Fundamental Constants: Basic Physics and Units

670. WE-Heraeus-Seminar

May 13 - 18, 2018
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm and Else Heraeus Foundation (Wilhelm und Else Heraeus-Stiftung) is a private foundation which supports research and education in science, especially in physics. A major activity is the organization of seminars. To German physicists the foundation is recognized as the most important private funding institution in their fields. Some activities of the foundation are carried out in cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft).

Scope of the 670. WE-Heraeus-Seminar:

The goal of the seminar is to bring together experts who share their interest in physics of fundamental constants. During the workshop the questions of a definition of fundamental constants, relation of these constants with physical laws, and of their minimal set will be considered. Together with discussion of basic ideas and theories, emphasis will be also placed on the high-precision experiments aiming determination of the fundamental constants. The impact of this experimental data for metrology applications as well as for our understanding of Nature will be also in the focus of discussions.

Topics covered in the seminar include the following questions:

- What are fundamental constants? How many of those do we need?
- Are fundamental constants varying in space and time?
- What are current best values of fundamental constants? How are they measured?
- How we can use future atomic and nuclear clocks to re-define the second?
- How violations of symmetries of Nature are related to the variation of fundamental constants?
- What are new data about the proton radius and how do they impact the values of fundamental constants?

The ceremony for awarding the prestigious Helmholtz Prize in 2018 will be part of the seminar. It is dedicated for outstanding scientific achievements in the field of "Precision Measurements in Physics, Chemistry and Medicine". Established in 1973, this prize is considered as the most prestigious one in the field of precision measurements and, since 2015, comes in two categories namely "fundamental principles" and "applications".

Introduction

Scientific Organizers:

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Registration:

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

Door Code:

(Key symbol button) 2 6 7 0 #
For entering the Physikzentrum
during the whole seminar

Program

Program

Sunday, May 13, 2018

17:00 – 21:00	Registration	
from 18:30	BUFFET SUPPER / Informal get together	
20:00 – 21:00	**Welcome lecture** Joachim Ullrich	**Linking the international system of units to fundamental constants**

Monday, May 14, 2018

08:00	BREAKFAST	
08:45 – 09:00	Scientific organizers	**Opening and welcome**
09:00 – 09:45	Jean-Philippe Uzan	**Fundamental constants, gravitation and cosmology - recent developments**
09:45 – 10:30	Christof Wetterich	**Are fundamental constants constant?**
10:30 – 11:00	COFFEE BREAK	
11:00 – 11:45	Yurii Dumin	**Is the cosmological Lambda-term a new fundamental constant?**
11:45 – 12:30	Vincenzo Salzano	**Measuring the speed of light with cosmological observations**
12:30	**Conference Photo** (in the foyer of the lecture hall)	
12:40	LUNCH	

Program

Monday, May 14, 2018

14:00 – 14:45	Marianna Safronova	**The search for variation of fundamental constants with atomic systems**
14:45 – 15:30	Ekkehard Peik	**Search for variations of the fine structure constant with atomic clocks**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Mikhail Kozlov	**Time variation of fundamental constants: Searches via microwave and infrared spectroscopy in space**
16:45 – 17:30	Wim Ubachs	**Physics beyond the Standard Model from hydrogen molecules**
17:30 – 19:00	**Poster session I**	
19:00	*DINNER*	

Program

Tuesday, May 15, 2018

08:00	*BREAKFAST*	
09:00 – 09:45	Jun Ye	**Optical atomic clock based on quantum matter**
09:45 – 10:30	Hidetoshi Katori	**Connecting optical lattice clocks at 10^{-18} uncertainty**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	David Hume	**Precision measurements with trapped-ion optical clocks at NIST**
11:45 – 12:30	Gesine Grosche	**Frequency comparison and dissemination via interferometric optical fibre links**
12:30	*LUNCH*	
14:00 – 14:45	Peter Thirolf	**Towards a test bench for time variation of fundamental constants: What do we know about the elusive ^{229}Th isomer?**
14:45 – 15:30	Robert Alexander Müller	**Hyperfine structure of doubly charged ^{229}Th and the excitation of its nuclear clock isomer**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Andrey Volotka	**Nuclear excitation in the two-photon decay of highly charged ions**
16:45 – 17:30	Rima Schüssler	**High-precision mass measurements with PENTATRAP**
17:30 – 19:00	**Discussion**	
19:00	*DINNER*	

Program

Wednesday, May 16, 2018

08:00	*BREAKFAST*	
09:00 – 09:45	Stefan Ulmer	**High-precision comparisons of the fundamental properties of protons and antiprotons at BASE**
09:45 – 10:30	Stefan Eriksson	**Spectroscopy of antihydrogen in the ALPHA experiment**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Masaki Hori	**Antiproton-to-electron mass ratio determined by laser spectroscopy of antiprotonic helium**
11:45 – 12:30	Tanya Zelevinsky	**Precision spectroscopy and EDMs with cold molecules**
12:30	*LUNCH*	
14:00 – 17:30	**Excursion** (leisurely hike in the vicinity)	
17:30 – 19:00	**Poster session II**	
19:00	*DINNER*	
20:00 – 21:00	**Evening lecture** Terry Quinn	**From artefacts to atoms - from the old to the new SI**

Program

Thursday, May 17, 2018

08:00	BREAKFAST	
09:00 – 09:45	Barry Wood	**Final measurements of the Planck constant**
09:45 – 10:30	Holger Mueller	**Measurement of the fine structure constant as test of the standard model**
10:30 – 11:00	COFFEE BREAK	
11:00 – 11:45	Vladimir Yerokhin	**QED theory of the Lamb shift of hydrogen and hydrogen-like ions for Rydberg constant and proton radius**
11:45 – 12:30	Sven Sturm	**The magnetic moment of highly charged ions: Test of strong field QED and access to fundamental constants**
12:30	LUNCH	
14:00	**Helmholtz Prize Cermony**	
	Klaus von Klitzing	**Quantum Hall effect and fundamental constants**
16:30	**RECEPTION**	
17:45	*Start to the shipping pier (about 20 minutes walk)*	
	JOINT DINNER on board cruising by the boat “MS Moby Dick” on the river Rhine	

Program

Friday, May 18, 2018

08:00	BREAKFAST	
09:00 – 09:45	Randolf Pohl	**Laser spectroscopy of muonic atoms - Nuclear physics and fundamental constants**
09:45 – 10:30	Francois Nez	**Hydrogen 1S-3S spectroscopy with a cw laser**
10:30 – 11:00	COFFEE BREAK	
11:00 – 11:45	Natalia Oreshkina	**Hyperfine splitting in simple ions for the search of the variation of fundamental constants**
11:45 – 12:30	José Crespo López-Urrutia	**Highly charged ions for fundamental studies**
12:30 – 12:45	Scientific organizers	**Poster awards, summary and closing remarks**
12:45	LUNCH	

End of the seminar and FAREWELL COFFEE **/ Departure**

Please note that there will be **no** dinner at the Physikzentrum on Friday evening for participants leaving the next morning.

Posters

Posters

1.	Andreas Bauch	**Satellite-based clock comparisons - a status report**
2.	Hendrik Bekker	**Spectroscopy of optical transitions in highly charged ions with applications to metrology and searches for the variation of fundamental constants**
3.	Matthew Bohman	**Toward sympathetic cooling of protons and antiprotons with a common endcap penning trap**
4.	William Bowden	**Development of NPL's next generation lattice clock**
5.	Halil Cakir	**The g-factor of Lithium-like systems**
6.	Isaac Fan	**A novel method to measure the quotient of gyromagnetic ratios in a comagnetometer system**
7.	Friedrich Hehl	**Physical dimensions and units, universal constants and their relativistic invariance**
8.	Nils Huntemann	**Comparison of two high-accuracy optical ion clocks for hundredfold improved bounds on Lorentz violation**
9.	Claus Lämmerzahl	**Proposed measurement of G in space**
10.	Richard Lange	**Coherent and incoherent methods of suppressing frequency shifts in optical clocks**
11.	Tobias Leopold	**A cryogenic Paul trap for quantum logic spectroscopy of highly charged ions**
12.	Tianhao Liu	**Frequency shifts for gaseous particles moving in electromagnetic fields: Application for Xe electric dipole moment experiments**

Posters

13.	Peter Micke	**Towards quantum logic spectroscopy of highly charged Ar^{13+}**
14.	Lukáš Félix Pašteka	**Structure of molecules and solids varying with fundamental constants**
15.	Sascha Rau	**The proton's atomic mass and the puzzle of light masses**
16.	Alexander Rischka	**Commissioning of the Penning-trap mass spectrometer PENTATRAP**
17.	Tim Sailer	**The ALPHATRAP g-factor experiment**
18.	André Schäfer	**Calibration & traceability challenges and its impact to the development of mechanical engineering**
19.	Julian Schmidt	**Optical trapping of ion Coulomb crystals**
20.	Marc Schuh	**Image charge shift in precision Penning traps**
21.	Bastian Sikora	**High-precision theory of the g-factor of bound fermions**
22.	Sebastian Ulbricht	**Gravitational influences on earth-based measurements of the free electron g-factor**
23.	Gulnara Vishnyakova	**Giant fiber-optic gyroscope for seismological measurements based on the Sagnac effect**
24.	Lars von der Wense	**A direct nuclear laser excitation scheme for ^{229m}Th**
25.	Thomas Waterholter	**Combination of two optical amplification methods on a 1880 km looped optical fiber link**

Abstracts of Lectures

(in chronological order)

Linking the international system of units to fundamental constants

Joachim Ullrich

Physikalisch-Technische Bundesanstalt, Brauschweig, Germany

In November 2018, it is anticipated that at the 26th meeting of the General Conference on Weights and Measures, CGPM, established by the Metre Convention in 1875, will decide to revise the International System of Units (SI). In the future, as outlined by Max Planck in his famous paper of 1900 postulating the “Planck constant”, it shall be based on fundamental constants of nature, the “defining constants”: the velocity of light, the charge of the electron, the Boltzmann, Avogadro and the Planck constants, the Cs hyperfine clock transition and the luminous efficacy.

In the talk I will provide an overview of the progress, challenges and future perspectives of the new “Quantum SI”, illustrated in Fig. 1, and discuss the question of whether or not the fundamental constants are indeed constant in time. New experiments are presently being devised, one of them based on next-generation optical clocks using transitions in highly-charged ions that are read out via quantum-logic schemes. They bear the chance to trace potential changes in the fine structure constant α on the level of $\Delta\alpha/\alpha \approx 10^{-20}$ per year.

Figure 1: Logo of the New SI with the defining constants and the seven base units.

Fundamental constants, gravitation and cosmology - recent developments

J. Uzan

CNRS/Institut d'Astrophysique de Paris, France

Fundamental constants play a central role in the laws of physics. Any detection of the variation of these constants would signal a violation of the Einstein equivalence principle, and thus the need to go beyond general relativity. After recalling the links between fundamental constants and theories of gravity, I will focus on recent developments to constrain their time variation, mostly concentrating on big-bang and stellar nucleosynthesis as well as the analysis of the observations by the Planck satellite. The connection with cosmology, in particular the physics of the dark sector and fine tuning issues will be discussed.

Are fundamental constants constant?

Christof Wetterich

Institut für Theoretische Physik Universität Heidelberg, Germany

The masses and couplings of fundamental particles depend on the values of scalar fields, as the Higgs field. If such a scalar field changes its value in the present epoch of cosmology, its coupling to atoms will result in observable variations of fundamental couplings and an apparent violation of the equivalence principle. Strict observational bounds limit the coupling of such a „cosmon" to atoms to be several orders of magnitude weaker than gravity.

Spontaneously broken scale symmetry in quantum gravity gives a reason for an almost massless scalar cosmon field as a Goldstone boson, and explains why its coupling to atoms is tiny. A scalar with these properties can be responsible for dynamical dark energy. The why now problem of dark energy may be solved by a substantial coupling of the cosmon to neutrinos, rendering the cosmic neutrino background potentially observable by the formation of huge neutrino lumps. A small coupling to atoms may be detected in future experiments.

Is the cosmological Lambda-term a new fundamental constant?

Yurii V. Dumin[1,2]

[1]Sternberg Astronomical Institute of Lomonosov Moscow State University, Russia
[2]Space Research Institute of Russian Academy of Sciences, Moscow, Russia
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The Lambda-term was introduced into the General Relativity equations by A. Einstein a hundred years ago and became a crucial ingredient of cosmological models in the recent twenty years. However, little is known about its nature and origin till now. In particular, it is still unclear if the Lambda-term is a new fundamental constant or represents just an effective contribution from the underlying field theory. So, in the first part of the report I am going to outline the current status of the Lambda-term in cosmology and its probable interpretation as "vacuum energy" in some kind of the field theory. Next, in the second part, I shall discuss in more detail one particular option of introduction of the effective Lambda-term, following from the Mandelstam–Tamm uncertainty relation. Apart from the possibility of natural appearance of this term in the cosmological equations, such an idea provides a unified explanation why it should be important both in the early Universe (during inflation) and at the later times.

Measuring the speed of light with cosmological observations

VincenzoSalzano[1] **and Mariusz P. Dąbrowski**[1]

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Varying constants theories have become well established alternative theories of gravity nowadays. In this talk we will focus on the "Varying speed of light" (VSL) theories, which have been long analyzed and debated in the last years, with multiple theoretical approaches but very few applications to observational data.

More in detail, we will discuss a new method we have developed aimed to measure the value of the speed of light at cosmological scales at different epochs (i.e. redshifts), using multiple and independent data from galaxy surveys. In particular, our cosmological ruler will be related to the characteristic properties imprinted in the clustering of galaxies, namely the Baryon Acoustic Oscillations (BAO); while our cosmological clock will be related to some peculiar spectral features of early-type galaxies which make them the so-called "cosmic chronometers".

We will apply this method on a series of mock data expected to be collected by future galaxy surveys (EUCLID and SKA among others) and consistently generated using the architectural properties and the sensitivity of the chosen observational surveys.

Given the way the method is built up, it can unequivocally test the constancy of the speed of light on cosmological scales and, thus, eventually confirm or reject VSL theories from a purely observational perspective.

References

[1] V. Salzano, Phys. Rev. D95 (2017) 084035
[2] V. Salzano, M. P. Dabrowski, R. Lazkoz, Phys. Rev. D93 (2016) 063521
[3] V. Salzano, M. P. Dabrowski, R. Lazkoz, Phys. Rev. Lett. 114 (2015) 101304

The search for variation of fundamental constants with atomic systems

Marianna Safronova

University of Delaware, USA

In many theories beyond the Standard Model of elementary particles and general relativity dimensionless fundamental constants become dynamic fields. I will give an overview of the atomic searches for the variation of fundamental constants, focusing on recent key results, future proposals, and relevance to the dark matter searches.

Search for variations of the fine structure constant with atomic clocks

Ekkehard Peik

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Optical clocks based on different atoms and ions are now reported with systematic uncertainties in the low 10^{-18} range, and experiments based on frequency comparisons and precise measurements of frequency ratios allow for improved tests of fundamental physics, especially quantitative tests of relativity and searches for violations of the equivalence principle [1]. The $^{171}Yb^+$ optical clock that is based on the extremely narrow S-F electric octupole transition possesses a favorable combination of small systematic uncertainty and high sensitivity for such tests because of the strongly relativistic character of the excited state. In comparisons of the $^{171}Yb^+$ single-ion clock, a ^{87}Sr optical lattice clock and primary Cs clocks at PTB we perform tests for temporal variations of the fine structure constant and the proton-to-electron mass ratio. A future nuclear clock based on the low-energy transition in Th-229 may significantly increase the sensitivity of such tests. Recent results on the nuclear moments of the Th-229 isomer provide first experimental indications on the sensitivity of the transition frequency to the value of alpha [2].

References

[1] M. Safronova *et al.*, arXiv 1710.01833
[2] J.Thielking *et al.*, arXiv 1709.05325

Time variation of fundamental constants: Searches via microwave and infrared spectroscopy in space

Mikhail Kozlov

Petersburg Nuclear Physics Institute, Russia

I will discuss sensitivity of microwave and infrared transitions to the variation of fundamental constants and constrains that follow from astrophysical observations in respective wavebands.

Physics beyond the Standard Model from hydrogen molecules

Wim Ubachs

Vrije Universiteit Amsterdam, Netherlands

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

Optical atomic clock based on quantum matter

Jun Ye

JILA/NIST/University of Colorado, USA

The progress of optical lattice clock to the accuracy of 2×10^{-18} has benefited from a broad range of technical innovations and the understanding of atomic interactions. I will discuss our recent work on a Fermi degenerate three-dimensional optical lattice clock, where we combine ultralong coherence time and high spatial resolution to achieve frequency measurement precision of 2×10^{-19}. I will discuss applications based on this new system, including advances in clocks and studies of few to many-body quantum physics.

Connecting optical lattice clocks at 10^{-18} uncertainty

Hidetoshi Katori

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Optical lattice clocks benefit from a low quantum-projection noise by simultaneously interrogating a large number of atoms trapped in optical lattices tuned to the "magic frequency". About a thousand atoms enable such clocks to achieve 10^{-18} instability in a few hours of operation, allowing intensive investigation and control of systematic uncertainties. It is now the uncertainty of the SI (International System of Units) second ($\sim 10^{-16}$) itself that restricts the absolute frequency measurements of such optical clocks. (1) We present ratio or difference frequency measurements between optical lattice clocks with different atoms and isotopes including Sr [1], Yb, and Hg; such efforts allow describing frequencies beyond SI uncertainty and provide an access to new physics. (2) In order to push the uncertainty of the optical lattice clocks to below 1×10^{-18}, we experimentally investigate higher order light shifts and determine an "operational magic frequency" [2] for Sr.

References

[1] T. Takano, R. Mizushima, and H. Katori, Appl. Phys. Exp. **10**, 072801 (2017).

[2] H. Katori, V. D. Ovsiannikov, S. I. Marmo, and V. G. Palchikov, Phys. Rev. A **91**, 052503 (2015).

Precision Measurements with Trapped-Ion Optical Clocks at NIST

David Hume

National Institute of Standards and Technology, USA

In recent years, atomic clocks based on optical resonances in single trapped ions have demonstrated fractional instabilities and inaccuracies below the level of 10^{-17}. At NIST we have developed optical clocks based on Hg^+ and Al^+. Previous frequency ratio measurements between these two clocks place a stringent constraint on the time-variation of the fine structure constant. Further analysis of this data can also place constraints on models of dark matter as ultralight bosons. I will review the general features of these experiments, and describe recent progress on the Al^+ standards, which use sympathetic cooling and quantum-logic spectroscopy. The total inaccuracy of this clock has been significantly reduced by suppressing uncertainty due to time dilation to below 10^{-18}. I will report on the latest accuracy evaluation of this clock and present preliminary results of recent frequency comparison measurements between the Al^+ clock and the optical lattice clocks at NIST.

Frequency comparison and dissemination via interferometric optical fibre links

G. Grosche

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Precision spectroscopy of atoms and molecules enables us to search for physics beyond the Standard Model using "precision rather than energy" [1]. By comparing different transitions of atomic/molecular frequency standards one can investigate the time-dependence of fundamental constants [1,2]. Local frequency comparisons have been routinely performed for over a decade, but as noted in 2007, "frequency comparisons between remote laboratories at the level of accuracy of current primary and optical frequency standards are not so straightforward" [2]. For optical clocks approaching 10^{-18} uncertainty [3], satellite based techniques are insufficient, but frequency transfer techniques using optical fibre have developed greatly in the last 15 years. In 2005, radio-frequency dissemination over a fibre length of 86 km was reported with near 10^{-17} resolution [4]; recent systems span fibre lengths over 1000 km, and a frequency transfer uncertainty (in loop experiments) down to 2×10^{-20} over 1400 km has been achieved [5]. I will outline some techniques for using optical telecommunication fibre in a large-scale interferometric set-up to enable remote frequency comparison and dissemination [5,6], and report on applications, e.g. [7,8].

References

[1] C. Orzel, "Searching for new physics through atomic, molecular and optical precision measurements", Phys. Scr. **86**, 068101, (2012); quoting Gerald Gabrielse, Harvard (page 1)

[2] S. Lea, "Limits to time variation of fund. constants from comparisons of atomic frequency standards", Rep. Prog. Phys. **70**, 1473 (2007) (quote: p. 1491)

[3] N. Huntemann, C. Sanner, B. Lipphardt *et al.*, "Single-Ion Atomic Clock with 3×10^{-18} Systematic Uncertainty", Phys. Rev. Lett. **116**, 063001 (2016)

[4] C. Daussy, O. Lopez, A. Amy-Klein *et al.*, "Long-Distance Frequency Dissemination with a Resolution of 10^{-17}", Phys. Rev. Lett. **94**, 203904 (2005)

[5] S. Raupach, A. Koczwara and G. Grosche, "Brillouin amplification supports 1×10^{-20} uncertainty in optical...", Phys Rev A **92**, 021801(R) (2015)

[6] G. Grosche, O. Terra, K. Predehl *et al.*, "Optical frequency transfer via 146 km fiber link with 10^{-19} relative accuracy", Opt. Lett. **34**, 2270 (2009)

[7] M. Vermeer, "Chronometric leveling", Report 83:2 of the Finnish Geodetic Institute, Helsinki; ISSN 0355-1962, ISBN 951-711-087-1 (1983)

[8] Ch. Lisdat, G. Grosche, N. Quintin *et al.*, "A clock network for geodesy and fundamental science", Nat. Commun. **7**, 12443 (2016)

Towards a test bench for time variation of fundamental constants: What do we know about the elusive 229Th isomer?

Peter G. Thirolf

Ludwig-Maximilians-Universität München, Garching, Germany

Today's most precise time and frequency measurements are performed with optical atomic clocks. However, it has been proposed that they could potentially be outperformed by a nuclear clock, which employs a nuclear transition instead of an atomic shell transition. There is only one known nuclear state that could serve as a nuclear clock using currently available technology, namely, the isomeric first excited state of 229Th. Since 40 years nuclear physicists have targeted the identification and characterization of the elusive isomeric ground state transition of 229mTh. Evidence for its existence until recently could only be inferred from indirect measurements, suggesting an excitation energy of 7.8(5) eV. Recently, the first direct detection of this nuclear state could be realized via its internal conversion decay branch, which confirms the isomer's existence and lays the foundation for precise studies of its decay parameters. Subsequently, a measurement of the halflife of the neutral isomer was achieved, confirming the expected reduction of 9 orders of magnitude compared to the one of charged 229mTh. Most recently, collinear laser spectroscopy was applied to resolve the hyperfine structure of the thorium isomer, providing information on nuclear moments and the charge radius. Thus a considerable increase of insight into the properties of this elusive nuclear state could be achieved in the last two years, paving the way towards an all-optical control and thus the development of an ultra-precise nuclear frequency standard. Moreover, a nuclear clock promises intriguing applications in applied as well as fundamental physics, ranging from geodesy and seismology to the investigation of possible time variations of fundamental constants.

Hyperfine structure of doubly charged ^{229}Th and the excitation of its nuclear clock isomer

R. A. Müller[1,2], **A. V. Volotka**[3], **S. Fritzsche**[3,4] **and A. Surzhykov**[1,2]

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After the first indications for possible time variations of the fine structure constant α from astrophysical measurements much effort has been spent to search for such variations in laboratory systems. Most of such experiments rely on the comparison of two precise atomic clocks based on transitions that scale differently with respect to α. Instead of atomic clocks, however, in the future nuclear clocks might be used for such a comparison. A particularly suitable candidate for such a scenario is the thorium isotope ^{229}Th, with the 7.8eV nuclear clock transition from its ground to the isomeric ^{229m}Th state. This transition is expected to be much more sensitive to possible variation of α than electronic transitions [1]. In order to get a more accurate estimate for this sensitivity, precise knowledge about the nuclear moments is necessary. In this contribution we present theoretical results for the hyperfine structure of doubly charged thorium which, in combination with experimental measurements, allow for a very precise determination of the nuclear moments of ^{229}Th and its nuclear isomer.

Apart from the nuclear moments also the exact energy of the nuclear clock transition still needs to be determined. There have been several attempts to perform spectroscopy on the nuclear clock transition with excited nuclei from a uranium source [2]. Moreover several scenarios have been proposed how to excite the nuclear isomeric in a controlled way via the electron shell. Out of these processes, nuclear excitation by two-photon electron transition (NETP) is a very promising candidate [3]. In our contribution we will give a detailed discussion how this process may be used in state-of-the-art experimental setups to excite ^{229}Th nuclei.

References

[1] V. V. Flambaum, Phys. Rev. Lett. **97**, 092502 (2006)
[2] B. R. Beck et al., Phys. Rev. Lett. **98**, 142501 (2007)
[3] A. V. Volotka *et al.*, Phys. Rev. Lett. **117**, 243001 (2017)

Nuclear excitation in the two-photon decay of highly charged ions

A. V. Volotka[1], A. Surzhykov[2,3], S. Trotsenko[1,4], G. Plunien[5],
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[6]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

A new mechanism for nuclear excitation by atomic transition is suggested and explored theoretically by studying the two-photon decay of highly charged ions [1]. This mechanism can be seen as a two-photon transition in the presence of an intermediate cascade state, which is given by the electron-nucleus state with the electrons in its ground level and the nucleus in an excited level. Similarly to the pure electronic two-photon decay, the presence of such a cascade leaves a clear footprint in the photon emission spectrum as sharp peaks in the energy regions when one of the photons has a frequency close to the nuclear excitation energy. Detailed calculations are performed for the E1E1 decay 1s2s $2^1S_0 \rightarrow 1s^2\ 1^1S_0$ in heliumlike $^{225}Ac^{87+}$ ion and for the resonant excitation of the known nuclear level at 40.09(5) keV above the nuclear ground state. The probability that such two-photon decay occurs via the nuclear excitation is found to be 3.5×10^{-9} and is, thus, similar to the corresponding values as obtained for the nuclear excitation by electron transition. The experimental observation of the proposed mechanism is discussed thoroughly as well as its possible applications for the search of low-lying isomeric states, energy storing, and controlled triggering.

References

[1] A. V. Volotka, A. Surzhykov, S. Trotsenko, G. Plunien, Th. Stöhlker, and S. Fritzsche **117**, 243001 (2016)

High-Precision Mass Measurements with PENTATRAP

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High-precision mass measurements at the level of 10^{-11} find applications, among others, in tests of special relativity [1], bound-state QED [2] and neutrino physics research [3]. The tool of choice to reach this precision is a Penning trap, where a mass measurement is performed by determining the cyclotron frequency in a strong magnetic field.

With first proof-of-principle mass measurements of xenon isotopes the novel high-precision Penning-trap mass spectrometer PENTATRAP [4] has recently demonstrated a relative mass precision of 10^{-11} using highly-charged ions. A unique feature of the experimental setup is the use of five cylindrical Penning traps [5], making simultaneous storage and measurement of several ion species possible.

In order to, for example, contribute to neutrino mass research, PENTATRAP is part of the ECHo collaboration [6], which aims to reach sub-eV sensitivity on the electron neutrino mass using ^{163}Ho. The precise determination of the *Q*-value of the electron capture process in ^{163}Ho, provided by PENTATRAP as a mass difference measurement of ^{163}Ho and the daughter nuclide ^{163}Dy, will be of utmost importance to reduce systematic errors in the analysis of the ^{163}Ho spectrum.

Recent PENTATRAP results as well as the status of the setup will be presented.

References

[1] S. Rainville *et al.*, Nature **438**, 1096 (2005)
[2] F. Köhler-Langes *et al.*, Nature Comm. **7**, 10246 (2016)
[3] S. Eliseev *et al.*, Phys. Rev. Lett. **115**, 062601 (2015)
[4] J. Repp *et al.*, Appl. Phys. **B107**, 983 (2012)
[5] C. Roux *et al.*, Appl. Phys **B108**, 997 (2012)
[6] L. Gastaldo *et al.*, Eur. Phys. J. ST **226**, 1623 (2017)

High-Precision Comparisons of the Fundamental Properties of Protons and Antiprotons at BASE

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The Baryon Antibaryon Symmetry Experiment (BASE-CERN) at CERN's antiproton decelerator facility conducts high-precision comparisons of the fundamental properties of protons and antiprotons, such as their charge-to-mass ratios, magnetic moments and lifetimes. Such experiments provide sensitive tests of charge-parity-time (CPT) invariance in the baryon sector.
BASE was approved in 2013 and has since used single-particle multi-Penning-trap techniques to measure the antiproton-to-proton charge-to-mass ratio with a fractional precision of 69 p.p.t. [1]. The antiproton magnetic moment has been measured with a fractional precision of 0.8 p.p.m. [2] and subsequently at the level of 1.5 p.p.b. [3]. At our matter companion experiment BASE-Mainz, we have performed proton magnetic moment measurements with fractional uncertainties of 3.3 p.p.b. [4] and 0.3 p.p.b. [5]. By combining the data of both experiments we provide a baryon-magnetic-moment based CPT test $g_{pbar}/g_p = 1.000\ 000\ 000\ 2(15)$, which improves the uncertainty of previous experiments [6] by more than a factor of 3000.

In this talk I will review the achievements of BASE at CERN.

References

[1] S. Ulmer *et al.*, Nature **524**, 196 (2015).
[2] H. Nagahama *et al.*, Nat. Commun. **8**, 14084 (2017).
[3] C. Smorra *et al.*, Nature **550**, 371 (2017).
[4] A. Mooser *et al.*, Nature **509**, 596 (2014).
[5] G. Schneider *et al.*, Science **358**, 1081 (2017).
[6] J. DiSciacca *et al.*, Phys. Rev. Lett. **110**, 130801 (2013).

Spectroscopy of antihydrogen in the ALPHA experiment

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Antihydrogen offers a unique way to test matter/antimatter symmetry. Antihydrogen can be trapped in the ALPHA-experiment at CERN for extended periods of time, offering an opportunity to study the properties of antimatter with high precision. Very recently, the two-photon optical transition to the first excited state in antihydrogen has been observed with a relative frequency precision of 200 parts in a trillion and the hyperfine spectrum in the microwave domain with a relative frequency precision of 400 parts in a million. Both the optical and microwave experiments yield results which are consistent with CPT-invariance within the precision of the measurements. The development of antihydrogen accumulation allows larger anti-hydrogen samples and therefore more precise measurements.

Here, I present an overview of antihydrogen synthesis and trapping in the ALPHA-experiment, together with the latest results on spectroscopy of the ground and first excited state in trapped antihydrogen. I present an outlook on the future of probing fundamental symmetry with antihydrogen including work in the era of CERN's new extra-low-energy antiproton source ELENA.

Antiproton-to-electron mass ratio determined by laser spectroscopy of antiprotonic helium

Masaki Hori

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The Atomic Spectroscopy and Collisions Using Slow Antiprotons (ASACUSA) collaboration is carrying out precise laser spectroscopy experiments on antiprotonic helium atoms. Employing buffer-gas cooling techniques in a cryogenic gas target, samples of atoms were cooled to temperature 1.5-1.7 K, thereby reducing the Doppler width in 13 single-photon resonance lines. By comparing the results with three-body quantum electrodynamics calculations, the antiproton-to-electron mass ratio was determined as 1836.1526734(15). Further improvements in the experimental precision are currently being attempted.

Precision spectroscopy and EDMs with cold molecules

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Molecules at cold and ultracold temperatures extend our capabilities for precision measurements beyond the possibilities that have been developed with cold atoms. An important area where molecules present new opportunities is the measurement of electric dipole moments (EDMs) of electrons or the closely related Schiff moments (SMs) of atomic nuclei, which would violate the time reversal symmetry of nature. We briefly review this field, and describe ongoing efforts to improve the precision on the SM measurements by using modern techniques of molecular quantum state control. Specifically, we describe the CeNTREX (Cold molecule Nuclear Time Reversal Experiment) collaboration's goals and progress toward measuring the SM in thallium nuclei with TlF molecules. The molecules are highly polarizable, leading to the enhancement of the measured effect which is a precession of the nuclear spin about an applied electric field. The relatively new techniques of cold molecular beams and optical cycling in molecules are essential components of the experiment. We also discuss other novel uses of ultracold molecules in fundamental physics.

From artefacts to atoms - from the old to the new SI

Terry Quinn

International Bureau of Weights and Measures, BIPM, France

My talk will outline the history of units from the origin of the metric system to recent discussions on how best to redefine the SI based on a set of constants, thereby eliminating from the SI the last remaining artefact, the International Prototype of the Kilogram - discussions sometimes fraught!

Final Measurements of the Planck Constant

Barry Wood

National Research Council, Ottawa, Canada

In November of this year, in Versailles France, the 58 countries that make up the member states of the Metre Convention are expected to approve a revision of the world's measurement system, the SI [1]. This will be the most sweeping change in the SI in 130 years. In essence the change is based on assigning fixed values to seven reference constants and deriving measurement units from those constants using the laws of physics [2]. Those seven constants include five fundamental constants of nature; the speed of light, the elementary charge, the Planck constant, the Boltzmann constant and the Avogadro constant.

Of these the Planck constant, *h*, is key to redefining the unit of mass, the kg. There are two approaches to measuring a highly accurate value for *h*. One uses a Kibble (or watt) balance to relate mass, gravity, velocity, voltage and resistance to *h* through the use of the Josephson and quantum Hall effects. The other uses the crystal density approach to 'count' the number of atoms of a near perfect crystal of enriched ^{28}Si of known mass, volume and lattice spacing. This yields a value of the Avogadro constant which is then related to the Planck constant through the Rydberg and fine structure constant, both of which are known to higher accuracy.

In cooperation with the CIPM, the CODATA Task Group on Fundamental Constants performed a special adjustment of the fundamental constants with the purpose of setting the fixed values of the reference constants of the revised SI. July 1, 2017 was the closing date for publication of any new results and this analysis is now complete [3] and approved.

I will review experiments from both Kibble balances and Avogadro projects that contributed to the fixing of the value of *h*. and how the final recommended value was set.

References

[1] https://www.bipm.org/en/worldwide-metrology/cgpm/

[2] https://www.bipm.org/en/measurement-units/rev-si/

[3] David B Newell, Franco Cabiati, Joachim Fischer, Kenichi Fujii, Saveley G Karshenboim, Helen S Margolis, Estefania de Mirandes, Peter J Mohr, Francois Nez, Krzysztof Pachucki, Terry J Quinn, Barry N Taylor, Meng Wang, Barry Wood and Zhonghua Zhang, 'The CODATA 2017 Values of *h*, *e*, *k*, and N_A for the Revision of the SI', *Metrologia* **55** L13, (2018)

Measurement of the fine structure constant as test of the standard model

Holger Mueller

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Measurements of the fine structure constant α, using methods from atomic, condensed-matter, and particle physics, are powerful tests of the overall consistency of theory and experiment across physics. We have measured $\alpha = 1/137.035999046(27)$, at 2.0×10^{-10} accuracy, via the recoil frequency of cesium-133 atoms in a matter-wave interferometer. We used multiphoton interactions such as Bragg diffraction and Bloch oscillations to increase the phase difference for the interferometer to over 12 million radians, which reduced the statistical uncertainty and enabled control of systematic effects at the 0.12 part-per-billion level. This is an unprecedented test of the standard model of particle physics, being the first direct measurement of α with an error below the 5th order quantum electrodynamics contribution in the electron's gyromagnetic anomaly. It also has implications for the unexplained anomaly of the muon's magnetic moment, and strongly constrains multiple dark sector candidates as well as substructure of the electron.

QED theory of the Lamb shift of hydrogen and hydrogen-like ions for Rydberg constant and proton radius

Vladimir Yerokhin

St. Petersburg Polytechnic University, Russia

Detailed theoretical understanding of the Lamb shift in hydrogen is essential for determination of the Rydberg constant and the proton charge radius from hydrogen spectroscopy. The well-known "proton charge radius puzzle" raised questions about the accuracy of this determinations, since the proton charge radius extracted from muonic hydrogen deviated by about 7 sigma from that of the electron hydrogen. In my talk I will review the present status, recent developments and open problems in the theory of the Lamb shift of hydrogen and light hydrogen-like ions.

The magnetic moment of highly charged ions: Test of strong field QED and access to fundamental constants

Sven Sturm

Max Planck Institute for Nuclear Physics, Heidelberg, Germany

The g-factor of highly charged ions can be determined with utmost precision in Penning trap experiments. From these measurements, it is possible to test QED in strong fields and to extract the most precise values for fundamental constants. In our experiments, we have performed the most sensitive test of bound-state QED and we have determined the atomic mass of the electron and recently the proton. I will present the experiments and recent developments.

Quantum Hall Effect and Fundamental Constants

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Fundamental constants and metrology are modern topics due to the expected introduction of a revised international system of units based on constants of nature. The discovery of the quantum Hall effect (QHE) has opened up a relatively simple experimental way of realizing an electrical resistance based on fundamental constants. This new type of resistor is more stable and more reproducible than any other resistor and has therefore been used successfully in metrology since 1990. Comparisons between different devices made of different materials with different geometries confirmed the universality of the quantized resistance with an uncertainty of less than 1 part in 10^{10}.

All experimental tests confirmed that the quantized Hall resistance $R_K = h/e^2$ depends exclusively on the Planck constant h and the elementary charge e. Since this combination of fundamental constants is identical with the fine structure constant α (beside some fixed numerical values), a new way has been found for the high precision determination of α.

The talk gives an overview about the contribution of the quantum Hall effect (along with the Josephson effect) to the development of a revised system of units and to metrology in general.

Laser spectroscopy of muonic atoms - Nuclear physics and fundamental constants

Randolf Pohl

Johannes Gutenberg-Universität Mainz, Germany

Laser spectroscopy of light muonic atoms and ions, i.e. a negative muon bound to a bare nucleus, is very sensitive to nuclear parameters such as charge and Zemach radii and polarizabilities. I will report on recent measurements by the CREMA Collaboration of the charge radii in light muonic atoms from hydrogen to helium, and the ongoing efforts to measure the Zemach radius of the proton.

Hydrogen 1S-3S spectroscopy with a cw laser

François Nez

Laboratoire Kastler Brossel, CNRS, Paris, France

The precise measurement of the frequency of the 1S-3S transition of the hydrogen (H) atom is of great interest for the proton charge radius (R_p) puzzle, which originates from the recent results of muonic hydrogen (μp) spectroscopy. Moreover the recent H (2S-4P) spectroscopy done at Garching shed new light to this puzzle as it gave a smaller value of R_p in agreement with μp experiment. The 1S-3S two-photon transition is excited, in an atomic hydrogen beam, using a 205 nm cw laser obtained by sum of frequencies in a non-linear crystal. The frequency of the transition is measured with respect to the cesium clock of the LNE-SYRTE using a frequency comb. The recording of the signal for different values of an applied magnetic field makes it possible to estimate the velocity distribution of the atoms of the beam and to deduce therefrom the second order Doppler effect. We recently measured the frequency of this hydrogen transition at 300K with a record uncertainty of 1.7×10^{-12}. The corresponding value of R_p is in very good agreement the last CODATA estimate of Rp. I will give the last developments of the experiment.

Hyperfine splitting in simple ions for the search of the variation of fundamental constants

Natalia Oreshkina

Max Planck Institute for Nuclear Physics, Heidelberg, Germany

Numerous few-electron atomic systems are considered which can be used effectively for observing a potential variation of the fine-structure constant and the electron-proton mass ratio. We examine optical magnetic dipole transitions between hyperfine-structure components in heavy highly charged H-like and Li-like ions with observably high sensitivity. The experimental spectra of the proposed systems consist of a strong single line, which simplifies significantly the data analysis and shortens the necessary measurement time. Furthermore, we propose systems for an experimental test of the variation of quark masses and discuss the expected level of accuracy in assessing its limitations. Finally, we establish which constraints on the variation of these fundamental constants could be provided by measurements with a hyperfine-structure highly-charged-ion clock and some reference clock, showing that a significant improvement of the current limitations can be reached.

Highly charged ions for fundamental studies

José R. Crespo López-Urrutia

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Highly charged ions (HCI) emit radiation in the range from the visible to the x-rays and are ubiquitous in astrophysical and fusion plasmas. They possess extremely narrow electric-dipole forbidden transitions from the infrared to the x-ray domain. Lacking laser-cooling possibilities, high-resolution spectroscopic frequency metrology studies were hindered by laboratory-production temperatures in the MK range. By applying sympathetic cooling in Coulomb crystals, we recently overcame this limitation, and are currently performing experiments with narrow-band lasers to study forbidden transitions of fundamental interest. For this purpose, we have developed cryogenic RF ion traps and appropriate techniques of HCI production, transfer, storage and cooling. Furthermore, using our electron beam ion traps as well as in combination with free-electron lasers and synchrotron radiation sources, we systematically investigate the electronic structure of HCI in the visible, VUV, EUV and x-rays regions seeking to identify ideal clock transitions for various fundamental studies.

Abstracts of Posters

(in alphabetical order)

Satellite-based clock comparisons – a status report

A. Bauch

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The comparison of distant clocks has always been an important part of time metrology. It is important in science in general, and last but not least in the context of long-term comparisons among clocks providing insight in potential variations of fundamental constants. During the past years, the performance of clocks has tremendously been improved so that satellite-based methods of comparison are challenged. Nevertheless, they constitute today the only means for bridging intercontinental distances and thus the state of the art is worth to be discussed.

I am going to report on two satellite-based methods, the reception of signals of Global Navigation Satellite Systems (GNSS), and Two-Way Satellite Time and Frequency Transfer (TWSTFT). When signals from the satellites of the Global Positioning System (GPS) started to be used for the purpose in the early 1980s, time-keeping was revolutionized. The methods of signal processing have improved to an extent that time transfer with ns-accuracy and frequency transfer with 10^{-16} relative instability have become feasible [1]. TWSTFT includes the exchange of modulated signals from ground-terminals via geo-stationary telecommunication satellites. It was introduced as early as 1980, but its routine use started in the early 1990s only. The method is very powerful, but the observed performance is inter alia limited by the allocated financial resources and the availability of suitable satellites. The most recent development [2] includes fully digital processing of the received signals and this proved to mitigate some performance limitations.

References

[1] G. Petit et al., Metrologia **52,** 301 (2015)
[2] Y. J. Huang et al., Metrologia **53**, 881 (2016)

Spectroscopy of optical transitions in highly charged ions with applications to metrology and searches for the variation of fundamental constants

H. Bekker [1] **and J. R. Crespo López-Urrutia** [1]

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Highly charged ions (HCI) have a much reduced sensitivity to external perturbations compared to the atoms and ions used in current state-of-the-art optical clocks. Furthermore, increased relativistic effects in HCI can lead to a high sensitivity to variation of the fine-structure constant, see e.g. [1,2]. For these reasons, many HCI with optical transitions have been proposed for use in clocks. However, for these, theory is not capable of predicting the energy level structures to the required precision. Therefore, we investigated several of the proposed HCI, which we produced, trapped, and collisionally excited in the Heidelberg electron beam ion trap (HD-EBIT). The wavelengths of subsequent fluorescence light were determined at the ppm-level using grating spectrometers [3, 4]. We present our latest results for several iridium charge states which are predicted to have transitions with an extremely high sensitivities to variation of the fine-structure constant. These results are also used to benchmark advanced atomic theory calculations and to provide a deeper insight into the suitability of the proposed HCI for metrology purposes.

References

[1] J.C. Berengut, V.A. Dzuba, and V.V. Flambaum Phys. Rev. Lett. **105**, 120801 (2010)

[2] M.G. Kozlov, M.S. Safronova, J.R. Crespo López-Urrutia, and P.O. Schmidt, *arXiv preprint arXiv:1803.06532(2018)*

[3] H. Bekker, O. O. Versolato, A. Windberger, *et al,* J. Phys. B **48**, 144018 (2015)

[4] A. Windberger, J.R. Crespo López-Urrutia, H. Bekker, *et al*, Phys. Rev. Lett. **114**, 150801(2015)

Coupled Penning Traps for Sympathetically Cooled Protons and Antiprotons

Matthew Bohman

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Trapped single particles provide an excellent testbed for probing fundamental symmetries at low energy. The proton and antiproton g-factors and charge-to-mass ratios, for example, provide stringent tests of CPT invariance. However, such experiments are often limited by high ion temperatures. Here we show a novel approach to couple single protons to laser cooled ions and present results from newly laser cooled ions in our experiment.

Development of NPL's next generation lattice clock

William Bowden

National Physical Laboratory and Oxford University, UK

We will present recent developments of Sr2—NPL's second generation lattice clock—highlighting key design changes made to improve its performance. These changes include: a pyramid MOT to simplify the optical system; in-vacuum build-up cavities for the optical lattice to better evaluate the resulting Stark shifts; and a triplet MOT operating at 2.9 um to replace the second stage cooling in the hopes of reducing the required cooling time.

Once operational, Sr2 will be integrated into Europe's existing optical clock network such that it can be compared to other frequency standards. Such comparisons will help provide stringent constraints on possible variations of fundamental constant. Furthermore, this distributed network of clocks will allow for testing cornerstones of general relativity such as Lorentz invariance and local position invariance.

The g-Factor of Lithium-like Systems

Halil Cakir

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The calculation of the g-factor of highly charged ions allows us to test QED effects in very strong fields. In the recent past, an accurate computation together with a precise measurement of the g-factor of H-like carbon allowed a significant improvement of the mass of the electron. A similar interplay between theory and experiment for the g-factor of Li-like ions is expected to improve the value of the fine-structure constant [1].

Currently, theoretical computations of the g-factor of Li-like ions are not on the same level of precision as experimental values [2]. In particular, an expansion in the nuclear coupling constant is not feasible for highly charged ions and one needs to take into account interactions with the nucleus to all orders.

In this context, we are in the progress of computing QED screening corrections to the g-factor of light and medium-heavy Li-like systems. We present our progress in the computation of screening effects using numerical schemes.

References

[1] V. A. Yerokhin *et al.*, Phys. Rev. Lett. **116**, 100801 (2016)
[2] A. Wagner *et al.*, Phys. Rev. Lett. **110**, 033003 (2013)

A Novel Method to Measure the Quotient of Gyromagnetic Ratios in a Comagnetometer System

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A novel technique to extract the quotient of gyromagnetic ratios in a comagnetometer system is presented. This technique aims to probe the quotient in a regime which is free from the spin-relaxation related systematic effects. It is based on the measurement of spin precession frequencies in a gaseous mixture of ^{129}Xe and ^{3}He at ultralow magnetic field. The resultant quotient value appears to be close to the literature value.

Physical dimensions and units, universal constants and their relativistic invariance

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1. A *physical quantity* can always be represented by a number (or by numbers) and by a *physical dimension*. One can read the physical dimension as a code of how to measure this quantity. The number/s depend on what system of units is chosen. A unit (like 'V' or 'kg') should be clearly distiguished from a physical dimension (here 'voltage' or 'mass', respectively).

2. *Quantity equations,* built up from physical quantities, are independent of the system of units chosen. The *SI* (International System of units) uses quantity equations [1].

3. Nowadays in classical mechanics we use *time, lenth,* and *action* and in classical electrodynamics, additionally, *electric charge* (from charge conservation) and *magnetic flux* (from Faraday's law) as fundamental dimensions. The notions action, electric charge, and magnetic flux are scalars in special relativity (SR) and in general relativity (GR) alike; they all can be cut into scalar 'portions.' Time and length are of a different character [2].

4. Fleischmann (1971) divided all *universal scalars* into those invaraint only in SR—scalars under Poincaré (inhomogeneous Lorentz) transformations—and those invariant even in GR—scalars under arbitrary coordinate transformations. Action, el. charge, and magn. flux are GR-scalars, the speed of light is only a SR-scalar [3].

5. The *Josephson* constant, $K_{\mathrm{J}} = 2e/h \overset{\mathrm{SI}}{\approx} 0.5\,P\mathrm{Hz/V}$, and the *von Klitzing* constant, $R_{\mathrm{K}} = h/e^2 \overset{\mathrm{SI}}{\approx} 25\,k\Omega$, are important for the new SI to come out later this year. For dimensional reasons, they both are GR-scalars [4,5].

6. The *speed of light* c is, by its own definition, merely a SR-scalar. It requires 2 distant point in space for its measurement. Hence it cannot be directly measured in a gravitational field, not even in a freely falling reference frame. This effect is responsible for the deflection of light near a star. The *universal constant* c_0, which is conventionally postulated to be a GR-scalar, seems to be operationally different from the speed of light c, see also [6,7]. The experimentally determined speed of gravitational waves c_{gr} can hopefully throw new light on this question [8,9].

[1] Wallot, Quantity Equations, Units, and Dimensions (in German) Leipzig 1953. [2] Post, Formal Structure of Electromagnetics, Amsterdam 1962. [3] Fleischmann, Lorentz and metric invariant scalars (in German) Z. Naturf. A 26, 331 (1971). [4] Hehl, Obukhov, Rosenow: Is the quantum Hall effect influenced by the gravitational field? PRL 93, 096804 (2004). [5] Hehl, Itin, Obukhov, On Kottler's path... Int. J. Theor. Phys. D 25, 1640016 (2016). [6] Braun, Schneiter, Fischer: Intrinsic measurement errors for the speed of light in vacuum, Class. Quantum Grav. 34, 175009 (2017). [7] Lämmerzahl and Hehl, Riemannian light cone from vanishing birefringence in premetric vacuum electrodynamics, PRD 70, 105022 (2004). [8] Cornish, Blas, Nardini, Bounding the speed of gravity with gravitational wave observations, PRL 119, 161102 (2017). [9] See the slides of my invited lecture: http://www.thp.uni-koeln.de/gravitation/mitarbeiter/Bremen2017_03.pdf

Comparison of two high-accuracy optical ion clocks for hundredfold improved bounds on Lorentz violation

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We employ two Yb^+ single-ion optical frequency standards that differ significantly with respect to trap geometry, control software and interrogation sequence. The clock frequency is determined by the $^2S_{1/2}$-$^2F_{7/2}$ electric octupole transition. The relative systematic uncertainty of the clocks has been evaluated to less than 4×10^{-18} [1]. In a long-term comparison of the two clocks for a period of six months, we find an agreement of the Yb^+ clock frequencies within the systematic uncertainty.

The two ions with their anisotropic electron momentum distributions in the metastable $^2F_{7/2}$ manifold are aligned along orthogonal quantization axes tilted with respect to Earth's axis of rotation. Therefore, a violation of Local Lorentz Invariance (LLI) would cause a modulation of the clocks' frequency difference resulting from the rotation of the earth in space. From the absence of such a sidereal modulation between both clocks on the 2×10^{-18} level, we deduce limits on a possible violation of LLI for electrons (and photons) in the range of 1×10^{-21}, an improvement on previous experiments [2] by two orders of magnitude.

References

[1] N. Huntemann et al., PRL **116**, 063001 (2016)
[2] T. Pruttivarasin et al., Nature **517**, 592 (2015)

Proposed measurement of G in space

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Since the gravitational constant *G* still is measured with large uncertainty only, a new experiment in space is proposed employing the classic gravity train mechanism. This requires a larger solid sphere with a cylindrical hole through its center, a small retroreflector which will undergo harmonic motion within the hole and a host spacecraft with laser ranging capabilities to measure round trip light-times to the retroreflector but separated a significant distance away from the sphere-retroreflector apparatus. Measurements of the period of oscillation of the retroreflector in terms of host spacecraft clock time using existing technology could give determinations of *G* nearly three orders of magnitude more accurate than current measurements on Earth. However, significant engineering advances in the release mechanism of the apparatus from the host spacecraft will likely be necessary. Issues regarding the stability of the system are addressed.

References

[1] M. Feldman, J.D. Anderson,. G. Schubert, V. Trimble, S.M. Kopeikin, C. Lämmerzahl, Classical and Quantum Gravity **33**, 125013 (2016)

Coherent and incoherent methods of suppressing frequency shifts in optical clocks

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No optical clock transition frequency is fully immune against shifts induced by external electric and magnetic fields. However, there are methods to average some of these perturbations to zero. For example, the electric quadrupole shift that is often encountered in ion clocks can effectively be eliminated by averaging the frequencies in three mutually orthogonal orientations of the magnetic field that controls the ion's quantization axis [1]. Operating the optical clock at each of the three orientations for the same amount of time can be viewed as an incoherent shift suppression scheme. In this case, the unperturbed transition frequency can be inferred only after the three measurements and its uncertainty is limited by the orthogonality of the magnetic field orientations and the stability of the perturbation. We devise an alternative approach based on coherent averaging during the Ramsey dark period of the ion interrogation sequence, suppressing the perturbation along one measurement cycle. Using the quadrupole shift prone $^2S_{1/2}$ to $^2D_{3/2}$ transition of $^{171}Yb^+$ [2], we demonstrate advantages of the coherent suppression scheme compared to the incoherent method.

References

[1] W. Itano, J. Res. Natl. Inst. Stand. Technol. **105**, 829 (2000)
[2] Chr. Tamm *et al.*, Phys. Rev. A **80**, 043403 (2009)

A cryogenic Paul trap for quantum logic spectroscopy of highly charged ions

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Certain optical transitions in highly charged ions (HCI) are sensitive probes for new physics beyond the standard model, particularly for any variation in the fine structure constant [1]. If these transitions could be probed with the same precision and accuracy as present state-of-the-art optical atomic clocks, it would be possible to detect variations below the fractional level of 10^{-18} per year.

However, the lifetime of HCI in ion traps is limited by charge exchange collisions with residual background gas in the vacuum chamber. To extend storage times to spectroscopically useful durations requires a vacuum level that can only be achieved in a cryogenic environment.

We have set up a newly designed cryogenic 3D Paul trap for simultaneous trapping of Be^+ and HCI. This allows for sympathetic cooling of the HCI [2] to the motional ground state in the Paul trap, corresponding to a temperature of 50 μK. This paves the way to a potential 10^9-fold improvement in spectroscopic precision and accuracy in HCI.

We will present the first results from our experiment, including a characterisation of the trap and demonstration of coherent manipulation and ground state cooling of single Be^+ ions.

References

[1] J.C. Berengut, Phys. Rev. Lett. **105**, 120801 (2010)
[2] L. Schmöger, Science **347**, 6227 (2015)

Frequency shifts for gaseous particles moving in electromagnetic fields: Application for Xe electric dipole moment experiments

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A nonzero electric dipole moment (EDM) for spin-1/2 particles would violate the time reversal symmetry [1]. The measurement of particle EDM provides a good window to search for physics beyond the standard model [2]. A class of EDM experiment deals with the spin precession of atomic nucleus under the electric field excitation. The signature of EDM in such experiments would represent a shift in the precession frequency proportional to the electric field strength. Any additional frequency shift that is correlated to the electric field must be well-understood or proven to be negligible.

The thermal motion of a gaseous atoms enclosed within a glass cell in inhomogeneous electromagnetic fields will cause three known frequency shifts in the Lamour frequency [3] that are proportional to the quadratic electric field E^2, to the quadratic transverse magnetic field B^2, and to the **E×B**. Here, we apply the Redfield theory [4] to derive analytic expressions for the three frequency shifts valid for ^{129}Xe and ^{3}He undergoing diffusive motion within a cylindrical cell. The theoretical predict ions for these three frequency shifts in typical Xe EDM experiments are given and compared to the value calculated by the existing formulas.

References

[1] M.A. Rosenberry and T.E. Chuup, Phys. Rev. Lett. **86**, 22 (2001)
[2] S. K. Lamoreaux and R. Golub, J. Phys. G Nucl. Part. Phys. **36**, (2009).
[3] J. M. Pendlebury, W. Heil, Y. Sobolev, et al., Phys. Rev. A **70**, 1 (2004).
[4] G. Pignol, M. Guigue, a. Petukhov, et al., Phys. Rev. A **92**, 053407 (2015)

Towards Quantum Logic Spectroscopy of Highly Charged Ar^{13+}

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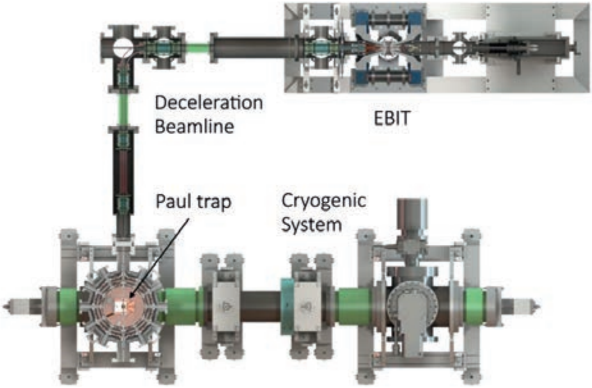
Highly charged ions (HCI) feature strongly enhanced relativistic, quantum electrodynamics and nuclear-size effects compared to neutral or singly-charged atomic systems, while they are much less sensitive to external perturbations. Hence, they are well suited for studying fundamental physics and constants. Furthermore, HCIs offer forbidden optical transitions that are extremely sensitive to any change of the fine-structure constant or electron-proton mass ratio, and present the possibility of novel optical clocks with unprecedented accuracy [1]. We have developed a new class of compact electron beam ion traps (EBIT) [2] to ease access to HCIs for such experiments. These devices have already demonstrated excellent performance in high-resolution measurements of dielectronic recombination by means of their electron beam. One of these devices provides HCIs for a cryogenic Paul trap, an evolved version of CryPTEx [3,4,5], aiming at HCI-based clock applications. Extracted from the EBIT and transferred through a deceleration beamline, HCIs will be re-trapped in a laser-cooled beryllium crystal in the Paul trap. Ultimately, quantum logic spectroscopy [6] will allow for the most accurate optical spectroscopy on HCIs. First results on the commissioning of this experiment will be shown.



References

[1] M. G. Kozlov et al., arXiv:1803.06532 Phys. (2018).
[2] P. Micke et al., Rev. Sci. Instrum. (submitted).
[3] M. Schwarz et al., Rev. Sci. Instrum. **83**, 083115 (2012).
[4] L. Schmöger et al., Science **347**, 1233 (2015).
[5] L. Schmöger et al., Rev. Sci. Instrum. **86**, 103111 (2015).
[6] P. O. Schmidt et al., Science **309**, 749 (2005).

Geometry of molecules and solids varying with fundamental constants

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We investigate the dependence of crystal lattice parameters and molecular bond lengths on the fine-structure constant α and proton-to-electron mass ratio μ. Precise experimental setups involved in the detection of variation of fundamental constant, scalar dark matter and gravitational waves, such as laser interferometers and resonant-mass detectors, are directly linked to measuring changes in material size. We present calculated and experiment-derived estimates of α- and μ-dependence of lattice constants and bond lengths of selected solid-state materials and diatomic molecules.

The Proton's Atomic Mass and the Puzzle of Light Masses

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At our cryogenic Penning-trap experiment in Mainz we have performed various ultra-high precision *g*-factor measurements on highly charged ions (HCI), resulting in the most stringent tests of bound state QED [1] and the most precise value for the electron's atomic mass [2]. While a new setup called ALPHATRAP at the Max-Planck-Institut für Kernphysik in Heidelberg with access to heavier HCI will allow to continue these *g*-factor measurements, the experiment in Mainz has been upgraded and shifted its focus to high-precision mass measurements of light ions. It is now termed LIONTRAP (Light ION TRAP).

To this end, a dedicated cryogenic Penning-trap setup consisting of five Penning traps, including a novel doubly compensated measurement trap, has been built. We recently measured the proton mass by comparing the cyclotron frequencies of a single proton and a bare carbon nucleus [3], achieving a relative mass uncertainty of 3.2E-11, a factor of three more precise than the CODATA value, and revealing a 3-sigma deviation with respect to this value. This, however, is not enough to explain recently arisen discrepancies in light ion mass measurements [4].

The status and results of LIONTRAP will be presented as well as the "light mass puzzle" discussed.

References

[1] Köhler-Langes et al., Nature Communications **7**, 10246 (2015)
[2] Sturm et al., Nature **506**, 467-470 (2014)
[3] Heiße et al., Phys. Rev. Lett. **119**, 033001 (2017)
[4] Hamzeloui et al., Phys. Rev. A **96**, 060501 (2017)

Commissioning of the Penning-trap mass spectrometer PENTATRAP

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The Penning-trap mass spectrometer PENTATRAP is currently in the commissioning phase at the Max-Planck-Institute for Nuclear Physics in Heidelberg. We are aiming at measurements of mass ratios using highly charged ions with a relative uncertainty of better than 10^{-11}. This allows, among others, contributions to neutrino physics, electron binding energy determination in highly charged ions and tests of special relativity. After a revision of the cryogenic setup and the ion transfer beamline we currently trapped the first cold single ion in our trap system. We showed full control over the three eigenmotions by coupling one of the radial motions to the axial motion. The transport between the traps was successfully demonstrated and first mass ratio measurements at the 5×10^{-10} precision level are currently in progress. This poster contribution will report on the technical setup and current commissioning measurements of $^{132}\mathrm{Xe}^{+17}/^{131}\mathrm{Xe}^{+17}$.

The ALPHATRAP g-factor Experiment

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The Penning-trap experiment ALPHATRAP, located at the Max-Planck-Institut für Kernphysik in Heidelberg, aims to measure the g-factor of bound electrons in highly charged ions (HCI) up to hydrogen-like $^{208}\text{Pb}^{81+}$. In the electrical field of the nucleus with a strength on the order of 10^{16} V/cm, bound-state quantum electrodynamics can be tested with highest precision in extreme conditions. To overcome current thermal limitations of the achievable precision, laser-cooling will be implemented. To this end, a Laser Ion Source (LIS) produces $^{9}\text{Be}^{+}$ ions, which can be laser cooled in the trap using a 313 nm laser system. The HCI, which cannot be directly addressed by the laser, will be sympathetically cooled by the $^{9}\text{Be}^{+}$ ions. As the production of HCI requires high energies, an in-trap production is not possible. Therefore, the trap is connected via a beamline to different ion sources to allow transport and injection of externally produced ions while maintaining a vacuum better than 10^{-16} mBar in the cryogenic trap.

Calibration & Traceability Challenges and its Impact to the Development of Mechanical Engineering

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With the brave new world of the many new facets of the internet of things (IoT) we presently see extensive changes in the market and even an ambivalence of new and old in metrology. We may talk of a "sensorization" in the market, expressed in a much higher quantity of sensors affordable to be employed. The IoT, integrated sensor systems of high complexity, up to the so called SelfX properties such as self-healing, self-coordination, self-organization, self-optimization or self-calibration keep us busy in the R&D depts., having a lot of the wind in its sails.

Thus questions dealing with the nature of metrology, as the representation and the traceability of the measured variables and the measurement uncertainty, seem to be not so important anymore.

This ambivalence must not be, I will prove this with some examples from HBM company metrological practice with mechanical quantities, important for the manufacturing of cars, machine tools as well as energy generation. Because the departure for new shores requires a solid base and everything origins from this point. As metrological traceability is defined property of a measurement result whereby the result can be related to a reference though a documented, unbroken chain of calibration, each contributing to the measurement uncertainty. Now large quantities of sensors are used in sensor networks, and they may have only average accuracy, however at least once in their life also they have to see a reference, otherwise any measurement is not defined.

Mechanical quantities are mostly traced back by very precise reference measuring chains based on strain gauges, such as provided by HBM company. The sophisticated traceability infrastructure is also based on that technology. This remains the essential foundation for all new developments. If we take Germany as an example, the secondary accreditation level "DAkkS" consists of as much as 204 labs for mechanical quantities thereof 77 labs for force/material testing, 44 labs for torque and 83 labs for pressure. There are HBM-solutions for all these quantities. They are the basis to master the challenges of the future and traceability remains the backbone for any development in mechanical engineering.

As Lord Kelvin said "If you can not measure it, you can not improve it".http://www.azquotes.com/quote/791855

References

[1] Sommer, K. D. "New Calibration & Traceability Challenges Caused by Smart Sensor Technologies & Digitally Networked Measurement Systems as Part of the IoT" 308. PTB-Workshop "Calculation of measurement uncertainty - recommendations for practice" organized by PTB, DAkkS & BAM Berlin (2018)

[2] Thomson, S. P. "The Life of William Thomson, Baron Kelvin of Largs" (1910)

Optical trapping of ion Coulomb crystals

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Ion Coulomb crystals are the key to many applications with trapped ions, as the crystal phonons mediate interaction between ions and allow coupling of electronic and motional states on the quantum level [1]. However, rf-micromotion in ion traps poses fundamental limits for applications with higher-dimensional Coulomb crystals [2] and in ultracold chemistry experiments. Optical dipole traps for trapped ions [3] do not exhibit this micromotion, but only trapping of single ions had been demonstrated thus far.

We now demonstrate trapping of ion crystals [4] consisting of up to six Barium ions in an optical dipole trap aligned with the crystal axis and without confinement by radio-frequency (RF) fields. The dependence on the trap parameters, in particular the interplay of beam waist, laser power and axial confinement by DC electric fields, is investigated. As a proof-of-principle experiment, we detect the center-of-mass and stretch modes for an optically trapped two-ion crystal. Finally, we present prospects for optical trapping of higher-dimensional Coulomb crystals.

References

[1] D.J. Wineland, Rev. Mod. Phys. **85**, 1103 (2013)
[2] R. Thompson, Contemp. Phys. 1,56, 63-79 (2015)
[3] A. Lambrecht et al., Nat. Phot. 11, 704-707 (2017)
[4] J. Schmidt et al., arXiv:1712.08385 (PRX accepted) (2017)

Image charge shift in precision Penning traps

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Penning-trap experiments can reach relative mass or g-factor precisions up to the few parts-per-trillion level (10^{-12}). At this level of precision the induced charges on the surface of the electrodes caused by the trapped ion shift the ion's frequencies significantly and systematically. This effect is called image charge effect. So far, the only approach to characterize this effect is to vary the number of trapped ions, leading to a change in the surface charge density, and to analyse the observed frequency shift. However, the exact number of ions for more than one ion in a trap is challenging. Both the number of ions and in addition, the ion-ion interaction provide a source of uncertainty for the final result. This poster will give an introduction to the investigation of the image charge shift with finite element simulations using Comsol Multiphysics as well as a semi-analytical approach, based on the idea by J.V. Porto from 2001. The results are compared to recent experimental studies.

High-precision theory of the g-factor of bound fermions

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The g-factor of electrons bound in highly charged ions can be measured and calculated with high accuracy. Comparisons between the theoretical and experimental values of the g-factor allow precision tests of QED and the determination of fundamental constants such as the electron mass [1] or the fine-structure constant.

In order to achieve a high theoretical accuracy in heavy hydrogenlike ions, the interaction with the nuclear potential needs to be taken into account exactly. We present partial results for our non-perturbative evaluations of the two-loop self-energy correction, which is currently the largest source of uncertainty.

Furthermore, we put forward a method to determine the muon mass employing the theory of the bound-muon g-factor. Our approach allows the improvement of the accuracy of the muon mass by one order of magnitude, provided the required experimental accuracy can be achieved [2].

References

[1] J. Zatorski *et al.*, Phys. Rev. A **96**, 012502 (2017)

[2] B. Sikora *et al.*, Access to improve the muon mass and magnetic moment anomaly via the bound-muon g factor, arXiv:1801.02501v1 [hep-ph]

Gravitational influences on Earth-based measurements of the free electron g-factor

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Today, the gyro-magnetic ratio of the free electron is known to very high accuracy of g/2=1,001 159 652 180 73(28) [1] and to improve this value is still an interest of current research. The free electron g-factor is measured by trapping the electron in an electromagnetic field configuration. The effects of external fields have to be known to high precision to compensate their contribution to the g-factor measurements. On Earth, the electron, as well as the electromagnetic field is effected by an (approximately homogeneous) gravitational field, which can be treated as a spacetime of constant acceleration (Rindler spacetime).

In this work, we discuss the changes of the electron's dynamics in a Penning trap, distorted by gravity, leading to direction dependent modifications of the coupling between magnetic field and spin.

References

[1] D. Hanneke, S. Fogwell, G. Gabrielse, PRL **100**, 120801 (2008)

Giant fiber-optic gyroscope for seismological measurements based on the Sagnac effect

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Long optical fiber links allow to disseminate frequency and time signals between distant laboratories [1,2]. We wish to re-instate the previously investigated "east" route between the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig and the Max-Planck-Institut für Quantenoptik (MPQ) in Garching (920 km, [3]) and combine it with a new "west" route between PTB and MPQ via Karlsruhe (940 km, currently being set-up, see the contribution of Dr. Th. Waterholter). Together these two links form a large loop which encloses area of about 20000 km^2 and is planned to run as passive interferometer for Sagnac effect measurements [4]. We are going to focus on Sagnac phase deviations caused by earthquakes and other geo- and seismological effects [5].

References

[1] G. Grosche et al., Optics Letters **34**, 2270 (2009)
[2] S. Droste et al., Physical Review Letters **111**, 110801 (2013)
[3] K. Predehl et al., Science **336**, 441 (2012)
[4] C. Clivati et al., Optics Letters 38, 1092 (2013)
[5] J. Salvermoser et al., Seismological Research Letters **88**, 935 (2017)

A first direct nuclear laser excitation scheme for ^{229m}Th

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Direct nuclear laser excitation of the low-lying nuclear isomer ^{229m}Th has been a long-standing objective. Until recently it was assumed that reaching this goal would require a significantly reduced uncertainty of the isomer's excitation energy. However, a new direct nuclear laser excitation scheme was proposed, which circumvents this requirement [1]. The scheme makes use of the isomer's internal conversion (IC) decay channel [2] and the recently confirmed short isomeric IC lifetime [3]. Further, it is based on already existing laser technology, thereby paving the way for a first nuclear laser excitation and the determination of the isomeric transition energy to a precision of 10^{-5} eV. This energy precision would be sufficient for the development of a single-ion nuclear clock based on ^{229}Th.

In the presentation the proposed concept of nuclear laser excitation will be detailed and the current status of experimental preparation will be given. Experiments will start this summer in collaboration with the University of Hannover.

References

[1] L. v.d. Wense *et al.*, PRL **119**, 132503 (2017)
[2] L. v.d. Wense *et al.*, Nature **533**, 47 (2016)
[3] B. Seiferle *et al.*, PRL **118**, 042501 (2017)

Combination of two optical amplification methods on a 1880 km looped optical fiber link

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We investigate optical frequency transfer over a looped 1880 km phase-stabilized fiber link, equipped with two different types of optical amplifiers. The link connects the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig and the Max-Planck-Institut für Quantenoptik (MPQ) in Garching via the Karlsruhe Institute of Technology (KIT). At KIT we have connected two link segments: the PTB-KIT part (600 km one-way), equipped with three fibre Brillouin amplifiers, and the MPQ-KIT part (340 km one-way), equipped with three bidirectional Erbium-doped fiber amplifiers. The link is currently looped at MPQ to characterize the link and the interaction between the two segments. We aim at a frequency transfer uncertainty below 1×10^{-18} (at ~40 000 s), allowing tests of the transportable Sr optical clock developed at PTB and chronometric levelling experiments with negligible link uncertainty contributions. To date, we have performed first tests with the composite phase-stabilized link and the individual segments.

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