Precision Atomic Physics Experiments to Probe for New Physics

817. WE-Heraeus-Seminar

23 – 27 September 2024

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 817. WE-Heraeus-Seminar:

Our current best description of nature at the quantum scale is based on the Standard Model of particle physics (SM), while Einstein's theory of relativity is based on a classical framework of space-time and describes cosmological scales. The fundamental incompatibility between the two descriptions is one of the big unsolved puzzles in physics. The existence of dark matter and dark energy and the apparent asymmetry between matter and antimatter are only two more of many more open questions that leave physicists puzzled.

This seminar brings together experts from different fields of physics to discuss precision experiments to probe for New Physics that might hint towards solving these puzzles. Topics include tests of Einstein's theory of relativity using precision measurements in laboratory and large scale experiments, e.g. using spectroscopy, atom and nanoscopic particle interferometers, lunar laser ranging and gravitational wave detectors. A particular focus lies on the search for 5th forces extending to cosmological observations, isotope shift spectroscopy of neutral atoms and ions interpreted via King plot analysis, torsion balances and free-falling macroscopic bodies.

Scientific Organizers:

Prof. Dr. Tanja Mehlstäubler	U Hannover and PTB Braunschweig, Germany E-mail: Tanja.Mehlstaeubler@ptb.de
Prof. Dr. Piet O. Schmidt	U Hannover and PTB Braunschweig, Germany E-mail: Piet.Schmidt@quantummetrology.de

Introduction

Administrative Organization:

Dr. Stefan Jorda
Elisabeth Nowotka

Wilhelm und Else Heraeus-Stiftung
Kurt-Blaum-Platz 1
63450 Hanau, Germany

Phone +49 6181 92325-12
Fax +49 6181 92325-15
E-mail nowotka@we-heraeus-stiftung.de
Internet: www.we-heraeus-stiftung.de

Venue:

Physikzentrum
Hauptstrasse 5
53604 Bad Honnef, Germany

Conference Phone +49 2224 9010-120

Phone +49 2224 9010-113 or -114 or -117
Fax +49 2224 9010-130
E-mail gomer@pbh.de
Internetwww.pbh.de

Taxi Phone +49 2224 2222

Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, 22 September 2024

17:00 – 20:00	Registration	
18:00	*BUFFET SUPPER, discussions and informal get-together*	

Monday, 23 September 2024

08:00	*BREAKFAST*	
09:30 – 09:45	Tanja Mehlstäubler Piet O. Schmidt	**Welcome and Introduction**
09:45 – 10:30	Julian Berengut	**Isotope shift theory for new physics searches**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Elina Fuchs	**New boson searches with isotope shifts**
11:45 – 12:30	Joonseok Hur	**Probing new physics with isotope-shift spectroscopy of trapped ions**
12:30 – 12:40	**Conference photo**	
12:40	*LUNCH*	

Program

Monday, 23 September 2024

14:00 – 14:45	Yoshiro Takahashi	**Quantum sensor for new physics with ultracold ytterbium atoms**
14:45 – 15:30	Gilad Perez	**New era in dark matter searches, the dawn of the (nuclear) clocks**
15:30 – 16:15	Sergei Eliseev	**PENTATRAP and the search for the fifth force**
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 19:00	**Discussion Round**	
19:00	*DINNER*	

Program

Tuesday, 24 September 2024

08:00	*BREAKFAST*	
09:00 – 09:45	Marianna Safronova	**Novel clocks, bosenovae, and mulimessenger**
09:45 – 10:30	Melina Filzinger	**Improved limits on the coupling of ultralight bosonic dark matter to photons from optical atomic clock comparisons**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Eric Cornell	**Precision measurements are having a moment: recent results in g-2 and electric dipoles of leptons**
11:45 – 12:30	Sven Sturm	**Precision tests of QED and CPT with penning traps**
12:30	*LUNCH*	
14:00 – 14:45	Stefan Ulmer	**Testing fundamental symmetries with antiproton spins**
14:45 – 15:30	Alessandro Spallicci	**Phenomenology, observations and experiments of extended theories of electro-magnetism**
15:30 – 16:15	**Poster Flashes**	
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 19:00	**Poster session I**	
19:00	*DINNER*	

Program

Wednesday, 25 September 2024

08:00	*BREAKFAST*	
09:00 – 09:45	Peter Wolf	**Experiments and proposals to search for ultralight dark matter**
09:45 – 10:30	Hans Hepach	**Measurement of gravitational coupling between micrometer-sized masses**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Christian Panda	**Matter-wave interferometry with atoms held in an optical lattice for one minute**
11:45 – 12:30	Agnes Fienga	**Tests of alternative theories of gravitation with planetary orbitography**
12:30	*LUNCH*	
14:00 – 19:00	**Excursion**	
19:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Thursday, 26 September 2024

08:00	*BREAKFAST*	
09:00 – 09:45	Maria Archidiacono	**Constraining neutrino physics with cosmology**
09:45 – 10:30	Diego Blas	**Detecting (high frequency) gravitational waves in the lab**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Alexey Elykov	**Search for new physics in electronic recoil data from XENONnT**
11:45 – 12:30	Meike List	**The MICROSCOPE mission: A space test of the weak equivalence principle**
12:30	*LUNCH*	
14:00 – 14:45	Jens Gundlach	**Gravitational experiments to test fundamental physics**
14:45 – 15:30	Riccardo March	**Lunar laser ranging constraints on nonminimally coupled gravity with a chameleon mechanism**
15:30 – 16:15	**Poster Flashes**	
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 19:00	**Poster session II**	
19:00	*DINNER*	

Program

Friday, 27 September 2024

08:00	*BREAKFAST*	
09:00 – 09:45	Michael Tobar	**Precision experiments to probe new physics using phonons, photons and spins**
09:45 – 10:30	Dima Budker	**CASPEr. WRESL, GNOME, SAPPHIRE, Chang-E, ... --- many ways to search for ultralight dark matter**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Dong Sheng	**Search for spin-dependent gravitational interactions at the Earth range**
11:45 – 12:30	Tanja Mehlstäubler Piet O. Schmidt	**Closing words and Poster Awards**
12:30	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Saturday; however, a self-service breakfast will be provided on Saturday morning

Posters

Posters

Hendrik Bekker	**Development of a dual-radiofrequency trap for matter and antimatter**
Ikbal Ahamed Biswas	**Tests of fundamental physics by precision spectroscopy with Yb+ ions**
Rohan Chakravarthy	**Hyperfine and Zeeman optical pumping and transverse laser cooling of a thermal atomic beam of dysprosium using a single 421nm laser**
Shuying Chen	**Quantum-logic based search techniques for highly forbidden transitions in highly charged ions**
Lei Cong	**Spin-dependent exotic interactions**
Florin Lucian Constantin	**Searching for new physics using acetylene precision spectroscopy**
José R. Crespo López-Urrutia	**Extending the spectral range of searches for fifth forces with highly charged ions**
Subhadeep De	**Progress of building a Ytterbium-ion optical atomic clock**
Daniel Gavilán Martín	**Searching for dark matter with a 1000 km baseline interferometer**
Thorsten Groh	**Probing physics beyond the standard model using ultracold mercury**
Leonie Hawkins	**A continuous high-flux atomic source for strontium clocks and atom interferometers**
Johannes Helgert	**Searching for physics beyond the standard model with precision isotope shift measurements in entangled Ba+ ions**
Max Luis Hellmich	**Search for variation of fundamental constants: Towards a highly charged ion clock**

Posters

Paul Holzenkamp	**The microwave cavity Penning trap for the LSYM project**
Chung Chuan Hsu	**Towards a large-scale Atomic Interferometer Observatory and Network (AION) using ultracold strontium atoms to search for Decihertz gravitational waves and ultralight dark matter**
Taiki Ishiyama	**Precise isotope shift measurement of a new clock transition in ytterbium atoms for new boson search**
Wei Ji	**Search for axions with spin-based levitated sensor**
Tarek Khatir	**Triple differential cross-section for electron-impact ionization of atoms and molecules**
Stepan Kokh	**Towards ground state cooling of a Beryllium - highly charged ion crystal at low secular frequency**
Jonas Kramer	**Phase noise cancellation for a fiber link connecting optical atomic clocks**
Sebastian Lahs	**Cs in cryogenic Ar matrix as a platform to measure P and T violations**
Christian Mancini	**Towards a test of the weak equivalence principle with squeezed strontium atoms**
Agnese Mariotti	**First observation of a nonlinear Ca King plot and ist implications on new physics and nuclear properties**
Maria Pasinetti	**The positron source at the LSym experiment**
Baptist Piest	**Implementation of Delta-Kick squeezing in an atom interferometer**

Posters

Shivani Ramachandran	**Influence of THz radiation on the Rydberg-induced background in Karlsruhe Tritium Neutrino Experiment (KATRIN)**
Jan Richter	**Controlling Resonant Photon Scattering on Relativistic Ion Beams using Strong External Electromagnetic Fields at the Gamma Factory**
Fritz Riehle	**Einstein's basement: A new sector for relativistic particles**
Sushree Subhadarshinee Sahoo	**Mirrorless lasing-enabled remote sensing of magnetic fields**
Gh. Saleh	**New experiment under ordinary conditions with common tools to verify the Planck's equation**
Vera Schäfer	**Towards precision spectroscopy of highly charged ions**
Nathaniel Sherrill	**Probing unified theories with quantum sensors**
Lukas Spieß	**Measuring the magnetic field properties of Ca^{14+}**
Luca Toscani De Col	**A solid-state approach to the Thorium nuclear clock: defect studies of Th: CaF2**
Malte Wehrheim	**Fundamental physics tests with an optical clock based on Ca14+**
Vitaly Wirthl	**Precision spectroscopy of the 2S-6P transition in atomic hydrogen and deuterium**
Vikrant Yadav	**Progress on the design and development of an all-optical transportable trapped-ion-based atomic clock**

Abstracts of Talks

(in alphabetical order)

Constraining Neutrino Physics with Cosmology

M. Archidiacono[1]

[1]Dipartimento di Fisica Aldo Pontremoli, Università degli Studi di Milano, Via Celoria 16, 20133 Milano, Italy

Investigating neutrino physics through observations of the Universe is crucial for addressing open questions in both cosmology and particle physics.
After reviewing current cosmological constraints on neutrino properties, I will show the potential of forthcoming large-scale structure data from the ESA Euclid mission to detect the neutrino mass sum and provide insights into the existence of light particles beyond the Standard Model.
I will also discuss how non-standard neutrino interactions, which may help to resolve the Hubble constant tension, can be constrained with future cosmological data.

Isotope shift theory for new physics searches

J. C. Berengut

School of Physics, University of New South Wales, Sydney NSW 2052, Australia

Different isotopes of the same atom produce slightly different spectra, mainly due to the changes in mass and charge distribution of the nucleus. The advent of ultra-high precision optical spectroscopy allows us to extract subtle effects that go beyond these leading causes of isotope shift. For example, we can use the differential isotope shift measurements to search for a hypothetical boson, with mass less than around 10^8 eV, that would couple neutrons to electrons via a Yukawa potential [1]. Strong limits have been placed on the coupling strength of such a boson using Hz-level optical spectroscopy of isotope chains in calcium [2,3] and ytterbium [4-8].

Higher-order nuclear effects can also be uncovered using isotope shift spectroscopy. For example, Yb nuclei are prolate spheroids rather than spherical, and this causes large changes in the higher-order charge distribution, $\delta\langle r^4\rangle$, between isotopes [10]. Isotope shift spectroscopy provides a unique insight into this fundamental parameter along the whole isotopic chain [8,9]. Distinguishing these competing sources of higher-order effects and placing limits on new physics can be done in a data-driven approach using the Generalised King Plot method [11].

References

[1] J. C. Berengut *et al.*, Phys. Rev. Lett. **120**, 091801 (2018).
[2] A. J. Krasznahorkay *et al.*, Phys. Rev. Lett. **116**, 042501 (2016)
[3] C. Solaro, S. Meyer, K. Fisher, J. C. Berengut, E. Fuchs, and M. Drewsen, Phys. Rev. Lett. **125**, 123003 (2020)
[4] T. T. Chang, B. B. Awazi, J. C. Berengut, E. Fuchs, and S. C. Doret, "*Systematic-free limit on new light scalar bosons via isotope shift spectroscopy in Ca^+"* (2023), arXiv:2311.17337 [physics.atom-ph]
[5] I. Counts *et al.*, Phys. Rev. Lett. **125**, 123002 (2020);
[6] N. L. Figueroa *et al.*, Phys. Rev. Lett. **128**, 073001 (2022)
[7] K. Ono *et al.*, Phys. Rev. X **12**, 021033 (2022).
[8] J. Hur *et al.*, Phys. Rev. Lett. **128**, 163201 (2022)
[9] M. Door, C.-H. Yeh *et al.*, "Search for new bosons with ytterbium isotope shifts" (2024), arXiv:2403.07792 [physics.atom-ph]
[10] S. O. Allehabi, V. A. Dzuba, V. V. Flambaum, and A. V. Afanasjev, Phys. Rev. A **103**, L030801 (2021).
[11] J. C. Berengut, C. Delaunay, A. Geddes, and Y. Soreq, Phys. Rev. Res. **2**, 043444 (2020)

Detecting (High frequency) Gravitational Waves in the Lab

D. Blas[1,2]

[1]Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain
[2]Institució Catalana de Recerca i Estudis Avanç (ICREA), Passeig Lluís Companys 23, 08010 Barcelona, Spain

Gravitational waves bring us information about some of the most mysterious phenomena of the Universe. Their frequency is connected to the properties of the emission process, and hence, by detecting them in a variety of frequencies, one can learn about different aspects of cosmology, dark matter or different astrophysical sources. In this talk, I'll review different set-ups proposed to detect gravitational waves in the MHz to GHz band by leveraging the advances on (quantum) metrology. I will also describe which information could we access through this detection. The prospects for this young field of research are very promising, though there are several challenges that need to be addressed, as I will describe.

References

[1] A. Berlin et al. *Phys.Rev.D* 108 (2023) 8, 084058. 2303.01518 [hep-ph]
[2] A. Berlin et al. *Phys.Rev.D 105 (2022) 11, 116011. 2112.11465* [hep-ph]
[3] N. Aggarwal et al. *Living Rev.Rel.* 24 (2021) 1, 4. 2011.12414 [gr-qc].

Precision measurements are having a moment: recent results in g-2 and electric dipoles of leptons

Eric Cornell[1]

[1]JILA, National Institute of Standards and Technology and Physics Dept., University of Colorado, Boulder, CO 80309 USA

Abstract: The past three years have seen three dipole-moment measurements of record-breaking accuracy – the magnetic dipole moments (aka “g-2”) of the muon and of the electron, and the electric dipole moment (EDM) of the electron. I will focus in on the latter measurement, performed at the University of Colorado. I will try to compare and contrast the relative implications of all these three measurements for the search for Beyond Standard Model physics. Finally, I will look into the future for eEDM work.

PENTATRAP and the search for the fifth force

M. Door[1], S. Eliseev[1], P. Filianin[1], J. Herkenhoff, K. Kromer[1], D. Lange[1], J. Nägele[1], Ch. Schweiger[1], and K. Blaum[1]

[1] Max-Planck-Institut für Kernphysik, Heidelberg, Germany[2] another Institute

High-precision Penning trap mass spectrometry is the most precise technique employed to measure masses of nuclides with half-lives as short as a few ten ms. Currently, there are about a dozen high-precision Penning-trap mass spectrometers located in North America and Europe. The majority of them are part of various Rare Ion Beam (RIB) facilities and aim at measurements of masses of short-lived nuclides with fractional uncertainties down to 10^{-9}. The other group encompasses four ultra-precise Penning trap mass spectrometers. Their major goal are mass-ratio measurements on long-lived and stable nuclides with fractional uncertainties of as small as a few ppt.

In this second group the PENTATRAP experiment is probably the most advanced. It is located at the Max-Planck Institute for nuclear physics and aims to perform mass-ratio measurements on a very broad range of long-lived nuclides to assist, e.g., experiments on the determination of the neutrino mass, on the search for the fifth force, on the investigation of atomic metastable states that can be suitable ion clock transitions and so on. In this talk I will (after a quite detailed introduction of Penning-trap mass spectrometry) present latest achievements and future plans with PENTATRAP which are related to the search for the fifth force.

Search for New Physics in Electronic Recoil Data from XENONnT

A. Elykov[1]

(on behalf of the XENON Collaboration)

[1]*Institute for Astroparticle Physics, Karlsruhe Institute of Technology, 76021 Karlsruhe, Germany*

The XENONnT detector is the latest iteration of the liquid xenon-based time projection chambers operated by the XENON Collaboration. It is located at the INFN Laoratori Nazionali del Gran Sasso in Italy, and hosts a target mass of 5.9 tonnes of liquid xenon. XENONnT managed to achieve an electronic-recoil (ER) background of (15.8±1.3) events/(tonne× year×keV), in the (1, 30) keV search region, which is the lowest ever achieved in a dark matter detector. This renders XENONnT sensitive to ER interactions from dark matter candidates besides Weakly Interacting Massive Particles, and to other physics beyond the Standard Model. Some commonly considered signal models include solar axions, an enhancement of the solar neutrino magnetic moment, pseudoscalar and vector bosonic dark matter, including axion-like particles and dark photons. In this talk, an overview of the XENONnT experiment will be presented, as well as the pathway for ER rare-event searches and latest key results.

Tests of alternative theories of gravitation with planetary orbitography

A. Fienga[1] **and O. Minazzoli**[2,3]

[1] Geoazur, Observatoire de la Côte d'Azur, France
[2] ARTEMIS, Observatoire de la Côte d'Azur, France
[3] Bureau des Affaires Spatiales, Monaco

In this presentation, we describe here how planetary ephemerides are built in the framework of General Relativity and how they can be used to test alternative theories. We focus on the definition of the reference frame (space and time) in which the planetary ephemeris is described, the equations of motion that govern the orbits of solar system bodies and electromagnetic waves.
After a review on the existing planetary and lunar ephemerides, we summarize the results obtained considering full modifications of the ephemeris framework with direct comparisons with the observations of planetary systems, with a specific attention for the PPN formalism. We then discuss other formalisms such as Einstein-dilaton theories, the massless graviton and MOND. We finally concludes on some comments and recommendations regarding misinterpreted measurements of the advance of perihelia.
Material discussed in the presentation are mainly extracted from [1]

References

[1] A. Fienga, O. Minazzoli, Living Reviews in Relativity, vol 27, 2024.

Improved Limits on the Coupling of Ultralight Bosonic Dark Matter to Photons from Optical Atomic Clock Comparisons

M. Filzinger[1], S. Dörscher[1], R. Lange[1], J. Klose[1], M. Steinel[1], E. Benkler[1], E. Peik[1], C. Lisdat[1], and N. Huntemann[1]

[1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Even though dark matter makes up the majority of the matter in our universe, its microscopic properties and non-gravitational interactions are still a mystery. One well-motivated dark matter model is that of ultralight bosons, which are expected to display coherent-wave behavior. The couplings of such ultralight bosonic dark matter (UBDM) to the standard model content would lead to oscillations of fundamental constants [1]. We improve constraints on the coupling of UBDM to photons based on long-term measurements of two optical frequency ratios [2]. In these optical clock comparisons, we relate the frequency of the $^2S_{1/2}$ (F = 0) ↔ $^2F_{7/2}$ (F = 3) electric octupole (E3) transition in $^{171}Yb^+$ to that of the $^2S_{1/2}$ (F = 0) ↔ $^2D_{3/2}$ (F = 2) electric quadrupole (E2) transition of the same ion, and to that of the $^1S_0$ ↔ $^3P_0$ transition in ^{87}Sr. By constraining oscillations of the fine-structure constant α with these measurement results, we significantly improve existing bounds on the scalar coupling of UBDM to photons for dark matter masses in the range of about $10^{-24} - 10^{-17}$ eV/c^2. Couplings to quarks and gluons can also be constrained with optical frequency ratio measurements by considering the effect an oscillating nuclear charge radius would have on electronic transitions [3].

References

[1] A. Arvanitaki et al., Phys. Rev. D 91, 015015 (2015).
[2] M. Filzinger et al., Phys. Rev. Lett. **126**, 253001 (2023).
[3] A. Banherjee et al., arXiv: 2301.10784 (2023).

New boson searches with isotope shifts

E. Fuchs[1,2], A. Wilzewski[2], L. Huber[3], M. Door[4], C. Yeh[2],
J. Richter[1,2], A. Mariotti[1], F. Kirk[1,2], A. Viatkina[2], A. Surzhykov[2],
L. Spieß[2], M. Wehrheim[2], S. Chen[2], S. King[2], P. Micke[2], P. Schmidt[1,2], H. Fürst[1,2],
T. Mehlstäubler[1,2], E. Benkler[2], M. Filzinger[2], M. Steinel[2], N. Huntemann[2],
J. Flannery[3], J. Home[3], R. Matt[3], D. Craik[3],
M. Rosner[4], N. Rehbehn[4], J. Crespo Lopez-Urrutia[4], P. Filianin[4], J. Herkenhoff[4],
K. Kromer[4], D. Lange[4], A. Rischka[4], C. Schweiger[4], S. Eliseev[4], K. Blaum[4],
I. Valuev[4], Z. Harman[4], N. Oreshkina[4], V. Yerokhin[4], C. Keitel[4],
J. Berengut[5], M. Heinz[6,7,4], T. Miyagi[6,7,4], A. Schwenk[6,7,4],
J. Bieron[8], L. Dreissen[9,3], G. Gaigalas[10], N. Shimizu[11], M. Robbiati[12]

[1]Leibniz University Hannover, Germany
[2] Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
[3]ETH Zurich, Switzerland
[4]Max-Planck-Institute of Nuclear Physics, Heidelberg, Germany
[5]University of New South Wales, Sydney, Australia,
[6]TU Darmstadt, Germany, [7]GSI Helmholtzzentrum für Schwerionenforschung
[8]Jagiellonian University, Krakow, Poland
[9]Vrije Universiteit Amsterdam, The Netherlands
[10]Vilnius University, Lithuania, [11]University of Tsukuba, Japan
[12]CERN, Geneva, Switzerland

Isotope shift spectroscopy has opened a window to probe light bosons with masses up to several MeV/c^2 that could act as mediators to a Dark Sector. As long as the isotope shifts of two transitions depend linearly on each other, the interpretation of the precise measurements is data-driven. However, the unprecedented experimental precision of isotope shift frequencies in atoms and singly and highly charged ions and of isotope masses has revealed large nonlinearities, not only in Ytterbium, but for the first time also in Calcium. I will show how theory input and generalized analyses enable a distinction between origins of the nonlinearity from higher-order Standard Model terms or New Physics, resulting in strong probes of the parameter space of the new bosons, as well as in new characterizations of the nuclear deformation of Yb and of the second-order mass shift and nuclear polarizability of Ca, yet with considerable uncertainties that motivate further studies.

References

[1] M. Door et al, Search for new bosons with ytterbium isotope shifts, arXiv.2403.07792 [physics.atom-ph] (2024).
[2] A. Wilzewski et al, First observation of a nonlinear Ca King plot and its implication on new bosons and nuclear properties [in preparation].
[3] E. Fuchs, F. Kirk, A. Mariotti, J. Richter, M. Robbiati, A global view on new physics searches with (non-)linear King plots [in preparation].

Measurement of Gravitational Coupling between Micrometer-Sized Masses

H. Hepach[1], M. Dragosits[2] and M. Aspelmeyer[1,2]

[1]IQOQI Vienna, Boltzmanngasse 3, 1090 Vienna, Austria
[2] University of Vienna, Boltzmanngasse 5, 1090 Vienna, Austria

The search for experimental evidence for quantum gravity is severely hindered by the relative weakness of the gravitational interaction as compared to the other known fundamental forces. Gravity also remains resistant to unification within the standard model of physics and appears to be fundamentally disconnected from quantum theory. It is therefore an important experimental undertaking to test gravity on all scales. Measurements of the gravitational interaction have usually been confined to mass ranges of kg and above. In a previous iteration of our experimental apparatus [1] we have demonstrated gravitational coupling between millimeter-sized gold spheres with sub-100mg mass using a rotational mechanical oscillator. In this talk we will report on our progress on extending the parameter space by reducing the source mass by more than three orders of magnitude. These improvements allow us to reach a source mass regime in the microgram range.

References

[1] T Westphal, H Hepach, J Pfaff, M Aspelmeyer, **Nature 591**, 225–228 (2021)

Probing new physics with isotope-shift spectroscopy of trapped ions

Joonseok Hur[1,*], Diana P. L. Aude Craik[1], Ian Counts[1], Eugene Knyazev[1], Luke Caldwell[2], Calvin Leung[1], Julian C. Berengut[3], Amy Geddes[3], Witold Nazarewicz[4], Paul-Gerhard Reinhard[5], Akio Kawasaki[6], Honggi Jeon[7], Wonho Jhe[7], and Vladan Vuletić[1]

[1] Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[2] JILA, NIST and University of Colorado, Boulder, Colorado 80309, USA
[3] School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia
[4] Facility for Rare Isotope Beams and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
[5] Institut für Theoretische Physik, Universität Erlangen, Erlangen D-91054, Germany
[6] National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan
[7] Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea
** Present address: refer to Affiliation 2*

Experiments with atomic systems have been providing tests for the Standard Model (SM) and probing physics beyond the SM, driven by unprecedented developments in precision in recent decades. In particular, it has been proposed to measure the isotope shifts in ionized atoms to probe new physics using King plots [1–3], two-dimensional graphs in which isotope shifts (ISs) are mapped to points. The Standard Model (SM) predicts at the leading order that the points should lie on a straight line for atoms with no nuclear spin, which may be violated by a Beyond-SM effect such as dark bosons with masses at MHz-level or lighter.

Since our initial study on IS spectroscopy of trapped singly-ionized Yb (Yb^+) atoms showed nonlinear King plots with 3 standard deviations σ in 2020 [4], several experiments have observed such nonlinearity with significances well beyond 5σ for clock transitions in Yb^+ and neutral Yb atoms [5–8].

The sources of the observed violation should be examined carefully to decouple the SM corrections arising from nuclear physics from possible new-physics contributions [2]. The pattern of the measured nonlinearity and its decomposition were suggested in our paper [4,5] as an effective method to investigate the sources of the nonlinearity. In particular, the pattern analysis and calculations on atomic and nuclear structures suggested that higher-order nuclear charge distribution dominates the observed nonlinearities [5,8]. The remaining small but significant nonlinearity has been unexplained and thus set for the bound on dark bosons.

This talk will introduce our earlier experiments and pattern analysis and present our latest work. A discussion on future research directions will follow.

[1] J. C. Berengut *et al.,* Phys. Rev. Lett. **120**, 091801 (2018)
[2] V. V. Flambaum, A. J. Geddes, and A. V. Viatkina, Phys. Rev. A **97**, 032510 (2018)
[3] C. Delaunay *et al.*, Phys. Rev. D **96**, 093001 (2017)
[4] I. Counts*, **J. Hur*** *et al.*, Phys. Rev. Lett. **125**, 123002 (2020) *equal contribution
[5] **J. Hur** *et al.*, Phys. Rev. Lett. **125**, 123002 (2020)
[6] K. Ono *et al.*, Phys. Rev. X **12**, 021033 (2022)
[7] N. L. Figueroa *et al.*, Phys. Rev. Lett. **128**, 073001 (2022)
[8] M. Door *et al.*, arXiv:2403.07792

The MICROSCOPE mission: A space test of the Weak Equivalence Principle

Meike List [1,2]
[1]Institute for Satellite Geodesy and Inertial Sensing (DLR), Bremen, Germany
[2] University of Bremen, Bremen, Germany

According to the Weak Equivalence Principle, all bodies should fall at the same rate in a gravitational field. The MICROSCOPE satellite, launched in April 2016, aimed to test the principle's validity at the 10^{-15} precision level, by measuring the electrostatic forces required to maintain two collocated test masses (of titanium and platinum alloys) exactly in the same orbit. A non-vanishing relative acceleration would correspond to a violation of the Weak Equivalence Principle. The scientific measurement was done by using ultra-sensitive differential electrostatic accelerometers (T-SAGE) on board of a drag-free controlled satellite, the mission lifetime was two and a half years.
In this talk I will summarize the mission planning, final design, and the obtained result for this so far best space test of the Weak Equivalence Principle. Additionally, I will give a short overview on possible constraints MICROSCOPE sets on fifth forces.

Lunar laser ranging constraints on nonminimally coupled gravity with a chameleon mechanism

R. March[1,2], O. Bertolami[3,4], M. Muccino[2] and S. Dell'Agnello[2]

[1]*Istituto per le Applicazioni del Calcolo, CNR, Via dei Taurini 19, 00185 Roma, Italy*
[2] *INFN-Laboratori Nazionali di Frascati (LNF), Via E. Fermi 40, 00044 Frascati, Italy*
[3]*Departamento de Física e Astronomia, Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal*
[4]*Centro de Física das Universidades do Minho e do Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal*

Nonminimally coupled (NMC) gravity is an extension of f(R) gravity theory which includes a nonminimal coupling between geometry and matter [1]. Such a coupling is introduced by adding in the action functional of gravity the product of the matter Lagrangian density by a function of the space-time Ricci curvature scalar. NMC gravity allows for the prediction of the rotation curves of galaxies, a solution for Hubble tension problem and the accelerated expansion of the Universe, suggesting this theory as a possible alternative to the standard scenario based on dark matter and dark energy.
In this communication we discuss the impact of NMC gravity on the dynamics of the Sun-Earth-Moon system. The structure of the gravitational field equations for the three-body system shows that the solution of such equations exhibits a screening mechanism which is a NMC version of the so-called chameleon mechanism which is typical of chameleon theories of gravity such as f(R) gravity. Because of screening, deviations from general relativity in the gravitational field outside of the three astronomical bodies are sourced by thin shells of mass close to the surfaces of the bodies: in the lunar crust, mainly in Earth's seawater, in the solar photosphere and in the top of the solar convection zone.
Such deviations give rise to a fifth force, which is typical of f(R) gravity theories, and to an extra non-Newtonian force which is typical of NMC gravity. Such forces depend on the mass density profiles in the thin shells of the bodies, so that they depend on composition and size of the bodies. Consequently, the Earth and Moon fall toward the Sun with different accelerations giving rise to a violation of the weak equivalence principle (WEP). Constraints on the thickness of the shells, that translate into constraints on the parameters of the NMC gravity model, are then obtained by means of a recent test of WEP based on lunar laser ranging data [2].

References

[1] O. Bertolami, C.G. Böhmer, T. Harko and F.S.N. Lobo, Phys. Rev. D **75**, 104016 (2007)
[2] R. March, O. Bertolami, M. Muccino and S. Dell'Agnello, Phys. Rev. D **109**, 124013 (2024)

Matter-wave interferometry with atoms held in an optical lattice for one minute

<u>Cristian D. Panda</u>, Matthew J. Tao, Miguel Ceja, James Egelhoff, Andrew Reynoso and Holger Müller
[1]*University of California, Berkeley, USA*

Exceptional levels of quantum control and coherence are instrumental in quantum metrology and sensing. Atom interferometers are powerful devices for probing fundamental physics and everyday sensing but have been limited to measurement times of a few seconds by using atoms in free fall.

We will describe how we realize interferometers with atoms suspended for an unprecedented 70 seconds in an optical lattice. For the first time, we (1) optimize the gravitational sensitivity of the lattice interferometer and (2) use a system of signal inversions and switches to suppress and quantify systematic effects. This enables measuring the attraction of a miniature tungsten source mass with record accuracy of 6.2 nm/s^2, less than a billionth of Earth's gravity and four times improved over the previous best measurements with freely falling atoms.

This performance demonstrates the advantages of lattice interferometry for fundamental physics measurements, particularly when probing localized potentials. We will then show how the lattice atom interferometer can overcome the limits of current atomic gravimeters for applications in the field, showing great promise for building next-generation lattice atom interferometers with applications in precision measurement and quantum inertial sensing.

References

[1] **Measuring gravitational attraction with a lattice atom interferometer,** Cristian D. Panda, Matthew J. Tao, Miguel Ceja, Justin Khoury, Guglielmo M. Tino, and Holger Müller, Nature **631**, 515–520 (2024).

[2] **Coherence limits in lattice atom interferometry at the one-minute scale,** Cristian D. Panda, Matthew Tao, James Egelhoff, Miguel Ceja, Victoria Xu, and Holger Müller, Nat. Phys. (2024).

[3] **Atomic gravimeter robust to environmental effects,** Cristian D. Panda, M Tao, M Ceja, A Reynoso, H Müller, Applied Physics Letters **123** (6) (2023).

Novel clocks, bosenovae, and mulimessenger astronomy

<u>M. S. Safronova</u>

Department of Physics and Astronomy,
University Delaware, Newark, DE, 19716, USA

The extraordinary advances in quantum control of matter and light have been transformative for atomic and molecular precision measurements enabling probes of the most basic laws of Nature to gain a fundamental understanding of the physical Universe. The development of high-precision optical atomic clocks enables searches for the variation of fundamental constants, dark matter, violations of Lorentz invariance, and tests of gravity. Deployment of high-precision clocks in space will open the door to new applications, including precision tests of gravity and relativity, searches for a dark-matter halo bound to the Sun, and gravitational wave detection in wavelength ranges inaccessible on Earth, and others. I will describe progress in development of new clock schemes and detection of transient exotic signals.

Search for spin-dependent gravitational interactions at the Earth range

Nian-Fu Zhai[1], Ao Shen[1], Zheng-Tian Lu[1], Dong Sheng[1]

[1]University of Science and Technology of China, Hefei, China
Email: dsheng@ustc.edu.cn

In this talk, we report an experimental search for an anomalous scalar coupling between the neutron spin and the Earth gravity on the ground. We develop an atomic gas comagnetometer to measure the ratio of nuclear spin-precession frequencies between ^{129}Xe and ^{131}Xe, and search for a change of this ratio to the precision of 10^{-9} as the sensor is flipped in the Earth gravitational field [1]. The null results of this search set an upper limit on the coupling energy between the neutron spin and the gravity on the ground at 5.3×10^{-22} eV (95% confidence level), resulting in a 17-fold improvement over the previous limit [2]. The results can also be used to constrain several other anomalous interactions. In particular, the limit on the coupling strength of axion-mediated monopole-dipole interactions at the range of the Earth radius is improved by a factor of 17. Currently we are updating our apparatus aiming for another order of magnitude of improvement in the measurement precision.

References

[1] S.-B. Zhang, Z.-L. Ba, D.-H. Ning, N.-F. Zhai, Z.-T. Lu, and D. Sheng, Phys. Rev. Lett. **130**, 201401 (2023)

[2] B. J. Venema, P. K. Majumder, S. K. Lamoreaux, B. R. Heckel, and E. N. Fortson, Phys. Rev. Lett. **68**, 135 (1992)

Testing Extended Theories of Electro-Magnetism (ETEM)

Alessandro D.A.M. Spallicci

Université d'Orléans and Centre National de la Recherche Scientifique
Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (LPC2E) UMR 7328
3A Avenue de la Recherche Scientifique, 45071 Orléans, France

We face the dichotomy of an ad-hoc dark Universe compatible with General Relativity (GR) but lacking experimental evidence and unsupported by the Standard Model (SM), while we record continuous successes of GR that undermine the efforts the reformulations of gravitation. We are aware that, despite neutrinos, cosmic rays and now gravitational waves, photons remain by large the main messengers of the cosmos. Thus, we analyse signals and see whether Extended Theories of Electro-Magnetism (ETEM) induce a (partial) reinterpretation of physics laws. The SM Extension (SME) induces a mass to a photon [1,2], the only free massless particle, compatible to the upper limits by Fast Radio Bursts [3-5] and solar wind [6,7]. Group velocity dispersion birefringence are the most widely searched ETEM effects. Further, all photons – massive as from the SME or from the de Broglie-Proca theory, or non-linear from the Born-Infeld, Heisenberg-Euler types - undergo a frequency shift in presence of an electromagnetic and/or Lorenz Symmetry Violation background [8,9]. This shift, added to expansion redshift, determines new cosmological scenarios, e.g., without recurring to dark energy [10-12] and possibly to dark matter. We discuss what (atom) interferometry could hopefully test beside the running experiments, e.g., BMV Toulouse, γ-γ CERN, DeLLlight Paris. The upper limit of this effect would be in the order of 3×10^{-18} in $\Delta\nu/\nu$ for an optical length equivalent to the Earth-Moon distance. The same apparatus could serve as a null test of the expansion at small scale.
Finally, we present the Heisenberg principle at cosmological scales. The minimal mass is drawn from the energy-time relation for the age of the universe. We read the Hubble constant as quantum measurement and reinterpret the tension accordingly [13,14].

References

[1] Bonetti L., dos Santos Filho L.R., Helayël-Neto J.A., Spallicci A.D.A.M., Phys. Lett. B, 764, 203 (2017)
[2] Bonetti L., dos Santos Filho L.R., Helayël-Neto J.A., Spallicci A.D.A.M.,Eur. Phys. J. C, 78, 811 (2018)
[3] Bonetti L., Ellis J., Mavromatos N.E., Sakharov A.S., Sarkisyan-Grinbaum E.K.G., Spallicci A.D.A.M., Phys. Lett. B, 757, 548 (2016)
[4] Bonetti L., Ellis J., Mavromatos N.E., Sakharov A.S., Sarkisyan-Grinbaum E.K.G., Spallicci A.D.A.M., Phys. Lett. B, 768, 326 (2017)
[5] Bentum M.J., Bonetti L., SPALLICCI A.D.A.M., Adv. Space Res., 59, 736 (2017)
[6] Retinò A., Spallicci A.D.A.M., Vaivads A., Astropart. Phys., 82, 49 (2016)
[7] Spallicci A.D.A.M., Sarracino G., Randriamboarison O., Helayël-Neto J.A., Dib A., Eur. Phys. J. Plus, 139, 551 (2024)
[8] Helayël-Neto J.A., Spallicci A.D.A.M., Eur. Phys. J. C, 79, 590 (2019)
[9] Spallicci A.D.A.M., Dib A., Helayël-Neto J.A., Phys. Lett. B, 885, 138873 (2024).
[10] Spallicci A.D.A.M., Helayël-Neto J.A., López-Corredoira M., Capozziello S., Eur. Phys. J. C, 81, 4 (2021)
[11] Spallicci A.D.A.M., Sarracino G., Capozziello S., Eur. Phys. J. Plus, 137, 253 (2022)
[12] Sarracino G., Spallicci A.D.A.M., Capozziello S.,Eur. Phys. J. Plus, 137, 1386 (2022)
[13] Capozziello S., Benetti M., Spallicci A.D.A.M., Found. Phys. 50, 893 (2020)
[14] Spallicci A.D.A.M., Benetti M., Capozziello S., Found. Phys. 52, 23 (2022)

Precision tests of QED and CPT with Penning traps

S. Sturm[1]

[1] *Max Planck Institute for Nuclear Physics, Heidelberg, Germany*

Experiments with single ions confined in a Penning trap enable access to a broad range of observables that are of fundamental importance for our understanding of fundamental physics. In the magnetic field of the trap, the cyclotron frequency of an ion can be determined with unique precision and gives direct access to the charge-to-mass ratio. This way, we have determined a number of fundamental parameters, such as the electron, proton, neutron and deuteron and helium [1,2] atomic masses with leading precision.

Furthermore, via the continuous Stern-Gerlach effect we can determine the internal (spin-)state of the stored particle non-destructively and so get access to the (Larmor) spin precession frequency. Consequently, we can measure the *g*-factors of almost arbitrary, also highly charged ions. Since the electric field found in such ions can reach extreme values up to 10^{16} V/cm, a comparison of the measured g with the prediction by theory yields stringent tests of quantum electrodynamics (QED) in strong fields. Recently, we have used our experiment ALPHATRAP to push these measurements up until hydrogenlike tin ^{118}Sn [3], where the field strength is two orders of magnitude higher than in any previous comparable measurements.

The possibility to determine the internal state of a single ion gives us access to systems that were previously difficult to handle, such as the molecular hydrogen ions. Currently, we are performing spectroscopy on HD^+. The development of the necessary toolbox will be a seminal step towards a possible future spectroscopy of the antimatter equivalent, $Hbar_2^-$, which could enable a unique test of charge-parity-time (CPT) reversal symmetry.

Our development of a novel technique to determine the Larmor frequency difference of two simultaneously crystallized particles has led to an orders of magnitude leap on the precision frontier. With our new project LSYM [4], we will simultaneously trap an electron and a positron in its motional ground state and coherently compare their Larmor frequencies at 14 digits precision. This way we will search for hypothetical tiny differences of their charge-to-mass ratio or *g*-factors, orders of magnitude better than previously possible, and so perform a stringent test of CPT in the lepton sector.

References

[1] S. Rau, Nature **585**, 43–47 (2020)
[2] S. Sasidharan, Phys. Rev. Lett. **131**, 093201 (2023)
[3] J. Morgner, Nature **622**, 53–57 (2023)
[4] www.lsym.de

Quantum sensor for new physics with ultracold ytterbium atoms

Yoshiro Takahashi[1]

[1] *Kyoto University, Kyoto, Japan*

We report our recent experiments for the precision measurement towards new physics beyond the Standard Model. Specifically, we perform precision isotope-shifts measurements for ultra-narrow optical clock transitions of four bosonic isotope pairs of ytterbium atoms loaded in a three-dimensional magic wavelength lattice. For the $^1S_0$ and $^3P_0$ clock transition, we achieve the part-per-billion precision [1]. In addition, we observe a new clock transition between the $^1S_0$ and $4f^{13}5d6s^2(J=2)$ states [2], and determine the isotope shifts with less than 10 Hz precision. These results, combined with other precision data using ytterbium atoms and ions, show the significantly large non-linearity of the King relation, and will allow us to obtain important information on the coupling strength of a new hypothetical particle mediating a force between electrons and neutrons with a generalized King plot approach [3].

We will also briefly report on qunatum sensor for a new gravity-like force using weekly-bound ytterbium molecules, and some future plans towards new physics beyond the Standard Model.

References

[1] K. Ono, et al., Phys. Rev. X 12, 021033 (2022).
[2] T. Ishiyama et al., Phys. Rev. Lett. 130, 153402 (2023).
[3] K. Mikami, et al., Eur. Phys. J. C 77, 896 (2017).

Precision Experiments to Probe New Physics using Phonons, Photons and Spins

M.E. Tobar[1]

1 Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, Crawley, WA 6009, Australia.

The Quantum Technologies and Dark Matter research laboratory has a rich history of developing precision tools [1], which have been adapted for testing fundamental physics at low energies. This includes the nature of Dark Matter and the search for new physics that may indicate unification of Quantum Mechanics with General Relativity. In particular, our work includes searches for Lorentz invariance violations in the photon, phonon and gravity sectors, possible variations in fundamental constants, searches for wave-like dark matter, test of quantum gravity and the determination of temporal geometric phases [2,3]. This includes experiments that take advantage of axion-photon coupling and axion-spin coupling to search for axion dark matter [4]. High acoustic Q phonon systems to search for Lorentz violations, high frequency gravity waves, tests of quantum gravity from the possible modification of the Heisenberg uncertainty principle [5,6], and clock experiments to search for wave-like dark matter, and perform a temporal Pound-Rebka experiment as a gravitational Aharonov-Bohm effect [3].

References

[1] EN Ivanov, ME Tobar, Frequency Stable Microwave Sapphire Oscillators, IEEE Microwave and Wireless Technology Letters, in *IEEE Microwave and Wireless Technology Letters*, vol. 33, no. 12, pp. 1642-1645, Dec. 2023.

[2] RY Chiao, H Hart, NA Inan, M Scheibner, J Sharping, DA Singleton, ME Tobar, "Energy level shift of quantum systems via the electric Aharonov-Bohm effect," Phys. Rev. A, vol. 107, 042209, 2023.

[3] RY Chiao, NA Inan, M Scheibner, J Sharping, DA Singleton, ME Tobar, "Gravitational Aharonov-Bohm effect," Phys. Rev D, vol. 109, 064073, 2024.

[4] A Quiskamp, BT McAllister, P Altin, EN Ivanov, M Goryachev, ME Tobar, Exclusion of ALP Cogenesis Dark Matter in a Mass Window Above 100 μeV, Phys. Rev. Lett. vol. 132, 03160, 2024.

[5] WM Campbell, ME Tobar, S Galliou, M Goryachev, "Improved Constraints on the Minimum Length with a Macroscopic Low Loss Phonon Cavity," Phys. Rev D, vol. 108, 102006, 2023.

[6] W Campbell, M Goryachev, ME Tobar, "The Multi-mode Acoustic Gravitational Wave Experiment: MAGE", Sci Rep 13, 10638, 2023.

Testing Fundamental Symmetries with Antiproton Spins

S. Ulmer[1,2], C. Smorra[2,3], B. M. Latacz[1,2,6], F. Abbass[2,3], B. P. Arndt[1,4,5], K. Blaum[4], J. A. Devlin[6], S. R. Erlewein[1,4,6], P. Geissler[1,6], J. I. Jaeger[1,4,6], M. Leonhardt[2,], D. Popper[2,3], G. Umbrazunas[1,8,], F. Völksen[2,], C. Will[4], E. J. Wursten[1], Y. Matsuda[7], C. Ospelkaus[9], W. Quint[5], A. Soter[8], J. Walz[3], Y. Yamazaki[1]

[1]RIKEN, Ulmer Fundamental Symmetries Laboratory, Saitama, Japan; [2]Institut für Experimentalphysik, HHU Düsseldorf, Germany, [3]Johannes Gutenberg-Universität, Mainz, Germany; [4]Max-Planck-Institut für Kernphysik, Heidelberg, Germany; [5]GSI - Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, [6]CERN, Geneva, Switzerland, [7]The University of Tokyo, Tokyo, Japan; Germany; [8]ETH, Zuerich, Switzerland; [9]PTB, Braunschweig, Germany;

The striking imbalance of matter and antimatter in our universe inspires experiments that compare the fundamental properties of matter/antimatter conjugates with high precision. The BASE collaboration at the antiproton decelerator of CERN is performing such high-precision comparisons with protons and antiprotons. Using advanced cryogenic Penning traps, we have performed the most precise comparison of the proton-to-antiproton charge-to-mass ratio with a fractional uncertainty of 16 parts in a trillion [1], and have invented a novel spectroscopy technique, that allowed for the first direct high-precision measurement of the antiproton magnetic moment with a fractional accuracy of 1.5 parts in a billion [2]. Together with our last measurement of the proton magnetic moment [3] this improves the precision of previous magnetic moment-based tests of the fundamental CPT invariance by more than a factor of 3000. A time series analysis of the sampled magnetic moment resonance furthermore enabled us to set first direct constraints on the interaction of antiprotons with axion-like particles (ALPs) [4], and most recently, we have used our ultra-sensitive single particle detection systems to derive constraints on the conversion of ALPs into photons [5]. In parallel we are working on the implementation of new measurement technology to sympathetically cool antiprotons [6] and to apply, on the long term, quantum logic inspired spectroscopy techniques [7]. In addition to that, we are currently developing the transportable antiproton-trap BASE-STEP, to relocate antiproton spectroscopy experiments from accelerator environment to dedicated precision laboratory space at Heinrich Heine University Düsseldorf. I will give a general introduction to the topic, and will review the recent results produced by BASE, with particular focus on recent developments towards an at least 10-fold improved coherent measurement of the antiproton magnetic moment.

References

[1] M. J. Borchert et al., Nature 601, 35 (2022).
[2] C. Smorra et al., Nature 550, 371 (2017).
[3] G. Schneider et al., Science 358, 1081 (2017).
[4] C. Smorra et al., Nature 575, 310 (2019).
[5] J. A. Devlin et al., Phys. Rev. Lett. 126, 041321 (2021).
[6] M. A. Bohman et al. Nature 596, 514 (2021)
[7] J. M Conrejo et al., *New J. Phys.* **23** 073045

Experiments and proposals to search for ultralight dark matter

J. Gué, A. Hees and P. Wolf

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

We briefly describe a few past experiments at SYRTE that use precision atomic and optical measurements to search for dark matter [1,2], before moving to more recent proposals elaborated mostly during the PhD thesis of Jordan Gué [3,4,5]. We consider three types of ultralight (<< eV) dark matter: dilatons, axions and dark photons, with different types of coupling to standard matter. We model the resulting effects on different experiments, ranging from tests of the universality of free fall, through atomic clocks and atom interferometers, to gravitational wave detectors like LISA. We provide constraints on the coupling parameters from the experiments, and sensitivity estimates for the proposals, putting them into the context of existing bounds on such couplings.

References

[1] Hees, A.; Guéna, J.; Abgrall, M.; Bize, S. & Wolf, P., *Searching for an Oscillating Massive Scalar Field as a Dark Matter Candidate Using Atomic Hyperfine Frequency Comparisons*", Phys. Rev. Lett., 2016, **117**, 061301.
[2] Savalle, E.; Hees, A.; Frank, F.; Cantin, E.; Pottie, P.-E.; Roberts, B. M.; Cros, L.; McAllister, B. T. & Wolf, P, *Searching for Dark Matter with an Optical Cavity and an Unequal-Delay Interferometer*, Phys. Rev. Lett., 2021, **126**, 051301.
[3] Gué, J.; Hees, A.; Lodewyck, J.; Le Targat, R. & Wolf, P, *Search for vector dark matter in microwave cavities with Rydberg atoms*, Phys. Rev. D, 2023, **108**, 035042.
[4] Jordan Gué, Aurélien Hees, Peter Wolf, Etienne Savalle, Laurent Chevalier, Pierre Brun, *Improved modelling for dark photon detection with dish antennas*, arXiv:2403.13448, (2024).
[5] Gué, J.; Hees, A. & Wolf, P., *Violation of the equivalence principle induced by oscillating rest mass and transition frequency, and its detection in atom interferometers*, arXiv:2401.14742, (2024).

Abstracts of Posters

(in alphabetical order)

Development of a dual-radiofrequency trap for matter and antimatter

H. Bekker[1,2], V. Mikhailovskii[1,2], N. R. Sheth[1,2], G. Qu[1,2], Y. Zhang[1,2], C. Smorra[2,3], M. Hori[1,2,4], F. Schmidt-Kaler[2], H. Häffner[5], D. Budker[1,2,5]

[1]Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, 55128 Mainz, Germany
[2] Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany
[3] Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany
[4] Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom
[5] Department of Physics, University of California, Berkeley, California 94720, USA

We will report on the commissioning of our room-temperature radiofrequency (RF) trap operating at 1.6 GHz capable of trapping several electrons for 100s of milliseconds [1]. In the future, we plan to switch over to trapping positrons from a source which is currently being designed. This will allow us to investigate the fascinating interactions between normal and antimatter. For these purposes we are currently investigating the co-trapping of species with extremely different charge-to-mass ratios. By applying a second RF frequency in the MHz regime we aim to co-trap calcium ions and electrons. The successful development of these novel techniques will allow us to investigate the predicted but never observed bound states of positrons and neutral atoms. Together with the development of transportable antiproton traps, we envision these techniques to make antihydrogen production and antimatter research in general more accessible to precision tabletop experiments [2].

References

[1] Matthiesen, Clemens, Qian Yu, Jinen Guo, Alberto M. Alonso, and Hartmut Häffner. "Trapping Electrons in a Room-Temperature Microwave Paul Trap." *Physical Review X* **11**, no. 1 (January 29, 2021): 011019.

[2] Leefer, Nathan, Kai Krimmel, William Bertsche, Dmitry Budker, Joel Fajans, Ron Folman, Hartmut Häffner, and Ferdinand Schmidt-Kaler. "Investigation of Two-Frequency Paul Traps for Antihydrogen Production." *Hyperfine Interactions* **238**, no. 1 (December 28, 2016): 12.

Tests of Fundamental Physics by Precision Spectroscopy with Yb^+ Ions

I. A. Biswas[1], F. Kirk[1,2], J. Yu[1], C. Yeh[1], A. Singh[3], L. S. Dreissen[1], K. C. Grensemann[1], H. A. Fürst[1], E. Fuchs[1,2], T. E. Mehlstäubler[1]

[1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
[2] Institut für Theoretische Physik, Leibniz Universität Hannover, Hannover, Germany
[3] Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany

Precision spectroscopy with trapped ions has emerged as an exceptionally sensitive probe for exploring physics beyond the Standard Model. We present two works based on Yb^+ spectroscopy performed at PTB: a test of local Lorentz invariance using a single $^{172}Yb^+$ ion, as well as isotope-shift measurements of $^{168,170,172,174,176}Yb^+$. These measurements allow us to set bounds on a potential fifth force between neutrons and electrons and to gain new insights into the nuclear charge distribution. We also outline our plan to perform multi-ion spectroscopy on $^{173}Yb^+$ ions.

Quantum gravity effects may lead to the spontaneous violation of Lorentz symmetry and in particular to atomic energy shifts. Using high-precision spectroscopy of atomic states with non-spherical electron orbitals, we have set world-leading bounds on the components of the two-tensor coefficient $c_{\mu\nu}$ of the Standard Model Extension [1].

Applying the King plot method [2,3], we use our isotope-shift measurements to set bounds on a fifth force between electrons and neutrons. Moreover, we present a new method to extract higher-order changes in the nuclear charge distribution along the Yb isotope chain from data.

References

[1] D. Colladay and V. Alan Kostelecký Phys. Rev. D **58**, 116002 (1998)
[2] W. H. King, J. Opt. Soc. Am. **53**, 638 (1963)
[3] J. C. Berengut et al., Phys. Rev. Lett. **120**, 091801 (2018)

Hyperfine and Zeeman optical pumping and transverse laser cooling of a thermal atomic beam of dysprosium using a single 421nm laser

R. Chakravarthy[1, 2] , J. S. Rebeirro[1, 2], D. Antypas[3], J. B. Kim[4] and D. Budker[1,2,5]

[1]*Johannes Gutenberg University, Mainz, Germany*
[2] *Helmholtz Institute Mainz, Mainz, Germany*
[3]*University of Crete, Iraklio, Greece*
[4] *Korea National University of Education, Chungcheongbuk-do, South Korea*
[5] *University of California, Berkeley, USA*

We demonstrate the effect of optical pumping on the 421.291 nm transition $4f^{10}6s^2$(J = 8) →$4f^{10}6s6p$((J = 9) of ^{163}Dy. The experiment was performed with an atomic beam and detection based on fluorescence and frequency-modulation transmission spectroscopies. An electro-optic modulator was used to generate five sidebands required to pump the hyperfine levels of the J = 8 state. The atoms were simultaneously laser cooled using a 421.291 nm transition with a doppler limit of 19.8 cm/s. The optically pumped and laser cooled atoms will be used in fundamental-physics experiments such as a search for parity violation in this system. A previous measurement of parity violation in dysprosium led to a measurement of zero due to limited statistical sensitivity and optically pumping and laser cooling the atoms is expected to provide significant improvements to the sensitivity to measurement of parity violation in dysprosium.

References

[1] A.T. Nguyen, D. Budker, D. DeMille and M. Zolotorev, Phys. Rev. A 56(5), 3453-63 (1997)
[2] N.A. Leefer, A. Cingoz and D. Budker, Optics Letters 34(17), 2458-2550 (2009)
[3] N.A. Leefer, A. Cingoz, B. Gerber-Siff, A. Sharma, J.R. Torgerson and D. Budker, Phys. Rev. A 81(4), 043427 (2010)

Quantum-logic based search techniques for highly forbidden transitions in highly charged ions

S. Y. Chen[1], L. J. Spieß[1], A. Wilzewski[1], M. Wehrheim[1], K. Dietze[1], I. Vybornyi[2], K. Hammerer[2], J. R. Crespo López-Urrutia[3] and P. O. Schmidt[1,4]

[1]*QUEST Institute for Experimental Quantum Metrology, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*
[2]*Institute of Theoretical Physics, Leibniz Universität Hannover, Hannover, Germany*
[3]*Max-Planck-Institut für Kernphysik, Heidelberg, Germany*
[4]*Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany*

Optical clocks are the most precise measurement devices, with applications in frequency metrology and fundamental physics. Highly charged ions (HCI) are promising candidates for use as a reference in optical clocks, as demonstrated in Ar^{13+} [1]. To establish a next-generation HCI optical clock at the state-of-the-art precision, an HCI possessing a sub-Hz natural linewidth transition is required. Numerous candidate systems have been explored theoretically, but experimental challenges remain due to the considerable uncertainty of the transition frequencies, which typically fall within the THz range. In this work, we conduct an experimental and theoretical investigation of search techniques based on a two-ion crystal system confined within a linear Paul trap, with the goal of identifying an ultra-narrow clock transition (8 mHz) in our forthcoming HCI clock element, Ni^{12+} [2]. These techniques include Rabi excitation, the optical dipole force (ODF) [3], and linear continuous sweeping (LCS). LCS has been proved to facilitate a search process that is three orders of magnitude faster than other techniques. So far, the ODF method has recently been proven effective in identifying the Ni^{12+} logic transition. More recently, the search for the Ni^{12+} clock transition with LCS method has also been successful. This demonstrates the first direct observation of an optical transition with sub-Hertz linewidth in any HCI. The aforementioned methods may also be useful in the search for weak lines in other molecules or neutral atom systems.

References

[1] S. A. King, L. J. Spieß, *et al*., Nature **611**, 43-47 (2022).
[2] S. Chen, *et al*., arXiv:2406.04015 [physics.atom-ph].
[3] F. Wolf, *et al*., Nature **530**, 457–460 (2016).

Spin-dependent Exotic Interactions

Lei Cong[+],[*], Wei Ji[#],[*], Pavel Fadeev, Filip Ficek, Min Jiang, Victor V. Flambaum, Haosen Guan, Derek F. Jackson Kimball, Mikhail G. Kozlov, Yevgeny V. Stadnik, Dmitry Budker

Helmholtz Institute Mainz, 55099 Mainz, Germany
and so on

*[+]conglei1@uni-mainz.de, [#]wei.ji.physics@gmail.com; *Equal contribution*

The fifth force may arise due to "new physics" beyond the Standard Model. We focus on the spin-dependent fifth forces that are mediated by new particles, such as spin-0 particles (axion and axion-like particles) and spin-1 particles (e.g., light Z' particle or massless paraphoton). These new ultralight particles are also candidates for dark matter and dark energy, and may also break fundamental symmetries. Spin-dependent interactions between fermions have been extensively searched for in experiments, employing methods such as comagnetometers, nitrogen-vacancy spin sensors, and precision measurements of atomic and molecular spectra [1, 2, 3]. Our research involves a theoretical reassessment of exotic spin-dependent forces [4]. It produces a systematic and complete set of interaction potentials expressed in terms of reduced coupling constants. We conduct an extensive analysis of the existing body of experimental literature on spin-dependent fifth forces, which produces systematic exclusion plots. This leads to a comprehensive understanding of the current research landscape and provide insights for further research.

References

[1] Wei Ji, Weipeng Li, Pavel Fadeev, Filip Ficek, Jianan Qin, Kai Wei, Yong-Chun Liu, & Dmitry Budker (2023). Physical Review Letters, 130(13), 133202.

[2] Xing Rong, Mengqi Wang, Jianpei Geng, Xi Qin, Maosen Guo, Man Jiao, Yijin Xie, Pengfei Wang, Pu Huang, Fazhan Shi, Yi-Fu Cai, Chongwen Zou, and Jiangfeng Du (2018). Nature Communications, 9(1), 739.

[3] Filip Ficek, Pavel Fadeev, Victor V. Flambaum, Derek F. Jackson Kimball, Mikhail G. Kozlov, Yevgeny V. Stadnik, and Dmitry Budker (2018). Physical Review Letters, 120(18), 183002.

[4] Pavel Fadeev, Yevgeny V. Stadnik, Filip Ficek, Mikhail G. Kozlov, Victor V. Flambaum, and Dmitry Budker (2019). Physical Review A, 99(2), 022113.

Searching for New Physics using acetylene precision spectroscopy

F.L. Constantin[1]

[1]*Laboratoire PhLAM, CNRS UMR 8623, Villeneuve d'Ascq, France*

The nature of dark matter (mass, spin, couplings) is not known. Scalar dark matter (DM) candidates at sub-eV energy ranges are modelled as a classical field oscillating at the relevant Compton frequency. Couplings of DM fields to the Standard Model (SM) fields induce oscillations of the fundamental constants that translate into oscillations of the resonances of the atoms, molecules and ultra-stable optical cavities. Such effects are addressed here using acetylene laser spectroscopy.
Acetylene rovibrational energy levels in its ground electronic state may be predicted accurately using global Hamiltonians. Ab-initio quantum molecular theory calculations provide energy levels in extended ranges and transition dipole moments. Sensitivity to variations of the fundamental constants of the frequencies of the acetylene transitions was modelled [1] and enhanced sensitivity to proton-electron mass ratio variation was demonstrated in the microwave range [2]. In addition, many acetylene line parameters are present in Hitran, Geisa, Exomol databases. The transitions in the 1.54 µm domain probed by sub-Doppler spectroscopy were recommended for secondary frequency references and length standards. Located in the C band of the fiber optic telecommunications wavelengths, they may be addressed with ultrastable laser signals involved in phase-stabilized optical fiber links. The REFIMEVE network enables remote access to a signal with fractional accuracy at 10^{-14} level, fractional stability of 10^{-15} and relative fractional stability of 10^{-19} at 1s timescale. Oscillations of the fundamental constants may be probed by monitoring the fractional variation between the frequency of the optical network laser and an acetylene transition. This approach enables probing couplings of DM fields to electrons and photons in an extended energy range from 4.6×10^{-15} eV to 4.6×10^{-6} eV. Constraints in this range from measurements of sub-Doppler and linear absorption acetylene lines are subsequently estimated [3].

References

[1] F.L. Constantin, Vibrational Spectroscopy **85**, 228 (2016)
[2] F.L. Constantin, Proc. CLEO Europe & EQEC 2023, paper ED-1.4
[3] F.L. Constantin, Proc. EFTF-IFCS 2023, 10272076

Extending the spectral range of searches for fifth forces with highly charged ions

José R. Crespo López-Urrutia
Max-Planck-Institut für Kernphysik, Heidelberg

Atomic probes of fundamental interactions based on precision spectroscopy have been essential for the development of quantum mechanics, nuclear physics, quantum electrodynamics, and searches for new physics. Preparation of highly charged ions (HCI) with a defined number of bound electrons greatly extends the periodic table in the charge dimension, and makes available a large class of species for spectroscopic studies from the optical to the X-ray region for fundamental physics studies [1]. Searches for fifth forces using a combination of frequency metrology and King-plot methods will benefit from these properties, since HCI offer many forbidden transitions of enhanced sensitivity also in the extreme ultraviolet range, now within reach for frequency combs. While our spectroscopic studies of Ca and Xe HCI [2,3] already explored these possibilities, we are preparing investigations on HCI of Cf and Th, and working on applying our extreme-ultraviolet frequency comb to various HCI.

[1] M. G. Kozlov, et al., Rev. Mod. Phys. **90**, 045005 (2018)
[2] N. Rehbehn, et al., Phys. Rev. A **103**, L040801 (2021)
[3] N. Rehbehn, et al., Phys. Rev. Lett. **131**, 161803 (2023)
[4] J. Nauta, et al., Opt. Express **29**, 2624 (2021)

Progress of Building a Ytterbium-ion Optical Atomic Clock

S. De[*], S. Ghosh, V. Jangam, A. Mondal, S. Banerjee, S. Johnson, and S. Majhi.

Inter-University Centre for Astronomy and Astrophysics (IUCAA),
Post Bag 4, Ganeshkhind, Pune 411007, Maharashtra, India.

We are focused on indigenizing quantum phenomena-based technologies for accurate sensing and performing precision measurements to explore the fundamental aspects of science. For that, we are developing an ultrahigh accurate and highly stabilized optical reference at 1550 nm derived from a ytterbium-ion-based optical clock. We are currently building the trap set up to probe its highly forbidden electric octupole (E3) transition at the 467 nm wavelength. This transition is chosen due to its high sensitivity to the possible fine-structure constant variation and Lorentz symmetry violation. To excite that clock transition, an ultra-stable sub-Hz line-width laser will be produced by referencing to an indigenously developed ultra-stable Fabry-Pérot cavity designed for 1550 nm wavelength, which we have already fabricated [1], and installing at present. Upon building the optical clock, the change of its tick rates gets altered by unimaginably tiny perturbations of the energy states associated with the clock transitions. The resulting shift in tick rates of the clock allows for the probe of any variations of the fine-structure constant, breaking of Lorentz symmetry, time dilation, geodetic measurement, and so on. For such scientific explorations, the lab-based clocks must be part of a geographically distributed "optical clock network," which is expected to shape up in India in the coming years as few groups have started developing optical clocks in the recent past [2]. Therefore, the ultra-stable, nearly monochromatic 1550 nm photons generated using the reference clocks must be disseminated from one lab to another within the pan India clock network using "phase stabilized optical fibers". We have already developed the optical and electronic hardware required for that technology and tested its performance using a 3.3 km geographically distributed network also in fiber spools of up to 77 km lengths [3]. For complete indigenization, we are developing our own 1550 nm laser system, a transportable Fabry-Pérot cavity, and the laser will be frequency stabilized with respect to the cavity using an in-house developed LockBox [4]. In the meeting, I shall describe the present status of our ongoing work towards building the ytterbium-ion optical clock.

References

[1] S. Banerjee, et al., Int. J. of Mech. Sciences **250**, 108299 (2023).
[2] S. De, A. Sharma, Atoms **11**, 71 (2023).
[3] S. Johnson, et al., Indian Patent App No – 202321045035 (2024).
[4] S. Johnson, et al., communicated (2024).

Searching for dark matter with a 1000 km baseline interferometer

<u>Daniel Gavilan-Martin</u>[1, 2,] , Grzegorz Łukasiewicz[3, 4] , Mikhail Padniuk[3] , Emmanuel Klinger[5] , Magdalena Smolis[3], Nataniel L. Figueroa[1,2], Derek F. Jackson Kimball[6], Alexander O. Sushkov[7,8,9,10] Szymon Pustelny[3], Dmitry Budker[1,2,11], and Arne Wickenbrock[1,2]

[1]Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany
[2]Helmholtz-Institut Mainz, GSI Helmholtzzentrum für Schwerionenforschung, 55128 Mainz, Germany
[3]Marian Smoluchowski Institute of Physics, Jagiellonian University in Kraków, Łojasiewicza 11, 30-348, Kraków, Poland
[4]Doctoral School of Exact and Natural Sciences, Jagiellonian University in Kraków, Łojasiewicza 11, 30-348, Kraków, Poland
[5]Institut FEMTO-ST – UMR 6174 CNRS, SupMicroTech-ENSMM, Université de Franche-Comté, 25030 Besançon, France
[6]Department of Physics, California State University – East Bay, Hayward, CA 94542, USA
[7]Department of Physics, Boston University, Boston, MA 02215, USA
[8]Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215, USA
[9]Photonics Center, Boston University, Boston, MA 02215, USA
[10]Department of Physics & Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA
[11]Department of Physics, University of California, Berkeley, CA 94720, USA

Axion-like particles (ALPs) arise from well-motivated extensions to the Standard Model and could account for dark matter. ALP dark matter would manifest as a nearly monochromatic field oscillating at an (as of yet) unknown frequency. The frequency depends on the ALP mass, which could plausibly range from 10^{-22} eV/c^2 to 10 eV/c^2. We report on a direct search for ALP dark matter through the ALP-nucleon interaction by interfering the signals of two atomic K-Rb-^{3}He comagnetometers, with one situated in Mainz, Germany, and the other in Kraków, Poland. We use the ALP dark matter's spatiotemporal coherence properties assuming the standard halo model of dark matter in the Milky Way to improve the sensitivity and exclude spurious candidates. The search extends over nine orders of magnitude in ALP mass. In this range, no significant evidence of an ALP signal is found. We thus place new upper limits on the ALP-neutron and ALP-proton couplings of $g_{aNN} < 10^{-5}$ GeV^{-1} and $g_{aPP} < 5 \times 10^{-4}$ GeV^{-1} at a mass of 10^{-22} eV/c^2 and extending to a mass of 4 x 10^{-14} eV/c^2 where the upper limits reach below $g_{aNN} < 10−9$ GeV^{-1} and $g_{aPP} < 10^{-7}$ GeV^{-1}, respectively. For both neutron and proton couplings, this work is an improvement of up to fourorders of magnitude compared to previous laboratory constraints.

References

[1] D. Gavilan-Martin, arXiv: 2408.02668
[2] M. Padniuk, Phys. Rev. Research 6, 013339 (2023)

Probing physics beyond the standard model using ultracold mercury

T. Groh and S. Heider and S. Stellmer

Physikalisches Institut, Universität Bonn, Germany

Dark matter searches for physics beyond the standard model (SM) range from cosmological observations to high-energy collision experiments and low-energy table-top experiments. The baryon asymmetry of the universe explained by recent baryogenesis theories requires a degree of CP-violation that might result in a measurable atomic electric dipole moment (EDM). High precision spectroscopy of atomic isotope shifts could probe for a new force carrier that directly couples neutrons and electrons [1, 2].

Mercury being one of the heaviest laser-coolable elements makes it an ideal platform for beyond SM physics like baryon asymmetry searches [3]. Excellent for isotope shift spectroscopy it possesses five naturally occurring bosonic isotopes, all of which we laser cool in our lab.

We present latest results on high-resolution deep UV isotope shift spectroscopy of all naturally occurring mercury isotopes on multiple transitions observing strong deviations from linearity. We analyze the nonlinearity origins using multidimensional King plot analysis. Furthermore, we report on recent improvements and upgrades on the machine for transferring magneto-optically trapped mercury atoms to a high power optical dipole trap giving an outlook to beyond the state-of-the-art measurements of the atomic EDM of mercury.

References

[1] Delaunay, PRD **96**, 093001 (2017)
[2] Berengut, PRL 120, 091801 (2018)
[3] Graner PRL 116, 161601 (2016)

A continuous high-flux atomic source for strontium clocks and atom interferometers

L. Iannizzotto Venezze[1], C. Baynham[1], R. Hobson[1], T. Walker[1], L. Hawkins[1], A. Josset[1], E. Pasatembou[1], O. Buchmüller[1]

[1]Imperial College London, United Kingdom
Email: l.hawkins@imperial.ac.uk

Atomic clocks suffer from the Dick effect, which is the noise arising from spurious drifts in the local oscillator frequency during the dead time in the clock sequence. Operating continuously, rather than in the pulsed manner of traditional clocks, would eliminate this effect [1]. We present the design of a continuous ultracold strontium source, which aims to generate a high atomic flux for clocks and atom interferometers. The source will be characterised via operation as a dead-time-free atomic clock, as part of the Ultra-precise, Shock-resistant Optical Clock (USOC) project.

The high-flux atomic source comprises two separate regions: one for Zeeman slowing atoms from a Sr oven and trapping in a 2D magneto-optical trap (MOT), and a second for trapping in a 3D MOT, with transport between the two via a moving optical molasses. The magnetic field required across the Zeeman slowing region will be provided by a combination of permanent magnets in Halbach configuration, with shim coils for fine-tuning the field. The second chamber will utilise mid-infrared 2923 nm light to realise a metastable MOT, addressing a cycling transition between the 5s5p $^3P_2$ and 5s4d $^3D_3$ states, which avoids ac Stark shifts of the clock transition [2]. It also relaxes laser frequency stabilisation requirements due to the broader transition linewidth compared to the 689 nm intercombination line, typically used for cooling Sr.

To realise a dead-time-free atomic clock, the Sr atoms are loaded into a continuous moving optical lattice, operating at the magic wavelength of 813 nm. In a third region of the chamber, continuous clock interrogation and normalised readout will be implemented, and presented in this poster.

References

[1]: R. Takeuchi et al., Continuous outcoupling of ultracold strontium atoms combining three different traps, Applied physics express, 2023-04, Vol.16 (4), p.42003.

[2]: R. Hobson et al., Midinfrared magneto-optical trap of metastable strontium for an optical lattice clock, Physical review. A, 2020-01, Vol.101 (1), Article 013420.

Searching for physics beyond the standard model with precision isotope shift measurements in entangled Ba^+ ions

J. Helgert[1] and L.S. Dreissen[1]

[1]LaserLaB, Department of Physics and Astronomy, Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, Netherlands

In the search of physics beyond the standard model, precision spectroscopy on atomic systems is a powerful tool complementing high-energy and astrophysical methods. Precision isotope shift measurements in combination with a King plot analysis have been instrumental as a probe for a hypothetical boson-mediated fifth force between hadrons and leptons. Particular accurate mass and spectroscopy measurements in ytterbium revealed puzzling anomalies. The extracted bounds on such a new coupling between electrons and neutrons are limited by larger uncertainties in nuclear deformation effects [1]. Singly ionized barium (Ba^+) suffers less from nuclear deformation and features two narrow quadrupole transitions with linewidths at the 10 mHz level. To reach lifetime limited interrogation times, a pair of entangled ions in a decoherence-free subspace can be used, where correlated noise does not lead to decoherence and uncertainties due to common-mode systematic effects are strongly reduced. By preparing the entangled state as a mixed ion crystal of two different isotopes, the phase evolution of the state is directly proportional to the isotope shift, which can be read out directly via a parity measurement [2]. By applying these techniques, we expect to reach a frequency resolution at the 10 mHz level, enabling a search for a fifth force between neutrons and electrons at couplings 100 times weaker than in any previously reported King plot analysis. Here we present the recent progress for the realization of such a trapped Ba^+ quantum sensor.

References

[1] M. Door et al., arXiv [physics.atom-ph]: 2403.07792 (2024)
[2] T. Manovitz et al., Phys. Rev. Lett. **123**, 203001 (2019)

Search for variation of fundamental constants: Towards a highly charged ion clock

L. Hellmich [1], **J. Kramer**[1], **U. Schwanke**[2] **and S. Worm**[1]

[1]DESY Zeuthen, Zeuthen, Germany
[2] Humboldt-Universität zu Berlin, Berlin, Germany

The measurement of the temporal variation of fundamental constants would be strong evidence for new physics. In particular, many different theories predict the variation the fine-structure constant α. Atomic clocks are a highly precise tool of measuring variations of α, as the clock transition may change with α.
We are aiming to build a highly charged ion (HCI) clock and compare it to a Sr-lattice clock as a reference. HCI clocks are expected to have extremely high sensitivities to α-variations, while exhibiting very low systematic uncertainties. In [1], they found that one exciting candidate ion for a highly charged ion clock is Cf^{15+} or Cf^{17+}. We show how our setup could set new limits on variations of fundamental constants. Furthermore, we estimate with Monte-Carlo simulations how those limits translate to constraints on ultra light scalar dark matter models. We find our analysis in good agreement with existing studies [2], hinting at an improvement on the constraint of the scalar-photon coupling d_γ by one order of magnitude.

References

[1] S. G. Porsev et al., Phys. Rev. A 102, 012802 (2020)

[2] G. Barontini et al., EPJ Quantum Technol. 9, 1 (2022)

The microwave cavity Penning trap for the LSYM project

P. Holzenkamp, B.B. Bauer, L. Holtmann, M. Pasinetti, F. Raab, A. Thoma, S. Sasidharan, S. Sturm

Max-Planck Institute for Nuclear Physics, 69117 Heidelberg, Germany

LSYM is a cryogenic Penning trap experiment, aiming to drastically improve the precision of CPT tests for the electron and positron. Measuring the difference in their charge-to-mass ratio as well as their g-factors allows to look for asymmetries or determine stringent limits for them.
The trap is cooled to about 300mK to minimize transition rates out of the ground states of the cyclotron and axial motion respectively. To reach the ground state in the axial motion, cavity assisted side-band cooling will be employed. To ensure that the cyclotron motion is not accidentally excited by leaking 300K black-body photons or the phase noise of the microwave drive, a tunable filter is inserted into the microwave guide to strongly suppress photons close to the cyclotron frequency of the positrons. Furthermore, the main Penning trap ("CavityTrap") needs to support efficient spin control drives at the Larmor frequency and axial sideband cooling drives, while efficiently rejecting photons at the cyclotron frequency. Numerical simulations are used to design the CavityTrap geometry in order to simultaneously fulfill the requirements for the microwave cavity structure but also optimize the electrostatic potential of the Penning trap.
I will show the current status of the LSYM CavityTrap design.

Towards a large-scale Atomic Interferometer Observatory and Network (AION) using ultracold strontium atoms to search for Decihertz gravitational waves and ultralight dark matter

C.C. Hsu, M. Karzazi, Y Tang, J. Chen, J. Scheper, B. Panchumarthi, C. Lu, S. Zhang, K.E. Tkalčec, U. Schneider, T.L. Harte

Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

The Atom Interferometry Observatory and Network (AION) [1], a consortium of UK institutes, is developing a large-scale atom interferometer to search for fundamental physics effects, such as Decihertz gravitational waves, scalar- and vector-ultralight dark matter, fifth-force searches, and macroscopic tests of quantum mechanics.

Open questions about dark matter and gravitational waves hold the key to unlocking the intricacies of the universe. For example, dark matter explains why galaxies retain their structural integrity despite high rotational velocities, while gravitational waves offer fresh insights into early universe conditions close to the Big Bang. However, specific subclasses such as Decihertz gravitational waves and ultra-light dark matter remain elusive for current detectors.

We propose using atom interferometers to complement current detectors. Atom interferometers are sensitive to the Decihertz range, revealing crucial information to bridge this frequency gap for gravitational waves and to filter dark matter models. In an atom interferometer, atom clouds are split and recombined, generating interference fringes based on the relative phases of both arms. This phase is sensitive to passing gravitational waves and dark matter, inducing time-varying signals in the readout.

Large-scale atom interferometers demand large numbers of ultracold atoms at sub-nanokelvin temperatures for optimal signal-to-noise ratios and minimal momentum spreads. Rapid repetition rate and efficient atom transport to the interferometer are also vital to facilitate fast readouts and achieve our sensitivity goals.
The AION team at the University of Cambridge is developing technology for efficient cooling and atomic transport for large-scale atom interferometry. We are building a tabletop demonstrator, which will integrate into a long baseline interferometer for enhanced sensitivities. Here, we report on current progress towards preparing ultracold Strontium for the interferometer.

References

[1] Badurina, L., et al. *Journal of Cosmology and Astroparticle Physics, 2020(05)*

Precise isotope shift measurement of a new clock transition in ytterbium atoms for new boson search

T. Ishiyama[1], H. Kawase[1], K. Ono[1], T. Takano[1, 2], A. Sunaga[3], Y. Yamamoto[4], M. Tanaka[5], and Y. Takahashi[1]

[1]Graduate School of Science, Kyoto University, Kyoto, 606-8502, Japan
[2]JST-PRSTO, Tokyo, 102-0076, Japan
[3]Inst. of Chem. Eötvös Loránd University, 1117 Budapest, Hungary
[4]Accelerator Laboratory, High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
[5]Department of Physics, Graduate School of Science, Osaka University, Osaka 560-0043, Japan

The inner-shell orbital clock transition $^1S_0 \rightarrow 4f^{13}5d6s^2$ (J = 2) in neutral ytterbium (Yb) atoms has not only a very narrow natural linewidth but also high sensitivity to several new physics phenomena, for example, ultralight dark matter and the violation of local Lorentz invariance [1,2]. One of the new physics phenomena that can be explored with this transition is a new Yukawa-type interaction between electrons and neutrons. This new physics can be explored by measuring the isotope shifts (ISs) of more than two optical transitions and more than three isotope pairs in the same element and testing the King linearity [3,4].
In our previous paper [5], we reported the world's first observation of this transition for all isotopes with resolved Zeeman and hyperfine structures. In addition, we measured crucial parameters for precision measurements, such as magic wavelengths and the trap lifetime of the excited state.
In this poster presentation, we report the precision spectroscopy and isotope shift measurement of this transition [6]. By trapping atoms in a 3D magic-wavelength optical lattice and stabilizing the excitation laser with an optical frequency comb, the linewidth of atomic spectra is narrowed well below 100 Hz. Furthermore, we carry out an interleaved clock operation between 2 isotopes and determine ISs with total uncertainties of less than 10 Hz. Finally, we discuss the King linearity test and the constraint of the coupling constant for the new boson.

References

[1] V. A. Dzuba *et al.*, PRA **98**, 022501 (2018).
[2] M. S. Safronova *et al.*, PRL **120**, 173001 (2018).
[3] C. Delaunay *et al.*, PRD **96**, 093001 (2017).
[4] K. Mikami et al., Eur. Phys. J. C 77, 896 (2017).
[5] T. Ishiyama *et al.*, PRL **130**, 153402 (2023).
[6] T. Ishiyama *et al.*, in preparation.

Search for axions with spin-based levitated sensor.

Felix Ahrens[12], Wei Ji[3], Dmitry Budker[34], Chris Timberlake[5], Hendrik Ulbricht[5], and Andrea Vinante[12]

[1]CNR - Istituto di Fotonica e Nanotecnologie, 38123 Povo, Trento, Italy
[2]Fondazione Bruno Kessler (FBK), 38123 Povo, Trento, Italy
[3]Hemlholtz Institute Mainz & Johannes Gutenberg University, Mainz, Germany
[4]University of California Berkeley, Berkeley, US
[5]School of Physics and Astronomy, University of Southampton, UK

Axions and axion-like particles (collectively referred to here as axions) are promising candidates for ultralight dark matter. The gradient field of axions can couple to fermion spins, acting as a pseudomagnetic field that can be detected using spin-based sensors. We propose novel experiments utilizing magnetically levitated magnets with a high electron spin density to search for axions. These experiments will target axion interactions through their gradient coupling to electron spins [1].

References

[1] Ahrens, Felix, et al. *arXiv:2401.03774* (2024).

Triple differential cross-section for electron-impact ionization of atoms and molecules

T. Khatir[1], A. Tamin[2] and S. Houamer[2]

[1] CRNA, 02, Boulevard Frantz Fanon, B.P. 399. Alger RP, Algeria
[2] LPQSD, Department of Physics,Faculty of Sciences,University Sétif1 19000, Algeria
[3]LPCT, UMR CNRS 7019, University of Lorraine,BP 95823, METZ Cedex3,France
t.khatir@crna.dz

Triple differential cross sections (TDCSs) are presented for the electron impact ionization of atoms and molecules, using two models called 2CWZ and 3CWZ [1,2]. In these models, we utilize a Coulomb wave with variable charges Z(r) instead of an effective charge to describe the two outgoing electrons in the case of 2CW model, and all three electrons in the case of 3CWZ model. Additionally, the post-collision interaction (PCI) is incorporated and precisely treated at all orders of perturbation theory. The spherical static potential which enables to resolve the Schrödinger equation in the true distorted wave description, is used instead to calculate the variable charge Z(r). The results are systematically compared with recent experimental data and other theoretical predictions.

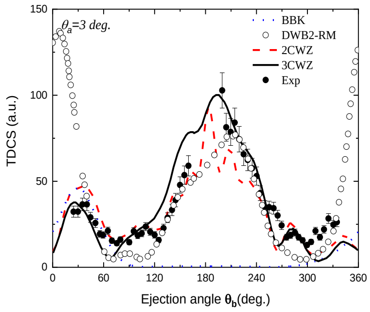


Fig.1. TDCS, in 10^{-4} au, for the electron impact ionization of argon 3p E_{sc}=500 ev,E_{ej}=205eV.

In figure 1, the DWB2-RM model [3] effectively describes various aspects of the TDCS. However, in all instances, it displays a binary peak that is notably larger than that of the recoil region, which contradicts the observed data [3]. Additionally, the 3CWZ model demonstrates a relatively accurate reproduction of the TDCS across most sections of the angular distribution. It is worth noting that BBK has previously been shown to inadequately capture the recoil region. In interpreting these findings, it's important to note that DWB2-RM is a robust model with the inherent capability to provide a generally accurate description of this reaction. However, it falls short in accounting for (PCI), which is crucial in this context. Unfortunately, this omission explains the observed shortcomings in Figure 1.

References

[1] T. Khatir, S. Houamer and C. Dal Cappello, J. Phys. B **52**, 245201 (2019)

[2] K. Bechane, S. Houamer, T. Khatir, A. Tamin and C. Dal Cappello, Phys Rev A **109,** 012812 (2024)

[3] F. Catoire, E. M. Staicu-Casagrande, M. Nekkab, D. Claude and K. Bartschat, J. Phys. B **39**, 2827 (2006)

Towards Ground State Cooling of a Beryllium - Highly Charged Ion Crystal at Low Secular Frequency

S. Kokh[1], V. M. Schäfer[1], E. A. Dijck[1], C. Warnecke[1], J. R. Crespo López-Urrutia[1], and T. Pfeifer[1]

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

Spectroscopy of ions and atoms for generalized King plot analysis is a rapidly developing field with the potential to detect traces of new physics, such as unknown particles or forces [1, 2]. Using highly charged ions (HCIs) gives access to previously unavailable transitions [3]. To reach the required sensitivity, high precision is required, and suppression of external perturbations is essential [4]. Our superconducting Paul trap shields external magnetic fields by 57 dB, a level comparable to dedicated magnetically shielded rooms [5]. However, the current setup limits our secular frequency due to thermal effects in the Paul trap resonator at high RF power. Therefore, we operate only in an intermediate Lamb-Dicke regime. We report on the progress towards ground-state cooling of sympathetically cooled HCIs in the given experimental setup.

References

[1] J. C. Berengut, et al., Phys. Rev. Res. **2**, 043444 (2020)
[2] M. S. Safronova, et. al., Rev. Mod. Phys. **90**, 025008 (2018)
[3] N.-H. Rehbehn, et al., Phys. Rev. Lett. **131**, 161803 (2023)
[4] P. Micke, et al., Nature **578,** 60-65 (2020)
[5] E. A. Dijck, et.al., Rev. Sci. Instrum. **94**, 083203 (2023)

Phase Noise Cancellation for a Fiber Link Connecting Optical Atomic Clocks

J. Kramer[1], L. Hellmich[1], U. Schwanke[2] and S. Worm[1]

[1]DESY Zeuthen, Zeuthen, Germany
[2]Humboldt-Universität zu Berlin, Berlin, Germany

Modern optical atomic clocks have been demonstrated to have fractional uncertainties on the order of 10^{-19} [1, 2], thereby enabling probing of a range of fundamental physics questions. In the search for dark matter, several theories predict time-dependent and clock-specific shifts in frequency, which could be detected by comparing different clocks [3], usually in different locations. This necessitates the long-distance transmission of ultra-stable frequency references with laser signals in fiber optic networks that typically operate at a wavelength of 1550 nm. During transmission, the signal undergoes a notable degradation due to a range of factors, including dispersion, alterations in the refractive index or cable length resulting from temperature fluctuations, vibrations, and other sources. These phenomena introduce phase noise and, consequently, frequency instability.

We are building an active frequency signal stabilization setup that involves reflecting a portion of the laser signal back at the remote end and recombining it with the original signal in a Michelson-interferometer-like setup [4, 5]. An acousto-optic modulator (AOM) induced frequency (and thus phase) shift is imposed on the remote laser signal, resulting in a heterodyne RF beat note within the interferometer. In a servo loop, also known as a "phase-locked loop," the phase information of the beat signal is utilized to drive the AOM in a manner that pre-corrects the acquired transmission phase noise and ensures a fixed phase relation between the local and remote clock signal.

References

[1] E. Oelker et al., ***Nature Photonics*** **13, no. 10,** 714–19, (2019).
[2] Alexander Aeppli et al., ***Physical Review Letters*** **133, no. 2** (2024).
[3] G. Barontini et al., ***EPJ Quantum Technology*** **9, no. 1** (2022).
[4] Long-Sheng Ma et al., ***Optics Letters*** **19, no. 21**, 1777–79 (1994).
[5] Seth M. Foreman et al., ***The Review of Scientific Instruments*** **78, no. 2** (2007).

Cs in cryogenic Ar matrix as a platform to measure P and T violations

S. Lahs, H. Dinesan, R. Ait-Ekioui, and D. Comparat

Université Paris-Saclay, CNRS, Laboratoire Aimé Cotton, Orsay, France

Searches for violations of the fundamental symmetries of parity P and time reversal T in atomic and molecular systems provide a powerful tool to test the physics of and beyond the standard model.

In our project, we are looking for new ways to perform such measurements. We work with cryogenic argon crystals that we dope with cesium atoms. This allows for the spectroscopy of large ensembles of atoms while still retaining some of the properties of a gas-phase system. We further demonstrate that the fields inside the crystal environment could allow for unique ways of detecting parity and/or time reversal violations.

References

[1] T. Battard, S. Lahs, C. Crépin & D. Comparat, *Phys. Rev. A*, *108*(4), 042820. (2023)
[2] S. Lahs, D. Comparat, *arXiv:2407.14694* (2024).

Towards a Test of the Weak Equivalence Principle with Squeezed Strontium Atoms

C. Mancini[1,2], L. Cacciapuoti[3], G. Ciappi[4], T. Mariani[4], E. Meli[4], G. Rosi[5], L. Salvi[5], G. M. Tino[5], P. Vezio[5], G. Vinelli[5]

[1] Scuola Superiore Meridionale, Largo San Marcellino 10, 80138 Napoli (NA), Italy
[2] INFN Sezione di Napoli, Complesso Universitario di Monte S. Angelo, Via Cinthia Edificio 6, I-80126 Napoli, Italy
[3] European Space Agency, Keplerlaan 1, 2201 AZ Noordwijk, Netherlands
[4] Dipartimento di Ingegneria Industriale (DIEF), Università di Firenze, Via di S. Marta 3, 50100 Firenze (FI), Italy
[5] Dipartimento di Fisica e Astronomia and LENS, Università di Firenze, INFN Sezione di Firenze, via Sansone 1, I-50019 Sesto Fiorentino (FI), Italy

Atom interferometers have been used and proposed for testing with high precision gravitational physics and searching for new physics, such as measuring Newton's constant G, investigating fifth forces, mid-frequency gravitational waves, and ultralight dark matter. Notably, using ultracold Sr atoms for their unique atomic properties has led to quantum sensors with extreme precision. The lowest uncertainty achievable in atom interferometers with N uncorrelated atoms is due to the standard quantum limit (SQL). Introducing entanglement among atoms can surpass the SQL, and the squeezing technique is very promising [1]. Recent squeezing experiments with Yb and Sr atoms have shown significant progress in optical clocks, but overcoming the SQL in interferometers with free-falling atoms remains a challenge.

In this poster I will illustrate our proposal [2] and our experimental efforts towards the generation of squeezed states. Our approach is based on exploiting the enhanced atom-light interaction obtained in a high-finesse optical resonator. I will illustrate the experimental apparatus that has been realised towards this goal and show some preliminary measurement results. We are optimizing the design of the resonator for increased robustness against vibrations, acoustic noise and temperature changes. The new cavity is made with a new high-performance ceramic, called Shapal Hi-M Soft. It is a hybrid composite material consisting of aluminium nitride and boron nitride. It has high thermal conductivity, high mechanical strength, excellent electrical insulation, ultra-high purity. The cavity is decoupled from the vacuum chamber thanks to springs and pins of Kalrez, in order to avoid vibrations. The goal is to design and realize a high precision test of the Weak Equivalence Principle in a gradiometer configuration beyond the SQL.

References

[1] M. Kitagawa, M. Ueda, Phys. Rev. A **47**, 5138 (1993)
[2] L. Salvi, N. Poli, V. Vuletić and G. M. Tino, Phys. Rev. Lett. **120**, 033601 (2018)

First observation of a nonlinear Ca King plot and its implications on new physics and nuclear properties

Agnese Mariotti[1], Jan Richter[1,2], Elina Fuchs[1,2], Alexander Wilzewski[2,6], Lukas J. Spieß[2,6], Malte Wehrheim[2,6], Shuying Chen[2,6], Steven A. King[2,6], Peter Micke[2,6], and Piet O. Schmidt[2,6], Anna Viatkina[2,7], Andrey Surzhykov[2,7], Erik Benkler[2], Melina Filzinger[2], Martin R. Steinel[2], Nils Huntemann[2], Diana Aude Craik[3], Jeremy Flannery[3], Jonathan Home[3], Luca Huber[3], Roland Matt[3], Julian C. Berengut[4], Michael K. Rosner[5], Nils-Holger Rehbehn[5], José R. Crespo López-Urrutia[5], Menno Door[5], Klaus Blaum[5], Vladimir A. Yerokhin[5], Igor A. Valuev[5], Natalia S. Oreshkina[5]

[1]Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany
[2]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[3]Institute for Quantum Electronics, Department of Physics, Eidgenössische Technische Hochschule Zürich, Otto-Stern-Weg 1, 8093 Zurich, Switzerland
[4]School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia
[5]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[6]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany
[7]Technische Universität Braunschweig, Universitätsplatz 2, 38106 Braunschweig, Germany

With 95% of the Universe's content still unexplained by modern physics, the motivations for new physics searches are becoming increasingly evident. In recent years, isotope shift measurement were established as a tool for low-energy tests of the Standard Model. In this work, we analyze new, highly precise isotope shift data in singly charged Ca^{+} and highly charged Ca^{14+}, and find a strong deviation from the first-order expectation of a linear behavior, known as the King relation [1]. In this analysis, we identify and estimate the leading higher-order Standard Model contributions, such as the second-order mass shift [2] and nuclear polarization, and set bounds on a new physics coupling between electrons and neutrons, resulting in the most stringent limits set by isotope shift measurements to date.

References

[1] King, W. H. "Comments on the article “Peculiarities of the isotope shift in the samarium spectrum”." *JOSA* 53.5 (1963): 638-639.

[2] Viatkina, Anna V., Vladimir A. Yerokhin, and Andrey Surzhykov. "Calculation of isotope shifts and King-plot nonlinearities in Ca^{+}." *Physical Review A* 108.2 (2023): 022802.

The positron source at the LSym experiment

M. Pasinetti[1], F. Raab[1], Paul Holzenkamp[1], B. -B. Bauer[1], A. Thoma[1], L. Holtmann[1], S. Sasidharan[1], S. Sturm[1]

1 Max-Planck-Institut für Kernphysik

The LSYM experiment is a new cryogenic Penning trap experiment currently being designed at the Max-Planck-Institut für Kernphysik of Heidelberg. The goal of LSYM is to conduct a stringent CPT test by comparing the properties of matter and antimatter with unprecedented precision by trapping simultaneously one electron and one positron in a Penning trap, thus performing a decoherence-free measurement. This project will present a few challenges, for instance the optimization of positron production and accumulation, given a rather weak radioactive ^{22}Na source (about 15 MBq). A positron trapping technique involving production of positronium atoms in a high Rydberg state is being tested [1]; furthermore, an efficient detection method is being set up. As positrons follow a β+ decay energy spectrum, they must undergo a moderation stage before entering the trap: the positron is then cooled to the ground-state of motion in the center of the trap. This poster illustrates the principles and techniques that will be used for the positron source at LSYM.

References

[1] S Fogwell Hoogerheide et al. “High efficiency positron accumulation for high-precision magnetic moment experiments”. In: *Review of Scientific Instruments* 86.5 (2015).

Implementation of Delta-Kick squeezing in an atom interferometer

B. Piest[1], R. Corgier[1], N. Mhammedi[1] and F. Pereira Dos Santos[1]

[1] *SYRTE, Observatoire de Paris, 61, Avenue de l'Observatoire, 75014 Paris, France*

Atom interferometers are versatile devices to detect accelerations or rotations with high sensitivity and accuracy and have important applications in geodesy, navigation and fundamental physics. The phase readout of light-pulse atom interferometers with classical input states is naturally limited by the quantum projection noise leading to the standard quantum limit. In this case, the sensitivity to accelerations is given by $1/(kT^2Sqrt(N))$ with the scale factor kT^2 and the atom number N. Increasing the sensitivity of atom interferometers is one of the main challenges in the field. Conducting experiments in long baseline facilities or microgravity can considerably increase the sensitivity. However, the practicability of this approach is ultimately limited by dimensional constraints of the apparatus. A different approach to further improve the performance of atom interferometers is given by circumventing the standard quantum limit using entangled states. This has successfully been demonstrated in recent experiments by the groups of J. Thomson [1] and C. Klempt [2], demonstrating a sensitivity of 1.7 dB below shot noise. These experiments made use of strong cavity-atom coupling in a high-finesse cavity and spin-collisions in a dipole trap, respectively.
In our experiment we strive to implement and analyze the recently proposed technique of Delta-Kick squeezing [3] and demonstrate an entanglement-enhanced gravimeter operating below shot noise. The entanglement is generated by the non-linear interatomic interactions of a focused Bose-Einstein condensate (BEC) of Rb-87 atoms which leads to momentum squeezing. The experiment is operated at SYRTE and has previously been used to investigate Casimir-Polder forces between Rb-87 atoms and a polished surface [4]. Since then, it is being prepared for the implementation of Delta-Kick squeezing. In this contribution, I will discuss the experimental setup, the planned implementation of the entanglement-enhanced interferometer and show our recent progress.

References

[1] G. Greve et al. Nature **610**, 472-477 (2022)
[2] C. Cassens et al. Arxiv: 2404.18668 (2024)
[3] R. Corgier et al. Phys. Rev. Lett. **127**, 183401 (2021)
[4] Y. Balland et al. Arxiv: 2310.14717 (2023)

Influence of THz radiation on the Rydberg-induced background in Karlsruhe Tritium Neutrino Experiment (KATRIN)

S. Ramachandran[1] , **E.Ellinger**[1] , **K. Helbing** [1]

[1]*Bergische Universität Wuppertal, Wuppertal, Germany*

The Karlsruhe TRitium Neutrino Experiment aims to determine the mass of the electron neutrino, to a precision of 0.2 eV at 90% C.L. This would be achieved by a high-precision measurement of the tritium β-decay spectrum close to its endpoint [1]. High source purity and low background levels are of utmost importance in precision experiments to reach their aimed sensitivity. The dominant contribution to the background in KATRIN, are electrons produced by thermal ionization of Rydberg atoms. These atoms originate from the walls of the main spectrometer vessel from radioactive decays due to ^{210}Pb contamination [1].

The emerging field of THz spectroscopy has several applications, one if it being to de-excite Rydberg atoms towards ground state. The idea is to drive $n \rightarrow n-1$ transitions of initially populated long lived states to short-lived levels from where spontaneous decay towards the ground state is fast [2]. THz de-excitation requires the simultaneous generation of multiple light frequencies in the mW power range [2,3]. Simulations using the distribution of most probable states, ionisation and stimulated de-excitation rates, were performed to determine the type, optimum intensity and linewidth of the source for our application. A custom made narrow band electronic source which is a Voltage-Controlled Oscillator (VCO), with an Amplifier/Multiplier Chain (AMC) coupled to a frequency synthesizer was selected for this purpose. For testing the influence of THz radiation on Rydberg states created in a KATRIN-like scenario, a test stand at the University of Wuppertal was developed. First measurements and tests with THz sources were also carried out in the main spectrometer of the KATRIN beamline. The development of the test setup, a summary of the different measurements and the results drawn is discussed. The sources of systematics encountered from the test stand measurements are illustrated which is also one of the causes of low signal to background ratio. A higher rate trend was observed for frequencies corresponding to the desired hydrogen transitions. Some of the bound states of Rydberg hydrogen might be excited which makes it prone to ionisations. The use case of THz radiation is to also confirm the Rydberg nature of the background.

References

[1] *F.M. Fränkle et al.*, KATRIN background due to surface radioimpurities. Astroparticle Physics,Volume 138, (2022)

[2] *M. Vieille-Grosjean et al.,* Induced THz transitions in Rydberg caesium atoms for application in antihydrogen experiments*, Eur. Phys. J. D (2021) 75:27*

[3] *Enrico Ellinger.* (2020). Probing background reduction in KATRIN by induced de excitation of Rydberg atoms with terahertz radiation. Neutrino 2020. https://doi.org/10.5281/zenodo.4123758

Controlling Resonant Photon Scattering on Relativistic Ion Beams using Strong External Electromagnetic Fields at the Gamma Factory

J. Richter[1,2], M. W. Krasny[3,4], J. Gilles[1,5], A. Surzhykov[1,5]

[1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[2] Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany
[3]LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Tour 33, RdC, 4, pl. Jussieu, 75005 Paris, France
[4]CERN, BE-ABP, 1211 Geneva 23, Switzerland
[5]Institut für Mathematische Physik, Technische Universität Braunschweig, Mendelssohnstrasse 3, D-38106 Braunschweig, Germany

The Gamma Factory, which is one of the proposals currently investigated within the CERN Physics Beyond Colliders studies, aims at developing a source of narrow-band photons with energies up to 400 MeV, offering a variety of possible Standard Model tests [1,2]. The fundamental aspect of the Gamma Factory is rooted in the resonant scattering process of relativistic ion beams at the LHC and counter-propagating laser photons, involving a strong enhancement of the photon frequencies caused by the Lorentz transformation between the laboratory reference frame and the rest frame of the ions [3]. In this theoretical study, we analyse resonant scattering with special attention paid to the effect of external electromagnetic fields which are strongly enhanced in a storage ring setup due to the relativistic movement of the ions. Calculations in He-like Ca ions reveal a notable impact of the external fields on the total cross section, the angular distribution and polarization of scattered photons, for realistic magnetic field strengths. This opens different applications within the Gamma Factory project as for instance for the calibration of the Lorentz factor.

References

[1] D. Budker, J. R. Crespo López-Urrutia, et al., Annalen der Physik, 532(8):2000204, 2020.
[2] R. Balkin, M. W. Krasny, et al., Annalen Phys., 534(3):2100222, 2022.
[3] A. Volotka, D. Samoilenko, et al., Ann. Phys.(Berlin), 534(2100252), 2022.

Einstein’s basement: A new sector for relativistic particles

<u>F. Riehle</u> and S. Ulbricht

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

We present a model treating the energy-momentum relation of relativistic particles as the upper branch of a generalized energy-momentum relation of quasi particles emerging from a forbidden crossing between the constant energy of a massive particle and the photon line [1]. The lower branch, a regime dubbed as Einstein’s basement, gives rise to quasi particles with different kinematics that is analyzed in the low-velocity limit. Allowing for gravitational interaction between those particles, we find both attraction and repulsion, depending on their velocity with respect to an absolute space. This absolute frame only is relevant for the lower branch and does not affect the relativistic dynamics of regular matter. However, assuming interaction between particles of both branches, Lorentz violating effects on regular matter can occur. We briefly discuss whether our approach can be used to model dark matter phenomena.

References

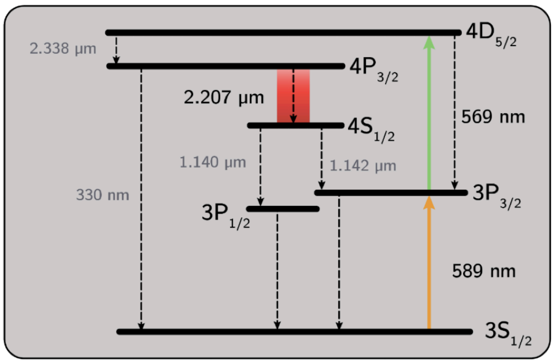
[1] F. Riehle and S. Ulbricht, Einstein's basement -- a model for dark matter and an expanding universe? arXiv: 2402.13679 (2024)

Mirrorless lasing-enabled remote sensing of magnetic fields

S. S. Sahoo[1], **O. Tretiak**[1], **R. Aramyan**[1], **A. Akulshin**[2] **and D. Budker**[1]

[1]*Helmholtz Institute Mainz, Johannes Gutenberg University, Mainz, Germany*
[2]*Swinburne University of Technology, Melbourne, Australia*

The study of mirrorless lasing (ML) has been of great interest in recent years because of its potential application to remote sensing of magnetic fields in the upper mesosphere [1]. ML is achieved by stepwise excitation of sodium atoms with resonant laser beams leading to the generation of infrared directional light [2]. The use of this phenomenon for on-sky measurement necessitates simulating the mesospheric conditions in a laboratory setting. Hence, in this work, we investigate the fundamental properties of ML such as the threshold condition and the effect of buffer gas to find the parameter range optimized for enhanced sensitivity of the ML process demonstrated with a sodium vapor cell.



References

[1] R. Zhang Phys. Rev. Lett. **127**(17), 173605 (2021).

[2] Akulshin et. al., Opt. Lett. **43**, 5279-5282 (2018).

New Experiment Under Ordinary Conditions With Common Tools to Verify the Planck's Equation

Gh. Saleh

Saleh Research Centre, Amsterdam, Netherlands

Utilizing a simple lens, we choose filters at will (red, yellow, green, blue, and violet). Then, we apply the filter to the lens and locate a thermometer at its focal point. It is evident that the temperature shown on the thermometer is lowest when using the red filter, highest with the violet filter, and the green filter falls in the middle. These results confirm the validity of Planck's universally accepted relation. Despite our common perception of red light as warm and blue light as cool, the experimental data clearly demonstrate the opposite.
On the other hand, we evaluate the results of two experiments conducted by physicists at the University of Michigan and the MIT. These experiments indicate that Planck's equation does not hold at a very small scale from the light source. The main reason for this is that at very close distances to the source ($d = \varepsilon$ or equivalently at $t = \varepsilon$), the amount of energy significantly exceeds the amount of energy that Max Planck predicted. This is because photons exhibit both linear and rotational motions. In the experiments conducted by the University of Michigan and MIT, the total energy was measured, whereas in Planck's experiment, only the linear energy was measured, not the rotational energy. The discrepancy in energy measurements (between the two university experiments and Planck's experiment) indicates the presence of rotational motion of photons or missing rotational energy.
In this paper we are going to show why red light appear warmer than blue one.

References

[1] Chandler, David L. “Breaking the Law, at the Nanoscale.” MIT News | Massachusetts Institute of Technology, news.mit.edu/2009/heat-0729. Accessed 29 July 2009.

[2] Thompson, Dakotah, et al. " Hundred-fold enhancement in far-field radiative heat transfer over the blackbody limit." Nature 561.7722 (2018): 216-221.

[3] Saleh, Gh. "Discovery of the Hundred-Year-Old Lost Mathematical and Physical Relationship Between the Classical Kinetic Energy of Photons and Planck's Everlasting Experimental Equation in the Universe (Planck-Saleh Energy Equation)" Saleh Theory, 28 Jun. 2024, https://www.saleh-theory.com/article/discovery-of-the-hundred-year-old-lost-mathematical-and-physical-relationship-between-the-classical-kinetic-energy-of-photons-and-plancks-everlasting-experimental-equation-in-the-universe-planck-saleh-energy-equation

Towards precision spectroscopy of highly charged ions

V.M. Schäfer, S. Kokh, E. A. Dijck, C. Warnecke, R. Henninger, F. Mayer, J.R. Crespo López-Urrutia and T. Pfeifer

[1]*Max Planck Institute for Nuclear Physics, Heidelberg, Germany*

Spectroscopy of highly charged ions (HCIs) promises greater sensitivity to potential new physics effects, such as the variation of fundamental constants or traces of fifth forces [1,2]. At the same time suppression of common error sources could allow for even more precise frequency measurements than what is currently possible in singly charged ions [3]. Together with recent advances in groundstate cooling and quantum logic spectroscopy of HCIs [4,5], this makes them an ideal candidate to search for experimental traces of proposed candidates for dark matter or new forces.
I will give an overview over the different HCI precision spectroscopy experiments in Heidelberg and present their different setups and goals.

References

[1] J. C. Berengut et al., Phys. Rev. Lett. **105**, 120801 (2010)
[2] M. S. Safronova, et. al., Rev. Mod. Phys. **90**, 025008 (2018)
[3] M. G. Kozlov et al., Rev. Mod. Phys. **90**, 045005 (2018)
[4] L. Schmöger et al., Science **347**, 6227 (2015)
[5] P. Micke, et al., Nature **578,** 60-65 (2020)

Probing unified theories with quantum sensors

Xavier Calmet and Nathaniel Sherrill

University of Sussex, Brighton BN1 9QH, United Kingdom

Precision searches for new physics often constrain low-energy coefficients within an effective field theory (EFT). The model-independent basis of EFTs makes them an ideal choice in the absence of clear new-physics signatures. However, should a signal be detected, investigations of those high-energy mechanisms predicting the measured EFT coefficients then becomes essential. This contribution explores how unified field theories can be linked to EFTs describing interactions of ultralight scalar fields coupled to the Standard Model. Searches for these types of fields are currently under intense inspection with quantum-sensor and other precision experiments. By embedding a scalar multiplet in the gauge sector of a unified theory, we provide a mechanism for a time-varying unified coupling constant. Assuming this multiplet saturates the dark-matter density, first constraints are placed on coupling-constant variations using atomic-clock comparisons (PTB), pulsar-timing arrays (NANOGrav), and equivalence-principle tests (MICROSCOPE).

References

[1] X. Calmet and N. Sherrill, Phys. Lett. B **852**, 138620 (2024)

Measuring the magnetic field properties of Ca^{14+}

L. J. Spieß[1], S. Chen[1], A. Wilzewski[1], M. Wehrheim[1], J. Gilles[1,2], A. Surzhykov[1,2], E. Benkler[1], M. Filzinger[1], N. Huntemann[1], C. Cheung[3], S. G. Porsev[3], A. I. Bondarev[4,5], M. S. Safronova[3], J. R. Crespo Urrutia-López[5], and P. O. Schmidt[1,6]

[1]*Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*
[2] *Technische Universität Braunschweig, Braunschweig, Germany*
[3]*Department of Physics and Astronomy, University of Delaware, Newark, Delaware, USA*
[4]*Helmholtz-Institut Jena, Jena, Germany*
[5]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*
[6]*Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany*

Highly charged ions (HCI) have extreme properties which makes them ideal candidates to probe fundamental physics [1]. Particularly, HCI with a low number of electrons enable precision calculations which can be compared to precision measurements. In particular, relativistic and QED contributions to the g-factor are used for the most precise tests of strong field QED using Penning traps. This though so far has only been shown for ground-state g-factors. The second-order Zeeman shift has also never been experimentally observed in any HCI.
With our recent establishment of high precision spectroscopy of highly charged ions [2] for use in an optical clock [3], we can access these unexplored atomic parameters with unprecedented precision. Here we demonstrate measurements of the first- and second-order magnetic field response of an optical dipole-allowed transition in Carbon-like Calcium, without prior knowledge. This is achieved by estimating the magnetic field using the co-trapped Be^+ ion. These types of measurements probe the properties of an excited state in HCI which is not easily accessible in Penning traps. The experimental results are compared to state-of-the-art theoretical calculations.

References

[1] M. G. Kozlov *et al.*, Rev. Mod. Phys. **90** (2018)
[2] P. Micke *et al.*, Nature **578,** 60-65 (2020)
[3] S. A. King *et al.*, Nature **611**, 43-47 (2022)

A solid-state approach to the Thorium nuclear clock: defect studies of Th: CaF2.

F. Schaden[1], T. Pronebner[1], I. Morawetz[1], L. Toscani De Col [1], M. Bartokos[1], K. Beeks[2], T. Sikorsky[1], T. Schumm[1]

[1]Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, Vienna, Austria
[2]Laboratory for Ultrafast Microscopy and Electron Scattering (LUMES), Institute of Physics, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
E-mail: luca.col@tuwien.ac.at

The Thorium nuclear clock project has had major progress in the last year, with the first laser excitation of the isomeric nuclear state [1]. Together with the four-wave mixing tunable VUV laser, the key element of the laser excitation experiment was the Th doped CaF_2 crystal grown with the vertical gradient freeze (VGF) method [2]. This method guarantees single crystal growth through accurate control of the temperature gradient applied to the mixture of CaF_2 and Th placed on top of a CaF_2 seed crystal. The resulting crystal geometry is being studied with EXAFS experiments in collaboration with Okayama University indicating that a charge compensation scheme with two interstitial fluorides is formed, to account for the Th^{4+} dopant.

What is still not known about the crystal structure are the defects inside the doped crystal, that could prove useful for different excitation schemes [3], taking advantage of electronic bridge processes, where electronic states couple to the nuclear ground state increasing the nuclear transition probability. To characterize the presence of defects like color centers and self-trapped excitons, a spectroscopy setup at EPFL takes advantage of a UV detection system after a crystal is irradiated by a fs laser in the VUV range: UV fluorescence from the crystal is observed but still not detected and resolved.

Lastly, other crystal growing methods are under development: an induction-heating micro pulling down (μ-PD) furnace is being optimized for faster growth of $^{229}Th:CaF_2$ with the goal of producing smaller crystals, possibly increasing the concentration even further. The same furnace is also being used for Bridgman growth: this technique is being developed to study the feasibility of a ThF_4 crystal, characterizing the transparency in the VUV region of this material.

References

[1] J. Tiedau*, M. V. Okhapkin*, K. Zhang*, et al. and F. Schaden*, T. Pronebner, I. Morawetz, et al *Laser Excitation of the Th-229 Nucleus*. Phys. Rev. Lett., 132, 182501. (2024)

[2] K. Beeks, T. Sikorsky, et al. *Growth and characterization of thorium-doped calcium fluoride single crystals*. Sci Rep 13, 3897 (2023)

[3] B. Nickerson, M. Pimon, et al. *Nuclear excitation of the Th 229 isomer via defect states in doped crystals.* Phys. Rev. Lett. 125.3 (2020).

Fundamental physics tests with an optical clock based on Ca14+

Alexander Wilzewski[1], Malte Wehrheim[1], Lukas J. Spieß[1], Shuying Chen[1], Steven A. King[1], Peter Micke[1], and Piet O. Schmidt[1,2]
Diana A. Craik[3], Jeremy Flannery[3], Jonathan Home[3], Luca I. Huber[3], and Roland Matt[3]
Anna Viatkina[1] and Andrey Surzhykov[1,4]
Jan Richter[1,5], Agnese Mariotti[5], and Elina Fuchs[5]
Julian C. Berengut[6]
Michael K. Rosner[7], Nils-Holger Rehbehn[7], and José R. Crespo López-Urrutia[7]
Menno Door[7] and Klaus Blaum[7]
Erik Benkler[1]
Melina Filzinger[1], Martin R. Steinel[1], and Nils Huntemann[1]

[1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
[2] Institut für Quantenoptik, Hannover, Germany
[3]Institute for Quantum Electronics, Zurich, Switzerland
[4]Technische Universität Braunschweig, Braunschweig, Germany
[5]Institut für Theoretische Physik, Hannover, Germany
[6]University of New South Wales, Sydney, Australia
[7]Max-Planck-Institut für Kernphysik, Heidelberg, Germany

The measurement of isotope shifts allows for precision tests of the Standard Model while also being sensitive to nuclear parameters. Here, we measure isotope shifts in highly charged Ca^{14+} ions using our established optical clock infrastructure. The highly charged ions (HCI) are produced in an electron beam ion trap. Individual HCI are then co-trapped with a single Be+ ion for sympathetic cooling and quantum logic readout. Clock operation is performed by stabilizing a laser at 570 nm to the $^3P_0$ -> $^3P_1$ fine structure transition in Ca^{14+}. Absolute frequencies are determined through comparison to the optical clock based on the Yb^+ octupole transition at PTB achieving a fractional uncertainty of $2*10^{-16}$. From this, the isotope shifts are derived with a fractional uncertainty of $2*10^{-10}$. By combining this result with improved spectroscopy data in singly charged calcium from the ETH Zurich and precise measurements of the nuclear masses from the MPIK Heidelberg we can place bounds on a hypothetical fifth force coupling neutrons and electrons.

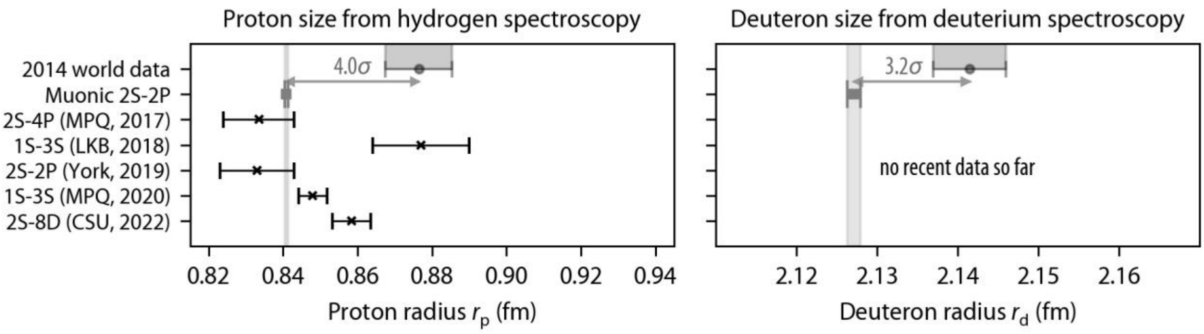
Precision spectroscopy of the 2S-6P transition in atomic hydrogen and deuterium

V. Wirthl[1], L. Maisenbacher[1,2], D. Taray[1], O. Amit[1],

R. Pohl[3], T. W. Hänsch[1,4], Th. Udem[1,4]

[1]Max Planck Institute of Quantum Optics, Garching, Germany
[2] University of California, Berkeley, USA
[3] Johannes Gutenberg University, Mainz, Germany
[4] Ludwig Maximilian University, Munich, Germany

Both atomic hydrogen and deuterium can be used to determine physical constants and to test bound-state Quantum Electrodynamics (QED). By combining at least two transition frequency measurements in each isotope, the proton and deuteron radii, along with the Rydberg constant, can be determined independently [1]. This is particularly interesting because of the tensions within the recent hydrogen measurements, which leaves room to speculate about possible new physics [2], as well as because no recent deuterium measurements are available such that a discrepancy with muonic deuterium persists [3]:



Using our improved active fiber-based retroreflector to suppress the Doppler shift [4], we recently measured the 2S-6P transition in hydrogen with a relative uncertainty below one part in 10^{12}, allowing one of the most stringent tests of bound-state QED. Here, we report on the preliminary result. We also performed a preliminary measurement of the same transition in deuterium. In contrast to hydrogen, the 2S-6P measurement in deuterium is complicated by the simultaneous excitation of unresolved hyperfine components, possibly leading to quantum interference between unresolved lines [5]. Our detailed study of these and other effects in deuterium demonstrates the feasibility of determining the 2S-6P transition frequency with a similar precision as for hydrogen.

References

[1] R. Pohl et al., Metrologia **54**, L1 (2017)
[2] A. Brandt et al., Phys. Rev. Lett **128**, 023001 (2022)
[3] R. Pohl et al., Science **353**, 669–673 (2016)
[4] V. Wirthl et al., Opt. Express **29**(5), 7024-7048 (2021)
[5] Th. Udem et al., Ann. Phys. **531**, 1900044 (2019)

Progress on the design and development of an all-optical transportable trapped-ion-based atomic clock

V. Yadav[1], P. Chandramouli[1] and A. Sharma[1]

[1]*Indian Institute of Technology Tirupati, Yerpedu, India*

Precision spectroscopy has led to the realization of tabletop experimental tools enabling frequency metrology. A technological outcome of this endeavour has been the genesis of atomic clocks and their subsequent evolution in a more compact and portable form factor with favourable SWaP (Size, Weight and Power). Portable atomic clocks are poised to become a promising technology to enhance the Positioning, Navigation & Timing (PNT) infrastructure that drives modern-day communication, navigation, and timing applications. While the last few decades have witnessed an unprecedented revolution in portable microwave atomic clocks, the future beholds the evolution of all-optical portable atomic clocks. All-optical atomic clocks utilize dipole-forbidden optical transitions using off-the-shelf diode lasers. Making such clocks portable would lead to their integration into upcoming classical (6G and beyond) and quantum communication technology through enhanced frequency stability and timing resolution.

We present our progress towards the development of an all-optical transportable trapped-ion-based atomic clock. The clock candidate is a single calcium ion ($^{40}Ca^+$) that will be confined in an end-cap ion trap under ultra-high vacuum conditions. The trapped ion in a dynamic quadrupole potential is sensitive to deformities in the trap structure and distortion in potential. We present finite element simulations demonstrating the electrostatic, thermal, and mechanical analysis of the trap. Furthermore, detection of trapped single ion shall be enabled by a high numerical aperture (NA) lens with sub-micron resolution imaging system. We shall also present our optical simulations using multiple-element lens system to minimize aberrations and produce diffraction-limited image. Hollow cathode lamp (HCL) based laser frequency stabilization will be utilized to frequency stabilize the cooling and repumping lasers on suitable transitions involved in laser cooling of the trapped ion. Initial spectroscopy using HCL is also presented.

References

[1] C. Orzel, Advances In Atomic, Molecular, and Optical Physics **67**, 337-375 (2018)

[2] A. D. Ludlow et al., Review of Modern Physics **87**, 637 (2015)