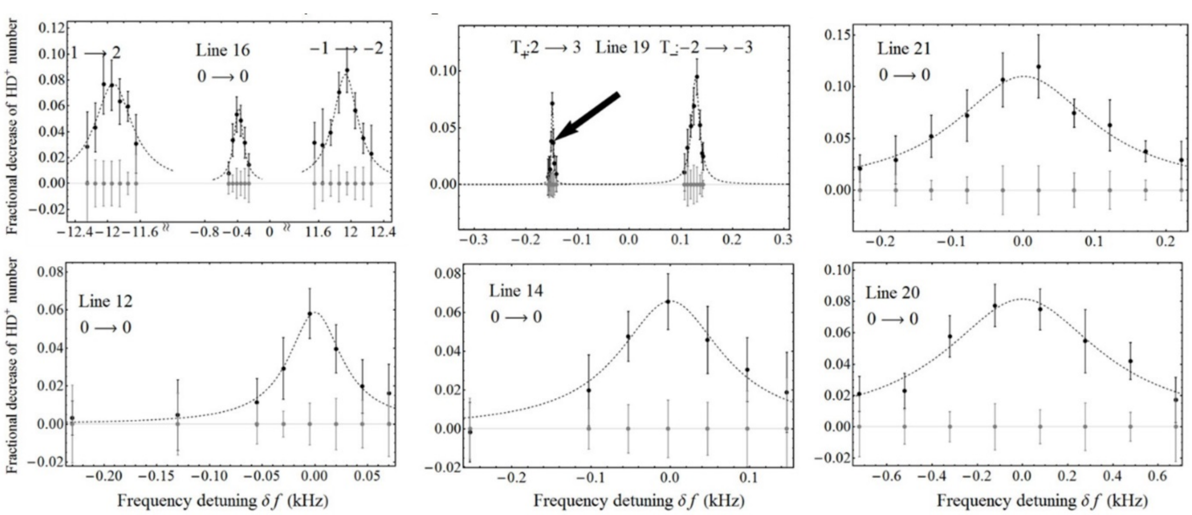


Fig. 1. 6 hyperfine components of the fundamental rotational transition. The line center frequencies of the components differ by values of the order 10 MHz. The arrow indicates an ultranarrow Zeeman component (4 Hz FWHM).

References

[1] V. Korobov, *et al.*, *Fundamental Transitions and Ionization Energies of the Hydrogen Molecular Ions with Few ppt Uncertainty*, Phys. Rev. Lett. **118**, 233001 (2017).

[2] S. Alighanbari, *et al.*, *Rotational spectroscopy of cold and trapped molecular ions in the Lamb-Dicke regime*, Nat. Phys. **14**, 555 (2018).

[3] U. Bressel, *et al.*, *Manipulation of Individual Hyperfine States in* HD^+ *and Frequency Metrology*, Phys. Rev. Lett. **108**, 183003 (2012).

[4] J. Biesheuvel, *et al.*, *Probing QED and fundamental constants through laser spectroscopy of* HD^+, Nat. Commun. **7**, 10385 (2016).

[5] K.B. Jefferts, *Hyperfine structure in the molecular ion* H_2^+, Phys. Rev. Lett. **23**, 1476 (1969).

[6] V. Korobov, *et al.*, *Theoretical Hyperfine Structure of the Molecular Hydrogen Ion at 1 ppm Level*, Phys. Rev. Lett. **116**, 053003 (2016).

[7] F. Heiße *et al.*, *High Precision Measurement of the Proton's Atomic Mass*, Phys. Rev. Lett. **119**, 033001 (2017).

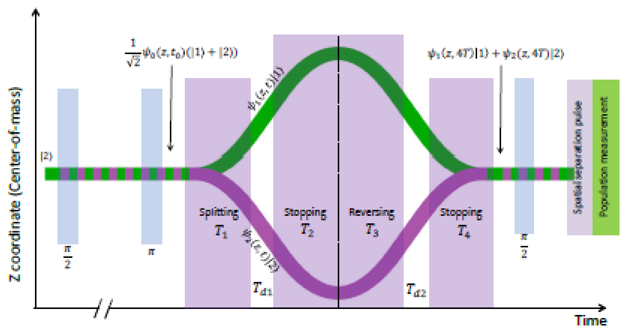
[8] S. L. Zafonte and R. S. Van Dyck Jr, *Ultra-precise single-ion atomic mass measurements on D and He-3*, Metrologia **52**, 280 (2015).

Quantum waves and gravity

W. P. Schleich

Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, Albert-Einstein-Allee 11, 89081 Ulm, Germany; Hagler Institute for Advanced Study at Texas A&M University, Texas A&M; AgriLife Research, Texas A&M University, College Station, TX 77843, USA; Institute for Quantum Science and Engineering (IQSE), Texas A&M University, College Station, TX 77843, USA; Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA

Atom interferometry represents a powerful tool to probe the interface of quantum and gravity. It is conventional wisdom that the corresponding phase shift caused by gravity scales quadratically with the time the atom spends in the interferometer. The recent experimental realization of the Stern-Gerlach interferometer [1] displays a cubic rather than a quadratic phase shift. We illustrate this phenomenon in quantum phase space using the Wigner function [2] and, in particular, compare and contrast the sensitivity of this device to uncertainties to the one predicted in the Humpty-Dumpty discussion [3].



References:

[1] O. Amit, Y. Margalit, O. Dobkowski, Z. Zhou, Y. Japha, M. Zimmermann, M.A. Efremov, F.A. Narducci, E.M. Rasel, W.P. Schleich, and R. Folman, *T^3–Stern-Gerlach matter-wave interferometer*, to be published

[2] E. Giese, W. Zeller, S. Kleinert, M. Meister, V. Tamma, A. Roura, and W.P. Schleich, *Interface of gravity and quantum mechanics illuminated by Wigner phase space*, in: "Atom Interferometry", Varenna Summer School 2013

[3] B.G. Englert, J. Schwinger, and M.O. Scully, *Is spin coherence like Humpty-Dumpty? I. Simplified Treatment*, Foundations of Physics **18**, 1045 (1988); J. Schwinger, M.O. Scully, and B.G. Englert, *Is spin coherence like Humpty-Dumpty? II.* General Theory, Z. Phys. D **10**, 135 (1988); M.O. Scully, B.G. Englert, and J. Schwinger, *Is spin coherence like Humpty-Dumpty? III. The effects of observation*, Phys. Rev. A **40**, 1775 (1989)

Choreographing Quantum Spin Dynamics with Light: from Cavity QED to Rydberg Dressing

M. Schleier-Smith[1]
[1]Physics Department, Stanford University, 382 Via Pueblo Mall, Stanford, CA 94305

I will report on recent advances in generating optically controlled long-range interactions among neutral atoms, with an eye towards applications in quantum state engineering for metrology. In one approach, we couple spin-1 atoms to an optical cavity to realize a photon-mediated spin mixing process [1] that opens prospects for fast optical generation of twin Fock states. In a second platform, we induce long-range Ising interactions among cesium atoms in their hyperfine clock states by Rydberg dressing, and observe “one-axis twisting” dynamics that promises to enable locally controlled spin squeezing. Each of these systems offers fertile new ground for engineering spatially structured entanglement and exploring its implications for quantum sensing.

[1] E. Davis, G. Bentsen, L. Homeier, T. Li, and M. Schleier-Smith. *Phys. Rev. Lett.* **122** 010405 (2019).

Twists, gaps, and superradiant emission on a millihertz linewidth optical transition.

J. K. Thompson

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

I will describe superradiant pulses of light generated from an optical transition that does not like to radiate light: the millihertz linewidth optical transition in strontium [1]. This new source of light may allow us to overcome thermal and technical limitations on laser frequency stability [2,3]. The pulses of light are generated by laser cooling and trapping an ensemble of 10^5 strontium atoms inside a high finesse optical cavity to achieve a collective enhancement in the radiation rate.

We observe that cavity-mediated spin-exchange interactions emerge when the cavity is tuned away from resonance with the atomic transition frequency [4]. The spin exchange interactions manifest in the experiment as a many-body energy gap and as one-axis twisting dynamics. The energy gap may prove useful for enhancing atomic coherence times, while the one-axis twisting dynamics may prove useful for creating entanglement [5].

If time permits, I will also discuss the creation of highly spin squeezed states [6] and efforts to apply these states in a proof-of-principle matter wave interferometer [7].

[1] "Superradiance on the milliHertz linewidth strontium clock transition," M.A. Norcia, M.N. Winchester, J.R.K. Cline, J.K. Thompson, Sci. Adv. 2016;2:e1601231 (2016).
[2] "Frequency measurements of superradiance from the strontium clock transition," M. A. Norcia, J. R.K. Cline, J. A. Muniz, J. Ye, J. K. Thompson, Phys. Rev. X 8, 021036 (2018).
[3] "Prospects for a millhertz linewidth laser," D. Meiser, J. Ye, D.R. Carlson, M. J. Holland, Phys. Rev. Lett. 102, 163601 (2009).
[4] "Cavity-Mediated Collective Spin-Exchange Interactions in a Strontium Superradiant Laser," M.A. Norcia, R. Lewis-Swan, J.R.K. Cline, B. Zhu, A.M. Rey, J.K. Thompson, Science 361, 259-262 (2018).
[5] "Robust spin squeezing via photon-mediated interactions on an optical clock transition." R.J. Lewis-Swan, M.A. Norcia, J.R. K. Cline, J.K. Thompson, A.M. Rey, Phys. Rev. Lett. 121 (7), 070403 (2018).
[6] "Deterministic Squeezed States with Collective Measurements and Feedback," K.C. Cox, G.P. Greve, J.M. Weiner, and J.K. Thompson, Phys. Rev. Lett. 116, 093602 (2016).
[7] "Spatially homogeneous entanglement for matter-wave interferometry created with time-averaged measurements," K.C. Cox, G.P. Greve, B. Wu, and J.K. Thompson, Phys. Rev. A 94, 061601(R) (2016).

Quantum metrology with non-classical states of Bose-Einstein condensates

T. Zibold, M. Fadel, B. Décamps, Y. Li, P. Colciaghi, and P. Treutlein

Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland.

We report experiments on quantum metrology with non-classical states of Bose-Einstein condensates on an atom chip (for a recent review of the field see [1]). Using chip-based microwave near-field potentials we control collisional interactions in a two-component BEC of 87Rb atoms. This allows us to generate spin-squeezed states with typically 8 dB of spin-squeezing according to the Wineland criterion. These states are useful for quantum metrology, which we demonstrate experimentally by performing atom interferometry with a precision of 7 dB beyond the standard quantum limit.

To further study the non-classical correlations in the spin-squeezed state, we perform high-resolution imaging of the spin state of an expanded condensate [2]. This allows us to directly measure the spin correlations between spatially separated regions of various shapes, confirming the presence of entanglement in this system of indistinguishable atoms. Our data show bipartite correlations strong enough for Einstein-Podolsky-Rosen (EPR) steering: we can predict measurement outcomes for non-commuting observables in one spatial region based on corresponding measurements in another region with an inferred uncertainty product below the Heisenberg bound. This demonstrates the EPR paradox with a massive many-particle system. This method could be exploited for entanglement-enhanced imaging of electromagnetic field distributions.

Furthermore, we detect multi-partite Bell correlations in our squeezed condensate using a quantum-mechanical witness inequality [3,4]. Concluding the presence of Bell correlations is unprecedented for an ensemble containing more than a few particles. Our work shows that the strongest possible non-classical correlations are experimentally accessible in many-body systems, and that they can be revealed by collective measurements. This opens up new perspectives for using many-body systems in a variety of quantum information tasks.

[1] L. Pezzè, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein, *Quantum metrology with nonclassical states of atomic ensembles*, Rev. Mod. Phys. **90**, 035005 (2018).

[2] M. Fadel, T. Zibold, B. Décamps, and P. Treutlein, *Spatial entanglement patterns and Einstein-Podolsky-Rosen steering in Bose-Einstein condensates*, Science **360**, 409 (2018).

[3] R. Schmied, J. D. Bancal, B. Allard, M. Fadel, V. Scarani, P. Treutlein, and N. Sangouard, *Bell correlations in a Bose-Einstein condensate*, Science **352**, 441 (2016).

[4] F. Baccari, J. Tura, M. Fadel, A. Aloy, J.-D. Bancal, N. Sangouard, M. Lewenstein, A. Acín, and R. Augusiak, *Bell correlations depth in many-body systems*, arXiv:1802.09516 (2018).

Physics beyond the Standard Model from hydrogen molecules

W. Ubachs
Department of Physics and Astronomy, LaserLaB, Vrije Universiteit Amsterdam, Netherlands

The hydrogen molecule is the smallest neutral chemical entity and a benchmark system of molecular spectroscopy. The comparison between highly accurate measurements of transition frequencies and level energies with quantum calculations including all known phenomena (relativistic, vacuum polarization and self energy) provides a tool to search for physical phenomena in the realm of the unknown: are there forces beyond the three included in the Standard Model of physics plus gravity, are there extra dimensions beyond the 3+1 describing space time ? Comparison of laboratory wavelengths of transitions in hydrogen may be compared with the lines observed during the epoch of the early Universe to verify whether fundamental constants of Nature have varied over cosmological time. These concepts, as well as the precision laboratory experiments and the astronomical observations used for such searches of new physics will be discussed.

Antimatter under the Microscope: High-Precision Comparisons of the Fundamental Properties of Antiprotons and Protons

S. Ulmer[1], K. Blaum[2], P. Blessing[1,3], M. Bohman[1,2], M. Borchert[1,4], J. A. Devlin[1], J. A. Harrington[1,2], A. Mooser[1,2], C. Smorra[1], M. Wiesinger[1,2], Y. Matsuda[5], C. Ospelkaus[4], W. Quint[3], J. Walz[5,7], E. Wursten[6], Y. Yamazaki[1]

[1]RIKEN, Ulmer Fundamental Symmetries Laboratory, Saitama, Japan; [2]Max-Planck-Institut für Kernphysik, Heidelberg, Germany; [3]GSI - Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany; [4]Leibniz University, Hannover, Germany; [5] The University of Tokyo, Tokyo, Japan; [5]Johannes Gutenberg-Universität, Mainz, Germany; [6]CERN, Geneva, Switzerland; [7]Helmholtz-Institut Mainz, Mainz, Germany;

E-mail: stefan.ulmer@cern.ch

According to the Standard Model of particle physics, the Big Bang has produced equal amounts of matter and antimatter. On the other hand, cosmological observations imply that the visible part of the universe is entirely made out of matter. This striking inconsistency, one of the hottest topics of modern physics, inspires experiments to compare the fundamental properties of matter-antimatter conjugates at lowest energy and with high precision. The BASE collaboration at the CERN antiproton decelerator is performing such high-precision comparisons with protons and antiprotons. Using advanced, ultra-stable, cryogenic particle traps and superconducting detectors with single particle sensitivity, we have performed the most precise measurement of the proton-to-antiproton charge-to-mass ratio with a fractional precision of 11 significant digits [1]. In another measurement, we have invented a novel spectroscopy method, which allowed for the first ultra-high precision measurement of the antiproton magnetic moment with a fractional precision of 1.5 parts in a billion [2]. Together with our recent measurement of the proton magnetic moment [3] this improves the precision of previous experiments [4] by more than three orders of magnitude.

In my talk I will review the recent achievements of BASE and will outline strategies to further improve our high-precision studies of matter-antimatter symmetry. In future studies we will profit from the high sampling rate of our experiments and will apply time-base methods to investigate our antimatter datasets for time dependent phenomena imposed by physics beyond the Standard Model.

[1] S. Ulmer *et al.*, Nature 524, 196 (2015).
[2] C. Smorra *et al.*, Eur. Phys. Journ. Spec. Top. 224, 16 (2015).
[3] G. Schneider *et al.*, Science 358, 1081 (2017).
[4] J. DiSciacca et al., Phys. Rev. Lett. 110, 130801 (2013).

Observation of superradiant emission on a narrow intercombination

H. Winter[1], T. Laske[1], A. Hemmerich[1,2]
[1]Institut für Laser-Physik, Universität Hamburg, 22761 Hamburg, Germany.
[2]Zentrum für optische Quantentechnologien, Universität Hamburg, 22761 Hamburg, Germany.

Cold samples of calcium atoms are prepared in the metastable $^3P_1$ state inside an optical cavity resonant with the narrow band (375 Hz) $^1S_0 \rightarrow {}^3P_1$ intercombination line at 657 nm. We observe superradiant emission through hyperbolic secant shaped pulses released into the cavity with an intensity proportional to the square of the particle number, a duration much shorter than the natural lifetime of the $^3P_1$ state (Fig. 1), and a delay time fluctuating from shot to shot in excellent agreement with theoretical predictions [1]. Our incoherent pumping scheme to produce inversion on the $^1S_0 \rightarrow {}^3P_1$ transition should be extendable to allow for continuous wave laser operation. This laser would operate in the so called bad-cavity regime, which can in principle lead to extremely narrow emission linewidth [2], immune to fluctuations of the laser cavity length.

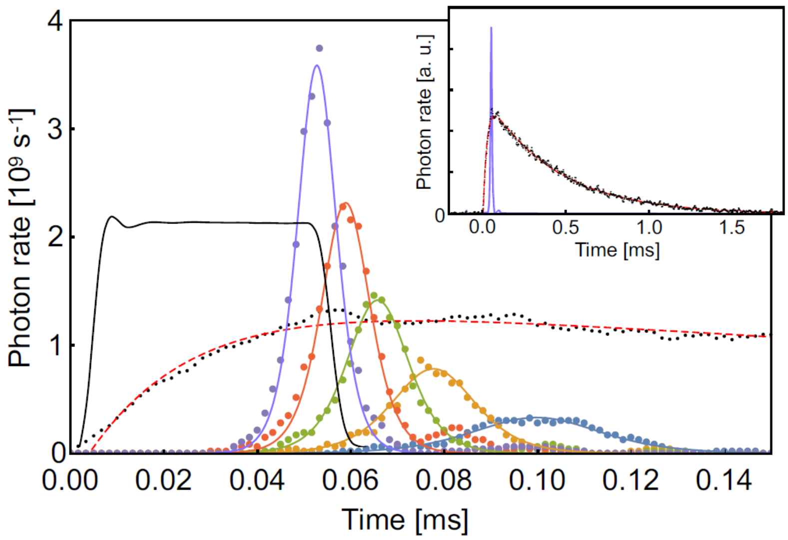


Figure 1. The inset (upper right corner) compares the natural non-cooperative exponential decay with an observed life time of 420 µs (black dots) with the case when a short (≈ 10 µs) superradiant pulse is emitted (blue graph). The red dashed line is a fit with two exponential functions. In order to present both graphs in the same plot, their vertical axes are scaled differently. The main panel shows superradiant light pulses for particle numbers N = 12800, 19700, 26500, 34000, 42300 from right to left. The solid black line indicates the pump pulse that acts to populate the $^3P_1$ state. The black dots, modeled by the dashed red line graph, repeat the natural decay curve of the inset.

[1] M. Gross and S. Haroche, Phys. Rep. 93, 302 (1982).
[2] D. Meiser, J. Ye, D. R. Carlson, and M. J. Holland, Phys. Rev. Lett. 102, 163601 (2009).

Spin-squeezed atomic crystal

D. Kajtoch[1, 2], E. Witkowska[2], A. Sinatra[2]
[1] Institute of Physics, PAS - Aleja Lotników 32/46, PL-02668 Warsaw, Poland.
[1] Laboratoire Kastler Brossel, ENS-PSL, CNRS, UPMC-Sorbonne Université and Collège de France Paris, France.

I will present our recent work [1] concerning a method to obtain a regular arrangement of two-level atoms in a three dimensional optical lattice with unit filling, where all the atoms share internal state coherence and metrologically useful quantum correlations. Such a spin-squeezed atomic crystal is obtained by adiabatically raising an optical lattice in an interacting two-component Bose-Einstein condensate. The scheme could be directly implemented to a microwave transition with state-of-the-art techniques and used in optical-lattice atomic clocks with bosonic atoms to strongly suppress the collisional shift and benefit from the quantum correlations at the same time.

[1] D. Kajtoch, E. Witkowska, E. Sinatra, *Spin-squeezed atomic crystal*, EPL 123, 20012 (2018).

Molecular Lattice Clock

T. Zelevinsky[1]
[1]Department of Physics, Columbia University, 538 West 120th Street, New York, NY 10027-5255, USA.

Atomic clock based metrology is at the forefront of high-precision measurements and tests of fundamental physics. On the other hand, molecules offer a range of distinct energy scales that have inspired new protocols in precision measurement and quantum information science. We have constructed a fundamentally new type of lattice clock that is based on vibrations in diatomic strontium molecules, where coherent Rabi oscillations between weakly and deeply bound molecules persist for tens of milliseconds [1]. This clock is made possible by a careful control of molecular quantum states, and by a state-insensitive "magic" lattice trap that weakly couples to molecular vibronic resonances and enhances the coherence time between molecules and light by several orders of magnitude. This enhancement results in a clock quality factor of nearly a trillion. The technique of extended coherence across the entire molecular potential depth is applicable to long-term storage of quantum information in qubits based on ultracold polar molecules, while the vibrational clock enables novel precise probes of interatomic forces, tests of ultrashort-range Newtonian gravitation, and model-independent searches for electron-to-proton mass ratio variations.

[1] S. S. Kondov, C.-H. Lee, K. Leung, C. Liedl, I. Majewska, R. Moszynski, and T. Zelevinsky, *Molecular lattice clock with long vibrational coherence,* arXiv:1904.04891.

Testing quantum and gravity interplay with composite quantum particles

M. Zych[1]
[1]ARC Centre for Engineered Quantum Systems·, University of Queensland, 4072 St Lucia, Brisbane, Australia.

A major goal of modern physics is to understand and test the regime where quantum mechanics and general relativity both play a role. However, new effects of this regime are usually thought to be relevant only at high energies or in strong gravitational fields, beyond the reach of present day experiments. I will discuss a promising route towards testing joint effects of quantum theory and general relativity, focused on low-energy but composite quantum systems. The key insight is that quantized internal energy of particles such as atoms, ions or molecules leads to new phenomena. In particular, coherence of such systems, in the context of matter-wave interference experiments, can be measurably affected by relativity even at low-energies and in weak gravitational fields through time dilation [1-4]. I will explain the resulting new phenomena and prospects for their tests. I will further discuss new insights into the Einstein Equivalence Principle (EEP) stemming from this approach [5]. Most importantly, for composite systems testing validity of the EEP in quantum theory requires measuring more parameters than for classical systems, and to do so one needs conceptually new experiments. I will present the first such test [6] probing quantum aspects of the universality of free fall, and sketch ideas for future experiments [7,8]. I will close with a brief outlook of the relevance of studying quantized mass-energy effects for metrology and quantum information processing.

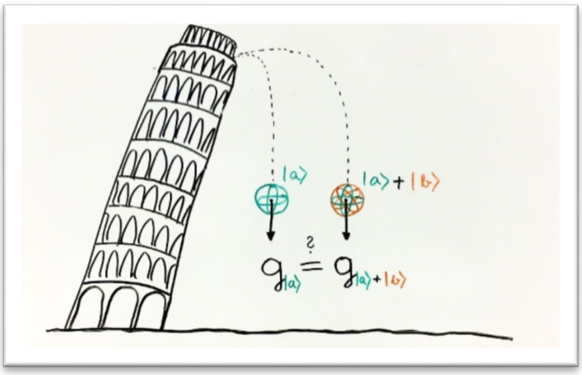


Figure 1. Testing validity of the EEP in quantum theory requires testing equivalence of the internal energy operators. An examples includes testing universality of free-fall for a system in a superposition of different mass-energy eigenstates such as in ref. [6].

[1] M. Zych, F. Costa, I. Pikovski, and C. Brukner, “Quantum interferometric visibility as a witness of general relativistic proper time,” *Nature Comm*. **2**, 505 (2011).
[2] I. Pikovski, M. Zych, F. Costa, and C. Brukner, “Universal decoherence due to gravitational time dilation,” *Nature Physics* **11**, 668–672 (2015).
[3] P. Bushev, J. Cole, D. Sholokhov, N. Kukharchyk, and M. Zych, *New J.Phys* **18**, 093050 (2016).
[4] A Roura Gravitational redshift in quantum-clock interferometry, arXiv:1810.06744 (2018).
[5] M. Zych, and C. Brukner, “Quantum formulation of the Einstein Equivalence Principle,” *Nature Physics* (2018).
[6] G. Rosi, et al.,“Quantum test of the equivalence principle for atoms in coherent superposition of internal energy states.,” *Nature Comm*. **8**, 15529 (2017).
[7] P. J. Orlando, R. B. Mann, K. Modi, and F. A. Pollock, “A test of the equivalence principle(s) for quantum superpositions,” *Classical and Quantum Gravity* **33** 19LT01 (2016).
[8] R. Geiger, and M. Trupke, “Proposal for a Quantum Test of the Weak Equivalence Principle with Entangled Atomic Species,” *Phys. Rev. Lett.* **120** 043602 (2018).

Phase magnification by two-axis countertwisting for detection-noise robust interferometry

F. Anders[1], L. Pezzè[2], A. Smerzi[2] and C. Klempt[1]

[1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover, Germany

[1]QSTAR, INO-CNR and LENS, Largo Enrico Fermi 2, I-50125, Firenze, Italy

Entanglement-enhanced atom interferometry has the potential of surpassing the standard quantum limit and eventually reaching the ultimate Heisenberg bound. The experimental progress is, however, hindered by various technical noise sources, including the noise in the detection of the output quantum state. The influence of detection noise can be largely overcome by exploiting echo schemes, where the entanglement-generating interaction is repeated after the interferometer sequence. We studied an echo protocol that uses two-axis countertwisting as the main nonlinear interaction. (see fig. 1)

We demonstrate that the scheme is robust to detection noise and its performance is superior compared to the already demonstrated one-axis twisting echo scheme. In particular, the sensitivity maintains the Heisenberg scaling in the limit of a large particle number. The protocol can be implemented with spindynamics in spinor Bose-Einstein condensates. Our results thus outline a realistic approach to mitigate the detection noise in quantum-enhanced interferometry.

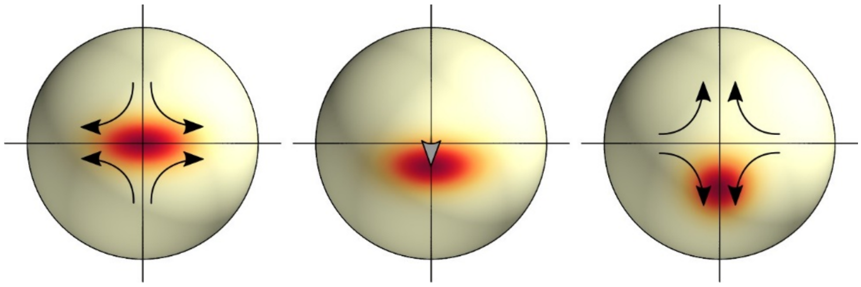


Figure 1. Schematic visualization (Husimi distributions) of the echo protocol using TACT. Black arrows visualize the action of the nonlinear Hamiltonian. From left to right: Preparation of a squeezed state, Interferometric phase imprint, Inverse nonlinear dynamics leads to anti-squeezing and phase magnification.

[1] Anders, F., L. Pezzè, A. Smerzi, and C. Klempt, *Phase magnification by two-axis countertwisting for detection-noise robust interferometry*, Phys. Rev. A 97, 043813 (2018).

Fine and hyperfine structure of ^{173}YbF & YbOH

G. Aufderheide, W. R. Ballard, E. C. Koskelo, A. T. Preston, & R. J. Mawhorter
Department of Physics and Astronomy, Pomona College, Claremont, California, 91711, USA.

J. - U. Grabow
Institut für Physikalische Chemie & Elektrochemie, Gottfried-Wilhelm-Leibniz-Universität Hannover
30167 Hannover, Germany.

H. Wang[a] & T. C. Steimle
School of Molecular Science, Arizona State University, Tempe, Arizona 85287, USA,
& a) State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai, China.

^{174}YbF has been used for some time in attempts to determine the electrostatic T,P violating electron electric dipole moment (eEDM). It was recently pointed out [1] that ^{173}YbF may be an avenue for determining an EDM induced by the magnetic quadrupole moment (MQM). As in the eEDM case, here the molecular properties of ^{173}YbF are experimentally advantageous. We report a detailed analysis of the fine and hyperfine structure in the $X^2\Sigma^+$ state from a combined analysis of rotational and optical transitions. Numerous hyperfine components in the N=4 > 5 and N=3 > 4 rotational transitions were recorded using a separated field pump/probe microwave optical double residence technique (PPMODR). Fourier transform microwave spectroscopy (FTMW) was used to record five features of the N=0 > 1 rotational transition. This rotational data was combined with precisely measured (0,0) $A^2\Pi_{1/2}$ - $X^2\Sigma^+$ optical transitions of a cold molecular beam sample. Resulting fine and hyperfine parameters will be discussed and compared with recent theory [2].
It has recently been proposed that polyatomic molecules like isoelectronic YbOH can considerably extend the sensitivity of molecular studies of parity non-conserving effects [3]. The optical spectra of YbF and YbOH are quite similar, and preparatory work for an FTMW study of YbOH, building directly on our recent PPMODR observations of YbOH [4], will also be reported.
The research at Arizona State University was supported by a grant from the Heising Simons Foundation (Grant 2018-0681).

[1.] B. G. C. Lackenby and V. V. Flambaum, *Time reversal violating magnetic quadrupole moment in heavy deformed nuclei*, Phys. Rev. D **98**, 115019 (2018).
[2.] L. F. Pašteka, R. J. Mawhorter, and P. Schwerdtfeger, *Relativistic coupled-cluster calculations of the ^{173}Yb nuclear quadrupole coupling constant for the YbF molecule,* Mol. Phys. **114**, 1110 (2016).
[3.] I. Kozyryev and N. R. Hutzler, *Precision Measurement of Time-Reversal Symmetry Violation with Laser-Cooled Polyatomic Molecules*, Phys. Rev. Lett. **119**, 133002 (2017).
[4.] S. Nakhatea, T. C. Steimle, N. H. Pilgram, and N. R. Hutzler, *The pure rotational spectrum of YbOH*. Chem. Phys. Lett. **715**, 105 (2019).

High Precision Spectroscopy of $^{177}HfF^+$ and $^{179}HfF^+$

W. R. Ballard, R. J. Mawhorter
Department of Physics and Astronomy, Pomona College, Claremont, California, 91711, USA.

The molecular ion HfF^+ can be used to study a wide variety of parity non-conserving (PNC) effects. In addition to being the test bed for one of the most precise investigations of the electron's electric dipole moment (eEDM) [1], it has also been identified as a candidate system for extending the study of T, P-odd effects into the nuclear realm [2], which are primarily due to enhancements in the interaction of electrons with the nuclear magnetic quadrupole moment (MQM). Here the high deformation of both of the odd isotope nuclei ^{177}Hf and ^{179}Hf plays an important role [3]. Even more recently, the scalar-pseudoscalar nucleus-electron neutral current (SP) interaction has been studied for both of the odd spin HfF+ isotopologues [4], and $^{177}HfF^+$ has been identified as a strong candidate for studying the PNC effect due to the nuclear weak quadrupole moment [5].

Among all of the heavy atoms currently used in molecular PNC studies, hafnium is unique in having two relatively abundant odd isotopes with nuclear spin and large deformation, i.e. a large electric nuclear quadrupole moment (NQM). ^{179}Hf has the largest NQM of any naturally stable element, and ^{177}Hf is not far behind. Measuring the resulting spectroscopic splittings of a few hundred MHz with kHz accuracy is tantamount to precisely determining the electric field gradient (EFG) at the nucleus, exactly where the interesting PNC interactions occur. These measurements in turn provide sensitive tests of the related theoretical calculations of the effective internal electric fields needed to convert experimental PNC parameters into the sought-after values like the eEDM.

Building on optical studies of $^{180}HfF^+$ [6,7] and detailed microwave studies of isoelectronic HfO [8,9], we will use theoretical eQq values [4] to make reasonably accurate predictions of the rotational spectra of $^{177}HfF^+$ and $^{179}HfF^+$. The goal is to enable their measurement and provide EFG values to benchmark related theoretical methods. A detailed comparison of values for both isotopologues significantly strengthens these tests, and doing so directly for these relevant HfF^+ systems adds extra interest as well.

[1] W. Cairncross, et al., *Precision Measurement of the Electron's Electric Dipole Moment Using Trapped Molecular Ions*, Phys. Rev. Lett. **119**, 153001 (2017).
[2] V. V. Flambaum, D. DeMille, and M. G. Kozlov, *Time-Reversal Symmetry Violation in Molecules Induced by Nuclear Magnetic Quadrupole Moments*, Phys. Rev. Lett. **113**, 103003 (2014).
[3] B. G. C. Lackenby and V. V. Flambaum, *Time reversal violating magnetic quadrupole moment in heavy deformed nuclei*, Phys. Rev. D **98**, 115019 (2018).
[4] A. N. Petrov et al., *Evaluation of CP violation in* HfF^+, Phys. Rev. A **98**, 042502 (2018).
[5] L. V. Skripnikov et al., *HfF+ as a candidate to search for the nuclear weak quadrupole moment*, Rev. A **99**, 012517 (2019).
[6] B. J. Barker et al, *The Molecular Frame Electric Dipole Moment and Hyperfine Interactions in Hafnium Fluoride*, J. Chem. Phys. **134**, 201102 (2011).
[7] K. C. Cossel et. al, *Broadband velocity modulation spectroscopy of* HfF^+*: Towards a measurement of the electron electric dipole moment,* Chem. Phys. Lett. **546, 1** (2012).
[8] R. D. Suenram et al., *Pulsed-nozzle Fourier-transform microwave spectroscopy of laser-vaporized metal oxides*, J. Chem. Phys. **92**, 4724 (1990).
[9] A. Lessari et al., *Rotational spectrum of jet-cooled* HfO_2 *and HfO*, J. Chem. Phys. **117**, 9651 (2002).

An optical frequency standard based on $^{171}Yb^+$ and its applications for fundamental physics

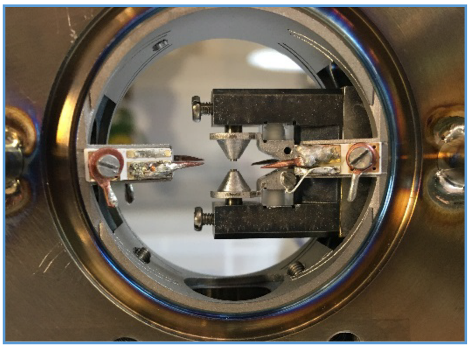
C. F. A. Baynham[1,2], E. A. Curtis[1], R. M. Godun[1], B. I. Robertson[1], P. Gill[1,2]

[1] Time and Frequency, National Physical Laboratory, Teddington, UK

[2] Clarendon Laboratory, Oxford University, Oxford, UK

Recent years have seen the optical atomic clock (OC) graduate from a promising timekeeping technology to one of the most sensitive instruments in the physicist's toolbox. The current rapid progress of OCs is revealing unexplored frontiers in the search for new physics [1-3].

At the National Physical Laboratory (NPL), UK, an optical frequency standard based on a single ion of 171-ytterbium has been constructed. The Yb ion possesses a metastable F-state with a natural lifetime of 8 years. The octupole (E3) transition between the S and F states has a natural linewidth of ~1 nHz [4] and can be used as the basis of a frequency standard with estimated fractional accuracy in the 10^{-18} range. A second such system is also being built to validate this performance, and an international network of optical-fibre links permits real-time comparisons with other clocks across Europe.



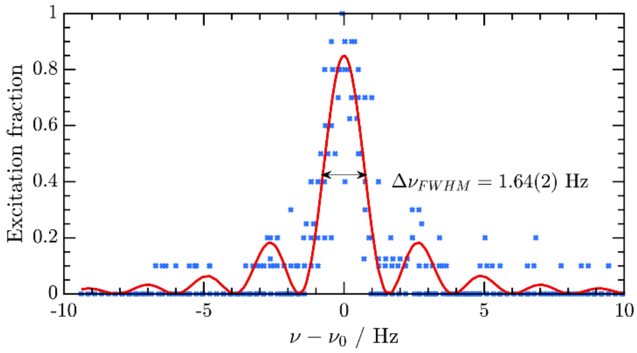


Figure 1. *(left)* Image of the new ion trap, under construction. The flange diameter is 40 mm. *(right)* Quantum excitation fraction of the E3 transition driven with 500 ms pulses, Fourier-limited to 1.6 Hz.

Although highly stable and accurate clocks are useful in themselves, the ytterbium system also benefits from enhanced sensitivity to various predicted fundamental effects. For instance, the frequency of the E3 transition is particularly sensitive to variation in the fine structure constant, α, with a sensitivity coefficient of -5.95, the highest of OC candidates currently used [2].

Some extensions to the Standard Model predict variation in α on different timescales; one candidate solution for the dark matter problem is a light dilaton, whose presence could cause oscillations in fundamental constants at a frequency characteristic of the dilaton mass – from $\tau = 0.4$ fs to 130 years [3]. Additionally, optical clocks can test for violations of Lorentz invariance, transients in dark matter composition, long-term drift of α and more. In this work, we present an overview of the NPL Yb^+ system and the possibilities for fundamental physics that it presents.

[1] Godun, R. M., et. al. (2014). *Frequency Ratio of Two Optical Clock Transitions in $^{171}Yb^+$ and Constraints on the Time Variation of Fundamental Constants*. Physical Review Letters, **113**(21), 210801. DOI:10.1103/PhysRevLett.113.210801

[2] Dzuba, V. A., & Flambaum, V. V. (2008). *Relativistic corrections to transition frequencies of Ag I, Dy I, Ho I, Yb II, Yb III, Au I, and Hg II and search for variation of the fine-structure constant.* Physical Review A, **77**(1), 1–6. DOI: 10.1103/PhysRevA.77.012515

[3] Safronova, M. S., *et.al.* (2018). *Search for new physics with atoms and molecules.* Reviews of Modern Physics, **90**(2), 025008. DOI:10.1103/RevModPhys.90.025008

[4] Roberts, M., *et. al.* (2000). *Observation of the $^2S_{1/2}$–$^2F_{7/2}$ electric octupole transition in a single $^{171}Yb^+$ ion.* Physical Review A, **62**(2), 020501. DOI:10.1103/PhysRevA.62.020501

MAIUS-B: Towards dual-species matter-wave interferometry in space

D. Becker, M. D. Lachmann, B. Piest, E. M. Rasel
Institute of Quantum Optics, Leibniz University Hannover, Germany

Bose-Einstein condensation (BEC) was awarded with the Nobel Prize only 18 years ago. At that time one could only "speculate on areas for the application of BEC. The new ‘control’ of matter which this technology involves is going to bring revolutionary applications in such fields as precision measurement and nanotechnology."
Today, BEC interferometry is a cornerstone for applications of cold atoms on ground and in space and represents a new field in matter-wave optics. These interferometers strive to increase the sensitivity by coherently splitting and separating wave packets over macroscopic spatial and temporal scales. BECs, representing a textbook example for a macroscopic wave packet, are the ideal source for performing this kind of interferometry in very long baseline interferometers stretching out over seconds on ground and during even longer interferometry times in space.
After expending great effort, especially in mastering many technical challenges, BEC creation and interferometry was exploited for the first time in the extended free fall with a chip-based atom laser of Rb-87 in the QUANTUS collaboration [1,2]. Following, the design was further improved and successfully employed on a rocket based test of such a BEC interferometer onboard the MAIUS-1 mission, realizing the first demonstration of Bose-Einstein condensation and coherent matter wave manipulation in space [3].
To utilize this excellent system for precision measurements in space, we now aim for dual-species atom interferometry to perform tests of the universality of free fall on the upcoming sounding rocket missions MAIUS-2 and -3. The new setup contains K-41 as a second species in addition to Rb-87, an optical dipole trap and strong magnetic coils for Feshbach mixture studies, and will utilize Raman double-diffraction for enhanced interferometry.
On this poster, we give an overview of the planned sounding rocket mission and present the current status of the ongoing ground-based experiments to reach quantum degeneracy of the atomic mixture. We present the MAIUS-B physics package and the ground-based and transportable testbed for the creation of a dual-species BEC of Rb-87 and K-41. The modular design of the laser system allows for independent operation at 780 nm and 767 nm, including grey molasses cooling on the D1-transition of potassium. It further enables transportation to different testing facilities and easy extension regarding tests of future experiments.
The drop tower experiments and sounding rocket missions pave the way for future space experiments by NASA’s CAL II and the envisioned DLR-NASA project BECCAL, a multi-user facility for experiments on quantum matter, quantum optics and BEC interferometry. Among others, they will demonstrate important techniques necessary for satellite based quantum tests of the Einstein equivalence principle as pursued by the STE-QUEST mission, for satellite gravity gradiometry and future gravitational wave detection based on ultracold atoms.

[1] T. van Zoest et al., *Science* **328**, 1540-1543 (2010)
[2] H. Müntinga et al., *Phys. Rev. Lett.* **110**, 093602 (2013)
[3] D. Becker et al., *Nature* **562**, 391–395 (2018)

The QUANTUS & BECCAL projects are supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economic Affairs and Energy (BMWi) under the grant number 50 WP 1431 & 1700.

UV laser systems for sympathetic cooling of highly charged ions using $^9Be^+$

S. Bogen[1], J. Stark[1], L. Schmöger[1], C. Warnecke[1], L. Haaga[1], J. R. Crespo López-Urrutia[1]

[1]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

Cold highly charged ions (HCI) are promising candidates for developing novel optical clocks with potentially relative accuracies well beyond 10^{-19} [1][2], as well as searching for physics beyond the Standard Model [3]. In particular, some of them feature narrow optical transition with an enhanced sensitivity to a possible variation of the fine-structure constant α [2]. For high-precision optical frequency metrology, they have to be trapped and cooled to the motional ground state of the trapping potential [4][5]. As HCI do not have electric-dipole allowed optical transitions for laser cooling, the cryogenic Paul trap experiment CryPTEx [4][5][6] applies sympathetic cooling using directly laser-cooled $^9Be^+$ ions for reaching the mK temperature range.

These requisite co-trapped $^9Be^+$ cooling ions are produced in flight near the trap center by photoionization of ^9Be atoms with a laser at 235 nm based on Ref. [7]. The desired wavelength is obtained by cavity-enhanced frequency doubling of a 940 nm diode laser twice: first with a PPKTP crystal, and second with a BBO crystal. The outgoing radiation is resonant with the $2s\ ^1S_0 - 2p\ ^1P_1$ transition of the ^9Be atom, which is then used for resonance-enhanced two-photon-ionization. In the next step, thereby produced $^9Be^+$ ions are Doppler-cooled driving the $2s\ ^2S_{1/2} - 2p\ ^2P_{3/2}$ transition at 313 nm utilizing a laser built following the technique described in Ref. [8]. Two fiber lasers (1051 nm, 10 W and 1550 nm, 5 W) feed a PPLN crystal that produces 626 nm by sum-frequency generation. This beam is subsequently frequency-doubled to the required 313 nm by means of cavity-enhanced second harmonic generation using another BBO crystal.

[1] V. I. Yudin, A.V. Taichenachev and A. Derevianko, *Magnetic-dipole transitions in highly charged ions as a basis of ultraprecise optical clocks*, Phys. Rev. Lett. **113**, 233003 (2014).

[2] V. A. Dzuba, A. Derevianko and V. V. Flambaum, *Ion clock and search for the variation of the fine-structure constant using optical transitions in Nd 13^+ and Sm 15^+*, Phys. Rev. A **86**, 054502 (2012).

[3] M. G. Kozlov, M. S. Safronova, J. R. Crespo López-Urrutia and P. O. Schmidt, *Highly charged ions: Optical clocks and applications in fundamental physics*, Reviews of Modern Physics **90**, 045005 (2018).

[4] M. Schwarz et al, *Cryogenic linear Paul trap for cold highly charged ion experiments*, Rev. Sci. Instrum. **83**, 083115 (2012).

[5] L. Schmöger et al., *Coulomb crystallization of highly charged ions*, Science **347**, 6227 (2015).

[6] L. Schmöger et al., *Deceleration, precooling, and multi-pass stopping of highly charged ions in Be^+ Coulomb crystals*, Rev. Sci. Instrum. **86**, 103111 (2015)

[7] H.-Y. Lo et al., *All-solid-state continuous-wave laser systems for ionization, cooling and quantum state manipulation of beryllium ions*, Appl. Phys. B, **114**: 17-25 (2014)

[8] A.C. Wilson et al., *A 750-mW, continuous-wave, solid-state laser source at 313 nm for cooling and manipulating trapped $^9Be^+$ ions*, Appl. Phys. B, **105**: 741-748 (2011)

Quantum autoencoders: denoising entangled states

D. Bondarenko, P. Feldmann
Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstr. 2, 30167 Hannover, Germany.

Entangled states are an important resource that can be used in quantum computation, quantum communication, and the study of many-body systems. However, various sources of noise present challenges in the experimental preparation of such states. Thus, it is important to design denoising algorithms. An efficient way to denoise classical data is to use unsupervised learning with autoencoder neural networks. In this work we show how to use quantum neural networks [1] for unsupervised learning. We develop quantum autoencoders that learn how to denoise a particular quantum state. We demonstrate the effectiveness of quantum autoencoders by denoising GHZ states that are subject to spin flip errors or random unitary noise. We expect that this approach can be used to improve contemporary state-of-the-art experiments as well as to perform more general quantum unsupervised learning tasks.

[1] K. Beer, D. Bondarenko, T. Farrelly, T. Osborne, R. Salzmann, R. Wolf,
Efficient Learning for Deep Quantum Neural Networks, arXiv:1902.10445.

Spatial entanglement patterns and Einstein-Podolsky-Rosen steering in a Bose-Einstein condensate

P. Colciaghi, M. Fadel, T. Zibold, B. Decamps, Y. Li, P. Treutlein
Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland.

Atomic Bose-Einstein condensates (BECs) are highly controllable and well isolated quantum systems with long coherence times, and offer applications in metrology and quantum information processing. We experimentally prepare two-component Rubidium-87 BECs, consisting of a few hundred atoms, on an atom-chip. Using state-selective potentials to tune the collisional interactions (one-axis twisting dynamics), we prepare many-particle non-classical states. After a time-of-flight expansion, high-resolution images allow us to access sub-regions of the atomic density distribution of various shapes and measure the spin correlations between them.

We observe that bi-partitions violate a separability criterion, indicating the presence of entanglement between different spatial regions of our many-body system. In one of such partitions, entanglement is strong enough for Einstein-Podolsky-Rosen steering: measurement outcomes for non-commuting observables in one spatial region can be predicted based on a corresponding measurement in the other region with an inferred uncertainty product below the Heisenberg relation. This feature could be exploited for the imaging of electromagnetic and other field distributions with an uncertainty beyond the standard quantum limit.

We will also give an update on our efforts to prepare high-fidelity non-classical states of atomic ensembles and present the latest experimental results obtained with our apparatus.

Towards Constraining a Time Variation of Fundamental Constants with the Molecular Iodine Clock

A. F.L. Constantin[1]

[1]Laboratoire PhLAM, University Lille 1, CNRS UMR 8523, France.

The variability of fundamental constants is allowed in theories beyond the Standard Model [1]. This variability may be constrained by repetitive measurements in laboratory of frequency ratios between atomic or molecular clocks. The strategy for improving the constraint is to increase the accuracy of the clock transitions, to exploit transitions highly sensitive to a variation of fundamental constants, and to perform measurements during a long period of time. The molecular spectra are sensitive to a proton-electron mass ratio (μ) variation. The absolute frequency measurements of a rovibrational transition of SF_6 constrained a variation of μ at 5.6×10^{-14} yr^{-1} [2]. This contribution discusses progress towards constraining a time variation of fundamental constants through laboratory measurements of the optical transitions of the molecular iodine.

The Doppler-free reference lines of the molecular iodine have been used widely for laser frequency stabilization and provided a secondary frequency standard in the optical domain. A compact setup with a frequency-doubled Nd:YAG laser locked at 532 nm have 5×10^{-14} stability at 1 s and 6×10^{-14} uncertainty over one-month measurements [3]. The space applications of the molecular iodine optical clock were recently addressed [4]. The frequency uncertainties provided by some experimental setups are estimated at the 10^{-16} level [5].

The sensitivity to a variation of μ of the energy levels of $^{127}I_2$ in the ground X electronic state and in the excited B electronic state is calculated using vibrational terms, rotational constants and centrifugal distortion constants that have been determined in [6]. The sensitivity coefficient to a variation of μ is derived for selected sets of transitions of $^{127}I_2$ in different spectral domains and plotted in Fig. 1. In addition, the splitting between the X and B electronic states of $^{127}I_2$ provides sensitivity to a variation of the fine structure constant. The relation between a time variation of the fundamental constants and a time variation of the ratio between the frequency of the molecular iodine clock and the Cs atomic clock is explained. The variation of μ may be constrained at the 10^{-16} level with the experimental setup [5], by assuming negligible time variation for other fundamental constants.

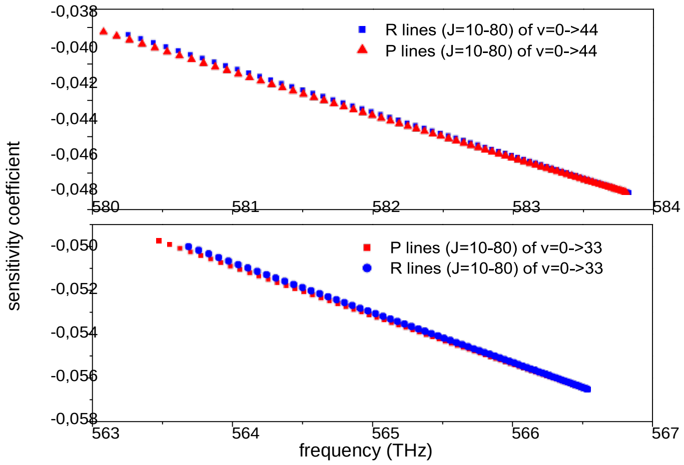


Figure 1. Dependence of the sensitivity coefficient on the transition frequency for selected bands of the B-X system of $^{127}I_2$.

[1] J.-Ph. Uzan, *The fundamental constants and their variation: observational and theoretical studies*, Rev. Mod. Phys. **75**, 403 (2003).

[2] A. Shelkovnikov *et al*., *Stability of the proton-to-electron mass ratio*, Phys. Rev. Lett. **100**, 150801 (2008).
[3] J. Ye, L.S. Ma, and J.L. Hall, *Molecular Iodine Clock*, Phys. Rev. Lett. **87**, 270801 (2001).
[4] C. Philippe *et al*., *A compact frequency stabilized telecom laser diode for space applications,* Proc. of SPIE **10562**, International Conference on Space Optics ICSO 2016, 1056253 (2017).
[5] N. Gürlebeck *et al*., *BOOST: A satellite mission to test Lorentz invariance using high-performance optical frequency references*, Phys. Rev. D **97**, 124051 (2018).
[6] S. Gerstenkom and P. Luc, *Description of the absorption spectrum of iodine recorded by means of Fourier transform spectroscopy : the (B-X) system*, J. Physique **46**, 867 (1985).

Engineered atomic state for precision interferometry

R. Corgier[1,2], E. Charron[2], N. Gaaloul[1], E. M. Rasel[1]
[1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover, Germany.
[2]Institut des Sciences Moléculaires d'Orsay, Université Paris-Saclay, 91405 Orsay Cedex, France.

Recent proposals in the field of fundamental tests of foundations of physics propose Bose-Einstein condensates (BEC) as sources of atom interferometry sensors [1].

Atom chip devices have allowed to build transportable BEC machines with high repetition rates as demonstrated in the QUANTUS project [2]. The proximity of the atoms to the chip surface is, however, limiting the optical access and the available interferometry time necessary for precision measurements. In this context, a fast and perturbation-free transport of the atoms is required.

We present a detailed theoretical analysis of the implementation of shortcut-to-adiabaticity protocols for the fast transport of neutral atoms with atom chips [3]. The objective is to engineer transport ramps with durations not exceeding a few hundred milliseconds to provide metrologically-relevant input states for an atomic sensor. Aided by numerical simulations of the classical and quantum dynamics, we study the behavior of a Bose-Einstein condensate in an atom chip setup with realistic anharmonic trapping. We detail the implementation of fast and controlled transports over large distances of 1-2 millimeters, *ie* distances 1000 times larger than the size of the atomic cloud. A subsequent optimized release and collimation step demonstrates the capability of our transport method to generate ensembles of quantum gases with expansion speeds in the picokelvin regime as illustrated in the figure. With such low expansion rates, atom interferometry experiments with seconds of drift time are possible. The performance of this procedure is analyzed in terms of collective excitations [4] reflected in residual center of mass and size oscillations of the condensate. We further evaluate the robustness of the protocol against experimental imperfections. Such a procedure has been applied in the Quantus 2 experiment leading to only 5 micrometers of residual dipole oscillation amplitude in the final trap after a 1.5mm transport during 150ms ramp [5] and allows an efficient delta-kick-collimation (DKC) [6,7] to the pK level. Thanks to the optimal control theory, we highlight how one can extend this method for the double species transport problem relevant for universality of free fall tests.

[1] D. N. Aguilera et al. Class. Quantum Grav. **31,** 115010 (2014)
[2] J. Rudolph et al. New J. Phys. **17**, 079601 (2015)
[3] R. Corgier, et al. New J. Phys. **20**, 055002 (2018).
[4] S. Stringari, Phys. Rev. Lett. **77**, 2360 (1996)
[5] Rudolph J 2016 Matter-Wave Optics with Bose-Einstein Condensates in Microgravity Ph.D. thesis Leibniz University of Hanover
[6] H. Müntinga et al. Phys. Rev. Lett. **10**, 093602 (2013)
[7] T. Kovachy et al. Phys. Rev. Lett.**14**, 143004 (2015)

A cryogenic Penning trap system for precision measurements with (anti-)protons

J. M. Cornejo[1], M. Niemann[1], T. Meiners[1], J. Mielke[1], M. J. Borchert[1,2] S. Ulmer[2], C. Ospelkaus[1,3]

[1] Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany.

[2] Ulmer Fundamental Symmetries Laboratory, RIKEN, Wako, Saitama 351-0198, Japan.

[3] Physikalisch-Technische Bundesanstalt Braunschweig, Bundesallee 100, 38116 Braunschweig, Germany

High-precision experiments in selected sectors of the Standard model of particles physics have enabled the most stringent tests of CPT and Lorentz violations [1,2]. In the baryonic sector, rapid progress has been achieved in recent years by means of g-factor measurements of protons and antiprotons with Penning traps [2,3]. These measurements rely on state preparation and cooling of individual ions by means of image current detection (see, e.g., Ref. [3]). Alternative cooling and detection schemes have the potential to improve the sensitivity to these tests with protons and antiprotons by speeding up the required measurement time [4]. For this purpose, we present an experimental setup to sympathetically cool protons and antiprotons by means of free-space coupling with a single laser-cooled $^{9}Be^{+}$ ion [5]. In order to demonstrate this mechanism for the first time in a Penning trap, we have developed and commissioned a segmented Penning trap to couple identical ions. In this contribution, we will show the status of the project emphasizing the latest results on Doppler cooling of $^{9}Be^{+}$ clouds as well as single ion detection.

[1] E. Abouzaid, M. Arenton, A.R. Barker, *et al.*, *Precise measurements of direct CP violation, CPT symmetry, and other parameters in the neutral kaon system,* Phys. Rev. D **83**, 092001 (2011).
[2] C. Smorra, S. Sellner, M.J. Borchert, J. Harrington, T. Higuchi, , H. Nagahama, T. Tanaka, A. Mooser, G. Schneider, M. Bohman, K. Blaum, Y. Matsuda, C. Ospelkaus, W. Quint, J. Walz, Y. Yamazaki and S. Ulmer, *A parts-per-billion measurement of the antiproton magnetic moment*, Nature **550**, 371 (2017).
[3] G. Schneider, A. Mooser, M. Bohman, N. Schön, J. Harrington, T. Higuchi, H. Nagahama, S. Sellner, C. Smorra, K. Blaum, Y. Matsuda, W. Quint, J. Walz and S. Ulmer, *Double-trap measurement of the proton magnetic moment at 0.3 parts per billion precision,* Science **358**, 1081 (2017).
[4] D.J.Wineland, C.R. Monroe, W.M. Itano, D. Leibfried, B.E. King and D. Meekhof, *Experimental issues in coherent quantum-state manipulation of trapped atomic ions,* J. Res.NIST **103,** 259 (1998).
[5] T. Meiners, M. Niemann, J. Mielke, M. Borchert, N. Pulido, J.M. Cornejo, S. Ulmer and C. Ospelkaus, *Towards sympathetic cooling of single (anti-)protons,* Hyperfine Interact. **239**, 26 (2018).

Atom interferometers with specular reflection

F. Di Pumpo[1], A. Friedrich[1], E. Giese[1], A. Roura[1], W. P. Schleich[1,2],
D. M. Greenberger[3], E. M. Rasel[4]

[1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, Albert-Einstein-Allee 11, D-89069 Ulm, Germany.

[2]Hagler Institute for Advanced Study and Department of Physics and Astronomy, Institute for Quantum Science and Engineering (IQSE), Texas A&M AgriLife Research, Texas A&M University, College Station, TX 77843-4242, USA.

[3]City College of the City University of New York, New York, NY 10031, USA.

[4]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover, Germany.

Effects based on quantum clock interference rely on atom interferometers with a non-vanishing proper time difference [1]. We propose an atom interferometer consisting of two beam splitters to separate and recombine the two branches of the interferometer, and two specular mirrors in the middle [2,3] that invert the incoming momentum, see Fig. 1 . We show that with the help of specular reflection the difference in proper time between the two branches of the resulting geometry is non-vanishing, in contrast to the familiar Mach-Zehnder interferometer [4,5] with mirrors that rely on a diffractive mechanism. Finally, we propose a realization of specular mirrors by strongly detuned evanescent light fields.

The QUANTUS project is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number 50WM1556 (QUANTUS IV).

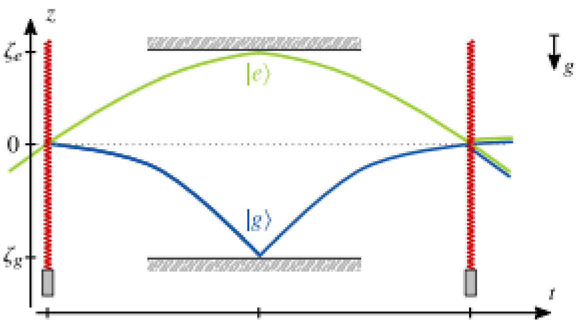


Figure 1. Specular mirror interferometer in laboratory frame utilizing Raman beam splitters.

[1] Zych et al., *Quantum interferometric visibility as a witness of general relativistic proper time,* Nat. Commun. **2**, 505 (2011).
[2] Giese et al., *Proper time in atom interferometers: Diffractive versus specular mirrors,* Phys. Rev. A **99**, 013627 (2019).
[3] Di Pumpo et al., *Specular mirror interferometer,* in preparation (2019).
[4] Müller et al., *A precision measurement of the gravitational redshift by the interference of matter waves,* Nature **463**, 926–929 (2010).
[5] Greenberger et al., *Relativistic effects in atom and neutron interferometry and the differences between them,* Phys. Rev. A **86**, 063622 (2012).

High accuracy measurements of Casimir-Polder atom surface potential for fundamental physics

H. Bricha[1], N. Fabre[1], F. Correia[1], M. Ducloy[1], F. Perales[1] and G. Dutier[1]
A. Cronin[2], S. Scheel[3]
[1]Laser Physics Lab, University Paris 13, Villetaneuse, France.
[2]Tucson, University of Arizona, USA
[3]Institute of Physics, University of Rostock, Germany

Atomic transmission nano gratings experiment is revisited with a novel low velocity metastable argon beam. Since 20 years atomic diffraction through nano gratings allow short range van der Waals interaction observations with supersonic beams. Theoretical Casimir-Polder (or van der Waals) potential determination has remained nevertheless in 10% range due to two independents limitations. First and the most important, nano gratings fabrication technique was within few nanometers geometrical uncertainty, which is unfortunately amplified on the potential strength modeling. And second, for supersonic beam velocity, a small matter wave dephasing is imprinted from atom surface potential during the passage into the nano grating. Both have been improved recently thanks to a novel low atomic beam velocity ranging from 20 to 130 m/s [1] and local clean room facilities leading to 1 nm geometrical uncertainty.

Preliminary results at atomic velocity of 32 m/s and with a usual nano grating demonstrate atom surface potential uncertainty as good as the best previous measurements. The use of recently made nano grating allows us to expect 1% accuracy on the Casimir-Polder potential. Such an improvement would raise a novel constraint by one order of magnitude more on the hypothetical 5th force [2] at short distance.

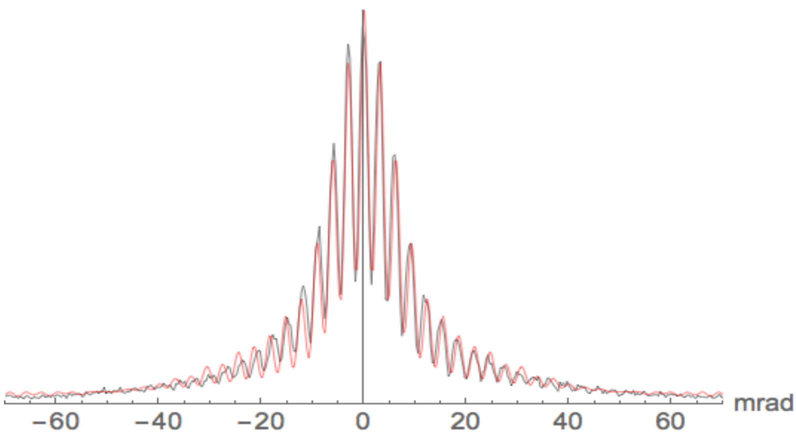


Figure 1. In black. Experimental atomic diffraction spectrum at a velocity of 32 m/s through a nano grating of 100 nm pitch and 60 nm slit. In red, theoretical model.

[1] T Taillandier-Loize, S A Aljunid, F Correia, N Fabre, F Perales, J M Tualle, J Baudon, M Ducloy and G Dutier, "A simple velocity-tunable pulsed atomic source of slow metastable argon", J. Phys. D: Appl. Phys. **49** 135503 (2016)

[2] I. Antoniadis, S. Baessler, M. BŸchner, V.V. Fedorov, S. Hoedl, A. Lambrecht, V.V. Nesvizhevsky, G. Pignol, K.V. Protasov, S. Reynaud, Yu. Sobolev, "Short-range fundamental forces", C. R. Physique **12**, 755 (2011)

Universal atom interferometry simulator for precision sensing

F. Fitzek[1,2], H. Ahlers[1], E. M. Rasel[1], K. Hammerer[2], N. Gaaloul[1]
[1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, Deutschland.
[2]Institut für Theoretische Physik, Leibniz Universität Hannover, Welfengarten 1, Deutschland.

Quantum sensors based on light-pulse atom interferometers allow for high-precision measurements of inertial and electromagnetic forces, accurate determination of fundamental constants as the fine structure constant α or to test foundational laws of modern physics as the equivalence principle. The full potential, i.e. sensitivity of these schemes unfolds when large interrogation times or macroscopic arm separation could be implemented. Both directions, however, imply a substantial deviation from an ideal interaction of light with atomic systems. Indeed, real-life complications as finite pulse areas and fidelities, momentum width broadening of the cold clouds, atomic interactions or light fields distortions limit the measurements but more dramatically hinder a reasonable systematics study. This is mainly due to the limited number of analytical cases and to the realistic numerical calculations being intractable.
In this study, we present an efficient numerical solver of the time dependent dynamics of atom-light interactions in position space. It is designed to allow for a flexible simulation of a wide range of non-ideal effects. This approach is also aimed to be cross-regime, valid for different types of beam splitters (Bragg, Raman and Bloch) and free from approximations incompatible with a metrological use.

Quantum Interference of Clocks and the Twin Paradox

A. Friedrich[1], S. Loriani[2], E. Giese[1] and the Hannover-Ulm team[1,2]
[1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ^{ST}),
Universität Ulm, Albert-Einstein-Allee 11, D-89069 Ulm, Germany.
[2]Institut für Quantenoptik, Leibniz Universität Hannover,
Welfengarten 1, D-30167 Hannover, Germany.

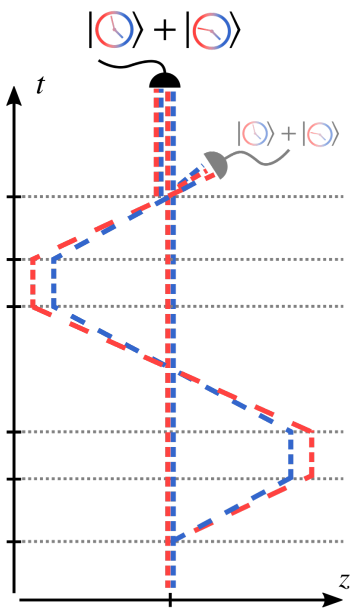


Fig. Twin-paradox in quantum clock interferometry.

Light-pulse atom interferometry has become a standard tool for the realization of high precision experiments, quantum sensing applications as well as tests of relativity. The latter relies on the fact that the phase of a matter wave is partially determined by proper time [1] and hence atom interferometers are in principle susceptible to special- and general-relativistic time dilation. On the other hand the proper time of a classical observer is defined operationally [2, 3] as the quantity an ideal clock [4] placed at the observer's position measures while the observer moves along a worldline. This relative definition of time directly leads to the twin paradox when two classical clocks are compared after moving along two different worldlines where they experience different amounts of time dilation. However, contrary to the classical clocks used in the formulation of general relativity, today's most accurate clocks are atomic clocks and thus quantum objects which obey the superposition principle. Consequently, an atomic clock can be brought into a superposition of moving along different worldlines which is impossible for classical clocks. This is naturally achieved by combining atomic clocks with atom interferometry in the form of quantum clock interferometers [4, 5]. This combination directly suggests that a *single* quantum clock traveling in *superposition* along two different worldlines experiences a twin paradox with itself. In our contribution we demonstrate which type of atom interferometers implement such a quantum twin paradox and how it manifests in an interferometer. Furthermore, we show how to generally describe quantum clock interference and reveal its sensitivity to different types of time dilation.

[1] L. De Broglie, *Recherches sur la thorié des quanta, Migration-université en cours d'affectation* (1924)

[2] A. Einstein, *Zur Elektrodynamik bewegter Körper*, Ann. Phys. **322** 10 (1905)

[3] A. Einstein, *Dialog über Einwände gegen die Relativitätstheorie*, Naturwissenschaften **6**, 48 (1918)

[4] C. Møller, *The Ideal Standard Clocks in the General Theory of Relativity*, Helv. Phys. Acta, Suppl. **4**, CERN-57-08 (1956)

[5] M. Zych, F. Costa, I. Pikovski, and Č. Brukner, *Quantum interferometric visibility as a witness of general relativistic proper time*, Nat. Commun. **2**, 505 (2011).

[6] A. Roura, arXiv 1810.06744, *Gravitational redshift in quantum-clock interferometry* (2018)

Degenerate gases at the frontiers of matter-wave interferometry

N. Gaaloul[1]
[1]Institut für Quantenoptik, Leibniz Universität Hannover

Long drift times of several seconds promise to boost the current performance of atom interferometers by orders of magnitude in probing fundamental laws of physics or measuring inertial forces. To take advantage of the available free fall time, the choice of degenerate gases as slowly expanding sources is natural. Novel methods of quantum engineering such as controlled matterwave dynamics at the pK level or coherent superposition of atomic states split by thousands of photon recoils are reported in this contribution.
Based on these optimal microscopic arrangements, realistic scenarii for long-baseline or space experiments aiming to test Einstein's weak equivalence principle at levels better than 10^{-15} and detect gravitational waves in the infrasound band will be detailed.

Rotational and Magnetic Field Interferometry with Ring-Trapped Bose-Einstein Condensates

A. J. L. Helm[1], T. P. Billam[2], A. Rakonjac[3], S.L. Cornish[3], and S. A. Gardiner[3],

[1]The Dodd–Walls Centre for Photonic and Quantum Technologies, Department of Physics, University of Otago, Dunedin 9016, New Zealand.

[2]Joint Quantum Center (JQC) Durham–Newcastle, School of Mathematics, Statistics and Physics, Newcastle University, Newcastle upon Tyne NE1 7RU, United Kingdom.

[3]Joint Quantum Center (JQC) Durham–Newcastle, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom.

The interactions present in a Bose-Einstein condensed sample are typically deleterious to interferometric protocols, however maintaining an essentially constant density within an ideal toroidal trapping configuration in principal avoids these issues [1]. We have proposed a specific method of atom interferometry using a spinor Bose-Einstein condensate with a time-varying magnetic field acting as a coherent beam splitter [2], tested with fully three-dimensional integrations of the spinor Gross-Pitaevskii equation. Our protocol creates long-lived superpositional counterflow states, which are of fundamental interest and can be made sensitive to both the Sagnac effect and magnetic fields on the sub micro-Gauss scale. Our protocol can maximize the classical Fisher information [3] for any rotation, magnetic field, or interrogation time and so has the maximum sensitivity available to uncorrelated particles. Precision can increase with the interrogation time and so is limited only by the lifetime of the condensate

[1] P.L. Halkyard, M.P.A. Jones, and S.A. Gardiner, *Rotational response of two-component Bose-Einstein condensates in ring traps, Physical Review A* **81**, 061602 (2010).

[2] J.L. Helm, T.P. Billam, A. Rakonjac, S.L. Cornish, and S.A. Gardiner, *Spin-Orbit-Coupled Interferometry with Ring-Trapped Bose-Einstein Condensates*, Phys. Rev. Lett. **120**, 063201 (2018).

[3] S.A. Maine, *Mean-Field Dynamics and Fisher Information in Matter Wave Interferometry*, Phys. Rev. Lett. **116,** 230404 (2016).

Testing atom neutrality with atom interferometer

M. Bordoux, B. Allard, A. Gauguet[1]
Laboratoire Collisions Agrégats Réactivité (LCAR), University Paul Sabatier, 118 route de Narbonne 31062 Toulouse, France.

Precisely testing the electrical neutrality of matter is significant in the extension of the standard model, and for testing astrophysical models. Despite many experimental efforts made in the recent decades, the improvements are relatively small. I will survey the current status of the laboratory experiments and astrophysical observations. I will discuss the possibility of testing atom neutrality with an atom interferometer using the Electrical Aharonov-Bohm phase shift [1]. This idea can be effectively implemented with ultra-cold atoms and the so-called large momentum transfer beam splitters [2]. I will present the dedicated experimental setup that we are building.

[1] C. Champenois et al., The hydrogen atom, Springer, 554 (2001).
[2] A. Arvanitaki et al. Phys. Rev. Lett. 100, 120407 (2008).

Spectroscopy of the molecular ion HD^+ in the Lamb-Dicke regime: towards determination of fundamental constants at the 10^{-10} level

S. Alighanbari[1], F. L. Constantin[1,2], G. S. Giri[1], V. Korobov[3], S. Schiller[1]
[1]Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany
[2]Laboratoire PhLAM CNRS UMR 8523,University Lille 1, Villeneuve d'Ascq, France
[3]Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Russia

Precision measurements with cold atoms and molecules allow testing the predictions of quantum electrodynamics, determining fundamental constants, probing their possible time variation, and searching for new fundamental interactions. The effective control of atoms' and molecules' external and internal degrees of freedom paves the way to increased accuracy. Molecular hydrogen ions (MHIs) are three-body quantum systems for which comparison of *ab initio* theory and experiment can provide an independent determination of the Rydberg constant, of the mass ratios of electron to proton and electron to deuteron, and ultimately also of the proton's and deuteron's charge radius. This program is enabled by recent strong advance in *ab initio* theory [1, 2], which has reached ≈ 1×10^{-11} inaccuracy.

On the experimental side, the spectroscopy of MHI has so far been limited by Doppler broadening even at the low temperatures (10 mK) achieved using sympathetic cooling, leading to line resolution not better than 5×10^{-7} [3, 4]. Recently, we have for the first time achieved Doppler-free spectroscopy of the fundamental rotational transition of HD^+ at 1.3 THz, enabled by the transverse confinement of the MHI clusters in the Lamb-Dicke regime [2]. Line resolution of 1×10^{-9} was achieved.

In this contribution we present an up to 300-fold further decrease in linewidth, to the 3×10^{-12} level (Fig. 1, arrow). This line resolution is now better than the theoretical inaccuracy of the *ab initio* prediction. This excellent resolution allows us to probe systematic shifts very sensitively. For example, we determined an upper limit of 1×10^{-11} for the light shift induced by 266 nm radiation on the rotational transition, and also resolved the ultra-small pure rotational Zeeman shift (0.55 kHz/G). To date, we measured 6 hyperfine transitions, including a number of Zeeman components (Fig. 1). Our resolution of the hyperfine structure improves on the best previous measurements of any MHI by a factor of 10 [5].

With the data obtained we are able to test the recently improved theory of the spin structure of the molecular ion [6] at the 0.1 kHz uncertainty level. We are also currently analysing the data towards determining the fundamental constant $R_{\infty}m_e(m_p^{-1} + m_d^{-1})$ with a goal uncertainty on the low-10^{-10} level. Our value can then be compared with the combined results from atomic hydrogen spectroscopy and mass spectrometry in Penning traps [7, 8]. The results of the analysis will be presented at the conference.

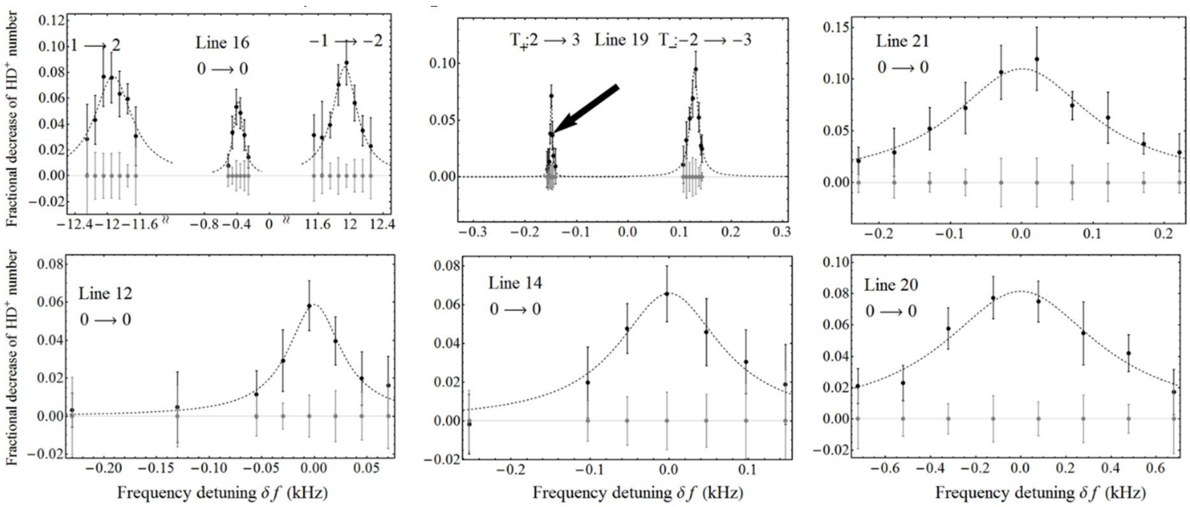


Fig. 1. 6 hyperfine components of the fundamental rotational transition. The line center frequencies of the components differ by values of the order 10 MHz. The arrow indicates an ultranarrow Zeeman component (4 Hz FWHM).

References

[1] V. Korobov, *et al.*, *Fundamental Transitions and Ionization Energies of the Hydrogen Molecular Ions with Few ppt Uncertainty*, Phys. Rev. Lett. **118**, 233001 (2017).

[2] S. Alighanbari, *et al.*, *Rotational spectroscopy of cold and trapped molecular ions in the Lamb-Dicke regime*, Nat. Phys. **14**, 555 (2018).

[3] U. Bressel, *et al.*, *Manipulation of Individual Hyperfine States in* HD^+ *and Frequency Metrology*, Phys. Rev. Lett. **108**, 183003 (2012).

[4] J. Biesheuvel, *et al.*, *Probing QED and fundamental constants through laser spectroscopy of* HD^+, Nat. Commun. **7**, 10385 (2016).

[5] K.B. Jefferts, *Hyperfine structure in the molecular ion* H_2^+, Phys. Rev. Lett. **23**, 1476 (1969).

[6] V. Korobov, *et al.*, *Theoretical Hyperfine Structure of the Molecular Hydrogen Ion at 1 ppm Level*, Phys. Rev. Lett. **116**, 053003 (2016).

[7] F. Heiße *et al.*, *High Precision Measurement of the Proton's Atomic Mass*, Phys. Rev. Lett. **119**, 033001 (2017).

[8] S. L. Zafonte and R. S. Van Dyck Jr, *Ultra-precise single-ion atomic mass measurements on D and He-3*, Metrologia **52**, 280 (2015).

Towards optically trapped 2d ion crystals and Rydberg atoms

M. Grau[1], C. Fischer[1], O. Wipfli[1], J. P. Home[1]

[1]Institute for Quantum Electronics, ETH Zürich, Otto-Stern-Weg 1, 8093 Z Zürich, Switzerland.

Due to the long coherence times that can be achieved and the exquisite degree of control exhibited, trapped ions are well suited for precision experiments such as optical clocks and tests of fundamental physics. Additionally arrays of trapped ions are an attractive platform for quantum simulation due to the intrinsic long range Coulomb interaction that can be used to engineer tunable spin-spin couplings. However, current trapping techniques are limited in number of ions that may be trapped and still adequately controlled, and suffer from other deleterious effects such as micromotion and so-called anomalous source of heating from nearby surfaces. We are developing a new apparatus to trap arrays of ions in optical lattices, which combine the flexible geometry found in neutral atom experiments with the high degree of control and large interaction strengths found in ion experiments. Arrays of around 40 ions could be trapped with inter-ion distances of under 10 microns, with no micromotion, and also with low residual heating rates due to off-resonant scattering and laser fluctuations. This will be made possible by using a deep lattice potential formed by the large optical intensity in a high-finesse optical cavity. Operating the optical lattice at a wavelength that traps both neutral atom and ions will allow us to deterministically load neutral atoms in a designed geometry before photoionizing in-situ. A complementary approach to quantum simulation with long- range interactions could be to optically trap the ion core of a two electron Rydberg atom. If autoionization were suppressed by exciting the Rydberg electron to high angular momentum states, then the intrinsic Rydberg dipoles could be used as a spin simulator. Experimental progress towards these two goals will be described.

Quantum Logic Spectroscopy with a $^{40}Ca^+/^{27}Al^+$ mixed ion crystal

M. Guevara-Bertsch[1,2], M. Guggemos[1,2], D. Heinrich[1,2], C.F. Roos[1,2], R. Blatt [1,2]

[1]Insitut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Innsbruck, Austria.

[2]Institute für Experimentalphysik, Universität Innsbruck, Innsbruck, Austria.

The search for more precise and accurate frequency standards has played a key role in the development of basic science, precision measurements and technical applications [1, 2]. Recently, with the inclusion of essential ingredients from quantum information science, by means of Quantum Logic Spectroscopy (QLS) [3], it is possible to perform high precision spectroscopy of atoms that could potentially be applied in the development of high accuracy optical clocks but lack suitable transitions for efficient laser cooling, internal state preparation, and detection. QLS consists of the combined implementation of an auxiliary “logic” ion, which is stored in a miniature linear radio-frequency trap, together with a “spectroscopy” ion. The “logic” ion is then used to cool down the initially hot “spectroscopy” ion via the Coulomb interaction and additionally allows the preparation and detection of the internal state of the “spectroscopy” ion.

Our research focuses on the implementation of QLS to perform optical spectroscopy of the $^{27}Al^+$ ion. A single $^{40}Ca^+$ ion (“logic” ion) and a single $^{27}Al^+$ ion (“spectroscopy” ion) are loaded by means of laser-ablation and trapped in a linear Paul trap. Due to the observation of long sympathetic cooling times before crystallization, we developed a new technique that allows us to detect the loading and cooling of an initially hot (“spectroscopy”) ion [4]. By monitoring the motional state of the Doppler-cooled (“logic”) ion we are able to detect the presence of the hot (“spectroscopy”) ion in the trap and then to observe when the two-ion crystal of Ca^+ and Al^+ is finally cooled. Once the crystal is in its motional ground state by laser cooling the Ca^+ ion, we interrogate the “spectroscopy” ion and map its internal state onto the Ca^+ ion via the common vibrational state.

We performed QLS for a measurement of the $(3s^2)\ {}^1S_0 \leftrightarrow (3s3p)\ {}^3P_1, F = 7/2$ intercombination transition in $^{27}Al^+$. Ramsey spectroscopy is used for probing the transition in $^{27}Al^+$ and the $(4s^2)S_{1/2} \leftrightarrow (4s3d)D_{5/2}$ clock transition in $^{40}Ca^+$ in interleaved measurements. By using the precisely measured frequency of the clock transition in $^{40}Ca^+$ as a frequency reference we determine the frequency of the intercombination line to be $\nu^1{}_{S_0 \leftrightarrow {}^3P_1, F=7/2} = 1\ 122\ 842\ 857\ 334\ 736(93)$ Hz and the landé g-factor of the excited state to be $g_{\ {}^3P_1, F=7/2}$= 0.428132(2) [5].

[1] C.W. Chou, D.B. Hume, J.C.J koelemeij, D.J. Wineland, T. Rosenband, Phys.Rev.Lett 104, 070802(2010)

[2] C.W. Chou, D.B. Hume, T. Rosenband, D.J. Wineland, Science 329,729 (2005)

[3] P.O. Schmidt, T.Rosenband, C. Langer, W.M Itano, J.C. Bergquist, D.J. Wineland, Science 309, 729 (2005).

[4] M.Guggemos, D. Heinrich, O.A. Herrera-Sancho, R. Blatt, C.F. Roos, New J. Phys. 17, 103001 (2015)

[5] M.Guggemos, M.Guevara-Bertsch, D. Heinrich, O.A. Herrera-Sancho, R. Bltt, C.F. Roos, to be publisched

Highly accurate optical frequency ratio measurements for exploring fundamental physics

C. Guo, V. Cambier, J. Calvert, M. Favier, L. De Sarlo, S. Bize

LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, 61 avenue de l'Observatoire 75014, Paris, France.

Optical frequency ratio measurements are key to improving the accuracy of optical frequency spectroscopy of nearly forbidden atomic transitions. These are transitions with sub-Hz linewidths ($Q \sim 10^{16}$) and the accuracy and uncertainty of these frequency measurements can be independently verified by comparison to each other. Optical frequency ratios can also be used to search for variations in fundamental constants, specifically the fine structure constant, α, and the proton/electron ratio [1]. Additionally, highly accurate optical frequency sources are beginning to be utilized in geodesy [2], where currently achievable spectroscopy of an atomic optical transition frequency blow a fractional uncertainty of 10^{-18} can be used to determine the height of the atomic frequency source above the geoid down to a resolution of less than 1 cm [3].

Atomic transitions are sensitive to environmental factors. Due to this sensitivity, it follows that utilizing the least sensitive atomic species would be ideal. Mercury was partially chosen as an atomic species for use in a clock at LNE-SYRTE due to its low sensitivity to black body radiation induced Stark shift and DC Stark shift [4, 5]. The LNE-SYRTE mercury lattice clock is in a unique position of being able to access strontium clock frequency in-house, and strontium and ytterbium ion frequencies at PTB and NPL via utilizing a phase compensated optical fiber network [6, 7]. We will present recent progress on frequency ratio measurements between ^{199}Hg and ^{87}Sr, ^{199}Hg and ^{171}Yb^{+}(E3). Particularly, the ^{199}Hg/^{171}Yb^{+}(E3) ratio is expected to be highly sensitive to variations in α [8], further incentivizing the choice. Recent progress of using a 2D-MOT to improve the mercury lattice clock will also be reported.

[1] JP. Uzan, *Varying constants, gravitation and cosmology*, Living reviews in relativity **14**, 1 (2011).

[2] W. F. McGrew, et al, *Atomic clock performance enabling geodesy below the centimetre level*, *Nature* **564**, 7734 (2018).

[3] T. E. Mehlstäubler, et al, *Atomic clocks for geodesy*, Reports on Progress in Physics **81**, 6 (2018).

[4] M. Petersen, et al, *Doppler-Free Spectroscopy of the $^1S_0 - {}^3P_0$ Optical Clock Transition in Laser-Cooled Fermionic Isotopes of Neutral Mercury*, Phys. Rev. Lett **101**,18 (2008).

[5] R. Tyumenev, et al, *Comparing a mercury optical lattice clock with microwave and optical frequency standards*, New J. Phys. **18**, 11 (2016).

[6] C. Lisdat, et al, *A clock network for geodesy and fundamental science*, *Nature Commun.* **7** (2016).

[7] F. Riehle, *Optical clock networks*, *Nature Photon.* **11**, 1 (2017).

[8] A. D. Ludlow, et al, *Optical atomic clocks*, Rev. Mod. Phys. **87**, 2 (2015).

Quantum-enhanced screened scalar field detection

D. Hartley[1], C. Käding[2], R. Howl[3], I. Fuentes[3]
[1]Faculty of Physics, University of Vienna, Boltzmanngasse 5, 1090 Wien, Austria.
[2]School of Physics & Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom
[3]School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom

Screened scalar field models arise naturally from low energy limits of many models beyond General Relativity and the Standard Model, including string theory and Higgs portal "hidden sector" dark energy models. A screening mechanism alters the properties of the scalar field (such as effective mass or matter coupling strength) near matter, and thus matches experimental data both at the solar system scale and cosmological scales. Some of the best bounds on these models currently come from atom interferometry experiments. We propose an experiment to use a Bose-Einstein condensate phononic interferometer to improve these bounds and potentially entirely eliminate the simplest screening models. These improvements stem from quantum metrology techniques, which we may take advantage of since the quantum state of a Bose-Einstein condensate can be experimentally measured and controlled. These improvements are achievable within current experimental capabilities.

Attractive force on atoms due to blackbody radiation

P. Haslinger[1], M. Jaffe[2], V. Xu[2], O. Schwartz[2], M. Sonnleitner[4], M. Ritsch-Marte[3], H. Ritsch[4], and H. Müller[2]

[1]Technische Universität Wien, Atominstitut, Austria
[2]Department of Physics, UC Berkeley, USA
[3]Division for Biomedical Physics, Medical University of Innsbruck, Austria
[4]Institute for Theoretical Physics, University of Innsbruck, Austria

Atom interferometry has proven within the last decades its surprising versatility to sense with high precision tiniest forces. In this talk I will present our recent work, using an optical cavity enhanced atom interferometer to sense for an on the first-place counterintuitive inertial property of blackbody radiation[1].
Blackbody (thermal) radiation is emitted by objects at finite temperature with an outward energy-momentum flow, which exerts an outward radiation pressure. At room temperature e. g. a cesium atom scatters on average less than one of these blackbody radiation photons every 10^8 years. Thus, it is generally assumed that any scattering force exerted on atoms by such radiation is negligible. However, particles also interact coherently with the thermal electromagnetic field [2] and this leads to a surprisingly strong force acting in the opposite direction of the radiation pressure. Using atom interferometry, we find that this force scales with the temperature of the heated source object (293 – 450 K) to fourth power [1]. The force is in good agreement with that predicted from an ac Stark shift gradient of the atomic ground state in the thermal radiation field [2].

[1] P. Haslinger, M. Jaffe, V. Xu, O. Schwartz, M. Sonnleitner, M. Ritsch-Marte, H. Ritsch, H. Müller, *Attractive force on atoms due to blackbody radiation*, Nat. Phys. **14** 257–260 (2018)

[2] M. Sonnleitner, M. Ritsch-Marte, H. Ritsch, *Attractive Optical Forces from Blackbody Radiation*, Phys. Rev. Lett. **111** 23601 (2013).

The Design of a Laser System for BECCAL – a Quantum Gas Experiment on the ISS

V. A. Henderson[1,2*], A. Wenzlawski[3], A. I. Bawamia[2], J. Marburger[3], A. Wicht[2], P. Windpassinger[3], M. Krutzik[1,2], A. Peters[1,2], E. Rasel[6], W. Schleich[7], and the BECCAL Collaboration[1-8]

[1]Humboldt-Universität zu Berlin, Berlin, Germany

[2]Ferdinand-Braun-Institut, Leibniz Institut für Höchstfrequenztechnik, Berlin, Germany

[3]Johannes Gutenberg-Universität, Mainz, Germany

[4]ZARM, Universität Bremen, Bremen, Germany

[5]DLR Institute for Space Systems, Bremen, Germany

[6]Leibniz Universität Hannover, Hannover, Germany

[7]Universität Ulm, Ulm, Germany

[8]DLR Simulations-und Softwaretechnik, Braunschweig, Germany

BECCAL (Bose-Einstein-Condensate – Cold Atom Laboratory) is a cold atom experiment designed to be operated on the ISS. It is a collaboration between DLR and NASA, built upon the heritage of previous sounding rocket and drop tower experiments such as MAIUS [1,2], QUANTUS [3], JOKARUS [4], FOKUS [5] and KALEXUS [6] as well as NASA's CAL [7]. This multi-user facility will enable us to explore fundamental physics research with Rb and K BECs and ultra-cold atoms in microgravity, facilitating prolonged timescales and ultra-low energy scales compared to those achievable on Earth.

The complexity of the light fields required presents a unique challenge for laser system design, especially in terms of the stringent size weight and power limitations. To address this we combine microintegrated diode lasers (from FBH) [8,9] with miniaturized free-space optics mounted onto Zerodur boards (from JGU) [10], all interconnected via fibre optics. These technologies have proven their reliability in many qualification tests and successful sounding rocket missions. We will present an overview of the current design of the BECCAL laser system, alongside the requirements, concepts and heritage which have formed it.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economic Affairs and Energy (BMWi) under grant number DLR50WP1702.

[1] V. Schkolnik et al., *Appl. Phys. B* 122 (2016), p. 217
[2] D. Becker et al., *Nature* 562, (2018) p. 391
[3] J. Rudolph et al., *New J. Phys.* 17 (2015), 065001
[4] V. Schkolnik et al., *EPJ Quantum Technology* 4 (2017), p. 9
[5] M. Lezius et al., *Optica*. 12 (2016), p. 1381
[6] A. Dinkelaker et al., *Appl. Opt.* 56 (2017), p. 1388
[7] E. R. Elliot et al., *npj Microgravity* 4, (2018) 16
[8] M. Schiemangk et al., *Appl. Opt.* 54 (2015), p. 5332
[9] A. Wicht et al., *Proc. of SPIE 10085* (2017)
[10] H. Duncker et al., *Appl. Opt.* 53 (2014), p. 4468

Testing the EEP with quantum clocks

T. A. Hensel[1,2], P. K. Schwartz[1], D. Giulini[1]

[1]) Institute for Theoretical Physics
Leibniz University Hanover
Appelstraße 2
D-30167 Hanover

[2]) Institute of Quantum Optics Leibniz
University Hanover Welfengarten 1
D-30167 Hanover
hensel.edu@mail.de

It has been two decades now since the first data for a free-fall comparison of a quantum object and a macroscopic object has been taken [1], paving the way towards UFF tests in the quantum realm. Yet it was widely debated, whether a pure quantum test of the EEP, especially UGR would in principle be possible ([2] and [3]). This debate is not yet concluded, as can be seen by the most recent contributions of A. Roura [4] and (forthcoming) S. Loriani [5]. This proves the continued relevance of the topic and interest of the scientific community in it, which led us to an investigation of state of the art tests of the Universality of Gravitational Redshift (UGR) with atom interferometers.
We conduct a theoretical study of tests of the EEP with Quantum Clocks with particular focus on the UGR by analyzing the extensive and ongoing discussion in the frame of a bachelor's thesis. Eventually, we conclude that UGR tests utilizing atom interferometers are in principle possible, while it remains debatable whether such a test has already been carried out.
To this end, first the classical Einstein Equivalence Principle (EEP) and corresponding tests will be presented. Second, the "clocks-from-rocks" or "redshift" debate initiated by Holger Müller et al.[6] is analyzed and their arguments how tests of the Weak Equivalence Principle (WEP) bound UGR are carefully evaluated. The claim of 10.000 fold improvement of the limit of UGR tests will be cautiously examined.
We connect this debate with the idea of gravitational dephasing in quantum systems from Magdalena Zych [7]. In this part we develop a derivation of a general expression for the visibility in a Mach-Zehnder interferometer. This is done by calculating an explicit Hamiltonian for systems with internal degrees of freedom and propagating it to obtain a phase difference corresponding to a difference in proper time. We apply M. Zych's explanation for the loss of visibility due to gravitational time dilation. Lastly, we present a derivation of the systems Hamiltonian responsible for the dephasing effect. This is a WKB-like approximations of the Hamiltonian and has - in a generalized form - recently led to the discovery of a new, mass-sensitive term in the Hamiltonian that might be useful to test the EEP with atom interferometry [8]. This investigation leads to the conclusion that atom interferometric tests of UGR are in principle possible. Carrying on the ideas of testing the EEP, a possible formulation of a Quantum Equivalence Principle (QEP)[9] is reviewed, accompanied with experimental proposals to test this QEP and a new idea of its experimental verification constructing a Rydberg-clock.

References

[1] A Peters, K Y Chung, and S Chu. “High-precision gravity measurements using atom interferometry”. In: *Metrologia* 38.1 (Feb. 2001), pp. 25–61. doi: 10.1088/0026-1394/38/1/4.

[2] Domenico Giulini. “Equivalence Principle, Quantum Mechanics, and Atom-Interferometric Tests”. In: *Quantum Field Theory and Gravity: Conceptual and Mathematical Advances in the Search for a Unified Framework*. Ed. by Felix Finster, Olaf Müller, Marc Nardmann, Jürgen Tolksdorf, and Eberhard Zeidler. Basel: Springer Basel, 2012, pp. 345–370.

[3] Peter Wolf, Luc Blanchet, Christian J Bordé, Serge Reynaud, Christophe Salomon, and Claude Cohen-Tannoudji. “Does an atom interferometer test the gravitational redshift at the Compton frequency?” In: *Classical and Quantum Gravity* 28.14 (June 2011), p. 145017. doi: 10.1088/0264-9381/28/14/145017.

[4] Albert Roura. “Gravitational redshift in quantum-clock interferometry”. In: *arXiv* (2018).

[5] Sina Loriani et al. “Interference of Clocks: A Quantum Twin Paradox”. In: *in preparation* (2019).

[6] Holger Müller, Achim Peters, and Steven Chu. “A precision measurement of the gravitational redshift by the interference of matter waves”. In: *Nature* 463.7283 (Feb. 2010), pp. 926–929. doi: 10.1038/nature08776.

[7] Magdalena Zych, Fabio Costa, Igor Pikovski, and Časlav Brukner. “Quantum interferometric visibility as a witness of general relativistic proper time”. In: *Nature Communications* 2 (Oct. 2011), p. 505. doi: 10.1038/ncomms1498.

[8] Philip Klaus Schwartz and Domenico Giulini. “Post-Newtonian corrections to Schrödinger equations in gravitational fields”. In: *Classical and Quantum Gravity* (Mar. 2019). doi: 10.1088/1361-6382/ab0fbd.

[9] M. Zych and C. Brukner. “Quantum formulation of the Einstein Equivalence Principle”. In: *ArXiv e-prints* (Feb. 2015). arXiv: 1502.00971[gr-qc].

Single-Atom-Resolved Fluorescence Detection

M. Hetzel[1], C. Pür[1], A. Hüper[1], J. Geng[1], W. Ertmer[1], L. Santos[2], C. Klempt[1]

[1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany.

[2]Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany.

Atom interferometers, which belong to today's most precise sensors, are fundamentally limited by the standard quantum limit (SQL) when operated with uncorrelated particles. Within our project, we will employ spin-dependent collisional interactions in Bose-Einstein condensates to generate metrologically useful entanglement to overcome this limitation. The new level of precision is then given by the Heisenberg limit, which necessitates the precise determination of the atom number with an error below the single atom level. In a new dedicated apparatus we demonstrate our single-particle resolving detection scheme with fluorescence imaging of a 3D-MOT filled with ^{87}Rb atoms [1, 2]. In contrast to absorption imaging, the signal-to-noise ratio (SNR) is greatly enhanced due to the long lifetime of the MOT and the large signal of photons scattered per atom and per unit time. Using our single-particle resolving detection, we stabilize the number of atoms in the MOT with single-atom precision by introducing a controlled loss mechanism. We outline a path to approach the Heisenberg limit in phase sensitivity with mesoscopic ensembles.

[1] D.B. Hume, I. Stroescu, M. Joos, W. Muessel, H. Strobel, M. K. Oberthaler, *Accurate Atom Counting in Mesoscopic Ensembles*, Phys. Rev. Let. **111**, 253001 (2013).

[2] I. Stroescu, D. B. Hume, M. K. Oberthaler, *Double-well atom trap for fluorescence detection at the Heisenberg limit*, Phys. Rev. A **91** 013412 (2015).

Progress in an experiment to measure the electric dipole moment of the electron using YbF molecules

K. C. J. Ho[1], P. M. F. Yzombard[1], J. A. Devlin, I. M. Rabey,
M. R. Tarbutt[1], B. E. Sauer[1], E. A. Hinds[1]
[1]Centre for Cold Matter, Imperial College London, London SW7 2AZ, United Kingdom

The existence of a permanent electron electric dipole moment (eEDM) violates both parity and time-reversal symmetry. Measuring a non-zero eEDM at the current levels of experimental sensitivity would be a demonstration of physics beyond the Standard Model. The current limit on the eEDM is set by the ACME collaboration using ThO molecules [1], $|d_e| < 1.1\times10^{-29}$ e cm.

We report progress in a YbF molecular beam experiment designed to measure the eEDM. We have increased the signal detected by a factor of 100 compared to our previous measurement [2] through better state preparation (Fig. 1), and more effective molecule detection [3]. This gives us a statistical sensitivity of ~ 3×10^{-28} e cm per day, which will allow us to measure $|d_e|$ at the 3×10^{-29} e cm level.

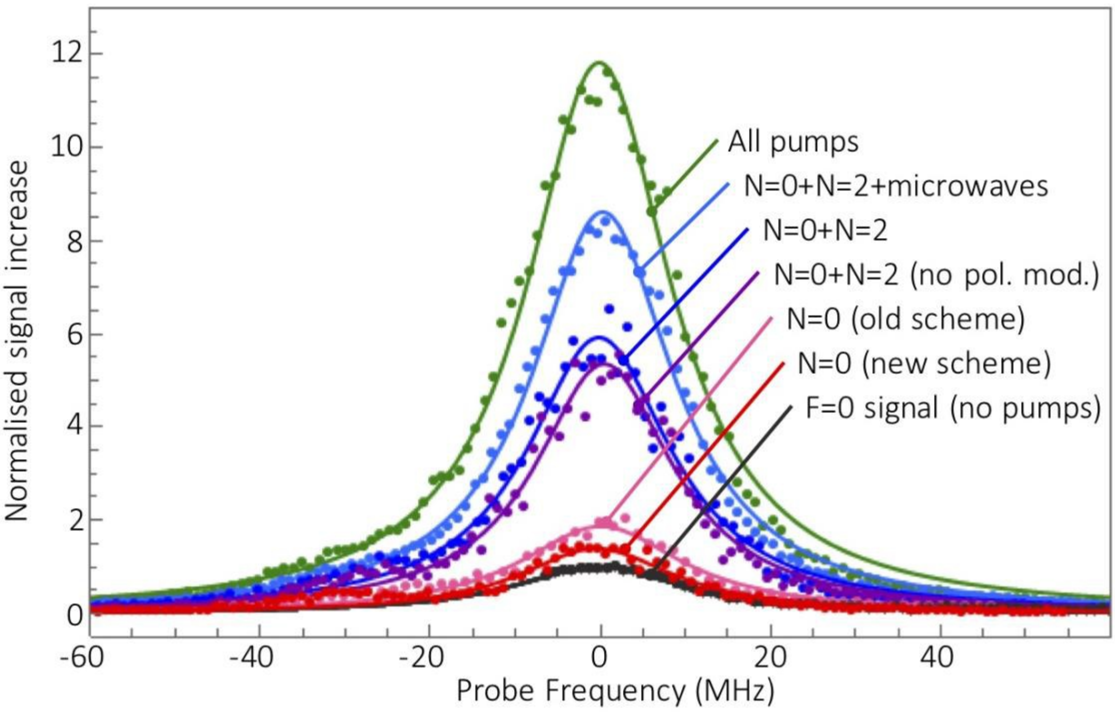


Figure 1. Better state preparation. We increase the population in the initial state of our experiment by pumping population from the higher rotational levels.

[1] ACME Collaboration, *Improved limit on the electric dipole moment of the electron*, Nature **562**, 355 (2018)
[2] 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**, 493 (2011).
[3] I. M. Rabey, PhD Thesis, Imperial College London (2017)

Cavity-enhanced non-destructive detection of atoms in a strontium optical lattice clock

R. Hobson[1], W. Bowden[1], A. Vianello[1,2], I. R. Hill[1], P. Gill[1,2]

[1]National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, United Kingdom.

[1]Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2AZ, United Kingdom.

By the measures of fractional frequency stability and systematic frequency uncertainty, optical lattice clocks exhibit remarkable performance at the 10^{-18} level [1,2]. Here we present progress toward a strontium optical lattice clock with improved stability, exploiting a new technique of cavity-enhanced non-destructive detection of atoms. The detection scheme relies on the interaction between cold, trapped strontium atoms and modes of an optical cavity with a finesse of 13000. The atom-cavity interaction causes the cavity modes to be shifted in frequency by an amount proportional to the number of atoms inside the cavity [3]. The frequency shift is detected and tracked using a carefully-designed set of laser probe frequencies (fig. 1), allowing us to measure the atom number without destroying the atomic sample. Ultimately, this technique should allow the preparation of spin-squeezed states, underpinning ultra-high-stability optical clocks to search for new physics beyond the standard model.

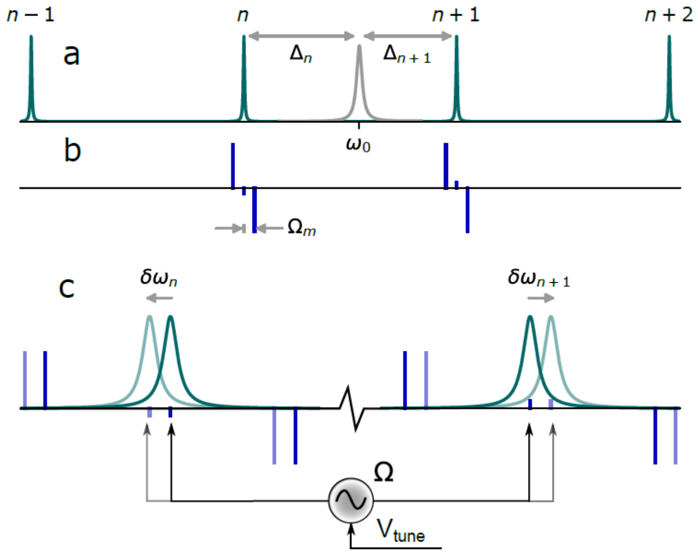


Figure 1. (a) The cavity modes in green are evenly spaced around the atomic transition in grey. (b) The cavity is probed with a set of discrete laser frequencies. (c) The nearest cavity modes are shifted away from atomic resonance when atoms are in the cavity; this shift is tracked by the RF modulation source.

[1] W. F. McGrew, X. Zhang, R. J. Fasano, S. A. Schäffer, K. Beloy, D. Nicolodi, R. C. Brown, N. Hinkley, G. Milani, M. Schioppo, T. H. Yoon and A. D. Ludlow, *Atomic clock performance beyond the geodetic limit*, Nature **564**, 87-90 (2018)

[2] I. Ushijima, M. Takamoto, M. Das, T. Ohkubo, and H. Katori, *Cryogenic optical lattice clocks*, Nature Photonics 9, 185 (2015)

[3] G. Vallet, E. Bookjans, U. Eismann, S. Bilicki, R. Le Targat and J. Lodewyck, *A noise-immune cavity-assisted non-destructive detection for an optical lattice clock in the quantum regime*, New Journal of Physics 19 (2017)

A three mode inertial sensor for the measurement of the acceleration of earth

A. Idel[1], F. Anders[1], P. Feldmann[2], J. Peise[1], L. Santos[2], C. Klempt[1]

[1]Institute of quantum optics, Leibniz University Hannover, Welfengarten 1, 30167 Hannover, Germany.

[2]Institute for Theoretical Physics, Leibniz University Hannover, Appelstraße 2, 30167 Hannover, Germany.

Atom interferometers can measure the gravitational acceleration by sensing gravitational phase shifts on spatially displaced superposition states. Future large-scale atomic gravimeters will employ Bose-Einstein condensed samples due to their well-controlled spatial mode and the low expansion rates. These gravimeters are fundamentally limited by the Standard Quantum Limit (SQL). The SQL can be overcome by engineering entangled input states for the interferometer. Such entangled states are routinely produced in the spin degree of freedom and concepts for their transfer to the spatial degree of freedom are outstanding. Here, I present an atomic gravimeter that creates superpositions in three spin states and transfers these superpositions to momentum states. The concepts can be employed in the future to demonstrate an atomic gravimeter beyond the SQL.

Setup for test of Lorentz symmetry with ion Coulomb crystals

D. Kalincev, H. A. Fürst, C.-H. Yeh, A. P. Kulosa, and T. E. Mehlstäubler
QUEST Institute, Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany.

We present details on our new experimental setup for measuring a potential Lorentz violation signal using a trapped multi-ion Coulomb crystal of the even isotope $^{172}Yb^{+}$. The high angular momentum states within the *F* manifold of Yb^{+} ions provide an excellent probe for measuring a possible violation of the Lorentz symmetry in the electron-photon sector [1]. A recent experiment uses frequency comparison of two independent $^{171}Yb^{+}$ single-ion optical clocks and does not show any indication of Lorentz symmetry breaking to a level of $\Delta C_0^{(2)} = 8 \cdot 10^{-21}$ [2].

Our approach instead follows the proposal of Shaniv et al. [3]. The idea is to detect a possible Lorentz violation via dynamical decoupling of the *F* manifold. This method is advantageous over, e.g., the implementation of quantum correlation [4] as it does not suffer from laser-induced AC-Stark shifts. In addition, interrogation of multiple ions is more straightforward. The averaging time to reach the reported sensitivity record of $\Delta C_0^{(2)} = 8 \cdot 10^{-21}$ would be approximately 24h when using 2 ions, about 45 times faster than the recent limit reported in Ref. [2].

To interrogate the octupole transition at 467 nm, we use a home-built slave laser setup in the infrared that is frequency doubled and provides stable output power at the desired wavelength. The master oscillator is derived from an ultrastable clock laser used in Ref. [2]. The weak coupling of the laser to the long-lived *F* state and fluctuating magnetic fields due to 50 Hz line currently limits coherent excitation. Therefore, we drive the transition using rapid adiabatic passage and improve the uncertainty of the absolute frequency from 700 kHz [5] by two orders of magnitude. We resolve the Zeeman manifold of the *F* state and identify the transition most suitable for the test of Lorentz violation. For characterization of the rf-setup and the proposed dynamical decoupling method we implement the composite rf-pulse scheme in the *S* ground state manifold.

[1] V. A. Dzuba et al., *Strongly enhanced effects of Lorentz symmetry violation in entangled Yb⁺ ions*, Nature Physics **12**, 465-468 (2016).
[2] C. Sanner et al., *Optical clock comparison for Lorentz symmetry testing,* Nature **567**, 204-208 (2019).
[3] R. Shaniv et al., *New Methods for Testing Lorentz Invariance with Atomic Systems*, Phys. Rev. Lett. **120**, 103202 (2018).
[4] T. Pruttivarasin et al., *Michelson-Morley analogue for electrons using trapped ions to test Lorentz symmetry,* Nature **517**, 592-595 (2015).
[5] M. Roberts et al., *Observation of an Electric Octupole Transition in a Single Ion*, Phys. Rev. Lett. **78,** 1876 (1997).

Atom Chip technology for use under UHV conditions

A. Kassner[1], H. Heine[2], W. Herr[2], E. M. Rasel[2], M. C. Wurz[1]
[1]Institute of Micro Production Technology (IMPT), Leibniz Universität Hannover, An der Universität 2 30823 Garbsen, Germany.
[2]Institute of Quantum Optics, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover

The miniaturization and further development of atom chips as a source of Bose-Einstein condensates (BECs) in transportable quantum gravimeters for use in the field or on board sounding rockets represents a manufacturing challenge with regard to the integration of the chips and their reliability. Since the operation takes place under ultra-high vacuum conditions, the use of non-adhesive connection techniques is given the highest priority. In addition, optical access to the chip surface is required for laser interferometry and laser cooling in order to realize a magneto-optical trap. In order to reduce the number of laser beams required, optical gratings are used on the chip surface to enable single beam operation. These require planar surfaces. In the following, the manufacture of the atom chip on a micro technological basis and the joining of the chip to a carrier system using transient liquid phase bonding are described. Furthermore, first approaches for backside contacting of the chip by vertical interconnect access are investigated.

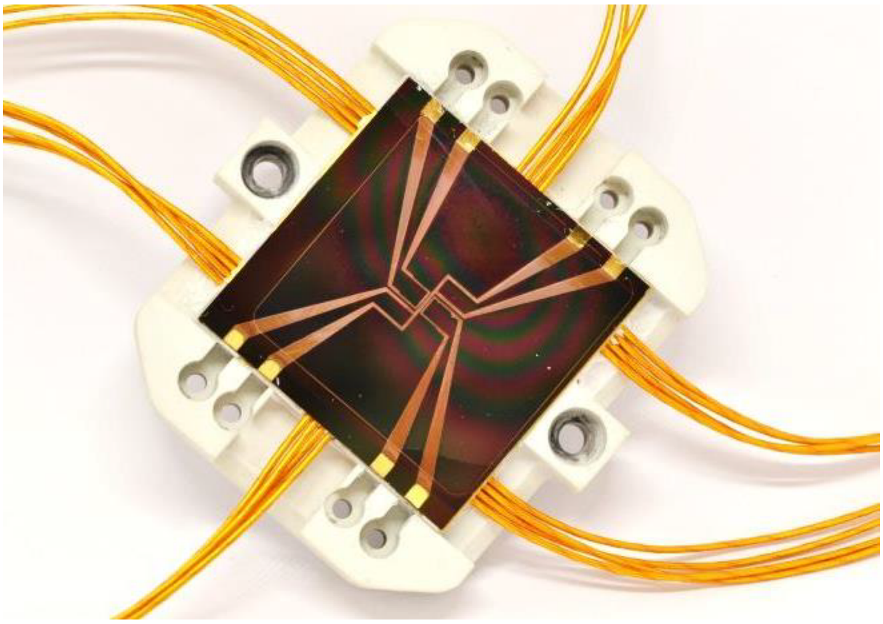


Figure 1. Atom chip system consisting of chip, ceramic carrier and mesoscopic structures. The dimensions of the chip are 35x35mm.

Heisenberg scaling of quantum logic spectroscopy with warm ions and a new setup for quantum logic spectroscopy of H_2^+

D. Kienzler[1,2,3], Y. Wan[1,2], S. D. Erickson, J. J. Wu[1,2], A. C. Wilson[1,2], D. J. Wineland[1,2,4], D. Leibfried[1,2] and N. Schwegler[3], J.P. Home[3]

[1]National Institute of Standards and Technology, Time and Frequency Division 688, 325 Broadway, Boulder, CO 80305, USA.

[2]Department of Physics, University of Colorado, Boulder, CO 80305, USA.

[3]Institute for Quantum Electronics, Eidgenössische Technische Hochschule Zürich, Otto-Stern-Weg 1, HPF E10, 8093 Zurich, Switzerland.

[4]Department of Physics, University of Oregon, Eugene, OR 97403, USA

I will present experimental results from NIST on a quantum-logic-spectroscopy method based on a mixed-species geometric phase gate as proposed in [1]. Our results demonstrate its basic behavior, show how it can be applied as a technique for identifying transitions in currently intractable atoms or molecules, demonstrate its reduced temperature sensitivity, and observe quantum-enhanced frequency sensitivity when applied to larger ion chains, ideally achieving Heisenberg scaling. Additionally, I will present progress on a new experiment setup aiming to implement quantum logic spectroscopy of H_2^+.

[1] Leibfried, D. Appl. Phys. B (2017) 123: 10. doi.org/10.1007/s00340-016-6589-3

Feshbach Resonances in an Optical Collider for Ultracold Atoms

R. Thomas, M. Horvath, A. B. Deb, and N. Kjærgaard
.Department of Physics, QSO-Centre of Quantum Science, and Dodd-Walls Centre for Photonic and Quantum Technologies, Department of Physics, University of Otago, New Zealand

Ultracold atomic and molecular systems near Feshbach resonances have been put forward as a candidate to measure variations of fundamental constants, notably the electron-proton mass ratio [1]. Here, we use a laser-based collider to probe a narrow magnetic resonance of rubidium above threshold [2]. In particular we demonstrate a scheme to extract the resonance position in the presence of thermal broadening. We also consider Beutler-Fano spectroscopy of heteronuclear potassium-rubidium scattering in the ^{40}K $|9/2,9/2\rangle$ +^{87}Rb $|2, 2\rangle$ channel [3] where we follow the Fano profile (see Fig. 1) in a parameter space spanned by energy and magnetic field. From the trajectory we infer a value for the background scattering length of $a_{bg} = -185.80(35)\ a_0$.

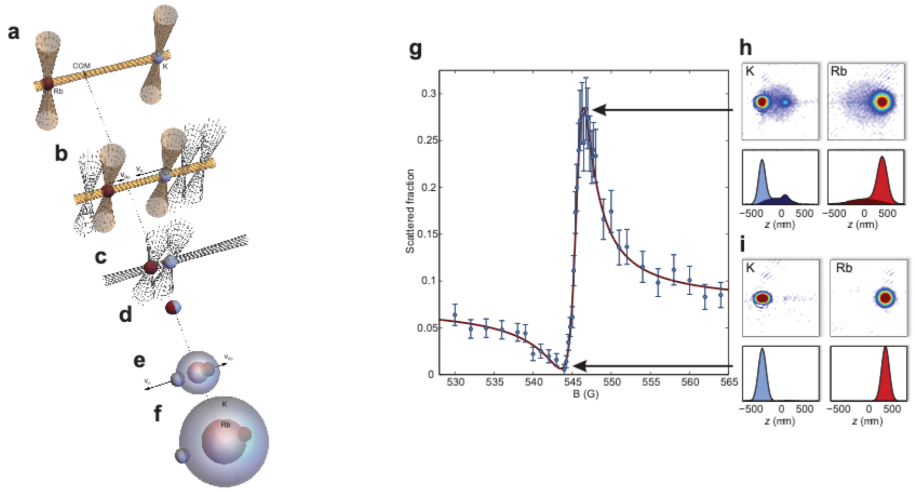


Figure 1. Optical collider procedure. **a** 87Rb (red, left) and 40K (blue, right) atoms are held in two crossed optical dipole traps separated by ~3 mm; COM indicates the center-of-mass for pairs of K and Rb atoms. **b** The two traps are accelerated towards each other, keeping $m_{Rb}v_{Rb} = -m_K v_K$, so that the COM of K and Rb pairs remain at rest in the lab frame. **c** When the wells are separated by ~60 μm, the trapping laser beams are switched off. **d** The atomic clouds collide in free space. **e,f** The K and Rb collision halos expand at different rates. We image the K halo at the time represented in (**e**), and then wait to image Rb until its halo has expanded to the equivalent size (**f**). **g** Measured scattered fraction (circles) as a function of magnetic field for a collision energy E/k=52 μK. **h,i** Absorption images and density profiles of K (**h**) and Rb (**i**) acquired at the magnetic fields indicated by the arrows

[1] C. Chen and V. Flambaum, *Enhanced Sensitivity to Fundamental Constants In Ultracold Atomic and Molecular Systems near Feshbach Resonances*, Phys. Rev. Lett **96**, 230801 (2006).
[2] M. S. J. Horvath, R. Thomas, E. Tiesinga, A. B. Deb, and N. Kjærgaard, *Above-threshold scattering about a Feshbach resonance for ultracold atoms in an optical collider*, Nature Communications **8**, 452 (2017).
[3] R. Thomas, M. C. Chilcott, E. Tiesinga, A.B. Deb, and N. Kjærgaard, *Observation of bound state self-interaction in a nano-eV atom collider*, Nature Communications **9**, 4895 (2018).

Quantum non-demolition measurement of strongly-interacting atomic media

J. Kong[1], R. Jiménez-Martínez[1], V. G. Lucivero[2], C. Troullinou[1], G. Tóth[3,4], and M. W. Mitchell[1,5]

[1] ICFO–Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain

[2] Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

[3] Department of Theoretical Physics, University of the Basque Country UPV/EHU, P.O. Box 644, E-48080 Bilbao, Spain

[4] IKERBASQUE, Basque Foundation for Science, E-48011 Bilbao, Spain

[5] ICREA – Instituci´o Catalana de Recerca i Estudis Avan¸cats, 08010 Barcelona, Spain

Quantum entanglement is one of the most nonclassical feature of quantum theory, however it's notoriously sensitive to decohering processes. For this reason, many implementations take elaborate measures to remove entropy from their environments, e.g. cryogenics or optical cooling. Here we demonstrate that the opposite strategy, actively promoting strong interactions and thermalization, can excel in generating and preserving en- tanglement. We produce and detect 1.9 dB spin squeezing, and at least $1:5 \times 10^{13}$ of the $5:3 \times 10^{13}$ measured atoms form singlets, which persist for tens of thermalization times, with entanglement bonds extending thou- sands of times the nearest-neighbor distance. The results show that collective measurement can produce very complex entangled states, and that the hot, strongly interacting media now in use for extreme atomic sensing can operate beyond the standard quantum limit.

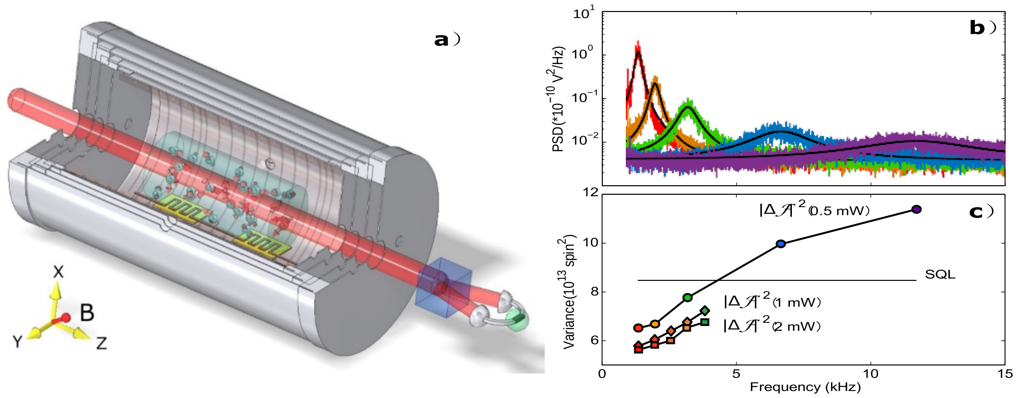


Figure 1: Experimental Principle. **a)** Experimental setup. A vapor of ^{87}Rb contained in a glass cell with buffer gas to slow diffusion, which is housed in magnetic shielding and field coils to control the magnetic environment, and the magnetic field is applied along the [1, 1, 1] direction. **b)** Spin noise spectra [1] with different bias field strengths characterizes the vapor enters the so-called spin-exchange-relaxation-free (SERF) regime. The density is maintained at $n_{Rb} = 3.6 \times 10^{14}$ atoms/cm^3. **c)** The total spin variance $|\Delta F|^2$ including a transition to squeezed/entangled states as the system enters the SERF regime. The total spin variance is estimated by Kalman filter (KF) technique [2], and compared against spin squeezing inequalities [3] to detect and quantify entanglement. Black solid-line shows the standard quantum limit (SQL). Round, diamonds and squares symbols show $|\Delta F|^2$ measured with 0.5 mW, 1 mW and 2 mW probe light, respectively.

References

[1] V. G. Lucivero, R. Jiménez-Martínez, J. Kong, M. W. Mitchell, *Phys. Rev. A* **93**, 053802 (2016).

[2] R. Jiménez-Martínez, *et al.*, *Phys Rev Lett* **120**, 040503 (2018).

[3] G. Tóth, M. W. Mitchell, *New Journal of Physics* **12**, 053007 (2010).

$^{171}Yb^{+}$ clock comparison for Local Lorentz Invariance testing and clock improvement to the 10^{-19} regime

R. Lange[1], N. Huntemann[1], C. Sanner[1,2], M. Abdel Hafiz[1], H. Shao[1], Chr. Tamm[1], E. Peik[1]
[1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany.
[2]JILA, Boulder, CO 80309, USA.

Comparisons of high-accuracy frequency standards have become a suitable method to search for physics beyond the Standard Model [1]. The long-term comparison of our two $^{171}Yb^{+}$ single-ion optical clocks as a test of Local Lorentz Invariance (LLI) is a recent example of such a search for new physics [2]: In operation over a period of seven months with a duty cycle of up to 95 % per day, a relative frequency difference of the clocks of 2.8×10^{-18} was obtained. This is well within the 3×10^{-18} systematic uncertainties of both frequency standards that are based on the $^2S_{1/2} \rightarrow {}^2F_{7/2}$ electric octupole (E3) [3] transition at 467 nm. Due to the electronic structure of the $^2F_{7/2}$ state, the E3 transition frequency is very sensitive to violations of the spatial isotropy [4]. For our experimental setup, this violation would manifest itself in a modulation of the clocks' frequency ratio caused by the rotation of the earth in space. Analyzing our long-term data with respect to such modulations, we improve the current limits of LLI by two orders of magnitude.
The remaining dominant contributions to the clocks' uncertainties are the blackbody radiation (BBR) and the second-order Doppler shift, both larger than 1×10^{-18} [5] and directly related to trap imperfections. A new single-ion trap setup featuring fused silica insulators with low dielectric losses for smaller BBR shift, polished gold-coated electrodes for low motional heating rates, and large optical access for rigorous minimization of excess micromotion has been designed and taken into operation. The uncertainty due to trap temperature has been reduced by a factor of two and a low motional heating rate of 4 quanta/s allows for more than a tenfold improvement of the related contributions, reaching the low 10^{-19} level. In addition, the low heating rate in combination with the clock laser's coherence time of several seconds [6] permits spectroscopy with sub-Hertz resolution on the E3 transition and will improve the frequency stability of the clock in the near future.

[1] M. S. Safronova, D. Budker, D. DeMille, D. F. Jackson Kimball, A. Derevianko and C. W. Clark, *Search for New Physics with Atoms and Molecules*, Rev. Mod. Phys. **90**, 025008 (2018).
[2] C. Sanner, N. Huntemann, R. Lange, Chr. Tamm, E. Peik, M. Safronova, and S. Porsev, *Optical clock comparison test of Lorentz symmetry*, Nature **567**, 204 (2019).
[3] N. Huntemann, M. Okhapkin, B. Lipphardt, S. Weyers, Chr. Tamm, and E. Peik, *High-Accuracy Optical Clock Based on the Octupole Transition in 171Yb+*, Phys. Rev. Lett. 108, 090801 (2012).
[4] A. Dzuba, V.V. Flambaum, M.S. Safronova, S.G. Porsev,T. Pruttivarasin, M.A. Hohensee, and H. Häffner, *Strongly enhanced effects of Lorentz symmetry violation in entangled Yb+ions*, Nature Physics **12**, 465 (2016).
[5] N. Huntemann, C, Sanner, B. Lipphardt, Chr. Tamm, E. Peik, *Single-Ion Atomic Clock with 3 × 10-18 Systematic Uncertainty*, Phys. Rev. Lett. 116, 063001 (2016).
[6] D.G. Matei, T. Legero, S. Häfner, C. Grebing, R. Weyrich, W. Zhang, L. Sonderhouse, J. M. Robinson, J. Ye, F. Riehle, U. Sterr, *1.5 um Laser with Sub-10 mHz Linewidth*, Phys. Rev. Lett. 118, 263202 (2017).

Towards direct laser cooling of barium monofluoride

R. Albrecht, T. Sixt, L. Hofer, M. Scharwaechter and T. Langen
5. Physikalisches Institut and Center for Integrated Quantum Science and Technology,
University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany.

We report on our progress towards the direct laser cooling and trapping of barium monofluoride molecules.

Laser cooling of molecules had long been considered impossible due to their complex vibrational and rotational level structure. However, beneficial Franck-Condon factors and selection rules allow for optical cycling in many molecular species, including barium monofluoride [1]. The latter holds particular promise for precision tests of fundamental symmetries [2,3].

In our experiment, molecules are generated through laser ablation of a sintered precursor target inside a cryogenic cell. Subsequently, the initially ~10^4 K hot molecules are precooled to the few Kelvin regime by collisions with a cold buffer gas of helium atoms. The precooled molecules exit the cell through a millimeter-sized aperture and enter a room-temperature high-vacuum region, where they form a cold and intense molecular beam. Combining this beam with magnetic remixing of dark states, we realize a quasi-cycling transition that is suitable for future laser cooling of this heavy diatomic molecule.

[1] M. Tarbutt, *Laser cooling of molecules*, Contemporary Physics **59**, 356-376 (2018).
[2] P. Aggarwal *et al.*, *Measuring the electric dipole moment of the electron inBaF*, Eur. Phys. J. D **72**, 197 (2018)
[3] E. Altuntas *et al.*, *Demonstration of a Sensitive Method to Measure Nuclear Spin-Dependent Parity Violation*, Phys. Rev. Lett. **120**, 142501 (2018)

Tuning coherence by state-dependent trap engineering in a two-component BEC

Y.Li[1], B. Décamps[1], P. Colciaghi[1], M. Fadel[1], T.Zibold[1], P. Treutlein[1]
[1] Department of Physics, University of Basel, Switzerland

We report on a series of experiments with two-component Bose-Einstein condensates (BEC) of rubidium 87 on an atom chip. In these experiments, we use state-dependent traps generated by microwave near fields to control collisions and create entanglement between the atomic spins in the BEC. By careful tuning of the potentials, we prepare high fidelity spin-squeezed states, control their decoherence and use them for fundamental experiments on quantum metrology and many-particle entanglement.

We optimize the squeezed-state preparation sequence by using a composite pulse and a relaxed trap to reduce the effect of atom losses and technical noise. These improvements allow us to achieve squeezing up to -8 dB below the standard quantum limit, significantly improved compared to our previous result [1,2].

We also explore how to improve the coherence times of the squeezed states which are mainly limited by interaction induced phase noise caused by atom loss. To counteract the decoherence by this so-called ‘clock shift’ effect, we follow a theoretical proposal [3]. By engineering the state-dependent potentials we can tune the atomic interactions in a way which allows us to minimize the clock shift so that the state coherence becomes robust against atom number fluctuations.

Our experimental findings are relevant for compact atomic clocks realized in similar cold or ultracold atomic systems where atomic interactions are a limiting factor [4]. Moreover, our results will be useful in experiments where we further explore spatial Einstein-Podolsky-Rosen steering and many-particle entanglement [5].

[1] M. F. Riedel, P. A. Böhi, Y. Li, T. W. Hänsch, A. Sinatra, and P. Treutlein, Nature 464, 1170 (2010).
[2]C. F. Ockeloen, R. Schmied, M. F. Riedel, and P. Treutlein, Phys. Rev. Lett. 111, 143001 (2013).
[3]K. Pawłowski, M. Fadel, P. Treutlein, Y. Castin, and A. Sinatra, Phys. Rev. A 95, 063609 (2017).
[4]R. Szmuk, V. Dugrain, W. Maineult, J. Reichel, and P. Rosenbusch, Phys. Rev. A 92, 012106 (2015).
[5]M. Fadel, T. Zibold, B. Décamps, and P. Treutlein, Science 360, 409-413 (2018).

Pulsed Quantum-State Reconstruction of Dark Systems

Y. Liu, J. Tian, R. B. and J. Cai
School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China
International Joint Laboratory on Quantum Sensing and Quantum Metrology, Huazhong University of Science and Technology, Wuhan 430074, China

Abstract We propose a novel strategy to reconstruct the quantum state of dark systems, i.e., degrees of freedom that are not directly accessible for measurement or control. Our scheme relies on the quantum control of a two-level probe that exerts a state-dependent potential on the dark system. Using a sequence of control pulses applied to the probe makes it possible to tailor the information one can obtain and, for example, allows us to reconstruct the density operator of a dark spin as well as the Wigner characteristic function of a harmonic oscillator. Because of the symmetry of the applied pulse sequence, this scheme is robust against slow noise on the probe. The proof-of-principle experiments are readily feasible in solid-state spins and trapped ions.

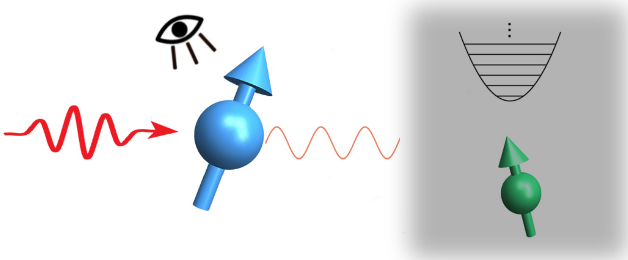


Figure 1. The diagram for state reconstruction of quantum dark systems. We employ an auxiliary quantum system as a measurement probe and apply a sequence of control pulses on the probe to tailor the information one can obtain about the dark system and achieve a full quantum state tomography.

[1] Yu Liu, Jiazhao Tian, Ralf Betzholz and Jianming Cai, *Pulsed Quantum-State Reconstruction of Dark Systems*, Phys. Rev. Lett. **122**, 110406 (2019).

Atom interferometric tests of general relativity over extended baselines

S. Loriani, D. Schlippert, C. Schubert, E.M. Rasel and N. Gaaloul
Institut für Quantenoptik and Centre for Quantum Engineering and Space-Time Research (QUEST), Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover, Germany

Matter wave interferometry provides a unique access to the interface of quantum theory and gravity. Whereas the laws of quantum mechanics are exploited to coherently manipulate electronic and motional states to create superpositions of trajectories and to infer metrological properties from phase measurements, the free propagation of the light beams and the atoms in spacetime is governed by general relativity. In this contribution, we illustrate the aptitude of atom interferometers for probing various aspects of general relativity, ranging from its postulates as the equivalence principle to its implications as gravitational waves and gravitational redshift.

To this end, we present a feasibility study [1] of the atomic source for a gravitational wave space antenna proposal based on matter wave interferometry [2], which complements existing and future detectors using light interferometers. This scheme exploits the excellent coherence properties of the atoms in a gradiometer setup to infer gravitational waves induced light travel delays between two space-craft. We identify the most promising atomic species configurations and assess their technological readiness.

Furthermore, freely falling atoms constitute excellent test masses for tests of the weak equivalence principle, which is a cornerstone of general relativity. A violation could be indicative of a fifth force, hint towards the nature of dark matter and eventually advance the quest to unify quantum theory with general relativity. The wide range of test masses accessible with quantum tests is essential to constrain parameters of alternative theories, and space-borne missions with long drift times in the order of seconds promise unprecedented sensitivity [3]. We show a two-fold mitigation strategy to tackle one of the major systematic limitations, the influence of gravity gradients, to pave the way for quantum equivalence principle tests that compete with and even surpass their classical counterparts [4].

Finally, the periodic phase evolution between electronic states naturally provides the notion of clocks. Combining this concept with large spatial superpositions as realised in atom interferometers [5], one can envision an experiment in which a single (quantum) clock is delocalised by travelling along two trajectories at the same time [6]. In principle, such a setup is susceptible to proper time dilation, a bizarre consequence of relativity. We draw the analogy to the twin paradox and show that certain light-pulse atom interferometers are sensitive to this time dilation. Moreover, we prove that it is of special relativistic origin only and may not directly be used for measurements of the gravitational redshift [7].

[1] S. Loriani et al., *Atomic source selection in space-borne gravitational wave detection*, arXiv:1812.11348 (2018), submitted to New Journal of Physics.
[2] J. Hogan et al., *Atom-interferometric gravitational-wave detection using heterodyne laser links*, Phys. Rev. A 94, 033632 (2016)
[3] D. N. Aguilera et al., *STE-QUEST — test of the universality of free fall using cold atom interferometry*, Class. Quantum Grav. **32**, 115010 (2014)
[4] S. Loriani et al., 10^{-18} *gravity gradient cancellation in space-borne quantum tests of the equivalence principle*, in preparation.
[5] T. Kovachy et al., *Quantum superposition at the half-metre scale*, Nature **528**, 530 (2015)
[6] M. Zych et al., *Quantum interferometric visibility as witness of general relativistic proper time*, Nat. Comm. 2, 505 (2011)
[7] S. Loriani et al., *Interference of Clocks: A Quantum Twin Paradox*, in preparation.

Prospects for a Cesium interferometer with tunable interactions

S. Manz[1], B. Gerstenecker[1], M. Lerchbaumer[1], T. Schumm[1]
[1]Atominstitut, TU Wien, Stadionallee 2, 1020 Wien, Austria

The matter-wave properties of atoms and the macroscopic behavior of BECs make interference experiments with ultracold atoms a useful tool for metrology applications. It has been shown that condensates can be split while controlling the relative phase, realizing a phase-preserving beam splitter. Utilizing this method, high sensitivity to small energy differences can be achieved with BEC interferometry.

The procedures developed in the past years led to the prospect of an integrated matter-wave sensor for high-precision measurements. In order to realize such a sensor, we are building an experimental setup for trapped BEC interferometry with Cesium. After achieving condensation in a dipole trap close to the surface of an atom chip, the single potential well will be continuously deformed into a double well. We thereby want to realize a Bosonic Josephson Junction with tunable interaction. The system will then allow measuring field gradients, which induce an energetic tilt of the double well. We aim at high sensitivity by reducing the scattering length of the ultracold atoms via Feshbach resonances and by shielding the experiment against external influences, while still maintaining a very compact setup size employing a commercial "BEC machine" by ColdQuanta.

The poster presentation will feature the main objectives and prospects as well as the current status of the experiment. It will also discuss the systematic energy budget to evaluate the challenges and constraints given by ambient and control fields.

Mass defect of electronic transitions in atoms, ions and atomic clocks.

V. J. Martínez-Lahuerta, S. Eilers, M. S. and K. Hammerer
[1]Institute for Theoretical Physics and Institute for Gravitational Physics (Albert-Einstein-Institute), Leibniz Univeristy Hannover, Appelstrasse 2, 30167 Hannover, Germany.

In this work we will present a low-order relativistic correction to the multipolar atom-light Hamiltonian for two bound particles corresponding to a simple model for Hydrogen-like atoms and ions. From this result we can systematically predict frequency shifts in atomic clocks based on trapped ions due to the mass defect and the quadrupole effect caused by external fields, as recently discussed in [1].

[1] V. Yudin and A.V.Taichenachev (Laser Phys. Lett. 15, 035703, 2018).

Quantum Logic Spectroscopy of Highly Charged Ions

P. Micke[1,2], T. Leopold[1], S. A. King[1], E. Benkler[1], L. J. Spieß[1], J. R. Crespo López-Urrutia[2], P. O. Schmidt[1,3]

[1]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany.

[2]Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany.

[3]Institut für Quantenoptik, Leibniz Universität Hannover, 30167 Hannover, Germany.

Highly charged ions (HCI) offer extreme properties which make them particularly sensitive to new physics, for example the variation of fundamental constants [1]. Next-generation clocks based on HCI were proposed more than a decade ago, owing to their insensitivity to external fields. However, optical spectroscopy was so far limited to the 10^{-7} fractional accuracy level due to the megakelvin temperatures at which HCI are produced and stored. We follow on from the pioneering work performed at the Max-Planck-Institut für Kernphysik, where boron-like Ar^{13+} was recaptured and sympathetically cooled in a linear Paul trap for the first time [2]. At the Physikalisch-Technische Bundesanstalt we extract HCI from a compact electron beam ion trap, transfer them to, and recapture them in a laser-cooled Coulomb crystal of Be^{+} ions [3,4,5], followed by the preparation of Ar^{13+}-Be^{+} two-ion crystals in their quantum-mechanical ground state of motion. A sub-Hz-stable, narrow-linewidth clock laser is used to probe the forbidden $^2P_{1/2} - {}^2P_{3/2}$ M1 transition at 441 nm by using the quantum logic technique for state preparation and detection [6]. This first demonstration of coherent laser spectroscopy of HCI improves upon the resolution of the most accurately measured HCI transition by nine orders of magnitude. Measuring the splitting of the six Zeeman components allows us to observe relativistic, interelectronic-interaction, and QED effects, as well as improve upon the previous experimental determination of the excited-state g-factor.

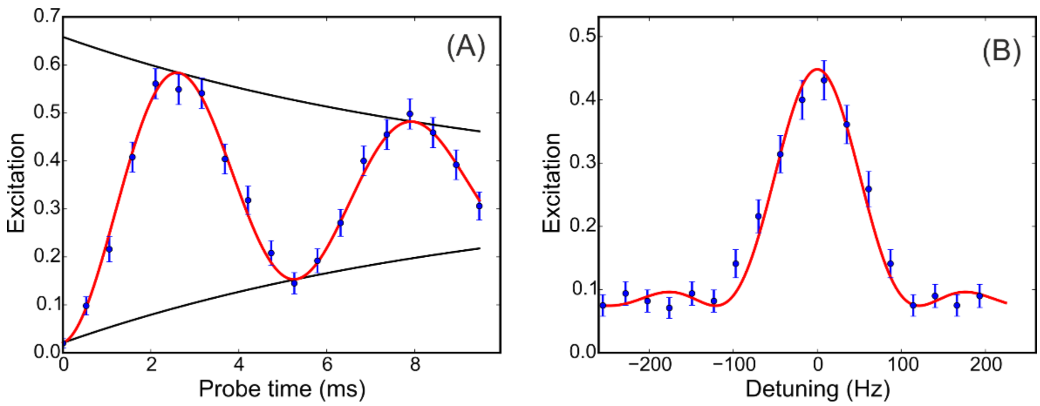


Figure 1. Rabi spectroscopy of HCI. (A) Coherent excitation of the Ar^{13+} M1 transition. The coherence decay is consistent with the excited-state lifetime of 9.6 ms. (B) Frequency scan with a probe time of 8 ms yielding a FWHM of about 110 Hz.

[1] M. G. Kozlov et al., *Highly charged ions: Optical clocks and applications in fundamental physics*, Rev. Mod. Phys. **90**, 045005 (2018)

[2] L. Schmöger et al., *Coulomb crystallization of highly charged ions*, Science **347**, 6227 (2015).

[3] P. Micke et al., *The Heidelberg compact electron beam ion traps*, Rev. Sci. Instrum. **89**, 063109 (2018)

[4] P. Micke et al., *Closed-cycle, low-vibration 4 K cryostat for ion traps and other applications*, Rev. Sci. Instrum. (accepted)

[5] T. Leopold et al., *A cryogenic radio-frequency ion trap for quantum logic spectroscopy of highly charged ions*, arXiv:1901.03082 (2019)

[6] P. O. Schmidt et al., *Spectroscopy Using Quantum Logic*, Science **309**, 5735 (2019)

Robustifying Twist-and-Turn Entanglement with Interaction-Based Readout

S. S. Mirkhalaf[1,2], S. P. Nolan[2], S. A. Haine[3]

[1]Institute of Physics, Polish Academy of Sciences, Warsaw, Poland

[2]QSTAR, Largo Enrico Fermi 2, 50125, Firenze, Italy

[3]School of Mathematics and Physics, The University of Queensland, Brisbane, Queensland, Australia.

[4]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom.

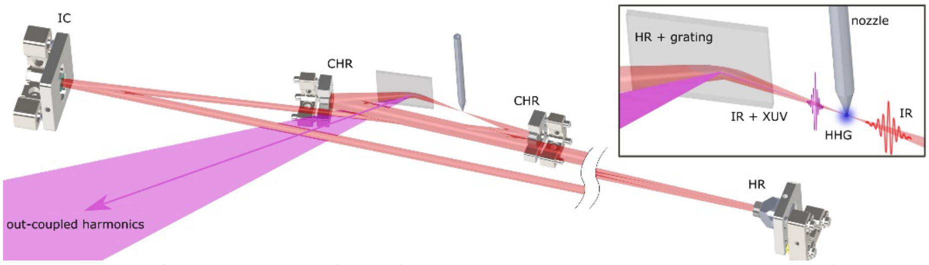
The use of multi-particle entangled states has the potential to drastically increase the sensitivity of atom interferometers and atomic clocks. The Twist-and-Turn (TNT) Hamiltonian can create multi-particle entanglement much more rapidly than ubiquitous one-axis twisting (OAT) Hamiltonian in the same spin system. In this paper, we consider the effects of detection noise - a key limitation in current experiments - on the metrological usefulness of these nonclassical states and also consider a variety of interaction-based readouts to maximize their performance. Interestingly, the optimum interaction-based readout is not the obvious case of perfect time reversal.

Development of a HHG frequency comb for XUV metrology of highly charged ions

J. Nauta[1], J.-H.Oelmann[1], A. Ackermann[1], P. Knauer[1], R. Pappenberger[1], J. Stark[1], S. Kühn[1], J. R. Crespo López-Urrutia[1], T. Pfeifer[1]

[1]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69118 Heidelberg, Germany.

Theoretical studies have shown that forbidden optical transitions in highly charged ions (HCI) are the most sensitive systems for probing the possible variation of the fine structure constant α [1]. Moreover, they have been proposed as novel frequency standards due to their low polarizability and insensitivity to black body radiation [2,3]. We plan to perform high resolution spectroscopy of cold HCI [4] in the extreme ultraviolet region (XUV), where many transitions, from dipole-allowed (E1) to highly forbidden, take place. To this end, we are developing an enhancement cavity to amplify femtosecond pulses from a phase-stabilized infrared frequency comb at a repetition rate of 100 MHz [5]. High-order harmonics will be generated in the tight focus of the cavity and can be used for direct frequency-comb spectroscopy of HCI to determine absolute transition energies. Recent progress and results will be presented, including velocity-map imaging of multi-photon ionization in the cavity focus.



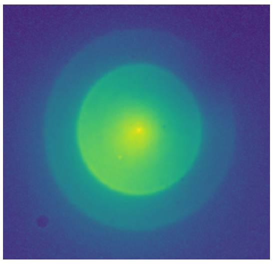


Figure 1. Left: Overview of the femtosecond enhancement cavity. Infrared (IR) pulses are coupled in through the in-coupling mirror (IC) and circulate in the cavity composed of four other high-reflective (HR) mirrors. In one of this mirrors, a shallow grating structure is etched. The inset shows high-order harmonic generation (HHG) inside the tight focus of the cavity, in between the two curved mirrors (CHR). The high-order harmonics (labeled XUV) propagate collinearly with the IR beam, and are coupled out of the cavity using the minus-first order diffraction of the grating. Right: one of the first velocity-map images taken at the cavity focus.

[1] J. Berengut, V. A. Dzuba, V. V. Flambaum, and A. Ong, *Optical Transitions in Highly Charged Californium Ions with High Sensitivity to Variation of the Fine-Structure Constant*, Phys. Rev. Lett. **109**, 070802 (2012).

[2] M. G. Kozlov, M. S. Safronova, J. R. Crespo López-Urrutia, and P. O. Schmidt, *Highly charged ions: Optical clocks and applications in fundamental physics*, Rev. Mod. Phys. **90**, 045005 (2018).

[3] A. Derevianko, V. A. Dzuba, and V. V. Flambaum, *Highly Charged Ions as a Basis of Optical Atomic Clockwork of Exceptional Accuracy,* Phys. Rev. Lett. **109**, 180801 (2012).

[4] L. Schmöger, O. O. Versolato, M. Schwarz, M. Kohnen, A. Windberger, B. Piest, S. Feuchtenbeiner, J. Pedregosa-Gutierrez, T. Leopold, P. Micke, A. K. Hansen, T. M. Baumann, M. Drewsen, J. Ullrich, P. O. Schmidt, and J. R. Crespo López-Urrutia, *Coulomb crystallization of highly charged ions,* Science **347**, 6227 (2015).

[5] J. Nauta, A. Borodin, H. B. Ledwa, J. Stark, M. Schwarz, L. Schmöger, P. Micke, J. R. Crespo López-Urrutia, and T. Pfeifer, *Towards precision measurements on highly charged ions using a high harmonic generation frequency comb,* Nucl. Instrum. Meth. B **408**, 285 (2017).

Towards Quantum Logic Inspired Cooling and Detection for Single (Anti-)Protons

A.-G. Paschke[1,2], M. Niemann[1], T. Meiners[1], J. Mielke[1], M. J. Borchert[1,3],J. M. Cornejo[1], G. Zarantonello[1,2], H. Hahn[1,2], T. Lang[1], C. Manzoni[4], M. Marangoni[4], G. Cerullo[4], U. Morgner[1], S. Ulmer[2], C. Ospelkaus[1,2]

[1] Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany.

[2] Physikalisch-Technische Bundesanstalt Braunschweig, Bundesallee 100, 38116 Braunschweig, Germany

[3] Ulmer Fundamental Symmetries Laboratory, RIKEN, Wako, Saitama 351-0198, Japan.

[4] IFN-CNR, Dipartimento di Fisica, Politecnico di Milano, Piazza L. da Vinci 32, Milano, 20133, Italy

We discuss laser-based and quantum logic inspired cooling and detection methods amenable to single (anti-)protons. These would be applicable e. g. in a g-factor based test of CPT invariance as currently pursued within the BASE collaboration. Towards this end, we explore sympathetic cooling of single (anti-)protons with atomic ions as suggested by Heinzen and Wineland [1,2]. In particular, we discuss recent experiments employing an engineered optical frequency comb spectrum to induce stimulated-Raman transitions in $^9Be^+$ ions which can be used for sympathetic ground state cooling of (anti-)protons by $^9Be^+$ ions at high magnetic fields [3].

[1] D. J. Heinzen and D. J. Wineland, *Quantum-limited cooling and detection of radio-frequency oscillations by laser-cooled ions*, Phys. Rev. A **42**, 2977 (1990).
[2] D. J.Wineland, C. R. Monroe, W. M. Itano, D. Leibfried, B. E. King and D. Meekhof, *Experimental issues in coherent quantum-state manipulation of trapped atomic ions*, J. Res. NIST **103,** 259 (1998).
[3] A.-G. Paschke et al., *Versatile Control of $^9Be^+$ Ions Using a Spectrally Tailored UV Frequency Comb*, Phys. Rev. Lett. **122**, 123606 (2019).

On nanodiamonds for matter-wave interferometry

J. S. Pedernales,[1] G. W. Morley,[2] M. B. Plenio[1]
[1]Institut für Theoretische Physik und IQST, Albert-Einstein-Allee 11, Universität Ulm, D-89069 Ulm, Germany
[1]Department of Physics, University of Warwick, Gibbet Hill Road, Coventry CV4 7AL, United Kingdom

I will present a novel protocol for the generation of macroscopic superpositions of spatially separated states of a nanodiamond hosting an NV center. The setup consists of a nanodiamond free-falling across a transversal magnetic field gradient, where the force exerted by the gradient on the NV center is responsible for the splitting of the wave function. However, due to the presence of diamagnetic forces acting on the diamond, the separation distance of the two superposed components of the wave function is limited to a maximum. We introduce a pulse sequence acting on the NV center that magnifies the separation, making it grow linearly in time. Remarkably, our pulse sequence can also protect the superposition from harmful experimental imperfections like misalignments of the setup with the gravitational field, interactions of the diamond with stray static electric fields or the interaction of the net magnetic moment of the diamond with the magnetic field gradient. Additionally, I will analyze the role played by the rotational degrees of freedom of the diamond and discuss on the effect of spin flips from the dangling bonds at the surface of the diamond as well as that of Casimir-Polder forces arising between the diamond and the magnets. All in all, the presented work aims at bringing the possibility of matter-wave interferometry with nanodiamonds closer to reality by alleviating several of the experimental requirements and pointing the needed technical improvements in order to reach it. This should ultimately pave the way for tests of theories that go beyond standard quantum mechanics, like spontaneous collapse models.

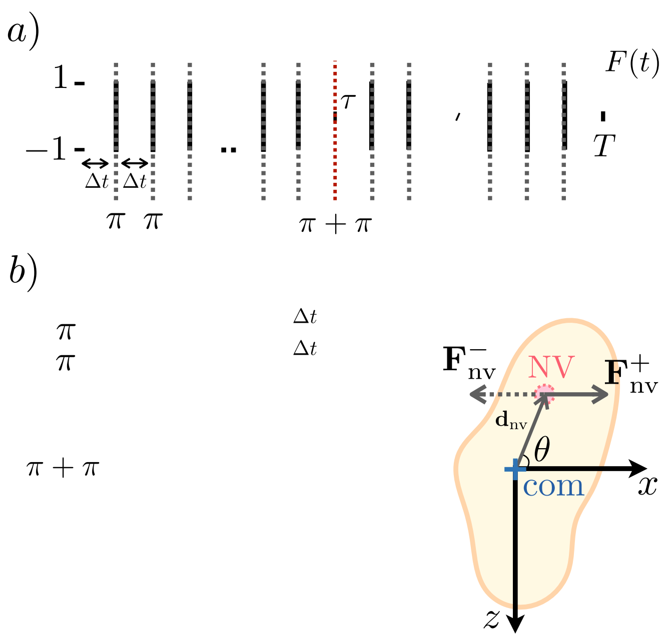


Figure 1. Summary of the setup. (a) Sequence of pulses acting on the NV center. (b) Schematics of the paths of the interferometer. (c) Irregular nanodiamond hosting an NV center and the forces acting on it.

The ALPS II experiment

J.H. Põld[1,2] for the ALPS collaboration

[1]Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Callinstraße 38, 30167 Hannover, Germany.

[2]Institut für Gravitationsphysik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany.

Any light particle search II (ALPS II) is a light-shining-through-a-wall experiment searching for hypothetical sub-eV elementary particles motivated by astrophysics and cosmology. These particles are not accessible with accelerator based experiments. ALPS II will be located at DESY in Hamburg. In its final version it will use 24 superconducting dipole magnets, ultra-stable lasers and two long- baseline, high finesse optical cavities that are housed in a 250m long vacuum system. A transition edge sensor and a heterodyne detection method are currently being developed as detection systems for ALPS II. The installation and commissioning of the experiment will start this year and first data are expected in 2021.

The physics case for ALPS II and the sensitivity of the experiment will be described. An explanation of the light-shining-through-a-wall approach will be provided as well as an overview of the ALPS II experiment.

Witnessing gravitational entanglement with Gaussian states

S. Qvarfort[1], S. Bose[1], A. Serafini[1]

[1]Department of Physics and Astronomy, University College London, Gower Street, WC1E 6BT London, United Kingdom

Is gravity a quantum force? This question was recently addressed by two proposals (see [1] and [2]) which explored the possibility of detecting entanglement that has been generated purely by a gravitational interaction. Successful detection of entanglement mediated by gravity would imply that gravity is fundamentally a quantum force. This poster will detail how the experimental scheme in [1] can be modelled with Gaussian states in the continuous variable framework with levitated nanospheres. We evaluate the entanglement generated by the Newtonian potential and propose the use of a specific continuous variable entanglement witnesses to simplify the detection. The approach also allows us to include other central-potential interactions, such as the Coulomb potential and the attractive Casimir effect. Paper reference: arXiv:1812.09776

[1] Bose, Sougato, et al. "Spin entanglement witness for quantum gravity." Physical Review Letters 119.24 (2017): 240401.

[2] Marletto, Chiara, and Vlatko Vedral. "Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity." Physical Review Letters 119.24 (2017): 240402.

Resonant gravimetry on the micrometer scale with phonons in BECs

D. Rätzel[1]
[1]Institut für Physik, Humboldt-Universität zu Berlin, Newtonstraße 15, 12489 Berlin, Germany

Bose-Einstein condensates (BECs) are very small and extremely cold systems of a large number of atoms. These properties are famously exploited for high precision measurements of forces using atom interferometry. A further way of utilizing BECs as sensors for forces is to measure the forces' effect on the collective oscillations of atoms in BECs. A specific example is the measurement of the thermal Casimir-Polder force due to a material slab [1]. The trapped BEC is brought close to a surface and the trapping frequency is modified by the force, which can be measured by exciting center of mass oscillations in of the whole BEC in the trap.

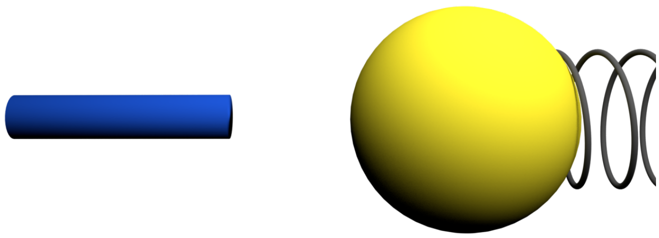


Fig. 1: The gravitational field of a gold sphere oscillating in front of a BEC creates phonons which may be used for sensing the gravitational field.

I will explain how BECs can be used to measure gravitational fields on the micrometer scale. Accelerations due to gravitational fields and their gradients give rise to effective external potentials. Moving the source of the gravitational field on resonance with elastic modes of BECs lead to the creation of phonons. For strong enough gravitational fields this effect can, in principle, be detected. For weaker gravitational fields, a squeezed probe state can be prepared and its change due to the interaction with the oscillating gravitational field may be measured. We illustrate our experimental proposal with the easily accessible example of the gravitational field of a small oscillating gold sphere in the milligram range.

High precision BEC based gravity sensors may be used for the measurement of gravitational fields due to very small objects, which would offer opportunities for new experiments investigating the interface of quantum mechanics and gravity. Due to the small extension of BECs (of the order of few micro-meters), their centre can be brought very close to the surface of the source masses, where the gravitational effects are stronger. Researchers around the world are attempting to bring very small massive systems, such as silica-spheres at almost the pico-gram range, into superposition states [3]. The envisioned ability to measure the gravitational field of masses in superposition states may lead to new exciting experiments, for example, about aspects of quantumness of gravity [4]. High precision sensors for oscillating gravitational fields may also be useful in performing searches for fifth forces (e.g. [5]) and measuring the gravitational field of light [6].

[1] Obrecht et al. *Measurement of the temperature dependence of the Casimir-Polder force* Phys. Rev. Lett. 98, 063201 (2007)
[2] Rätzel et al. Fuentes *Dynamical response of Bose-Einstein condensates to oscillating gravitational fields* New J. Phys. 20 (2018) 073044
[3] Kieselet al. *Cavity cooling of an optically levitated submicron particle.* Proceedings of the National Academy of Sciences 110.35 (2013): 14180-14185.
[4] Bose et al. "Spin entanglement witness for quantum gravity." Physical review letters 119.24 (2017): 240401.
[5] Burrage et al. *Radiative screening of fifth forces.* Physical review letters 117.21 (2016): 211102.
[6] Rätzel et al. *Gravitational properties of light—the gravitational field of a laser pulse.* New Journal of Physics 18.2 (2016): 023009.

Spin squeezing in a metrologically relevant regime

M. Huang[1], T. Mazzoni[2], K. Ott[1], C. L. G. Alzar[2], J. Reichel[1]

[1]Laboratoire Kastler Brossel, ENS-Université PSL, CNRS, Sorbonne Université, Collège de France, 24 rue Lhomond, 75005 Paris, France.

[2]LNE-SYRTE, Observatoire de Paris-Université PSL, CNRS, Sorbonne Université, 61 Avenue de lObservatoire, 75014 Paris, France.

Quantum projection noise (QPN) is a real-life limitation in today's atomic frequency standards [1], and is expected to become relevant for optical lattice clocks in the near future. It is particularly relevant for metrology devices that use trapped atoms, where density-dependent shifts impose upper limits on the atom number. Multiparticle entanglement – spin squeezing in particular – allows metrology beyond the QPN, making it an attractive option for such devices [2]. One particularly promising method of producing spin-squeezed states is by using an optical cavity, which enables quantum non-demolition (QND) measurement of the collective spin and controllable effective interactions [3, 4]. Recent experiments impressively demonstrate these principles and reach high levels of squeezing [2]. However, clock stability levels in these experiments do not exceed that of a standard quartz oscillator yet, and the lifetime of the squeezed states is generally short.

Here we present first spin squeezing results in our trapped-atom clock on a chip (TACC), which has a short-term stability in the will allow us to test entanglement-enhanced measurement in a metrological context. TACC is a microwave clock with magnetically trapped ultracold ^{87}Rb atoms, using an atom chip as a robust and miniature platform. With uncorrelated atoms, the clock reaches a stability of about 6×10^{-13} $s^{-1/2}$ [5] and extremely long coherence time due to spin self-rephasing [6]. We have integrated two fiber Fabry-Pérot cavities [7] on the clock chip (Fig. 1(a)). In first experiments with cavity-enhanced QND measurement, we have obtained more than 8 dB of metrologically relevant spin squeezing (Fig. 1c). Furthermore, we observe a "magnification" effect that amplifies the cavity signal that we attribute to spin self-rephasing. This effect improves the signal-to-noise ratio of the measurement, and thus reduces the impact of photon shot noise. I will present a tentative model to explain this surprising effect.

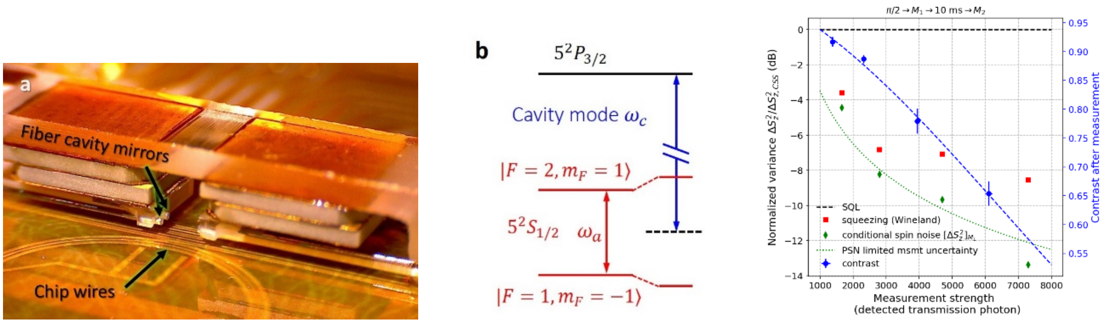


Figure 1. (a) Photograph of the fiber cavity assembly mounted on the clock chip. (b) Relevant energy levels of 87Rb. (c) Preliminary squeezing measurement results as a function of the average photon number detected in transmission.

[1] G. Santarelli, P. Laurent, P. Lemonde, A. Clairon, A. G. Mann, S. Chang, A. N. Luiten, and C. Salomon. Quantum Projection Noise in an Atomic Fountain: A High Stability Cesium Frequency Standard. Phys. Rev. Lett. **82**, 4619 (1999).

[2] L. Pezzè, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein. Quantum metrology with nonclassical states of atomic ensembles. Rev. Mod. Phys. **90**, 035005 (2018).

[3] M. H. Schleier-Smith, I. D. Leroux, and V. Vuletic. States of an Ensemble of Two-Level Atoms with Reduced Quantum Uncertainty. Phys. Rev. Lett. **104**, 073604 (2010).

[4] I. D. Leroux, M. H. Schleier-Smith, and V. Vuletic. Implementation of Cavity Squeezing of a Collective Atomic Spin. Phys. Rev. Lett., **104**, 073602 (2010).

[5] R. Szmuk, V. Dugrain, W. Maineult, J. Reichel, and P. Rosenbusch. Stability of a trapped-atom clock on a chip. Phys. Rev. A **92**, 012106 (2015).
[6] C. Deutsch, F. Ramirez-Martinez, C. Lacroˆute, F. Reinhard, T. Schneider, J. N. Fuchs, F. Piéchon, F. Laloë, J. Reichel, and P. Rosenbusch. Spin Self-Rephasing and Very Long Coherence Times in a Trapped Atomic Ensemble. Phys. Rev. Lett., **105**, 020401 (2010).
[7] 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**, 065038 (2010).

Production and preparation of highly charged ions for re-trapping in ultra-cold environments

M. K. Rosner[1], S. Kühn[1], J. Stark[1], M. Togawa[1], K. Fujii[2], P. Micke[1,3], J. R. Crespo López-Urrutia[1]

[1]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany.

[2]Department of Mechanical Engineering and Science, Graduate School of Engineering, Kyoto University, Kyoto 615-8540, Japan.

[3]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany.

Certain highly charged ions (HCI) exhibit an enhanced sensitivity to fundamental interactions due to the specifics of their level structure. Using such HCIs enables improvement in atomic clocks and frequency metrology. This will pave the way for more precise tests of fundamental physics beyond the Standard Model than achievable with atoms or singly charged ions, e. g. in the search for a possible time variation of the fine-structure constant α [1], [2]. Their narrow optical transitions make them suitable targets for quantum metrology, as recently demonstrated for Ar^{13+} [3].

An electron beam ion trap (EBIT) is used to produce ions in the desired charge states [4]. However, their high translational temperature within the EBIT requires a transfer of the HCI into a cooling trap in order to perform high-resolution laser spectroscopy or apply the method of quantum logic spectroscopy. In the present case a Coulomb crystal of laser-cooled Be^{+} ions that are prepared in a superconducting Paul trap is utilized for this purpose.

We present a setup comprising an EBIT and a beamline suitable for transfer, bunching, precooling and deceleration of extracted HCI. This enables re-trapping in the Paul trap, thermalization with prepared Be^{+} ions and subsequently Coulomb crystallization [5], [6]. In the EBIT, an electron beam is electrostatically accelerated and magnetically compressed to sequentially ionize neutral atoms injected into the trap center and generate HCIs. The ion optics, diagnostic elements and a decelerating/precooling unit of the beamline are used to prepare them for re-trapping.

Time-of-flight measurements were performed to determine the charge state distribution of extracted ions for various EBIT parameters. Furthermore a retarding field analyzer allows the determination of the mean kinetic energy as well as the energy spread of the extracted ions, which will subsequently be reduced in the precooling unit.

[1] M. Kozlov, M. Safronova, J. C. López-Urrutia and P. Schmidt, Highly charged ions: Optical clocks and applications in fundamental physics, Rev. Mod. Phys. 90, 045005 (2018).

[2] M. S. Safronova, V. A. Dzuba, V. V. Flambaum, U. I. Safronova, S. G. Porsev and M. G. Kozlov, Highly Charged Ions for Atomic Clocks, Quantum Information, and Search for α variation, Phys. Rev. Lett 113, 030801 (2014).

[3] P. Micke and et al, Unpublished, 2019.

[4] P. Micke, S.Kühn, L. Buchauer, J. R. Harries, T. M. Bücking, K. Blaum, A. Cieluch, A. Egl, D. Hollain, S. Kraemer, T. Pfeifer, P. O. Schmidt, R. X. Schüssler, C. Schweiger, T. Stöhlker, S. Sturm, R. N. Wolf, S.Bernitt and J. R. Crespo López-Urrutia, The Heidelberg compact electron beam ion traps, Rev. Sci. Instrum. 89, 063109 (2018).

[5] L. Schmöger, M. Schwarz, T. M. Baumann, O. O. Versolato, B. Piest, T. Pfeifer, J. Ullrich, P. O. Schmidt and J. R. Crespo López-Urrutia, Deceleration, precooling, and multi-pass stopping of highly charged ions in Be+ Coulomb crystals, Rev. Sci. Instrum. 86, 103111 (2015).

[6] L. Schmöger, O. O. Versolato, M. Schwarz, M. Kohnen, A. Windberger, B. Piest, S. Feuchtenbeiner, J. Pedregosa-Gutierrez, T. Leopold, P. Micke, A. K. Hansen, T. M. Baumann, M. Drewsen, J. Ullrich, P. O. Schmidt and J. R. Crespo López-Urrutia, Coulomb crystallization of highly charged ions, Science 347, 6227 (2015).

Matter wave interferometry for inertial sensing and tests of fundamental physics

D. Schlippert[1], H. Albers[1], S. Bode[1], C. Braxmaier[2], W. Ertmer[1], F. Guzmán[3], A. Herbst[1], C. Meiners[1], A. Rajagopalan[1], R. Rengelink[1], L. L. Richardson[3], C. Schubert[1], K. Stolzenberg[1], D. Tell[1], É. Wodey[1], E. M. Rasel[1]

[1]Leibniz Universität Hannover, Institut für Quantenoptik, Welfengarten 1, 30167 Hannover

[2]German Aerospace Center (DLR) – Institute of Space Systems & University of Bremen – Center of Applied Space Technology and Microgravity (ZARM), Robert-Hooke-Straße 7, 28359 Bremen

[3]College of Optical Sciences, University of Arizona, Tucson, AZ 85721, USA

Today's state-of-the-art atom inertial sensors require improvements in stability and accuracy in order to fully exploit their potential with large scale factors on very long baselines on ground and in space, as well as in dynamic environments, e.g. for inertial navigation. We report on recent developments concerning the commissioning of the Very Long Baseline Atom Interferometry test stand. Stretching over 15 m, the facility with its high-performance magnetic shield, Rb-Yb atom sources, and a low-frequency seismic attenuation system will allow us to take on the competition with the stability of superconducting gravimeters with absolute measurements. By operating in a differential mode, we furthermore anticipate tests of the Universality of Free Fall at levels of parts in 10^{13} and below [1,2].
We will moreover report on matter wave sensors enhanced with opto-mechanical resonators [3] as well as fully guided interferometry and discuss the potential of such systems in inertial sensing and fundamental physics.

The VLBAI test stand facility is funded by the DFG. We also acknowledge financial support from DFG through CRC 1227 (DQ-mat), project B07. The presented work is furthermore supported by CRC 1128 (geo-Q), project A02, by the Federal Ministry of Education and Research (BMBF) through the funding program Photonics Research Germany (contract number 13N14875), the German Space Agency (DLR) (PRIMUS-III; Grant No. 50WM1641), and by "Niedersächsisches Vorab" through the "Quantum- and Nano-Metrology" (QUANOMET) initiative within the project QT3.

[1] J. Hartwig et al., New J. Phys. **17,** 035011 (2015)
[2] D. Schlippert et al., Phys. Rev. Lett. **112,** 203002 (2014)
[3] F. Guzmán et al., Appl. Phys. Lett. **104,** 221111 (2014)

Folded multi-loop atom interferometer for gravitational wave detection

C. Schubert[1], D. Schlippert[1], S. Abend[1], W. Ertmer[1], E. M. Rasel[1]

[1]Gottfried Wilhelm Leibniz Universität Hannover, Institut für Quantenoptik, Welfengarten 1, 30167 Hannover, Germany.

We will present the concept of a terrestrial detector for gravitational waves based on atom interferometry. It utilizes symmetric beam splitters and relaunches of the atoms [1,2] to generate folded multi-loop geometries for a broadband detection mode [3] and a resonant detection mode [4] for increased sensitivity. The folded multi-loop geometries enable a setup with a single axis laser link in each of the two horizontal arms of the detector, resembling the setup for laser interferometers for gravitational wave detection [5,6,7]. In broadband mode, the detector covers frequencies between 0.1 Hz and 5 Hz with a peak strain sensitivity of 10^{-21} $Hz^{-1/2}$. The concept also eliminates stringent requirements onto the atomic source common to other proposals based on atom interferometry [8].

The presented work is supported by the CRC 1227 DQ-mat within the project B07, the CRC 1128 geo-Q within the projects A02, the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy – EXC-2123-B2, the German Space Agency (DLR) with funds provided by the Federal Ministry of Economic Affairs and Energy (BMWi) due to an enactment of the German Bundestag under Grant No. DLR 50WP1700, and "Niedersächsisches Vorab" through the "Quantum and Nano-Metrology (QUANOMET)" Initiative within the project QT3.

[1] H. Ahlers et al., *Double Bragg diffraction*, Phys. Rev. Lett. **116**, 173601 (2016).

[2] S. Abend et al., *Atom-Chip Fountain Gravimeter*, Phys. Rev. Lett. **117**, 203003 (2016).

[3] J. M. Hogan et al., *Atom-interferometric gravitational-wave detection using heterodyne laser links*, Phys. Rev. A **94**, 033632 (2016)

[4] P. W. Graham et al., *Resonant mode for gravitational wave detectors based on atom interferometry*, Phys. Rev. D **94**, 104022 (2016).

[5] B. P. Abbott et al., *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. **116**, 061102 (2016).

[6] W. Chaibi et al., *Low frequency gravitational wave detection with ground-based atom interferometer arrays*, Phys. Rev. D **93**, 021101(R) (2016).

[7] B. Canuel et al., *Exploring gravity with the MIGA large scale atom interferometer*, Scientific Reports 8, 14064 (2018).

[8] J. M. Hogan et al., *An atomic gravitational wave interferometric sensor in low earth orbit (AGIS-LEO)*, Gen. Relativ. Grav. **43**, 1953 (2011).

Atomic clocks with (un-)squeezed states

M. Schulte[1], V. J. Martinez-Lahuerta[1], P. O. Schmidt[2,3], K. Hammerer[1]

[1]Institute for Theoretical Physics and Institute for Gravitational Physics (Albert-Einstein-Institute), Leibniz University Hannover, Appelstrasse 2, 30167 Hannover.

[2]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig.

[3]Institute for Quantum Optics, Leibniz University Hannover, Welfengarten 1, 30167 Hannover.

We study quantum metrology with non-classical spin states and their specific application in optical atomic clocks. The phase variance of a large class of measurement protocols is evaluated analytically and optimised over the direction of the signal and measurement as well as over the squeezing strength. To assess applications in optical atomic clocks we then further numerically simulate the dynamics of symmetric spin systems and evaluate the attainable clock instability from this. For evaluating the instability we focus on the most relevant effects, namely realistic phase noise of the interrogation laser and full quantum statistics of the measurements.

Post-Newtonian corrections to Schrödinger equations in gravitational fields

P. K. Schwartz[1], D. Giulini[1,2]

[1]Institute for Theoretical Physics, Leibniz University Hannover, Appelstraße 2, 30167 Hannover, Germany.

[2]Center of Applied Space Technology and Microgravity, University of Bremen, Am Fallturm 1, 28359 Bremen, Germany.

In recent years, several promising opportunities to experimentally probe novel aspects at the interface of gravity and quantum mechanics have been proposed. However, to properly evaluate such ideas, a thorough understanding of the coupling of few-particle quantum-mechanical systems to gravitational fields is necessary. On a fundamental level, based on well-established principles, such an understanding is still lacking. In this work [1], we consider the simplest case to be imagined: a single quantum particle propagating in a given background gravitational field.

In the literature, there are two main approaches to the problem of obtaining post-Newtonian correction terms for the Schrödinger equation describing a particle in a curved spacetime: either, one starts with a classical description of the particle and quantises this by appropriately adapted standard procedures, or one takes a field-theoretic perspective and derives the Schrödinger equation as an equation for the positive frequency solutions of the minimally coupled classical Klein–Gordon equation.

Following the second approach, we extend a WKB-like 'non-relativistic' expansion of the Klein–Gordon equation after [2–4] to arbitrary order in 1/c. The results are compared with canonical quantisation of a free particle in curved spacetime following [5], appropriately generalised to the case of non-stationary metrics. Furthermore, using a more operator-algebraic approach, the Klein–Gordon equation and the canonical quantisation method are shown to lead to the same results for some special terms in the Hamiltonian describing a single particle in a general stationary spacetime, without any 'non-relativistic' expansion in powers of c.

[1] P. K. Schwartz and D. Giulini, *Post-Newtonian corrections to Schrödinger equations in gravitational fields,* Class. Quantum Grav. **36**, 095016 (2019).
[2] C. Kiefer and T. P. Singh, *Quantum gravitational corrections to the functional Schrödinger equation,* Phys. Rev. D **44**, 1067–1076 (1991).
[3] C. Lämmerzahl, *A Hamilton operator for quantum optics in gravitational fields,* Phys. Lett. A **203**, 12–17 (1995).
[4] D. Giulini and A. Großardt, *The Schrödinger–Newton equation as a non-relativistic limit of self-gravitating Klein–Gordon and Dirac fields,* Class. Quantum Grav. **29**, 215010 (2012).
[5] S. Wajima, M. Kasai, and T. Futamase, *Post-Newtonian effects of gravity on quantum interferometry,* Phys. Rev. D **55**, 1964–1970 (1997).

Dual-ion clock in a single trap for searches beyond the standard model

K. H. Shao, N. Huntemann, R. Lange, M. Brinkmann, M. Abdel Hafiz, B. Lipphardt, T. Mehlstäubler, Chr. Tamm and E. Peik
Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Frequency comparisons between optical clocks based on the same transition have been performed with fractional frequency uncertainties of 10^{-18} [1,2]. Comparisons between clocks referencing different atomic transitions, however, are suitable for searches for physics beyond the standard model [3].
The $^{171}Yb^{+}$ ion provides two reference transitions with very different sensitivity on a potential variation of the fine structure constant α. Therefore, the frequency ratio of the $^2S_{1/2}(F=0)$ - $^2D_{3/2}(F=2)$ electric quadrupole (E2) transition at 436 nm and the $^2S_{1/2}(F=0)$ - $^2F_{7/2}(F=3)$ electric octupole (E3) transition at 467 nm magnifies changes in α by a factor of seven. As the transitions also show different sensitivity to external perturbations, possible variations in the frequency ratio can also result from clock imperfections such as varying residual electric or magnetic fields. To distinguish clock imperfections from a variation in α, it is advisable to have an independent reference.
The $^2S_{1/2}$ - $^2D_{5/2}$ transition of $^{88}Sr^{+}$ ions appears to be an appropriate candidate, providing reduced sensitivity to variations in α and different sensitivity to external fields. Furthermore, it has been demonstrated that the $^{88}Sr^{+}$ clock transition frequency can be realized with a fractional uncertainty of 10^{-17}, essentially limited by the unknown but predominantly constant black body radiation shift [4].
Besides application for searches for “new physics”, co-trapping of $^{88}Sr^{+}$ and $^{171}Yb^{+}$ ions can also help to improve two major limitations of $^{171}Yb^{+}$(E3) clock: A significant reduction in the leading uncertainty due to blackbody radiation at room temperature and a compensation of motional heating permitting an extension of the coherent interrogation time from seconds to minutes. For the latter, sideband cooling on the $^{88}Sr^{+}$ ion needs to be performed, for which the required laser radiation causes negligible light shifts on the E3 transition. To improve the blackbody radiation shift uncertainty of $^{171}Yb^{+}$(E3) clocks by about one order-of-magnitude, the small relative uncertainty in the differential polarizability on the $^{88}Sr^{+}$ clock transition [5] needs to be transferred to that of the E3 transition. This can be achieved by monitoring the frequency shifts induced for both ions if they are perturbed with identical intensity of laser radiation at 10.6 μm.

[1] C. Sanner, *et al.*, *Optical clock comparison for Lorentz symmetry testing,* Nature **567**, 204 (2019).
[2] W.F. McGrew, *et al., Atomic clock performance enabling geodesy below the centimetre level,* Nature **564**, 87 (2018).
[3] M. S. Safronova, *et al., Search for new physics with atoms and molecules,* Rev. Mod. Phys**. *90***, 025008 (2018).
[4] P. Dubé, *et al., Sr^{+} single-ion clock,* J. Phys.: Conf. Ser. **723** 012018 (2016).
[5] P. Dubé, *et al., High-Accuracy Measurement of the differential scalar polarizability of a $^{88}Sr^{+}$ clock using the time-dilation effect,* Phys. Rev. Lett. **112**, 173002 (2014).

Cavity-enhanced Large Momentum Transfer Atom Interferometry

J. Siemß[1,2], S. Abend[2], K. Hammerer[1], N. Gaaloul[2]
[1]Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany.
[2]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany.

Large momentum transfer (LMT) schemes for atom interferometry with Bose-Einstein condensates combining Bragg pulses and Bloch oscillations allow for state-of-the-art momentum separation in an atom interferometer with up to 408 photon recoils ($\hbar k$) [1]. As their sensitivity is increased by enlarging the spatial separation of the two interferometer arms LMT techniques are likely to become integral parts of next generation sensors.

In our work, we study the implementation of LMT atom interferometers featuring twin optical Bloch lattices [1] in an optical cavity.
Using a cavity for atom interferometry provides in addition to a resonant enhancement of the intra-cavity intensity a significant reduction of wavefront distortions [2,3] that have proven to cause significant systematic effects in current state-of-the-art atom interferometry experiments [1,4,5].

To evaluate the benefits of cavity-enhanced atom optics involving symmetric optical lattices we perform analytical studies and employ a time-dependent Gross-Pitaevskii model. In particular, we investigate the scalability of such sensors to ultimately assess their suitability for atom interferometry based gravitational wave detectors featuring momentum separations of up to $1000\hbar k$ [6,7].

The presented work is supported by the CRC 1227 DQmat within the project A05.

[1] M. Gebbe et al., in preparation.
[2] P. Hamilton et al., *Phys. Rev. Lett.* **114**, 100405 (2015)
[3] M. Dovale-Álvarez et al., *Phys. Rev.* A **96**, 053820 (2017)
[4] Bade et al., *Phys. Rev. Lett.* **121**, 073603 (2018)
[5] Parker et al., Science **360**, 6385, pp. 191-195 (2018)
[6] S. Dimopoulos et al., *Phys. Lett.* B **678**, p. 37-40 (2009)
[7] W. Chaibi et al., *Phys. Rev.* D **93**, 021101(R) (2016)

Thorium solid-state nuclear clock

K. Beeks[1], T. Sikorsky, G. Kazakov, T. Schumm
[1]Institute for Atomic and Subatomic Physics, TU Wien, Stadionallee 2,
1020 Vienna, Austria

Thorium-229 is a unique isotope with the lowest long-lived nuclear-excited state of ~7.8eV (~160nm), making it accessible to laser manipulation [1]. This few-eV transition emerges from a cancelation of Coulomb and nuclear interactions for the two lowest nuclear energy levels. This makes it likely that the nuclear transition might have a strong sensitivity to the variation of fundamental constants [2]. A long-lived excited nuclear state with energy splitting of E≈2000THz will allow the construction of the Thorium nuclear clock that will rival today's most advanced optical atomic clocks [3]. Because the nucleus is unaffected by the chemical environment, it is no longer necessary to use isolated atom in electromagnetic or dipole traps. The nuclear clock can also be realized by implanting the Thorium-229 atoms into a VUV transparent material. Such solid-state nuclear clock will present a new platform for optical frequency standards [4].

We are developing a nuclear clock where Thorium-229 atoms are implanted into a calcium fluoride crystal. Due to a large number of interrogated atoms ($n \approx 10^{18} cm^{-3}$), a fractional instability level of 10^{-19} might be reached within the solid-state approach. For the solid-state nuclear clock, the readout scheme has yet to be developed. We propose an interrogation scheme based on nuclear quadrupole resonance spectroscopy (NQR).

The interaction of the nuclear quadrupole moment with the electric field gradient of the crystal causes the splitting of the nuclear states. This splitting can be interrogated with nuclear quadrupole resonance spectroscopy (NQR). DFT calculations of Thorium-229 doped into calcium fluoride predict electric field gradient of ~250V/$Å^2$ and nuclear quadrupole splitting of the order 300MHz for ground state and 500MHZ for the excited state [5]. These NQR transitions can be used for non-destructive readout of the nuclear state during clock operation.

[1] B. R Beck, C. Y. Wu, P. Beiersdorfer, G. Brown, J. A Becker, K. J Moody, J. B Wilhelmy, F. S Porter, C. A Kilbourne, and R. L Kelley, *Improved Value for the Energy Splitting of the Ground-State Doublet in the Nucleus 229Th* (2010).
[2] V. V. Flambaum, Phys. Rev. Lett. (2006).
[3] C. J. Campbell, A. G. Radnaev, A. Kuzmich, V. A. Dzuba, V. V. Flambaum, and A. Derevianko, Phys. Rev. Lett. (2012).
[4] G. A. Kazakov, A. N. Litvinov, V. I. Romanenko, L. P. Yatsenko, A. V Romanenko, M. Schreitl, G. Winkler, and T. Schumm, New J. Phys. (2012).
[5] P. Dessovic, P. Mohn, R. A. Jackson, G. Winkler, M. Schreitl, G. Kazakov, and T. Schumm, J. Phys. Condens. Matter (2014).

Quantum (Nano) Metrology: Definition, Characterization, Modeling and Applications. Some Computational Author's Models for Numerical Simulations

K. Marinova (Simeonova)[1]
[1]Institute of Mechanics, Bulgarian Academy of Sciences, acad. G. Bonchev, str., Bl. 4 1113 Sofia, Bulgaria

Recently studies on nanostructured materials (nanotubes, nanocomposites, nanoparticles, Nano Quantum Dots etc. possess exceptional properties (physic-mechanical, electronic, optical, electrical, magnetic), [1]. These nanomaterials possess very small nanosizes for example nanotubes (about 50-100nm in diameter and some microns in length) and chirality nanostructure. They have applications in many different areas: technique, engineering, computers, transistors, semiconductors, thin films, emitter, nanotechnology and so on. The definition of metrology in classical sense is a science of measurements. Cited [2], the next definition we give "Nanometrology includes length or size measurements (where dimensions are typically given in nanometers and the measurement uncertainty is often less than 1 nm) as well as measurements of force mass, electrical and other properties". Molecular measuring machine used for positional metrology has been shown in Figure 1. Investigations on modeling by classical quantum mechanics and nanomechanics for metrology, sensing and imaging in quantum optical technologies has been discussed in [3]. Nanometrology techniques for characterizations presented and analyzed in [4], as follows Atomic Force Microscopy (AFM); Scanning Force Microscopy (SFM); Scanning Tunneling Microscopy (STM); Raman Spectroscopy etc. High Research Transmission Electron Microscopy (HRTEM); Electrical Low Pressure Impactor (ELPI); SMPS (Scanning Sizer) has been presented in [4] too. Computational Author's Models for study of nanotubes, nanocomposites, nanoDots' Physic-mechanical, optical, electronic, magnetic and so on properties has been described in [5]. By author's numerical algorithms FORTRAN Programs graphics, reflecting different effects model's parameters have been obtained in [5].

References

[1]. Katya M. Simeonova, Ganka M. Milanova, ISCOM2007, Book of Abstracts, 24-30 September 2007, Peniscola, Spain, poster P123, Grant

[2]. Nanoparticles.org/

[3]. Jonathan P. Dowing, et al, OSA, Louisiana State University, Baton Rouge, LA 70803, USA

[4]. Katya M Simeonova, Summer Ethic School, DVD, University of Twente, Netherland, Oral Presentation, 2009, full financial support

[5]. Katya Simeonova, *Computational Modeling of Carbon Nanotubes' Electronic and Optical Properties*, XXV International Summer School "Nicolas Cabrera", Miraflores de la Sierra, Madrid, Spain, September, 9-14, 2018 (Grant)

Quantifying general quantum correlations in open quantum system for continuous-variable Werner states and Bell diagonal states using Wigner function

F. Siyouri

Equipe Science de la matière et du rayonnement, Département de Physique
Faculté des sciences, Universit_e Mohammed V - Agdal
Av. Ibn Battouta, B.P. 1014, Agdal, Rabat, Morocco

We investigate the ability of Wigner function to reveal and measure general quantum correlations in two-qubit open system. For this purpose, we analyze comparatively their dynamics for two different states, continuous-variable Werner states and Bell-diagonal states, independently interacting with dephasing reservoirs. Then, we explore the effects of decreasing the degree of non-Markovianity on their behavior. We show that the presence of
both quantum entanglement and quantum discord allow to have a negative Wigner function, in contrast to the result obtained for the closed two-qubit system [Quantum. Inf. Process 15 (2016) 4237-4252]. In fact, we conclude that negativity of Wigner function can be used to capture and quantify the amount of general non-classical correlations in open quantum systems.

A superconducting radio-frequency trap for long-time storage of highly charged ions

J. Stark[1], S. Bogen[1], L. Haaga[1], S. A. King[2], S. Kühn[1], T. Leopold[2], P. Micke[1,2], J. Nauta[1], J.-H. Oelmann[1], M. K. Rosner[1], L. Schmöger[1], L. Spieß[1], C. Warnecke[1], T. Pfeifer[1], P. O. Schmidt[2], J. R. Crespo López-Urrutia[1]

[1]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

[2]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Narrow optical transitions in highly charged ions (HCI) are excellent candidates for novel optical frequency standards due to their low susceptibility to external influences [1]. Precise measurements of their frequencies can be used to stringently test physics beyond the Standard Model, as some of them feature an enhanced sensitivity to a possible variation of the fine-structure constant or the proton-to-electron mass ratio [1,2,3]. However, motional cooling of HCI is challenging, since they lack fast-cycling transitions for direct laser cooling. At the cryogenic Paul trap experiment (CryPTEx) [4], this has been solved by employing sympathetic cooling using co-trapped laser-cooled $^{9}Be^{+}$ ions [5]. In principle, this method can be applied to many species of ions, including all possible HCI types.

Here, we present the first commissioning results of one of the successor experiments, the MPIK version of CryPTEx-II, in which the radio-frequency (RF) trap electrodes are integral elements of a novel, quasi-monolithic superconducting RF resonator made from ultra pure Nb. The confining pseudopotential is thus generated by extremely stable RF fields. At 4.2 K, where Nb has an extremely small thermal expansion coefficient, the resonator eigenmode at 34.439 MHz has a loaded quality factor $Q_l > 10^5$. This high value strongly confines ions at drastically reduced RF input voltages. Furthermore, the massive superconducting resonator completely encloses the trapping region and shields the ions from external magnetic field noise and other sources of anomalous heating. For suppressing effects of mechanical noise on the optical frequency determinations, a low-vibration cryogenic system was developed in collaboration with QUEST institute at PTB, where a twin setup with a normal-conducting RF trap is operated [6,7].

[1] M. G. Kozlov et al., Rev. Mod. Phys. **90**, 045005 (2018)
[2] V. A. Dzuba et al., Phys. Rev. A **86**, 054502 (2012)
[3] J. C. Berengut et al., Phys. Rev. Lett. **106**, 210802 (2011)
[4] M. Schwarz et al., Rev. Sci. Instrum. **83**, 083115 (2012)
[5] L. Schmöger et al., Rev. Sci. Instrum. **86**, 103111 (2015)
[6] P. Micke et al., arXiv:1901.03630 (2019)
[7] T. Leopold et al., arXiv:1901.03082 (2019)

From inertial sensing to inertial navigation – A comparison of CAI to conventional INS

B. Tennstedt[1], S. Schön[1]
[1]Institut für Erdmessung, Leibniz Universität
Hannover, Schneiderberg 50, 30167 Hannover,
Germany

In inertial navigation, a trajectory is calculated by integrating accelerations and rotation rates of a moving frame in a reference system. This allows an autonomous determination of the kinematic state of a vehicle (3D position, velocity and attitude), while being independent from external sensors, and therefore preventing attacks such as spoofing and jamming that could occur in case of GNSS. Since the basic signal is integrated, a major drawback of this attempt is the summation and increase of noise perturbating the signal, which leads to an at least quadratic increase in the position error. Even with state-of-the-art IMUs, the error in position can grow up to several meters after only a few seconds.
The high sensitivity and long term stability of cold atom interferometry seems promising in this regard. First estimations in [1] and [2] underline a great improvement of a navigation solution based on the lower white noise density in the measurements of a cold atom interferometer.
In this contribution, we will present some results from our investigation about utilizing a cold atom interferometer in a differential setup as an alternative to conventional inertial navigation systems, especially pointing out how well its error behavior can be described with a common INS sensor error model according to the IEEE specifications.

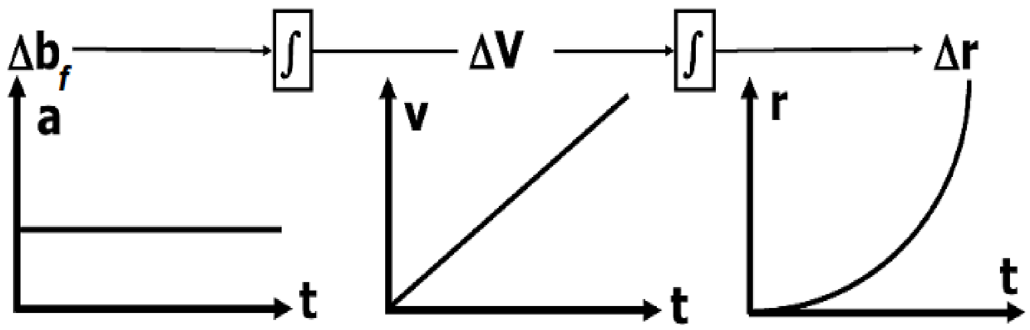


Figure 1. Severe problem in inertial navigation: Integrated errors leading to an exponential increase of the position error

[1] C. Jekeli, *Navigation Error Analysis of Atom Interferometer Inertial Sensor*, Navigation, 52: 1-14. doi:10.1002/j.2161-4296.2005.tb01726.x (2005).
[2] M. Bochkati, S. Schön, D. Schlippert, C. Schubert, E. Rasel, *Could Cold Atom Interferometry Sensors be the Future Inertial Sensors? First Simulation Results*, Proceedings of DGON Inertial Sensors and Systems, September 19th – 20th, Karlsruhe, Germany (2017)

Ultracold YbF Molecules for Measuring the Electron's Electric Dipole Moment

M. A. Trigatzis, J. Lim, S. C. Swarbrick, J. Zielinska, N. J. Fitch, B. E. Sauer, M. R. Tarbutt, E. A. Hinds
[1]Centre for Cold Matter, Blackett Laboratory, Imperial College London, Prince Consort Road, London, SW7 2AZ, United Kingdom.

Polar molecules can be used as exceptionally sensitive probes for new physics beyond the Standard Model. The sensitivity of experiments [1-4] which measure the electron's electric dipole moment (eEDM) can be improved by cooling the molecules. Along with other exciting applications, which include cold chemistry, quantum simulation and computation, this motivates the extension of laser cooling from atoms to molecules. We have laser cooled a beam of YbF molecules in one transverse dimension to below 100 μK [5] and have extended the technique to two dimensions. We demonstrate the feasibility of an eEDM measurement with spin coherence times exceeding 100 ms, a hundred times higher than in the previous YbF eEDM experiment.

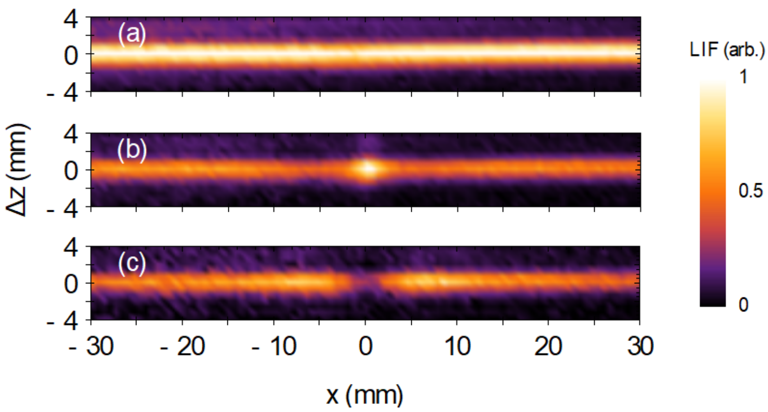


Figure 1. Laser induced fluorescence (LIF) images of a YbF beam, which propagates along z and intersects a probe laser which propagates along x, with (a) no laser cooling light, (b) blue-detuned cooling light, and (c) red-detuned cooling light. The enhanced (depleted) density at $x = 0$ is characteristic of Sisyphus cooling (heating).

[1] J. J. Hudson, D. M. Kara, I. J. Smallman, B. E. Sauer, M. R. Tarbutt, and E. A. Hinds, Nature **473**, 493 (2011).
[2] J. Baron *et al.* (The ACME Collaboration), Science **343**, 269 (2014).
[3] W. B. Cairncross, D. N. Gresh, M. Grau, K. C. Cossel, T. S. Roussy, Y. Ni, Y. Zhou, J. Ye, E. A. Cornell, Phys. Rev. Lett. **119**, 153001 (2017).
[4] V. Andreev *et al.* (The ACME Collaboration), Nature **562**, 355 (2018).
[5] J. Lim, J. R. Almond, M. A. Trigatzis, J. A. Devlin, N. J. Fitch, B. E. Sauer, M. R. Tarbutt and E. A. Hinds, Phys. Rev. Lett. **120**, 123201 (2018).

Impact of interactions on BEC interferometry

C. Ufrecht, A. Roura, W. P. Schleich

Institut für Quantenphysik, Universität Ulm, Albert-Einstein Allee 11, 89069 Ulm, Germany

In recent years, light-pulse atom interferometry with macroscopic arm separation and Bose-Einstein condensates as highly coherent atom sources has attracted a lot of attention. In this context, interactions between the atoms, which are often disregarded in the theoretical description, can, however, lead to significant effects such as mean-field phase shifts or phase diffusion. To better understand these effects, we discuss the problem in second quantization, where the inclusion of interactions is straightforward. Based on a clear separation of the atomic clouds along different paths in position or momentum space, we propose a method that leads to a path-dependent description involving a transformation to the rest frame for each individual path. In this picture phase contributions predicted by the non-interacting theory and effects generated by the interaction separate most clearly. As an application of this method we discuss how two-mode squeezing between momentum states driven by atomic interactions can be exploited to overcome the shot-noise limit [1].

[1] M. Kitagawa, M. Ueda, *Squeezed spin states*, Phys. Rev. A, **47**, 5138, (1993)

Gravitational Influence on Penning Trap based Free Electron g-factor Measurements

S. Ulbricht[1,2] , R. A. Müller[1,2], and A. Surzhykov[1,2]

[1]Physikalisch-Technische Bundesanstalt, Germany

[2]Technische Universität Braunschweig, Germany

Today, the gyromagnetic ratio of a free electron is known to a very high accuracy of g/2=1.001 159 652 180 73 (28) [1] and the improvement of this value is still an ongoing process in modern research. The g-factor is currently determined by spectroscopy of spin-flip and cyclotron transitions of a single electron in a Penning trap. These experiments, however, are not performed in an isolated environment, but in the gravitational field of the Earth. In this contribution, therefore, we present investigations of gravitational effects on the trapped electron *and* the Penning trap itself (fig. 1). More specifically, we investigate an electron bound to a Penning trap, both affected by a homogeneous gravitational field. Therefore the Hamiltonian of a Dirac-Fermion with anomalous coupling to an electromagnetic field is considered in the spacetime of homogeneous acceleration, e.g. Rindler spacetime. The distorted electromagnetic field of the Penning trap is given as an exact solution to covariant Maxwell equations in this spacetime. From that, we derived the relativistic corrections of order $1/c^2$ to transition frequencies, used to determine the free electron g-factor. As a consequence an extension of the g-factor formula introduced by L. S. Brown and G. Gabrielse [2] is presented.

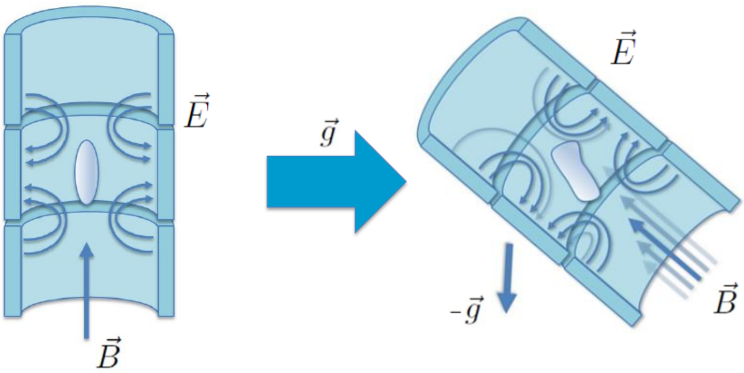


Figure 1. Left: The electron is trapped in an ideal Penning trap consisting of an electric quadrupole field and a constant magnetic field. Right: The presence of a gravitational field changes the dynamics of the trapped electron and the properties of the electromagnetic trapping field.

[1] D. Hanneke, S. Fogwell, and G. Gabrielse, *New Measurement of the Electron Magnetic Moment and the Fine Structure Constant***,** Phys. Rev. Lett. **100**, 120801 (2008).

[2] L. S. Brown and G. Gabrielse, *Geonium theory: Physics of a single electron or ion in a Penning trap,* Rev. Mod. Phys. **58**, 233 (1986).

Imaging of Coulomb crystals in the superconducting Paul trap CryPTEx-II

C. Warnecke[1], J. Stark[1], A. Ackermann[1], S. Bogen[1], L. Haaga[1], S. Kühn[1], J. Nauta[1], J. Oelmann[1], M. K. Rosner[1], L. Schmöger[1], T. Pfeifer[1], J. R. Crespo López-Urrutia[1]

[1]Max-Planck Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

Cold highly charged ions (HCI) can be used for extreme ultraviolet (XUV) frequency standards, since their electronic structure possesses highly forbidden transitions in that spectral range. They have also been proposed as excellent candidates for tests of Standard Model extensions [1,2]. On one side, they feature low susceptibility to external perturbations that hinder studies with atoms and singly charged ions. At the same time, they also have ultra-narrow optical transitions that are highly sensitive to possible variations of fundamental constants and to hyperfine interactions giving rise to possible non-linearities in isotopic shifts [2,3]. The latter could allow the exploration of Yukawa interactions between the bound electrons and hypothetical particles coupling to the nucleus. With the Cryogenic Paul Trap Experiment, CryPTEx, built at the Max Planck Institute for Nuclear Physics, a broad range of HCI can be trapped and sympathetically cooled by laser-cooled Be^+ ions forming Coulomb crystals. This reduces the typical temperature of trapped HCI by eight orders of magnitude down to 10 mK [4]. Its follow-up experiment, CryPTEx II uses as trap a novel, quasi-monolithic superconducting quadrupole resonator. It will trap ions with extremely stable radio-frequency potentials at lower heating rates than now possible. We have designed a 50-mm diameter magnifying objective covering a 500 micron field-of-view at a working distance of 57 mm, and optimized for 235, 313 and 445 nm imaging of the trapped ions. For stability, the 8-lens system directly is mounted on top of the superconducting resonator trap, and operates at 4 K. We discuss our design and present first commissioning results.

[1] M. S. Safronova et al., *Highly Charged Ions for Atomic Clocks, Quantum Information, and Search for α variation,* Phys. Rev. Lett. 113, 030801 (2014)

[2] M. G. Kozlov et al., *Highly charged ions: Optical clocks and applications in fundamental physics*, Rev. Mod. Phys. **90**, 045005 (2018)

[3] V. V. Flambaum, A. J. Geddes, and A. V. Viatkina, *Isotope shift, nonlinearity of King plots, and the search for new particles*, Phys. Rev. A 97 (2018)

[4] L. Schmöger et al., *Coulomb crystallization of highly charged ions*, Science **347** (6227): 1233-1236 (2015)

Control of tunneling in a triple-well atomtronic switching device

K. Wittmann Wilsmann[1], L. H. Ymai[2], A. Prestes Tonel[2], J. Links[3] and A. Foerster[1]

[1] Universidade Federal do Pampa, Bagé, Brazil

[2] Instituto de F´ısica da UFRGS, Porto Alegre, Brazil

[3] School of Mathematics and Physics, The University of Queensland, Brisbane, Australia.

The precise control of quantum systems will play a major role in the realiza- tion of atomtronic devices. As in the case of electronic systems, a desirable property is the ability to implement switching. Here we study a model of dipolar bosons confined to three coupled wells. The model describes interactions between bosons, tunneling of bosons between adjacent wells, and the effect of an external field. We conduct a study of the quantum dynamics of the system to probe the conditions under which switching behavior can occur. The analysis considers both integrable and non-integrable regimes within the model. Through variation of the external field, we demonstrate how the system can be controlled between various "switched-on" and "switched-off" configurations [1].

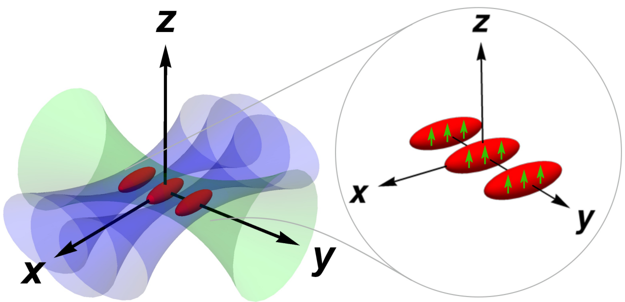


Figure 1: Schematic representation of the trap geometry. Three parallel lasers (blue) are crossed by a transverse beam (green). The cigar-shapes, in red, represent a dipolar BEC trapped in a triple-well potential, and the green internal arrows depict the orientation of the dipoles.

[1] K.W. Wilsmann, L.H. Ymai, A.P. Tonel, J. Links, and A. Foerster, *Control of tunneling in atomtronic switching*, Commun. Phys.**1**, 91 (2018). DOI:10.1038/s42005-018-0089-1.

Design and implementation progress of the Hannover Very Long Baseline Atom Interferometry facility

E. Wodey[1], D. Tell[1], C. Meiners[1],
R. J. Rengelink[1], K. H. Zipfel[1], C. Schubert[1],
D. Schlippert[1], W. Ertmer[1], E. M. Rasel[1]

[1]Leibniz University Hannover, Institute of Quantum Optics, Welfengarten 1, 30167 Hannover

Very Long Baseline Atom Interferometry (VLBAI) stands for ground-based atomic matterwave interferometry on large scales in space and time where the atomic wave functions interfere after multiple meters and several seconds of free evolution. Owing to the quadratic scaling of such an interferometer's leading order phase shift with its free evolution time, such dual species simultaneous accelerometers promise tests of the universality of free fall at the 10-13 level and beyond [1]. In addition, the large spatial extent of the interferometer allows testing the limits of quantum coherence at our macroscopic scale [2, 3] and under the influence of gravity [4].

In this poster, we discuss the design principles, implementation progress, and prospects for the Hannover Very Long Baseline Atom Interferometer. We describe in particular the three key components of the apparatus: the dual-species ultracold atoms source chambers, the 10.5 meter long magnetically shielded free fall baseline, and the vibration-isolated inertial reference.

The VLBAI facility is a major research instrument funded by the German Research Foundation (DFG). We also acknowledge financial support from DFG through the collaborative research centers 1227 "DQ-mat" (project B07) and 1128 "geo-Q" (project A02). The presented work is furthermore supported by the Federal Ministry of Education and Research (BMBF) through the funding program Photonics Research Germany (contract number 13N14875) and by "Niedersächsisches Vorab" through the "Quantum- and Nano-Metrology" (QUANOMET) initiative within the project QT3.

[1] J. Hartwig *et al.*, „Testing the universality of free fall with rubidium and ytterbium in a very large baseline atom interferometer", New J. Phys. **17,** 035011 (2015)
[2] S. Nimmrichter and K. Hornberger, „Macroscopicity of Machanical Quantum Superposition States", Phys. Rev. Lett. **110**, 160403 (2013)
[3] T. Kovachy *et al.*, „Quantum superposition at the half-metre scale", Nature **528**, 530-533 (2015)
[4] I. Pikovski *et al.*, „Universal decoherence due to gravitational time dilation", Nat. Phys. **11**, 668-672 (2015)

Towards precision quantum logic spectroscopy of single molecular ions

F. Wolf[1*], J. C. Heip[1], M. J. Zawierucha[1], P. O. Schmidt[1,2]
[1]Physikalisch-Technische Bundesanstalt, QUEST Institut, 38116 Braunschweig, Germany
[2]Leibniz Universität Hannover, Institut für Quantenoptik, 30167 Hannover, Germany

Precision spectroscopy has been a driving force for the development of our physical understanding. In particular laser cooling and manipulation has led to an advancement in precision spectroscopy. However, only few atomic and molecular species offer suitable transitions for laser cooling, limiting the variety of accessible species. This restriction can be overcome in trapped ion systems through quantum logic spectroscopy. Coherent laser manipulation, originally developed in the context of quantum information processing, allows to combine the special spectroscopic properties of one ion species (spectroscopy ion) with the excellent control over another species (logic or cooling ion) [1].
Here, we present the status of our experiment, aiming at high precision quantum logic spectroscopy of molecular ions. In the past, we have demonstrated a non-destructive internal state detection scheme for 24MgH+ ions [2], that relies on the detection of state dependent forces with a co-trapped 25Mg+ ion. We further developed a quantum enhanced force detection scheme, that makes use of the non-classical features of motional Fock states [3]. Recent progress on our new setup including a molecular beam line and a new linear Paul trap to store and investigate a wider range of molecular ions is shown.

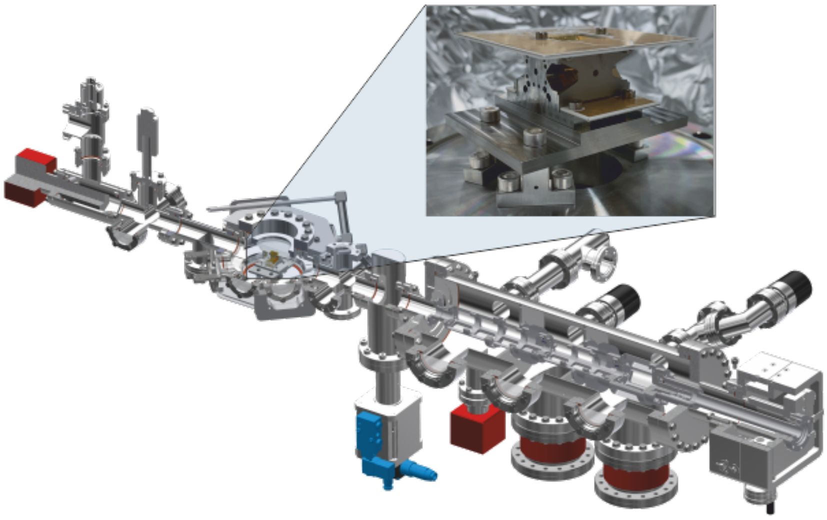


Figure 1. Molecular beam line with attached ion trap vacuum chamber. Photoionization of molecules from the molecular beam with a pulsed dye laser allows loading of a wide variety of molecular ions.

[1] P. O. Schmidt et al., Science 309, 749-752 (2005).
[2] F. Wolf et al., Nature 530, 457-460 (2016).
[3] F. Wolf et al., arXiv:1807.01875 (2018).

Program

<table>
<tr><th>Time</th><th>Wednesday,
12 June 2019</th><th>Thursday,
13 June 2019</th><th>Friday,
14 June 2019</th></tr>
<tr><td>09:00</td><td>M. Kasevich</td><td>J. Thompson</td><td>H. Müller</td></tr>
<tr><td>09:40</td><td>W. Schleich</td><td>M. Zych</td><td>K. Jungmann</td></tr>
<tr><td>10:20</td><td>BREAK</td><td>BREAK</td><td>BREAK</td></tr>
<tr><td>10:50</td><td>T. Zelevinsky</td><td>P. Treutlein</td><td>D. Leibrandt</td></tr>
<tr><td>11:30</td><td>M. Mitchell</td><td>D. Budker</td><td>M. Schleier-Smith</td></tr>
<tr><td>12:10</td><td>N. Huntemann</td><td>S. Gleyzes</td><td>S. Schiller</td></tr>
<tr><td>12:50</td><td>LUNCH</td><td>LUNCH</td><td>LUNCH</td></tr>
<tr><td>14:00</td><td>J. Eby</td><td>P. Kunkel</td><td>H. Winter</td></tr>
<tr><td>14:20</td><td>P. Feldmann</td><td>L. Morel</td><td>A. Aloy</td></tr>
<tr><td>14:40</td><td>M. Barrett</td><td>I. Fuentes</td><td>V. Flambaum</td></tr>
<tr><td>15:20</td><td>C. Champenois</td><td>P. Bouyer</td><td>B. Sauer</td></tr>
<tr><td>16:00</td><td>BREAK</td><td>BREAK</td><td>BREAK</td></tr>
<tr><td>16:30</td><td rowspan="2">W. Ubachs</td><td>K. Chabuda</td><td>E. Giese</td></tr>
<tr><td>16:50</td><td rowspan="2">S. Ulmer</td><td rowspan="2">M. Bonneau</td></tr>
<tr><td>17:10</td><td rowspan="2">E. Witkowska</td></tr>
<tr><td>17:30</td><td>J. Crespo López</td><td>S. Abend</td></tr>
<tr><td>17:50</td><td>P. Bushev</td><td></td><td>DEPARTURE</td></tr>
<tr><td>18:10</td><td rowspan="2">DINNER</td><td rowspan="2">DINNER</td><td rowspan="3"></td></tr>
<tr><td>19:00</td></tr>
<tr><td>20:00 –
22:00</td><td>Poster Session I</td><td>Poster Session II</td></tr>
</table>