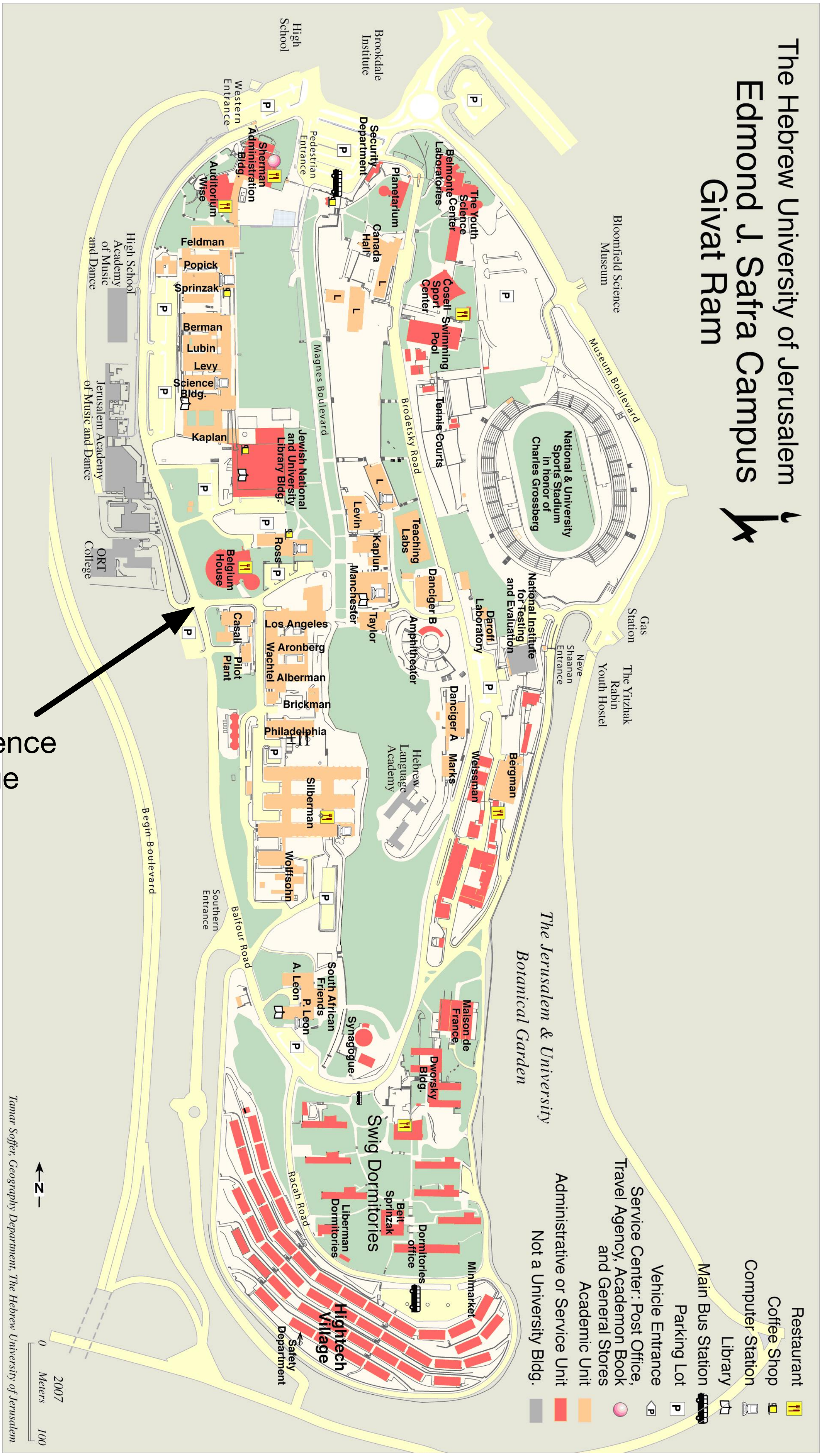
האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY of JERUSALEM
الجامعة العبرية في القدس
THE RACAH INSTITUTE OF PHYSICS

PSAS'2016

International Conference on
Precision Physics of Simple Atomic Systems

Program
and
Book of Abstracts



Conference Venue

Preface

The conference is devoted to precision studies of simple atoms and molecules in order to develop new approaches and to access various fundamental issues within and beyond atomic physics, and possible new physics. Applications include aspects from particle and nuclear physics, atomic and molecular physics, astrophysics, metrology, etc.

Conference topics include :

- Precision spectroscopy of hydrogen, its isotopes and other light atoms
- Precision frequency measurements and determination of fundamental constants
- Quantum electrodynamics and advanced quantum mechanics
- Study of pure leptonic systems, muonic and exotic atoms
- Study of few-electron ions with medium and high Z
- Search for variation of fundamental constants and tests of fundamental symmetries
- Structure of light nuclei and other hadronic effects
- Fundamental constants of particle physics
- Quantum Information
- Astrophysics and Cosmology
- New SI system

The scientific part of the conference is composed of 30m talks (throughout the day), and a poster session on Monday evening afternoon. The abstracts of all the presentations are collected in this booklet. This conference is generously supported by the Internation Union of Pure and Applied Physics (IUPAP) and the Hebrew University.

We have arranged the program such that there is ample time for discussions outside the sessions (during the coffee and lunch breaks) but also during the social events after the main sessions. We wish you all a very fruitful conference and many new cooperative efforts.

On behalf of the local organizing committee and the international program committee,

Guy Ron, Nadav Katz, and Savely Karshenboim

All sessions will take place in the Beyt Belgia library room. Lunches and coffee breaks will be served on the deck outside the library. The reception and the poster session will also take place on the deck. The conference dinner will take place at the Eucalyptus restaurant in Jerusalem (Felt alley, between Hativat Yerushalayim 14 and Dror Eliel st., Jerusalem), following the tour of the old city.

Relevant phone numbers for the workshop:

Name	**Local Phone Number**
Guy Ron	+972-505-703802
Nadav Katz	+972-542-563212
Belgium House (Conference venue)	+972-2-5660192
Campus security	+972-2-6585000

	22/5, Sunday	23/5, Monday (Registration @ 8:00-9:15AM) (Opening @ 9:15AM)	24/5, Tuesday	25/5, Wednesday	26/5,Thursday	27/5, Friday
9:00-9:30		Registration + Welcome	Retzker	Puchalski	Eides	Zientkiewicz
9:30-10:00		Budker	Keil	Bubin	Adkins	Vacchi
10:00-10:30	Arrival and Registration (starting 17:00)	Widmann	Pe'er	Natarajan	Crivelli	
10:30-11:00		Coffe Break	Coffe Break	Coffe Break	Coffe Break	Coffe Break
11:00-11:30		de Sarlo	Mukherjee	Sturm	Perez	Summary
11:30-12:00		Karshenboim	Bar-Gill	Harman	Rizzo	
12:00-12:30		Pachucki	Margalit	Antognini	Falke	
12:30-14:00		Lunch	Lunch	Lunch	Lunch	
14:00-14:30		Ubachs	Tour	Schimdt-Kaler	Carlson	
14:30-15:00		Salumbides		Donaire	Maisenbacher	
15:00-15:30		Korobov		Gazit	Krauth	
15:30-16:00		Coffe Break		Coffe Break	Coffe Break	
16:00-16:30		Łach		Altman	Kohl	
16:30-17:00		Czarnecki		Sun	Mooser	
17:00-17:30		Quint		Ebser	Lee	
17:30-18:00		Ficek		Barad	Nagahama	
18:00-21:00	Reception (19:30)	Poster Session (18:30)	Conference Dinner (19:00)			

Program

Sunday – 22/5

17:00 – 19:30	Registration
19:30	Reception

Monday 23/5

Session 1 (Chair – Guy Ron)	
8:00 – 9:15	Registration
9:15 – 9:30	Welcome (Prof. Igal Erel – Dean)
9:30 – 10:00	*Dark-OST: searching for oscillating and transient effects from the Dark Sector with atomic spectroscopy and nuclear resonance* - Budker
10:00 – 10:30	*Prospects of in-flight hyperfine spectroscopy of (anti)hydrogen for tests of CPT symmetry* – Widmann
10:30 – 11:00	Coffee Break
Session 2 (Chair – Nadav Katz)	
11:00 – 11:30	*Searching for variations of fundamental constants using the atomic clocks ensemble at LNE-SYRTE* – de Sarlo
11:30 – 12:00	*Progress in determination of the fundamental constants* – Karshenboim
12:00 – 12:30	*Precision tests of fundamental interactions* – Pachucki
12:30 – 14:00	Lunch
Session 3 (Chair –)	
14:00 – 14:30	*Physics beyond the Standard Model from molecular hydrogen* – Ubachs
14:30 – 15:00	*Precision measurements on diatomic hydrogen molecules in search for extra dimensions* – Salumbides
15:00 – 15:30	*Bound-state QED calculations and the hydrogen molecular ion spectroscopy* – Korobov
15:30 – 16:00	Coffee Break
Session 4 (Chair –)	
16:00 – 16:30	*Finite nuclear mass correction to the retardation of the atom-atom potential* – Łach
16:30 – 17:00	*New developments in the theory of simple atoms* – Czarnecki
17:00 – 17:30	*Bound-State Quantum Electrodynamics in Strong Fields Beyond the Furry Picture by g-Factor Measurements* – Quint
17:30 – 18:00	*Constraints on exotic interactions coming from the helium fine structure* – Ficek
18:30 -	Poster Session

Tuesday – 24/5

Session 1 (Chair –)	
9:00 – 9:30	*Robust Microwave Gates* – Retzker
9:30 – 10:00	*Close encounters with a BEC: Robust spatial coherence 5 um from a room-temperature atom chip and prospects for precision measurements of surface effects*- Keil
10:00 – 13:00	*Ultra-broadband two-mode quantum squeezing as a new resource for quantum information* – Pe'er
10:30 – 11:00	Coffee Break
Session 2 (Chair –)	
11:00 – 11:30	*Barium Ion - How Exact do we Know?* – Mukherjee
11:30 – 12:00	*NV centers in diamond – from quantum coherence to magnetic sensing* – Bar-Gill
12:00 – 12:30	*A self-interfering clock as a "which path" witness* – Margalit
12:30 – 14:00	Lunch
14:00 – 19:00	Tour of Jerusalem
19:00 -	Conference Dinner (Eucalyptus Restaurant)

Wednesday 25/5

Session 1 (Chair –)	
9:00 – 9:30	*Precision tests of few-body QED effects in the Li and Be+ fine structure* - Puchalski
9:30 – 10:00	*High precision calculations of small atoms and molecules using explicitly correlated Gaussians* – Bubin
10:00 – 10:30	*Relativistic calculation of 2s3s transitions in He-Like ions* – Natarajan
10:30 – 11:00	Coffee Break
Session 2 (Chair –)	
11:00 – 11:30	*Probing QED in strong fields via the magnetic moment of highly charged ions and its isotopic effect* – Sturm
11:30 – 12:00	*Theory of the g-factor of highly charged ions* - Harman
12:00 – 12:30	*From charge to magnetic radii* – Antognini
12:30 – 14:00	Lunch
Session 3 (Chair -)	
14:00 – 14:30	*Applying Quantum technologies with trapped ions for fundamental measurements* – Schmidt-Kaler
14:30 – 15:00	*Violation of the action-reaction principle in two-atom interactions: manifestation of the vacuum momentum* – Donaire
15:00 – 15:30	*Precision nuclear theory with uncertainty quantification: needs and capabilities* – Gazit
15:30 – 16:00	Coffee Break
Session 4 (Chair –)	
16:00 – 16:30	*High-precision Ramsey-comb spectroscopy on molecular hydrogen in the deep ultraviolet spectral region for possible tests of QED* – Altman

16:30 – 17:00	*Testing QED with precision spectroscopy of the helium atom* – Sun
17:00 – 17:30	*Dating water and ice with Atom Trap Trace Analysis of Ar-39* – Ebser
17:30 – 18:00	*Photonic fluids and analogue gravity in rubidium vapor* – Barad

Thursday 26/5

Session 1 (Chair –)	
9:00 – 9:30	*Narrow Pentaquarks and Chromoelectric Polarizability* – Eides
9:30 – 10:00	*Higher order corrections to positronium energy levels* – Adkins
10:00 – 10:30	*Positronium and Muonium 1S-2S Spectroscopy* – Crivelli
10:30 – 11:00	Coffee Break
Session 2 (Chair -)	
11:00 – 11:30	*Probing the Atomic Higgs Force and beyond* – Perez
11:30 – 12:00	*QED tests in magnetic fields* – Rizzo
12:00 – 12:30	*Advanced Lasers for High Resolution Spectroscopy* – Falke
12:30 – 14:00	Lunch
Session 3 (Chair -)	
14:00 – 14:30	*Two-photon exchange corrections to the Lamb shift in muonic helium* – Carlson
14:30 – 15:00	*Towards an improved measurement of the 2S-4P transition in atomic hydrogen* – Maisenbacher
15:00 – 15:30	*New insights on the proton radius puzzle via the Lamb shift measurement in µd, µ3He+ and µ4He+* - Krauth
15:30 – 16:00	Coffee Break
Session 4 (Chair -)	
16:00 – 16:30	*The MUSE Experiment at PSI* – Kohl
16:30 – 17:00	*The magnetic moment of the proton* – Mooser
17:00 – 17:30	*New Extraction of the Proton Radius from ep-Scattering Data* – Lee
17:30 – 18:00	*High precision investigations of the fundamental properties of the antiproton* – Nagahama

Friday 27/5

Session 1 (Chair -)	
9:00 – 9:30	*Precise Born-Oppenheimer calculations for excited states of hydrogen molecule* – Zientkiewicz
9:30 – 10:00	*Towards the high precision measurement of the hyperfine splitting of muonic hydrogen in the ground state* - Vacchi
10:00 – 10:30	
10:30 – 11:00	Coffee Break
Session 2 (Chair -)	
11:00 – 11:30	Summary
11:30 – 12:00	

Abstracts

Higher order corrections to positronium energies

Gregory S. Adkins[a]

[a] *Franklin & Marshall College, Lancaster, Pennsylvania USA*

Positronium spectroscopy is of continuing interest as a high-precision test of our understanding of binding in QFT. Positronium represents the purest example of binding in QFT as the constituents are structureless and their interactions are dominated by QED with only negligible contributions from strong or weak effects. Positronium differs from other Coulombic bound systems such as hydrogen or muonium in having maximal recoil (the constituent mass ratio m/M is one) and being subject to real and virtual annihilation into photons. Positronium spectroscopy ($n = 1$ hyperfine splitting, $n = 2$ fine structure, and the $2S - 1S$ interval) has reached a precision of order $1MHz$, and ongoing experimental efforts give the promise of improved results. Theoretical calculations of positronium energies at order $m\alpha^6 \sim 18.7MHz$ are complete, but only partial results are known at order $m\alpha^7 \sim 0.14MHz$. I will report on the status of the positronium energy calculations and present new results for order $m\alpha^7$ contributions.

High-precision Ramsey-comb spectroscopy in the deep-ultraviolet for testing QED

Robert K. Altmann[a] S. Galtier[a] L.S. Dreissen[a] and K.S.E. Eikema[a]

[a] *VU University Amterdam*

High- resolution spectroscopy of simple atomic and molecular systems is an excellent tool for precision test of bound- state Quantum-Electro Dynamics (QED). Recently a comparison between spectroscopy of atomic-hydrogen (1S-2S) and muonic-hydrogen (2S-2P) has led to a sizeable discrepancy between theory and experiment, which is now called the proton size puzzle (cf. [1]). A similar comparison using the He^+ ion could provide new insights towards resolving this conundrum. Moreover, recent developments in theory by Pachucki and co-workers have also made molecular hydrogen, an interesting species for precision tests (cf. [2]). However, ground state electronic transitions in He^+ and H_2 require extreme ultraviolet and deep ultraviolet radiation which poses great experimental challenges.

To enable high-resolution spectroscopy at such short wavelengths we have developed an excitation method based on pairs of amplified near-infrared frequency-comb pulses . We demonstrated this Ramsey-comb spectroscopy on Rb in the near-infrared with 5 kHz accuracy (cf. [3]). The mJ-level pulse energy also allows efficient conversion to shorter wavelengths by frequency doubling in crystals or high-harmonic generation. In this manner we recently demonstrated deep-UV two-photon Ramsey-comb excitation in Kr (2×212 nm) and achieved an accuracy of 110 kHz (3.6×10^{-11} relative uncertainty), a 30-fold improvement over previous measurements. Here we present our latest spectroscopic results of the EF $\leftarrow$ X two-photon transition in molecular hydrogen at 2×202 nm where we aim to improve the accuracy by two orders of magnitude to a level of tens of kHz.

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[1] A. Antognini *et al.*, Science **5** (2013) 339.

[2] G.D. Dickenson *et al.*, PRL **5** (2013) 110.

[3] J. Morgenweg *et al.*, Nature Physics **5** (2014) 10.

From charge to magnetic radii

A. Antognini[a,b] for the CREMA collaboration

[a] *Institute for Particle Physics, ETHZ, 8093 Zurich, Switzerland.*
[b] *Laboratory for Particle Physics, PSI, 5232 Villigen, Switzerland.*

We have measured several 2S-2P transitions in muonic hydrogen (μp), muonic deuterium (μd) and muonic helium ions (μ^3He, μ^4He). The proton charge radius obtained from μp is 20 times more precise than previously obtained from electron-proton scattering and hydrogen high-precision laser spectroscopy. Yet our value is 4% (7σ) smaller than the values from these determinations. New insight has been recently provided by the first determination of the deuteron charge radius from μd. When combining this measurement with the H/D isotopic shift of the 1S-2S transition we extract a proton charge radius confirming the small value as directly obtained from μp.

The status of the proton charge radius puzzle including the implications given by μd will be discussed in the first part of this contribution. The second part will be devoted to the new activities at PSI related with spectroscopy of muonic atoms which include measurements of the ground state hyperfine splitting in μp and μ^3He as well as activities related with high-Z muonic atoms. Zemach radii and eventually information about the magnetic radii can be extracted from the hyperfine splitting measurements. High-Z atoms spectroscopy provides nuclear charge radii to test many-body nuclear theories and are motivated also by atomic parity violation searches.

Photonic fluids and analogue gravity in rubidium vapor

Shimshon Bar-Ad

Sackler School of Physics and Astronomy, Tel Aviv University

The hydrodynamic representation of the nonlinear Schröedinger equation allows one to describe coherent light propagation in a Kerr-type nonlinear medium as a quantum fluid of interacting photons. This idea has given rise to experimental demonstrations of dispersive shock waves and to proposals for creating optical analogue event horizons, based on Unruh's prediction (1981) that a thermal spectrum of sound waves would be emitted from the sonic horizon in transonic fluid flow, in analogy to the emission of Hawking radiation from the event horizon of a black-hole. Most of the relevant experiments carried out to date involve nonlocal, usually thermal nonlinear media, but the non-locality diminishes the prospects of observing quantum fluctuations and their classical counterparts. I will discuss these issues in detail and present our plans for constructing a quasi-stationary analogue event horizon, using rubidium vapor as a local medium.

NV centers in diamond: from quantum coherence to magnetic sensing

Nir Bar-Gill

[a] *Dept. of Applied Physics, The Rachel and Selim Benin School of Engineering, Hebrew University, Jerusalem 91904, Israel*
[b] *Racah Institute of Physics, Hebrew University, Jerusalem 91904, Israel*

Nitrogen-Vacancy (NV) color centers in diamond provide a unique nanoscale quantum spin system embedded in a solid-state structure. As such they are well suited for studies in a wide variety of fields, with emerging applications ranging from quantum information processing to magnetic field sensing and nano-MRI (Magnetic Resonance Imaging).

In this talk I will introduce the field of NV centers, and describe our research into understanding and controlling these systems, with the goal of enabling fundamental research and future applications. I will present the techniques used for manipulation of the NV centers, and for enhancing their quantum coherence lifetime [1]. Specifically, I will describe our recent work on extending the coherence time of arbitrary quantum states [2]. I will then demonstrate how these approaches can be used for magnetic field sensing and nanoscale NMR (Nuclear Magnetic Resonance) and MRI [3].

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[1] Bar-Gill, N. et al., Nature Communications **4**, 1743 (2013).
[2] Farfurnik, D. et al., Phys. Rev. B 92, 060301 (2015).
[3] DeVience, S.J. et al., Nat. Nanotechnol. 10, 129-134 (2015).

High precision calculations on small atoms and molecules using explicitly correlated Gaussians

Sergiy Bubin[a] and Ludwik Adamowicz[b]

[a] *Department of Physics, School of Science and Technology, Nazarbayev University, Astana 010000, Kazakhstan*

[b] *Department of Chemistry and Biochemistry, University of Arizona, Tucson, Arizona 85721, USA*

Accurate treatment of electron correlation in small quantum systems such as few-electron atoms and molecules remains an important challenge for modern theoretical and computational approaches. The variational method in conjunction with explicitly correlated Gaussian (ECG) basis sets is one of the most capable, accurate, and conceptually simple methods for calculating the ground and excited states of small quantum systems. In this contribution we briefly review the basic theoretical foundations, recent developments, and then focus on two applications of the ECG method to Coulomb systems. In the first application we consider small atoms. In particular, we report our recent results for the lower S-states of a five-electron system – the boron atom. We demonstrate that at the nonrelativistic level of the theory the current calculations can reach about 10^{-10} relative accuracy for the total energies. We also consider the leading relativistic and QED corrections in this system. In the second application we discuss the applicability of the variational approach with the ECG basis sets to the calculations of small molecules without assuming the Born-Oppenheimer approximation, i.e. when all particles are treated on an equal footing. Due to the huge difference in the masses of the electrons and nuclei the latter move more slowly and their correlation functions have distinct localization around the equilibrium internuclear separations. This feature is hard to implement in explicitly correlated variational approaches with Gaussian type basis functions while maintaining an analytic integrability of all necessary matrix elements. We argue that the difficulties may be overcome by using complex ECGs, which we demonstrate with benchmark calculations on HD^+ molecular ion. We also consider more sophisticated cases of triatomic systems and discuss the performance of the complex ECGs there as well as the issues encountered.

Dark-OST: searching for oscillating and transient effects from the Dark Sector with atomic spectroscopy and nuclear resonance

D. Budker[a,b]

[a] *Helmholtz Institute, JGU Mainz*
[b] *UC Berkeley*

Axions, axion-like particles (ALPs), dilatons, and other ultralight (masses from 10-4 down to 10-22 eV) particles have been discussed as possible candidates for dark matter. An interesting feature of these ideas is that they lead to predictions of potentially observable transient and oscillating effects. I will describe how we are looking for these as well as the relation of such experiments to tests of fundamental symmetries (P, CP, T, CPT).

Two-photon exchange corrections to the Lamb shift in muonic helium

Carl E. Carlson

Physics Department, College of William and Mary, Williamsburg, Virginia 23187, USA

Theoretical corrections are important to interpret the Lamb shift energy splitting data in terms of the radius of the central nucleus. In this talk, we report a calculation of the two-photon exchange corrections to the Lamb shift in muonic ^{3}He atoms due to the nuclear structure of ^{3}He, using a dispersion relation framework.

Properties of bound electrons and muons

Andrzej Czarnecki[a] and Robert Szafron[a]

[a] *Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2E1*

The mass of the electron is best determined with hydrogen-like ions in a Penning trap. Binding in an ion removes the error due to the thermal motion of the electron. However, the price is that some properties of the electron are modified by the binding. These changes can be computed in QED but there are interesting complications. We present recent progress in the determination of the g-factor of a bound electron. This calculation is motivated by the 2014 improvement in the mass of the electron and makes further experimental progress possible.

We also report an improved determination of the electron spectrum in the decay of a bound muon. This study is motivated by the upcoming experiments Mu2e (Fermilab) and COMET (J-PARC) that will search for the exotic muon-electron conversion, in an effort to discover the non-conservation of the charged lepton flavor. High-energy electrons produced in the ordinary decays of muons are a background in these searches. In these experiments muons are stopped in an aluminium target. Thus, we have determined the modification of the decay spectum by the Coulomb field of a $Z = 13$ nucleus.

Searching for variations of fundamental constants using the atomic clocks ensemble at LNE-SYRTE

L. De Sarlo[a], R. Tyumenev[a], M. Favier[a], S. Bilicki[a], E. Bookjans[a], R. Le Targat[a], J. Lodewyck[a], D Nicolodi[a], Y Le Coq[a], M Abgrall[a], J Guéna[a], and S. Bize[a]

[b] *LNE-SYRTE, Observatoire de Paris, CNRS, PSL Research University, Sorbonne Universités, UPMC Univ. Paris 06, 61 avenue de l'Observatoire, 75014 Paris, France*

The ratio of two atomic transition frequencies is by definition independent on the unit of frequency and therefore its value depend only on fundamental constants. Repeated measurements of frequency ratios obtained in the laboratory are therefore a direct test of the stability of fundamental constants with respect to time and, via the motion of the Earth, gravitational potential, independent from any cosmological models. This represents a highly desirable property that makes this kind of measurement complementary to astrophysical tests. At LNE-SYRTE we operate an ensemble of atomic clocks both in the microwave (hyperfine transition in the ground state of Cs and ^{87}Rb) and in the optical part of the spectrum ($^1S_0 \rightarrow {}^3P_0$ in ^{87}Sr and ^{199}Hg). In the first part of this talk we will briefly review the constraints on variation of fundamental constants obtained so far by repeated measurement of atomic frequency ratios (see e.g. [1]). In the second part we will present our latest result, a direct (i.e. independent on any other frequency reference) measurement of the mercury/strontium clock transition frequency ratio with a relative uncertainty of 1.8×10^{-16} [2]. This result, in excellent agreement with a previous measurement obtained in Japan [3], demonstrates that optical clocks are approaching the accuracy required to constrain alternative theories of gravity and quantum mechanics.

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[1] J. Guéna *et al.*, Phys. Rev. Lett. **109**, 080801 (2012).
[2] R. Tyumenev *et al.*, submitted, available at arXiv:1603.02026 (2016).
[3] K. Yamanaka *et al.*, Phys. Rev. Lett. **114**, 230801 (2015)

Violation of the action-reaction principle in the van der Waals interaction of excited atoms

Manuel Donaire[a]

[a] *Laboratoire Kastler Brossel, UPMC-Sorbonnes Universités, CNRS, ENS-PSL Research University, Collège de France, F-75252 Paris, France*

Violation of the action-reaction principle is shown to occur in the van der Waals interaction between two atoms, one of which is excited [1, 2]. It is accompanied by the transfer of linear momentum to the electromagnetic vacuum. The vacuum momentum results from the asymmetric emission of virtual photons along the interatomic direction, which is a manifestation of the optical theorem. This momentum, of equal strength and opposite direction to the momentum gained by the two-atom system, is ultimately carried out by the photons emitted during the deexcitation process, which manifests itself in the directionality of spontanous emission. A quantitative prediction of this phenomenon is made in a two-alkali atom system (Fig.1).

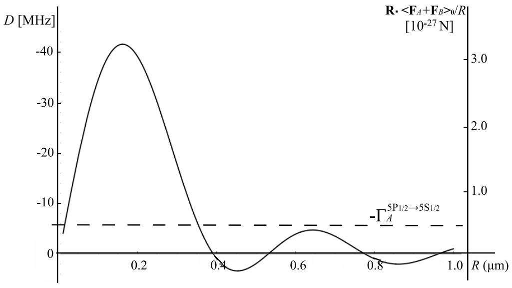

Figure 1: Graphical representation, as a function of the interatomic distance R, of the directionality of spontaneous emission, $D = \mathbf{R}\cdot\langle\mathbf{P}\rangle_\infty c/Rh$, and of the total force on a system composed by an atom of ^{87}Rb in the state 5P$_{1/2}$ and a ground state ^{40}K atom.

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[1] M. Donaire, to appear in *Phys. Rev. A*, arXiv:1603.08195.

[2] M. Donaire, R. Guérout and A. Lambrecht, *Phys. Rev. Lett.* **115**, 033201.

Precision Laser Spectroscopy of Positronium and Muonium

P. Crivelli[a]

[a] *ETH Zurich, Institute for Particle Physics, Otto-Stern-Weg 5, 8093 Zurich*

We report the status of our experiments aiming to improve the uncertainty of the current measurements of the 1S-2S transition frequency of Positronium and Muonium. The prospect of measuring the hyperfine splitting interval of the 2S state of positronium will also be presented.

Rare Noble Gas Isotopes: Dating Ice and Water

Sven Ebser[a], Zhongyi Feng[a], Lisa Ringena[a], Florian Ritterbusch[b], Arne Kersting[b], Stefan Beyersdorfer[b], Emeline Mathouchanh[b], Werner Aeschbach[b], and Markus K. Oberthaler[a]

[a] *Kirchhoff-Institute for Physics, Heidelberg, Germany*
[b] *Institute of Environmental Physics, Heidelberg, Germany*

Rare noble gases are outstanding physical systems for studying very different physical topics such as searching for physics beyond the standard model or dating ice and water. The employed atom optical tools and the technical challenges are very similar though: The high selectivity of resonant photon scattering during laser cooling and trapping is applied in order to distinguish the rare isotope from the abundant ones. To get a practical count rate despite the very low abundance a stable and highly efficient atom optical apparatus is needed, starting from the metastable noble gas source, including the transversal and longitudinal beam manipulation and finally the magneto optical trap and the detection of single atoms.

The Heidelberg ATTA (Atom Trap Trace Analysis) collaboration has focused on the rare argon isotope ^{39}Ar with an atmospheric isotopic abundance of $^{39}\mathrm{Ar}/\mathrm{Ar} = 8.23 \cdot 10^{-16}$. As an inert noble gas and with a half-life of 269 years, it is the perfect tracer to fill the dating gap for ice and water samples between 50 and 1000 years before present, a time period for which no other tracers exist. An atmospheric count rate of 3.6 atoms/h allowed the first demonstration of its applicability for groundwater dating [1]. Current measurements prove a reduction of the needed sample size down to 4 ml STP of argon (corresponding to about 10 L of water or 4 kg of ice). Such sample sizes are prerequisite for a convenient application of ^{39}Ar dating in ice and ocean studies.

I will discuss the atom optical techniques, which have been employed to reach this performance. More efficient cooling techniques such as bichromatic cooling and optical pumping are current developments and aim at enhancing the efficiency of the metastable noble gas source and the beam manipulation.

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[1] Ritterbusch *et al.*, GRL **41** (2014) 6758-6764.

Narrow Pentaquarks and Chromoelectric Polarizability

Michael I. Eides
Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA

The newly discovered pentaquark $P_c(4450)$ is interpreted as a bound state of charmonium $\psi(2S)$ and the nucleon[1]. The binding potential is due to the charmonium-nucleon interaction that in the heavy quark approximation is proportional to the product of the charmonium chromoelectric polarizability and the nucleon energy-momentum distribution. We use the large N_c expansion to estimate the quarkonium polarizability and calculate the nucleon properties in the framework of the mean-field picture of light baryons. Two almost degenerate states $J^P = (1/2)^-$ and $J^P = (3/2)^-$ are predicted at the position of the $P_c(4450)$ pentaquark. We find that the nucleon-$\psi(2S)$ bound state has a naturally narrow width in the range of tens of MeV. The unitary multiplet partners of the $P_c(4450)$ pentaquark and the generalization to $b\bar{b}$-nucleon pentaquark bound states are discussed.

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[1] M. I.Eides, V. Yu. Petrov, and M. V. Polyakov, Phys. Rev. D **93**, 054039 (2016).

Advanced Lasers for High Resolution Spectroscopy

Stephan Falke

TOPTICA Photonics AG

Laser spectroscopy is a driving force in fundamental research projects in various fields. The advances in laser technology is fueling the scientific findings. However, many experiments are suffering from the noise of an interrogating laser. For example, the stability of optical lattice clocks is in most cases limited by instability of the interrogating laser.

These lasers are typically external cavity diode lasers (ECDL) stabilized to external ultra-high finesse cavities and can reach instabilities even below 10^{-16}. This corresponds to a linewidth significantly below 1 Hz at frequencies of several hundred THz. We have built and characterized sub-Hz lasers. The three main ingredients for reaching such a performance are a *good* ECDL, a dedicated external cavity and a feedback circuit, which converts the length stability of the external cavity to a frequency stability of the stabilized ECDL. In order to integrate them into high-resolution spectroscopy experiments such as optical clocks, it usually is also required to count their frequency. Traditionally, this has been a measurement of the laser frequency in SI seconds, i.e., a connection to the frequency domain of microwaves. With optical clocks surpassing the best microwave clocks in accuracy and, even more significantly, in stability, the task is shifting towards comparing the relative frequency of two or more ultra-stable spectroscopy lasers. Frequency combs based on femtosecond lasers solve both tasks. Our commercial frequency comb uses difference frequency generation (DFG), which eliminates the carrier envelope offset frequency ν_{CEO}. The frequency of any comb tooth is hence simply described by $n \times \nu_{\mathrm{rep}}$, with n being an integer number and ν_{rep} the repetition rate of the femtosecond laser.

Using ultra-stable ECDLs, we not only characterize the comb but moreover we create a frequency comb with sub 1 Hz wide teeth, which can be referenced directly to a microwave frequency reference, such as a realization of the SI-second or GPS disciplined reference. The created stable frequency comb may also be used to compare optical frequencies directly. Moreover, it may also serve to transfer the stability of one ultra-stable laser to another frequency - either by stabilizing another ECDL or by generating a microwave inheriting the stability of the ultra-stable laser.

Constraints on the exotic interactions coming from the helium fine structure measurements

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Several theoretical models predict an unknown spin-dependent (exotic) interaction between particles. It can be shown, that the Lorentz invariance and rotational symmetry limit the form of the potential connected with such an exotic force to one of sixteen possible forms [1]. We have investigated the influence of these hypothetical potentials on the fine structure in atomic helium. By comparing differences between precise measurements and QED based calculations [2], we have found constraints on electron-electron coupling constants of these hypothetical exotic interactions. For some potentials and force-carrying boson mass ranges, the obtained results yield better constraints than other methods [3].

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Precision nuclear and atomic physics at the extreme

Doron Gazit[a]

[a] *Racah inst. of physics*

Precision experiments in the last decade have challenged our understanding of the Universe, and have given rise to fundamental questions. In terms of theory, these have highlighted the need to better determine uncertainties in theoretical predictions. In particular, discrepancies in the standard solar model due to precision determination of elements abundances have questioned theoretical evaluations of highly ionized atoms in a plasma, and as I will show, enlighten new sources of uncertainties. In addition, I will present new theoretical evaluation of proton-proton fusion, the key reaction in the energy production process in the Sun, with special emphasis on uncertainties. In addition, I will present our progress in the nuclear physics needed to analyze two of the heralds of modern particle physics experiments, in the direct search for dark matter and in the search for lepton number violation in neutrinoless double beta decay.

Theory of the g-factor of highly charged ions

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Quantum electrodynamic (QED) contributions in strong fields have been recently tested to high precision in Penning trap experiments: a measurement yielded a value for the g-factor of hydrogenlike silicon with a 5×10^{-10} fractional uncertainty, allowing to test certain higher-order QED corrections for the first time [1]. The measured g-factor is in excellent agreement with the state-of-the-art theoretical value, which includes QED contributions up to the two-loop level of the order of $(Z\alpha)^2$ and $(Z\alpha)^4$.

We also present theoretical results of a recent determination of the electron mass via measurement of the Larmor and cyclotron frequencies of a $^{12}\mathrm{C}^{5+}$ ion [2]. The electron mass was determined with an uncertainty more than an order of magnitude better than the established literature value by means of comparison of the theoretical prediction for $g\left(^{12}\mathrm{C}^{5+}\right)$ and the experimental frequencies. In order to reduce the uncertainty on the theory's side, the unknown two-loop higher-order correction to $g\left(^{12}\mathrm{C}^{5+}\right)$ was estimated.

A determination of the fine-structure constant α may be possible from a weighted difference of the g-factors of the H- and Li-like ions of the same element. This weighted difference in chosen to maximize the cancellation of nuclear effects between the two charge states. We show that the specific difference and its combination for two different elements can be used to extract a value for α from near-future bound-electron g-factor experiments with an accuracy competitive with or better than the present literature value [3].

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Progress in determination of the fundamental constants

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I will review the recent progress in the determination of the fundamental constants, such as the Rydberg constant, the fine structure constant, the electron-to-proton mass ratio, the Planck and Boltzmann constants etc.

Close encounters with a BEC: Robust spatial coherence 5 μm from a room-temperature atom chip and prospects for precision measurements of surface effects

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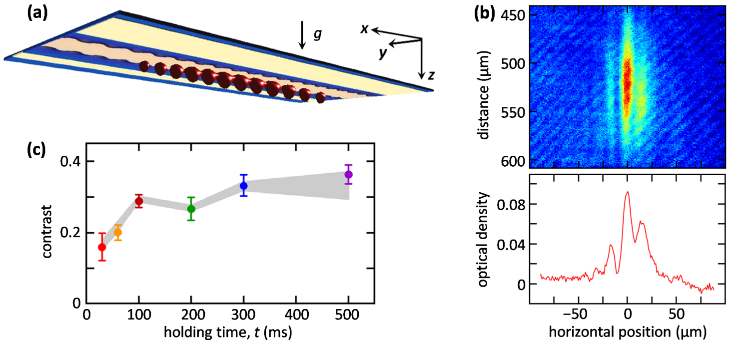
We study spatial coherence near a classical environment by loading a Bose-Einstein condensate into a magnetic lattice potential and observing diffraction. Even very close to a surface (5 μm), and even when the surface is at room temperature, spatial coherence persists for a relatively long time (≥ 500 ms) – as long or longer than the spin-flip lifetime! This is the first time fringes are observed from atoms trapped so close to the surface. In addition, the spatial coherence extends over several lattice sites, much longer than the atom-surface separation. We will discuss the interplay between spatial dephasing, inter-atomic interactions, and external noise, as well as applications that include the nascent field of atomic circuits (*"atomtronics"*). We will also discuss prospective applications for fundamental measurements enabled by such close encounters with the atom chip surface, *e.g.,* the Casimir-Polder force, non-Newtonian gravitational effects, *etc.*



(a) Artist's view of the trapped atom cloud a few μm below the atom chip surface. (b) High-contrast diffraction pattern observed after averaging 30 consecutive experimental cycles for a trap holding time of $t = 100$ ms. (c) Average contrast of the two first-order fringes, showing no loss of contrast (*i.e.,* no apparent dephasing) for at least 500 ms.

The Muon Scattering Experiment at PSI

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The proton is not an elementary particle but has a substructure governed by the interaction of quarks and gluons. The size of the proton is manifest in the spatial distributions of the electric charge and magnetization, which determine the response to electromagnetic interaction. Recently, contradictory measurements of the proton charge radius between muonic hydrogen and elecronic probes have constituted the proton radius puzzle, which has been challenging our basic understanding of the proton. The Muon Scattering Experiment (MUSE) in preparation at the Paul-Scherrer Institute has the potential to resolve the puzzle by measuring the proton charge radius with electron and muon scattering simultaneously and with high precision, including any possible difference between the two, and with both beam charges. The status of the MUSE experiment will be reported.

Bound-state QED calculations and the hydrogen molecular ion spectroscopy

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In the last few years we achieved substantial progress in determination of transition frequencies in the hydrogen molecular ions H_2^+ and HD^+. Particularly, the fundamental transitions for these ions were calculated with the fractional uncertainty of $7.5 \cdot 10^{-12}$. In our presentation we want to discuss the following topics:

- The contributions of orders $m\alpha^6$ and higher have been obtained in the nonrecoil limit. Still our recent work [1] shows that some care should be taken in order to properly evaluate a complete contribution at some fixed order of α. We suggest a new formalism based on the adiabatic multichannel approximation, which allows to pose the problem in a more rigorous way. This new approach makes possible both to calculate the nonrecoil corrections of orders $m\alpha^6$ and higher and to get estimates on the nonadiabatic contributions, or in other words to set properly error bars of our calculation.

- As an example of application of this new formalism we want to consider relativistic corrections of order $m\alpha^6$. New values for the hyperfine structure intervals will be presented, which allow to bring agreement with precision experimental data by Jefferts [2] to a level of 1 ppm.

- In the final part of our presentation we will try to discuss how precision spectroscopy of the hydrogen molecular ions may contribute to the proton-radius puzzle and provide an alternative way for determination of the Rydberg constant and the proton-to-electron mass ratio.

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Charge radii from light hydrogen-like muonic atoms - Shedding light on the Proton Radius Puzzle

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In 2010 the CREMA collaboration determined the rms charge radius of the proton via laser spectroscopy of the 2S-2P Lamb shift in muonic hydrogen [1, 2]. The obtained value is ten times more precise than the 2010 CODATA result but also seven standard deviations smaller. This problem is known as the Proton Radius Puzzle and is the currently largest discrepancy in the standard model of particle physics. In recent years the CREMA collaboration continued to measure the Lamb shift in several other muonic atoms and ions [3, 4]. These measurements will determine the charge radii of the deuteron, the helion, and the alpha-particle in the future.
This talk will give an update of our recent work, providing new preliminary charge radii and a discussion of their implications to the Proton Radius Puzzle. Special focus will be given to theory [5, 6], which currently limits the accuracy of possible charge radius extractions from muonic atom spectroscopy.

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Finite nuclear mass correction to the retardation of the atom-atom potential

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The interaction energy between two ground-state atoms behaves as 1/R^6. for distances smaller then that of the lowest transition wavelength, and so does the finite nuclear mass correction to the energy. For larger distances the interaction energy is modified by the retardation of the electromagnetic interactions and asymptotically falls-off as 1/R^7. We have derived the finite nuclear mass correction to the retardation of the atom-atom potential, and have shown that besides the expected contribution from the finite mass correction to atomic matrix elements another term is present.

Extraction of the proton radius from electron-proton scattering data

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I will present a new analysis of electron-proton scattering data (those published in 2010 by the Mainz A1 collaboration [1] and previous world compilations, e.g., [2]) to determine the proton electric and magnetic radii. The analysis enforces model-independent constraints of form factor analyticity and investigates a wide range of possible systematic effects [3].
Employing standard models for radiative corrections, our improved analysis yields proton electric radii for the Mainz and world data sets that are consistent, although a simple combination yields a value $r_E = 0.904(15)$ fm that is 4-σ larger than the CREMA muonic hydrogen determination. The Mainz and world values of the magnetic radius differ by 2.7σ, and a simple average yields $r_M = 0.851(26)$ fm.
I will discuss remaining possible deficiencies that, if addressed, could reconcile the values from muonic hydrogen spectroscopy and *ep*-scattering.

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Towards an improved measurement of the 2S-4P transition in atomic hydrogen

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Precision measurements of atomic hydrogen have long been successfully used to extract fundamental constants and to test bound-state QED. The extraction of the Rydberg constant R_∞ from hydrogen spectroscopy is currently limited by the measurements of hydrogen lines other than the very precisely known 1S-2S transition [1]. We are working towards an improved measurement of the 2S-4P transition to address this limitation. This will also allow for a more precise extraction of the proton r.m.s. charge radius r_p from electronic hydrogen, which currently disagrees by $4\,\sigma$ with the much more precise value extracted from muonic hydrogen spectroscopy [2].

To reach our accuracy goal for the transition frequency in the low kHz range, we implement for the first time a cryogenic beam of hydrogen atoms optically excited to the initial 2S state [3]. This strongly suppresses the first order Doppler shift of the one-photon 2S-4P transition, which is further suppressed by actively stabilized counter-propagating laser beams and time-of-flight resolved detection. In our system, quantum interference arising from spontaneous emission [4] leads to significant line distortions, which we have characterized experimentally. Coherent processes coupling distinct momentum states driven by the counter-propagating laser beams can cause an additional shift of the resonance and are currently under investigation.

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A self-interfering clock as a ”which path” witness

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In Einstein’s general theory of relativity, time depends locally on gravity; in standard quantum theory, time is global—all clocks ”tick” uniformly. We demonstrate [1] a new tool for investigating time in the overlap of these two theories: a self-interfering clock, comprising two atomic spin states. We prepare the clock in a spatial superposition of quantum wave packets, which evolve coherently along two paths into a stable interference pattern. If we make the clock wave packets ”tick” at different rates, to simulate a gravitational time lag, the clock time along each path yields ”which path” information, degrading the pattern’s visibility. In contrast, in standard interferometry, time cannot yield ”which path” information. This proof-of-principle experiment may have implications for the study of time and general relativity and their impact on fundamental effects such as decoherence and the emergence of a classical world.

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The magnetic moment of the proton

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T. Higuchi[a,e], Y. Matsuda[e], H. Nagahama[a,e], W. Quint[f], S. Sellner[a],
C. Smorra[a,g], T. Tanaka[e], J. Walz[b,c], and S. Ulmer[a]

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[d] *Max-Planck-Institut für Kernphysik* [e] *Graduate School of Arts and Sciences, University of Tokyo* [f] *GSI-Helmholtzzentrum für Schwerionenforschung* [g] *CERN, Switzerland*

One of the fundamental properties of the proton/antiproton is the spin magnetic moment $\mu_p/\mu_{\bar{p}}$. Up to 2014, the most precise value of μ_p was based on spectroscopy of atomic hydrogen [1]. Significant theoretical bound-state corrections had to be applied to indirectly determine μ_p with a relative precision of 9 ppb [2]. Recently, we improved this by a factor of 2.5 by directly measuring μ_p using a single proton in a double Penning trap [3]. In the BASE experiment at CERN [4] our method will be directly applied to measure $\mu_{\bar{p}}$. This will provide a 1000-fold improved test of the combined charge, parity and time invariance.
The measurement of μ_p was limited by residual magnetic field inhomogeneities and short-term fluctuations of the magnetic field, which led to linewidth broadening and systematic frequency shifts. A new Penning trap layout and a self-shielding coil were recently installed, which resulted in a ten times improved stability of the magnetic field. Together with upgraded detection systems these improvements allow for a measurement of μ_p with a fractional precision in the order of 10^{-10}. The status of the experiment will be presented.

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Barium ion how exact do we know?

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A singly charged barium ion is both simple as well as resourceful. It has relatively simple electronic structure like any other alkaline atom. However barium being a heavy element shows large enhancement of parity violation in its electronic structure. It also happens to be an important link to study nucleo-synthesis particularly in large stars in main sequence or the solar magnetic field. In this presentation, recent progress in atomic parity violation measurement with respect to the barium ion system will be discussed. In particular, our measurement on the dipole matrix elements [1,2] with precision below one percent level along with measurements done by other groups on the atomic transition frequencies provide a solid ground for the APV experiment. In this context, a new method to measure branching fractions with more than two branches that are only limited by statistics will be discussed. The results now provide stringent test for atomic many body calculations, particularly for large systems like barium.

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High-precision measurements of the fundamental properties of the antiproton

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The BASE collaboration at the antiproton decelerator of CERN aims to perform high-precision comparisons of the fundamental properties of the proton and the antiproton. This provides stringent tests of the charge, parity, time (CPT) invariance, and thus of the Standard Model. The BASE apparatus consists of an advanced Penning-trap system with highly-sensitive cryogenic detectors which allow us to store and detect even single particles. In 2014, we compared the charge-to-mass ratio of the proton to the antiproton with an unprecedented relative precision of 69 ppt [1]. The result constitutes to date, the most precise test of CPT invariance with baryons and is consistent with the Standard Model. For beamtime of 2015, we modified our apparatus to measure the g-factor of the antiproton. The g-factor of the proton has recently been measured by the BASE experiment at the University of Mainz with a relative precision of 3.3 ppb [2], whereas the g-factor of the antiproton has been measured to a level of 4.4 ppm [3]. By applying the technique used in [2] to the antiproton, a 1000-fold improvement in its g-factor precision is possible. Within this talk I will summarize the current status of BASE.

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Probing the Atomic Higgs Force and beyond

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We begin by arguing that we do not yet know whether light fermion masses originate from the Higgs mechanism, which especially in view of the flavor puzzle lead to a basic research problem. We then briefly review the LHC reach and conclude that only limited progress can be made on this frontier. It motivates us to propose an approach to probe Higgs boson couplings to the building blocks of matter: the electron and the up and down quarks, with precision measurement of isotope shifts in atomic clock transitions. We show that the attractive Higgs force between nuclei and their bound electrons induces measurable non-linearities in a King plot of two isotope shifts. We present an experimental method which, given state-of-the-art accuracy in frequency comparison, could potentially compete with and possibly surpasses the Large Hadron Collider in bounding the Higgs-to-light-fermion couplings. We then discuss how to translate the above potential sensitivity to constrain other forms of new physics.

$\alpha^6 m$ corrections to the ground Σ state of H_2

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We perform the calculation of higher order relativistic and quantum electrodynamic corrections to the Born-Oppenheimer potential for the ground Σ state of the hydrogen molecule and present improved results for the dissociation and the fundamental vibration energies. These results open the window for the high precision spectroscopy of H_2 and related low energy tests of fundamental interactions.

Ultra-broadband two-mode quantum squeezing as a new resource for quantum information

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I will present our measurement scheme for broadband squeezed light and time energy entangled bi-photons that is based on quantum interference between the generation amplitudes of bi-photons in two separated nonlinear media. Using an optical nonlinear medium as the homodyne device, we demonstrated direct squeezing detection for ultra-broadband two-mode squeezed light (80nm bandwidth and 140THz signal-idler separation), lifting the inherent bandwidth limitation of the standard homodyne measurement with photo-detectors.

Broadband two-mode squeezed light (or time-energy entangled bi-photons in the discrete, low power version), is in many ways the 'black sheep of the family' in quantum information. Although broadband squeezed light is easily produced with very high optical flux, and demonstrates extreme nonclassical behavior, it is rarely used in quantum information, mainly because of the inability to efficiently detect it with standard photo-detectors and homodyne techniques. Homodyne, the measurement of the two quadratures of a light field (the optical analog of quantum position and momentum), is a corner stone of quantum optics and quantum information, and is used in numerous applications, such as continues variable quantum computing, quantum key distribution, and sub-shot noise interferometric measurement. Standard optical homodyne uses the square-law nonlinearity of photo-detectors for mixing the input optical signal with a local-oscillator. Thus, the homodyne bandwidth is inherently limited by the electrical bandwidth of the photo-detectors, typically in the MHz to GHz range. Wider bandwidth measurement requires two (or more) homodyne setups with phase and frequency locks between the local-oscillators, which are complicated to prepare. Considering the growing interest in quantum optical squeezed states and the ease of generating broadband two-mode squeezing with an optical frequency separation, this limitation is critical for future utilization of quantum squeezing.

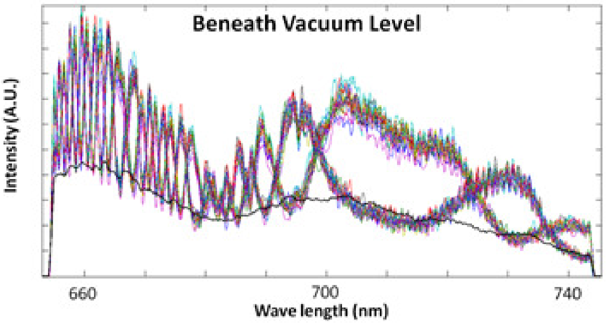

Figure 1: Figure 1: Ultra-broadband squeezing measurement. The parametric amplified spectrum for squeezed light input (color lines) is measured 25% below the vacuum noise level (black line). Due to accumulated spectral phase different frequencies enter the parametric amplifier with different varying quadrature orientation; hence, some frequencies are amplified while others are attenuated.

We replace the slow square-law photo-detectors with a nonlinear optical medium, using the pump-laser, originally used for generating the squeezed state, as the local-oscillator. By this we achieve a direct optical homodyne measurement, where the homodyne process generates an optical output, offering effectively unlimited measurement bandwidth. To demonstrate the optical homodyne scheme experimentally, we use parametric amplification with optical four-wave mixing in a photonic crystal fiber, pumped by a narrow band laser. We observe in a single measurement a reduction of 25% under the vacuum level, over the entire spectrum of 50nm bandwidth with 140THz frequency separation between the signal and the idler fields.

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Precision test of many-body QED in the Li and Be$^+$ fine stucture

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The inclusion of relativistic effects and correlations between electrons in atomic systems gives rise to some fundamental problems of theoretical methods a long time. For light atomic systems the best approach relies on nonrelativistic QED theory, where relativistic and QED effects are treated perturbatively, while the nonrelativistic Hamiltonian is solved using explicitly correlated basis sets. The helium fine structure is a very good example; it was calculated to the $m\,\alpha^7$ order and currently serves as one of the most precise QED tests in few-electron systems [1]. In this talk we present the significant improvent of theoretical prediction of the Li and Be$^+$ $2P_{3/2} - 2P_{1/2}$ splitting by the complete calculation of the $m\,\alpha^6$ and $m\,\alpha^7 \ln\alpha$ contributions [2, 3]. We derived closed formulas for QED corrections and performed numerical calculations using explicitly correlated basis sets with Hylleraas and Gaussian functions. Such calculations have been performed by Douglas and Kroll for the helium fine structure of ^3P_J levels in Ref. [4]. It took 40 years to extend their two-electron $m\alpha^6$ result to an atom with three electrons, indicating that accurate calculations of QED effects in many electron systems is a challenging task.

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Bound-State Quantum Electrodynamics in Strong Fields Beyond the Furry Picture by g-Factor Measurements

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Precise measurements of magnetic moments (g-factors) by quantum jump spectroscopy with individual particles in Penning traps have opened possibilities for fundamental tests of physical theories. The determination of the magnetic moment of the electron bound in highly charged ions is a sensitive test of the theory of bound-state quantum electrodynamics (QED). Simple systems are in the focus of the investigations, such as hydrogen-like, lithium-like, and boron-like ions [1, 2, 3]. Most physical effects contributing to g-factors of highly charged ions, for example, the relativistic, radiative, nuclear size or interelectronic-interaction contributions, are calculated using bound-state quantum electrodynamics in the infinite-nuclear-mass approximation. Here, the nucleus is considered as an external Coulomb potential fixed in space. This approach is usually denominated as the Furry picture of QED. We present recent experimental and theoretical results on the g-factors of highly charged calcium ions, which can only be interpreted by a QED description beyond the Furry picture [4]. Future investigations will be extended to heavier few-electrons ions at the HITRAP facility.

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Robust microwave gates

Alex Retzker

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In this talk I will review a set of decoupling techniques that aims to improve quantum sensing and quantum computing in various platforms with an emphasis on an ion trap setup which is based on microwave radiation. Moreover, a set of techniques that enables universal quantum computing to be carried out using dressed states will be presented. It will be shown how the presence of dressing fields enables the construction of robust single and multi-qubit gates despite the unavoidable presence of magnetic noise.

QED tests in magnetic fields

Carlo Rizzo[a]

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Magnetic fields are a very well known probe to investigate matter properties. I will present how magnetic fields can also be used to test QED predictions in vacuum and in bound systems. After a general overview of the field, I will concentrate myself on the experimental effort that we are pushing forward at the High Magnetic Field National Laboratory in Toulouse, France, to measure for the first time the vacuum magnetic birefringence and hopefully and g-factors of the electron in bound states at a level of interest for QED. I will show our last results in both activities.

Precision measurements on diatomic hydrogen molecules in search for extra dimensions

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String theories are promising candidates for future all-encompassing physical theories to supersede the Standard Model. For the mathematical consistency of such theories, extra spatial dimensions are invoked and are assumed to be compactified to explain non-observation up to now. While such proposals are motivated by high-energy physics, we propose to search for subtle effects at the low-energy scale in the spectra of simple molecules [1]. First principle calculations on the energy structure of the electronic ground state of molecular hydrogen neutrals [3] and ions [2] have achieved at present, transition energy accuracies of 20 ppb and 0.1 ppb, respectively, and continue to improve. The progress in the theoretical investigations is matched in the precision spectroscopy of neutral or ionic molecular hydrogens [5, 4]. Any deviation in the comparison between *ab initio* calculations and spectroscopic measurements may thus be interpreted in general as new physics, or in terms of particular hypotheses such as the presence of extra dimensions in ADD theory [6]. Using the latest measurements in [4] for example, the compactification size for the extra spatial dimensions of the 11-dim M-theory is constrained to be less than 0.6 microns.

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Applying Quantum technologies with trapped ions for fundamental measurements

Ferdinand Schmidt-Kaler,[a]

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I describe the plan to measure the gravitational constant g using a single ultra cold anti-Hydrogen atoms. For this, anti-Hydrogen ions are generated within the GBAR collaboration at the Elena storage ring at CERN, trapped, and cooled to temperatures of a few K. After photo-detachment of one e+, the free fall time of neutralized anti-H atoms is detected. Note, that only the sympathetic cooling with a Be+ ion allows to reach such low temperatures. State of the art cooling for anti-Hydrogen, even what could be expected from Doppler cooing of neutral H-atoms, reach order of magnitude higher temperature only. We aim for a sub-percent accuracy in δg/g. I describe the status of the experiment and the next steps.

Probing QED in strong fields via the magnetic moment of highly charged ions and its isotopic effect

Sven Sturm[a]

[a] *Max-Planck Institut für Kernphysik*

The validity of the Standard Model, particularly Quantum Electrodynamics (QED), has been exquisitely tested by precision experiments in the low-field regime. However, in the presence of strong fields higher-order contributions beyond the Standard Model might become significant. The ultra-precise measurement of the g-factor of highly-charged ions provides a unique possibility to probe the validity of the Standard Model in extreme electric fields up to 10^{16} V/cm [1, 2]. By measuring the Larmor- and cyclotron frequencies of single highly charged ions in a cryogenic Penning trap with previously unprecedented precision, we have been able to perform the most stringent test of QED in strong fields. Particularly the effect of the nucleus on the g-factor of the electron is a novel and unique access to nuclear size and structure information. Recently, we have been able to determine the isotopic effect of the g-factor in lithiumlike calcium isotopes $^{40}\mathrm{Ca}^{17+}$ and $^{48}\mathrm{Ca}^{17+}$, and thus to explicitly probe the relativistic interaction of the electrons and the nucleus [3]. Currently, a new setup, ALPHATRAP, is being commissioned at the Max-PIanck-Institut f?r Kernphysik in Heidelberg, which will push these experiments towards the heaviest elements up to hydrogenlike $^{208}\mathrm{Pb}^{81+}$. This will not only enable the most sensitive tests of QED, but also open a unique access to fundamental constants as the atomic mass of the electron and the finestructure constant α.

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Testing QED with precision spectroscopy of the helium atom

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Helium atom plays an important role in studying the quantum electrodynamic theory (QED) of a three-body bound system [1, 2]. It is also among a few systems that incredible precision can be achieved by calculations relying on quantum theory and fundamental physical constants. Theorists believe that the precision spectroscopy of the helium atom is an ideal platform for testing QED[3, 4] and the (1s2p)2^3P_J fine structure splitting of He-4 is potentially suitable for the determination of the fine structure constant with an accuracy at the ppb level [5].

We have built a helium precision spectroscopy system with a high-brightness beam of metastable helium atoms in a single quantum state. The structure of this system is plotted in Fig. 1. Using this system the 2^3P_1-2^3P_2 fine structure interval is measured to a precision of 360Hz[6].After correcting for the effect of quantum interference[7], the final result is plotted in Fig. 2 along with other measurements and calculated values.

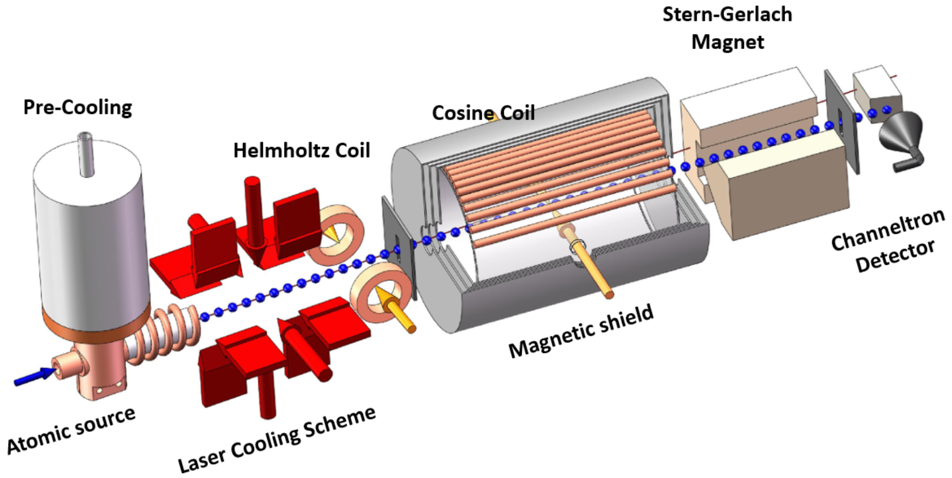

Figure 1: Setup of the helium precision sepctroscopy system

Next, we aim to measure the 2^3P_0-2^3P_2 fine-structure splitting at a precision of 0.1 kHz. Meanwhile, frequencies of the 2^3S-2^3P transition in He-4/He-3 will be determined using a frequency comb system, aiming for an absolute frequency accuracy around 1 kHz. The results will lead to the radius of the helium-3 nucleus, and hopefully will resolve the current discrepancies among several studies obtained with various methods.

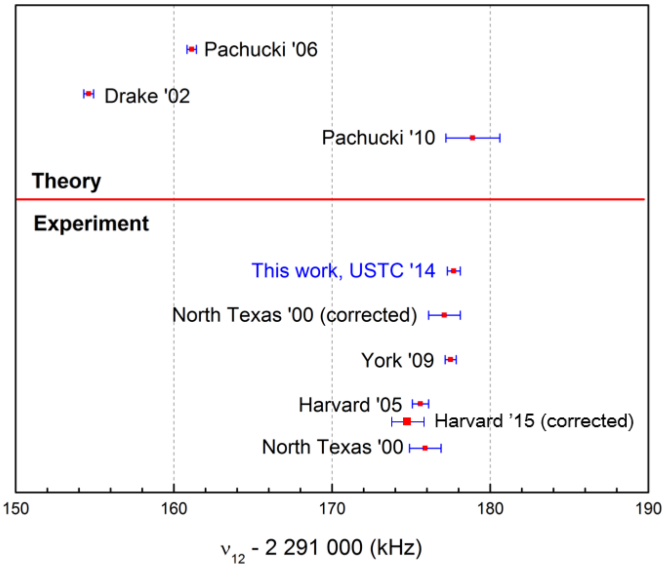

Figure 2: Theory and experiment results of the 2^3P_0-2^3P_1 interval of helium atoms

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Physics beyond the Standard Model from molecular hydrogen

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The spectroscopy of molecular hydrogen can be used for a search into physics beyond the Standard Model. Differences between the absorption spectra of the Lyman and Werner bands of H_2 as observed at high redshift and those measured in the laboratory can be interpreted in terms of possible variations of the proton-electron mass ratio $\mu = m_p/m_e$ over cosmological history. Investigation of some ten of such absorbers in the redshift range $z = 2.0 - 4.2$ yields a constraint of $|\Delta\mu/\mu| < 5 \times 10^{-6}$ at 3σ [1]. While such astronomical studies aim at finding quintessence in an indirect manner, laboratory precision measurements target such additional quantum fields in a direct manner. Laser-based precision measurements of dissociation energies, vibrational splittings and rotational level energies in H_2 molecules and their deuterated isotopomers HD and D_2 produce values for the rovibrational binding energies fully consistent with quantum ab initio calculations including relativistic and quantum electrodynamical (QED) effects [2]. Similarly, precision measurements of high-overtone vibrational transitions of HD^+ ions, also result in transition frequencies fully consistent with calculations including QED corrections [3]. These comprehensive results of laboratory precision measurements on neutral and ionic hydrogen molecules can be interpreted to set bounds on the existence of possible fifth forces [4] and of higher dimensions [5], phenomena describing physics beyond the Standard Model.

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Towards the high precision measurement of the hyperfine splitting of muonic hydrogen in the ground state

Andrea Vacchi

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The preparatory phase of the experimental program for the high precision measurement of the hyperfine splitting of muonic hydrogen in ground state, with pulsed intense muon beam, has been completed with a detailed study of the muon transfer from μ-p to oxygen and other higher Z atoms admixed to the hydrogen pressurized gas target at various temperatures. We describe the results obtained and the future program.

Prospects of in-flight hyperfine spectroscopy of (anti)hydrogen for tests of CPT symmetry

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A measurement of the ground-state hyperfine structure (GS-HFS) of antihydrogen can become one of the most sensitive tests of CPT symmetry on an absolute scale due to the fact that it is a small quantity on the energy scale and can be measured to very high precision. For this reason ASACUSA has chosen to perform a measurement of GS-HFS using a polarized antihydrogen beam [1, 2]. A major mile stone towards a hyoerfine measurement was the first observation of a beam of antihydrogen atoms in a field-free region by ASACUSA [3].
Similar arguments regarding the absolute sensitivity of CPT tests have been brought forward by A. Kostelecky et al. within their Standard Model Extension (SME) [4]. Their model is based on Lorentz-invariance violation and also has consequences for the GS-HFS of ordinary hydrogen, notably sidereal and annual variations, which have been tested using hydrogen masers to high precision [5]. In a recent extension to the non-minimal SME [6] further SME coefficients are found that depend on the orientation of the applied static magnetic field in the laboratory for some of the observable HFS transitions. ASACUSA has used the hyperfine spectrometer line originally developed for antihydrogen spectroscopy with a source of cold polarized hydrogen atoms and measured the $(F = 1, M = 0) \rightarrow (0, 0)$ (so-called σ) transition to few ppb and plans to extend the measurements to the $(F = 1, M = 1) \rightarrow (0, 0)$ π-transition which within the SME is sensitive to Lorentz and CPT violation. This talk discusses the results and prospects of in-beam GS-HFS measurements using the ASACUSA apparatus in both hydrogen and antihydrogen.

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Laser spectroscopy of the 2^3P_J fine structure splitting of helium

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The neutral helium is a precisely calculable bound-state quantum system. Its fine structure, in particular the splitting intervals among the $2^3P_J(J=0,1,2)$ levels, has been of great interest for verifying theoretical calculations including high-order QED effects and for the determination of the fine-structure constant α.
We had performed a laser spectroscopy on a beam of laser-cooled ^{4}He atoms(cf. [1])). The spectral probing is accomplished in a well-shielded space, isolated from the noise of the surrounding electric, magnetic, and optical fields. And the 2^3P_1-2^3P_2 fine-structure splitting is determined to be 2 291 177.69 ± 0.36 kHz. This result is in agreement with both the latest QED-based calculation and the most precise experimental measurements.
We have also studied the larger interval(2^3P_0-2^3P_2), which is more sensitive for the determination of fine-structure α. Heterodyned laser probing scheme has been applied in order to eliminate the unwanted EOM sideband and refrain amplitude modulation effect. Also, by increasing the signal to noise ratio is an alternative method to reach a better statistical uncertainty. Further improvements on the experimental accuracy and theoretical investigations can be used to check the consistency of QED with an increased precision and to determine the fine-structure constant.

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Poster Abstracts

Demonstration of a Bit-Flip Correction for Enhanced Sensitivity Measurements

Lior Cohen[1], Yehuda Pilnyak[1], Danny Istrati[1], Alex Retzker[1], Hagai Eisenberg[1]

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The sensitivity of classical and quantum sensing is impaired in a noisy environment. Thus, one of the main challenges facing sensing protocols is to reduce the noise while preserving the signal. Recently, a proposal to use a quantum error correction protocol to recover sensitivity in the presence of a bit-flipping noise was published [1]. The main idea is to use a protected entangled qubit to correct the bit-flip.

In this poster, we will present a linear optics implementation of this protocol on the polarization degree of freedom of photons and its experimental demonstration [2].

A pair of entangled photons is generated using non-collinear type II spontaneous parametric down conversion. One photon measures a birefringence phase and is vulnerable to a bit flip, while its pair is protected and used for the correction. The error correction is performed by polarization rotations and a projection on a polarizing beam splitter. Our proof of principle demonstration is a novel solution in case of short correlation time bit-flip. The results show a significant recovery of the interference oscillations and about 87% of the sensitivity, independent of the noise rate.

Additionally, we will describe how our scheme can be generalized to an arbitrary number of N photon pairs. In this case, the sensitivity is increased in principle by a factor of $\sqrt{N}$ compared to the shot noise limit, the limit of classical measurements, despite of the existing noise.

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The OLYMPUS Experiment at DESY

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The proton is not an elementary particle but has a substructure governed by quarks and gluons. The spatial distributions of the electric charge and magnetization determine the response to electromagnetic interaction. Recently, it has been demonstrated that the observed difference in the elastic electric-to-magnetic proton form factor ratio with unpolarized and polarized methods can be explained by hard two-photon exchange as a radiative correction previously unaccounted for. Calculations of this correction are model-dependent and need to be validated with precision measurements. The most direct verification is a comparison of positron-proton and electron-proton elastic scattering. The OLYMPUS experiment at DESY was designed to make a definitive, high precision measurement of the elastic e^+p/e^-p cross section ratio, in order to provide an end to the controversy. The status of the OLYMPUS experiment and analysis will be reported.

QED theory of the Lamb shift in muonic tritium and helium-3 ion

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[c] *Max-Planck-Institut für Quantenoptik, Garching, 85748, Germany*

The experimental activity of CREMA collaboration has delivered an accurate result on the Lamb shift in muonic hydrogen and preliminary results on the determination of the Lamb shift in muonic deuterium. The data on the Lamb shift in muonic helium ions, both for helium-3 and helium-4, are under evaluation. To interpret the spectroscopic results in the terms of the nuclear structure, an appropriate theory is required. Recently a number of publication on several light muonic atoms have been presented by various authors.

Here we consider the QED part of the theory of the muonic tritium and muonic helium-3 ion.

Precise measurements of $\alpha_{\beta\nu}$ in ^{6}He nuclei

Ish Mukul[a], Yonatan Mishnayot[b,c], Sergey Vaintraub[c], Micha Hass[a] and Guy Ron[c]

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[b] *Soreq Nuclear Research Center*
[c] *The Hebrew University of Jerusalem*

The low energy search of physics Beyond the Standard Model (BSM) frontier, is the precise measurements of well calculated Standard Model (SM) observables in traps, in order to find tiny deviations occur due to BSM effects. Measurements of $\alpha_{\beta\nu}$ in β^{-} decay of ^{6}He were done in GANIL using a Paul trap(cf. [1]).

We plan to repeat the $\alpha_{\beta\nu}$ measurements in β^{-} decay of ^{6}He using an Electrostatic Ion Beam Trap (EIBT), using an electrostatic trap to probe radioactive nuclei is an innovative concept, done for the first time since the development of the electrostatic trap for molecular and atomic physics research(cf. [2]). Simulations predict precision better than 1% for this measurement.

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Detection setup for recoil particles from the decay of trapped metastable ^{23}Ne

Ben Ohayon[a] and Guy Ron[a]

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In this poster, we present a 4π detection setup for precision measurement of TOF distribution of recoil ^{23}Na ions from the decay of trapped metastable ^{23}Ne atoms, using shakeoff electrons as a trigger.

Nuclear polarizability effects in muonic atoms

Krzysztof Pachucki[a] and Albert Wienczek[a]

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The nuclear charge radius can be determined from spectroscopic measurements in muonic atoms, provided the atomic structure is well known and the influence of nuclear excitation on atomic levels is properly accounted for. The latter is problematic due to the difficulty in solving quantum chromodynamics in low energy scale. We perform calculations in perturbative approach by the expansion in ratio of the nuclear excitation energy over the muon mass. We pay special attention on the nuclear mass dependence and separation of the so-called pure recoil corrections. We aimed to calculate the nuclear effects as accurately as possible, in order to extract precise nuclear charge radii from the muonic atom spectroscopy. Numerical results for muonic deuterium is obtained by using the AV18 potential with the help of a discrete variable representation method for solving the Schroedinger equation. The obtained result for the 2P-2S transition serves for determination of the nuclear charge radius from the spectroscopic measurement in muonic deuterium.

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Towards a Mass-Ratio Measurement of Tritium and Helium-3 at THe-Trap

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Klaus Blaum

Max Planck Institute For Nuclear Physics, Heidelberg, Germany

THe-Trap is a precision Penning-trap mass spectrometer [1] at the Max Planck Institute for Nuclear Physics (MPIK) in Heidelberg. It aims to measure the mass ratio of tritium to helium-3 with a relative uncertainty of a few tens parts per trillion (10 ppt). This value will provide a systematic check for the KATRIN experiment, which seeks to measure the anti-electron neutrino's mass. In 2014, in order to determine the systematic shifts occuring in the mass measurements, we measured the mass ratio of the non-mass doublet carbon-12 to oxygen-16 with a statistical uncertainty of 14 ppt [2], thus performing one of the most precise mass measurements in the world. In 2015, two mass measurements for He-3 were published with a discrepancy of 5 standard deviations [3,4], supplying us with the motivation to perform a third measurement which will hopefully settle the discrepancy. In the talk we will present the current status of the experiment and ideas for future measurements.

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HILITE - High-Intensity Laser Ion-Trap Experiment

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[b] *Helmholtz Institut Jena, Germany*
[c] *Institut für Optik und Quantenelektronik, Universität Jena, Germany*
[d] *Inter-University Accelerator Centre, New Delhi, India*
[e] *Physikalisches Institut, Universität Heidelberg*

We are currently setting up a Penning Trap experiment to investigate laser-ion interaction in high-intensity photon fields and study non-linear processes like multi-photon ionization of trapped ions. The setup is designed to be transported to different high-intensity laser facilities, like FLASH at DESY, or JETI/POLARIS in Jena. The trap is designed as an open-endcap Penning Trap, which allows free access from both sides to the trap center for particle loading and the laser beam[1]. Beside the two endcap electrodes it consists of an eight-fold split ring electrode for excitation and detection in the center and two conical-shaped capture electrodes for dynamic capturing of ions from external sources. Non-destructive detection of the ion motion is based on the FT-ICR (Fourier Transform Ion Cyclotron Resonance) technique, and implementing SWIFT [2] (Storage Waveform Inverse Fourier Transform) allows to select a specific ion species of interest, while the unwanted ones are ejected resonantly. The complete setup is located at the center of a horizontal, cryogen-free superconducting magnet with a field strength of up to 6 T and a field homogeneity of better than $\pm 10^{-4}$ T within a region of ±10 mm from the bore center. A dedicated pulse-tube cooler is used for cooling the trap and the electronics to 4.2 K which reduces the pressure down to 10^{-12} mbar and improves the storage properties. At the first stage a Ti:sapphire chirped-pulse-amplification laser system with 10 mJ pulse energy and a pulse duration of 30 fs will be used for ionizing the atoms.

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CO quasar observation and laboratory spectroscopy in search for a varying proton-electron mass ratio

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The spectra observed in the line-of-sight of far distant quasars are a tool to search for a possible variation of fundamental constants. The Lyman and Werner bands of the H_2 molecule have put constraints on a varying proton-electron mass ratio, μ, from investigation of some 10 of such sources. Recently also electronic absorptions of the carbon monoxide molecule have been reported that could in the same way be used for such studies [1]. For this purpose we have reinvestigated the vacuum-ultraviolet absorption spectrum of CO at the highest resolution available, using a Vacuum-ultraviolet Fourier-transform spectrometer at the SOLEIL synchrotron [2, 3], as well as two-photon Doppler free laser spectroscopy of the $A^1\Pi$ - $X^1\Sigma$ $(v',0)$ bands [4]. In addition a calculation of so-called K_i sensitivity coefficients was performed [1], yielding the wavelength shifts imposed on the spectral lines by a variation of μ. These data were used to perform a simultaneous analysis of H_2 [5] and CO spectra observed in the object J1237+0647 at redshift $z = 2.69$. This analysis results in a constraint on a varying constant of $\Delta\mu/\mu = (-0.6 \pm 5.6_{\text{stat}} \pm 3.1_{\text{syst}}) \times 10^{-6}$ for a look back time of 11.4 billion years into cosmic history.

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