Jan. 25^{th} : Session 1

Presentation title	Optical Atomic Clocks: Towards a New Definition of the Second
Name	Fritz Riehle
Affiliation	Physikalisch-Technische Bundesanstalt (PTB), Germany

Abstract

Optical atomic clocks like optical lattice clocks or single-ion clocks have outperformed the best cesium atomic clocks that realize the base unit of time in the International System of Units (SI) with respect to accuracy and stability. With fractional uncertainties in the 10^{-18} regime and fractional instabilities of a few 10^{-16} in one second optical atomic clocks are the most accurate measuring device at all. They boost novel and more accurate tests of fundamental theories like special and general theory of relativity, quantum electrodynamics, or the question for the constancy of fundamental constants. These investigations have a high potential for unexpected discoveries and new science. The availability of better clocks will lead to new fields of research and applications like relativistic geodesy where the Earth's gravitational potential can be determined by the local change of a high accuracy clock when compared with a remote reference clock. In the first part of this talk the status of optical clocks and selected applications is highlighted at the example of PTB's clocks.

These and other applications in turn will eventually ask for a new definition of the unit of time based on optical frequency standards thereby replacing the cesium standard in the SI. The second part of this talk addresses the question what will be the necessary prerequisites, report on the current status of the discussion and will make an attempt for a tentative roadmap towards such a redefinition of the second in the SI.

Jan. 25th : Session 1

Presentation title	Making the world's best atomic clock
Name	Jun Ye
Affiliation	JILA, National Institute of Standards and Technology and University of ColoradoBoulder, Colorado 80309-0440, USA E-mail: Ye@JILA.colorado.edu

Abstract

The relentless pursuit of spectroscopy resolution has been a key drive for many scientific and technological breakthroughs over the past century, including the invention of laser and the creation of ultracold matter. Our state-of-the-art laser now maintains optical phase coherence over multiple seconds and provides this piercing resolution across the entire visible spectrum. The new capability in control of light has enabled us to create and probe novel quantum matter via manipulation of dilute atomic and molecular gases at ultralow temperatures. For the first time, we control the quantum states of more than 1000 atoms so precisely that we achieve a more stable and accurate atomic clock than any existing atomic clocks, with both key clock characteristics reaching the 10^{-18} level. We are also on the verge of integrating novel many-body quantum states into the frontiers of precision metrology, ready to advance the measurement precision beyond the standard quantum limit. Such advanced clocks will allow us to test the fundamental laws of nature and find applications among a wide range of technological frontiers.

Jan. 25th : Session 1

Presentation title	Development of a mercury optical lattice clock at LNE-SYRTE
Name	Sébastien BIZE
Affiliation	LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06

Abstract

Among the different atomic species considered for optical clocks, neutral mercury has several favorable atomic properties that reduce the impact of systematic effects currently limiting the accuracy of optical lattice clocks. The $^1S_0$ – $^3P_0$ clock transition in Hg is weakly coupled to thermal radiation and to static electric fields. For instance blackbody radiation sensitivity in Hg is a factor of ~30 less than in Sr. Mercury has a high vapor pressure at room temperature, which allows eliminating large temperature gradients in the experimental setup due to heating systems. Furthermore the isotope 199 has a spin ½ which suppresses several systematic effects related to the lattice trap. Finally Hg atoms can be laser-cooled to rather low temperature of 30 μK with a single stage magneto optical trap (MOT), performed directly on $^1S_0$ – $^3P_1$ intercombination transition, and then straightforwardly loaded in the optical lattice. Also, the high vaper pressure makes possible the use of a 2D MOT. Mercury has 7 naturally occurring isotopes which are potentially interesting for a clock and more generally, for atomic physics. For applications in fundamental physics tests, mercury has a fairly high sensitivity to a variation of the fine-structure constant α.

The biggest challenges in the Hg-based optical lattice clock operation lie in the requirement for deep UV laser sources and in the reduced polarizability that makes obtaining deep lattice trap comparatively harder. In spite of these challenges, we have completed many of the steps towards the realization of a highly accurate Hg optical lattice clock. We will report on this work and on the recent experiments with our Hg optical lattice clock. This includes a new absolute frequency measurement near the limit imposed by Cs fountains and a measurement against a Rb fountain secondary frequency standard. This also includes a measurement of the Hg/Sr optical-to-optical frequency ratio. Such measurements are used to ascertain the consistency between these highly accurate standards in the view of a redefinition of the Si second based on optical transition. Ratios between Hg and others standards will also contribute testing the stability of natural constants. Coherent optical fiber links across Europe and the ACES space mission will offer the possibility to compare the Hg lattice clock to many other standards to further enhance the above applications.

Jan. 25th : Session 1

Presentation title	Cryogenic optical lattice clocks and frequency comparison between the clocks
Name	Masao Takamoto
Affiliation	JST-ERATO, RIKEN

Abstract

The recent progress of optical lattice clocks has shown their ability to reach the target fractional accuracy and stability at the 10^{-18} level, which takes over the present realization of the SI second based on Cs clocks by a few orders of magnitude and triggers the redefinition of the second. The improvement in accuracy has been achieved by reducing the uncertainty of Stark shift induced by the uncontrolled ambient blackbody radiation (BBR), which introduces a fractional frequency shift of $\sim 10^{-14}$ for the clock transition of Sr atoms in a room temperature environment. In order to reduce the BBR uncertainty, we have developed optical lattice clocks that interrogate Sr atoms inside a cryogenic environment. By comparing two such clocks, we have directly investigated the BBR shift and verified the agreement of two clocks with the uncertainty of 10^{-18} [1]. The similar physical properties of Sr and Yb atoms, such as transition wavelengths and vapor pressure, have allowed development of a compatible clock for both species [2]. A cryogenic Yb clock is evaluated by referencing a Sr clock and the frequency ratio of Yb and Sr clock transitions is determined with the fractional uncertainty of 10^{-17} by connecting the frequencies with an optical frequency comb. Finally, we present the evaluation of higher-order lattice light shifts induced by atomic hyper-polarizability and multipolar interactions aiming for the accuracy below 10^{-18}.

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Jan. 26th : Session 2

Presentation title	Precision measurements in gravitational physics with Sr atom interferometers and optical clocks
Name	Guglielmo M. Tino
Affiliation	Dipartimento di Fisica e Astronomia and LENS Università degli Studi di Firenze, INFN

Abstract

I will report on our experiments with atom interferometers and optical clocks based on cold Sr atoms.

I will discuss the results obtained with methods based on Bloch oscillations in a vertical optical lattice to measure gravity at small spatial scales [1,2] and to test the equivalence principle of general relativity for fermionic and bosonic particles and search for a possible spin-gravity coupling [3]. I will also describe the first results we obtained on large-momentum-transfer Bragg interferometry [4]. I will report on the development and characterization of a transportable Sr optical clock [5] and prospects for future experiments in gravitational physics using Sr atom interferometers and optical clocks in Earth laboratories and in space [6,7].

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Jan. 26th : Session 2

Presentation title	Relativistic geodesy in plate subduction zones – applications to crustal deformation monitoring
Name	Yoshiyuki TANAKA
Affiliation	Earthquake Research Institute, The University of Tokyo

Abstract

Development of optical lattice clocks with unprecedented precisions is going to realize relativistic geodesy based on direct measurement of gravity potential differences. Combined with satellite measurements and geodetic surveys at the Earth's surface, optical lattice clocks are expected to improve the static geoid to unify worldwide height systems. International comparisons among optical lattice clocks have been performed, by which not only spatial but also temporal variations in the geoid due to tides may even be detected in the near future.

In an island arc like Japan, located at a plate subduction boundary, crustal deformations can also affect potential measurements when their precisions reach 1 cm in height (10^{-18}). A typical vertical displacement rate is a several mm/yr, which is an order of magnitude faster than in the Eurasian continent. The gravity potential at a site varies due to its vertical motion and mass changes in the underground and the former effect is dominant. For example, a coseismic vertical displacement caused by the M-9 Tohoku earthquake in 2011 is 1 m at Oshika Peninsula whereas the latter effect is only 2 cm. In addition, in contrast to gravity measurement, the effect of mass changes due to shallow groundwater is negligible ($r^{-1} \ll r^{-2}$ for $r \sim 0$).

Height measurements by the Global Navigation Satellite System (GNSS) are affected by water vapor in the atmosphere. Particularly, seasonal variations are hard to discern from the noises. Seismological studies reveal that large earthquakes tend to occur more frequently in winter in the Nankai Trough. The corresponding seasonal fluctuation in the crustal deformation has not yet been identified. Optical lattice clocks can confirm whether seasonal height variations observed by the GNSS are apparent or not. Continuous comparative measurements between these two methods are important for more precise error evaluations of both short- and long-term crustal deformation monitoring. Optical lattice clocks which are free from atmospheric noises can detect height changes associated with earthquakes and volcanic eruptions more quickly and precisely than the GNSS.

Jan. 26th : Session 2

Presentation title	Remote frequency comparison of cryogenic optical lattice clocks
Name	Tetsushi Takano
Affiliation	JST-ERATO, The University of Tokyo

Abstract

The accuracy of recent optical lattice clocks reaches to 10^{-18} level[1,2], which allows us to explore cm-level distortion of time and space. The remote comparison of such clocks is of great importance in fundamental physics, such as, gravitational measurement[3], geodesy[4], and dark matter search[5]. Here we report a remote frequency comparison of cryogenic Sr clocks, one of which is located at the University of Tokyo (UTokyo) while the other is located at RIKEN, which is 15 km apart from UTokyo. We connect them by a 30-km-long telecom fiber link with the stability of 1×10^{-17} at 1s. After 11 measurements carried out over 6 months, frequency difference between the clocks is determined to be 0.7095(25)Hz which translates into a height difference of 15.16 m with an uncertainty of 5 cm. This result is consistent with a height difference independently measured by employing a levelling scheme. Furthermore, we continuously operate these clocks for a period of 3 days and achieved an experimental running time of 73 %. We discuss the future prospect for such precision measurements.

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Jan. 26th : Session 2

Presentation title	Intermittent operation of an optical lattice clock toward the redefinition of the second
Name	Tetsuya Ido, Hidekazu Hachisu, Fumimaru Nakagawa, and Yuko Hanado
Affiliation	National Institute of Information and Communications Technology

Abstract

An oscillation without phase jump is a prerequisite for clocks that maintain a time scale. That's why the time scales in most metrology laboratories employ hydrogen masers (HM) as source oscillators. HM have higher stability than Cs clocks, and there is no down-time unless any hardware trouble occurs. On the other hand, the operation of highly accurate atomic standards is not continuous since systematic shifts must be evaluated occasionally to keep its accuracy. When we choose source oscillators after the transfer to the "optical" SI second, we have to carefully investigate the balance of performance and reliability. HM is probably the best choice at this point. Then, the benefit using an optical frequency reference will be the capability to evaluate the HM frequency more rapidly than referring to microwave standards. Thus, we don't need to operate optical clocks continuously. The optical clock for time keeping can be utilized for other applications from time to time.

To investigate such a possibility of intermittent operations, we demonstrated a frequency evaluation of an HM over a few months with reference to a ^{87}Sr lattice clock. The HM is a part of the Japan Standard Time (JST) system and is linked to the International Atomic Time (TAI). Therefore, the result obtained over a few months has enabled the most accurate TAI-based absolute frequency measurement [1]. The results were also utilized for a feasibility study of steering HM frequency to generate a time scale. Referring the time differences recorded in the JST system, it was figured out that the intermittent evaluations of the HM frequency once in two weeks allow us to maintain the time scale in a few ns level.

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Jan. 26th : Session 3

Presentation title	Precise frequency measurement using optical frequency comb
Name	Hajime INABA
Affiliation	NMIJ, AIST

Abstract

Optical frequency comb is an indispensable tool not only for operating optical clocks as clock but also for comparing frequencies of optical clocks with different clock transition wavelength. Recent progress of optical clocks and appearance of the "super-clock" with an accuracy at the 10^{-18} level begin to surpass the frequency comparison capacity of the comb in the short averaging-time region. In this talk, I describe our studies as for precise frequency measurements using optical frequency combs.

Jan. 26th：Session 3

Presentation title	^{199}Hg optical lattice clocks and frequency ratio measurement of ^{199}Hg and ^{87}Sr optical lattice clocks
Name	Noriaki Ohmae
Affiliation	JST-ERATO, The University of Tokyo

Abstract

Uncertainties of many optical atomic clocks are now evaluated in the order of 10^{-18} which is far beyond the current definition of a second [1-3]. Frequency ratio of the clocks with different atomic species or transitions is the only way to describe such values without limitation from the uncertainty of the SI second. Such frequency ratios can be measured using an optical frequency comb. Moreover, frequency ratio with small uncertainty can be also a sensitive probe for the variation of fine structure constant α [4].

We developed a ^{199}Hg optical lattice clock and measured the clock frequency ratio of ^{199}Hg and ^{87}Sr optical lattice clocks with uncertainty of 8.4×10^{-17} using Er fiber frequency comb [5]. This uncertainty corresponds to the upper bound of α-variation of $\Delta\alpha/\alpha = 1.1 \times 10^{-16}$. For further precise measurement of the α-variation, reduction of the Hg clock uncertainty is indispensable. Current uncertainty of Hg clock is dominated by the uncertainty of lattice light shift. To evaluate lattice light shift more precisely, we are now developing 2nd setup of Hg clock to apply synchronous measurement [6] and to achieve larger lattice intensity and control of lattice light polarization as proposed in Ref. [7].

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Jan. 26th : Session 3

Presentation title	Precision Spectroscopy of Atomic Hydrogen and the Proton Size Puzzle
Name	Thomas Udem
Affiliation	Max-Planck Institute of Quantum Optics

Abstract

Precise determination of transition frequencies of simple atomic systems are required for a number of fundamental applications such as tests of quantum electrodynamics (QED), the determination of fundamental constants and nuclear charge radii. The sharpest transition in atomic hydrogen occurs between the metastable 2S state and the 1S ground state. Its transition frequency has now been measured with almost 15 digits accuracy using an optical frequency comb and a cesium atomic clock as a reference. A recent measurement of the Lamb shift in muonic hydrogen is in significant contradiction to the hydrogen data if QED calculations are assumed to be correct. We hope to contribute to the resolution of this so called 'proton size puzzle' by providing additional experimental input from the hydrogen side.

Jan. 26th : Session 4

Presentation title	Precision measurements for tests of Lorentz symmetry and search for α-variation
Name	Marianna Safronova
Affiliation	University of Delaware and Joint Quantum Institute, NIST and the University of Maryland, USA

Abstract

The modern theories directed toward unifying gravitation with the three other fundamental interactions suggest variation of the fundamental constants and violation of Lorentz symmetry. While the energy scale of such physics is much higher than that currently attainable by particle accelerators, both variation of the fine-structure constant α and Lorentz violation (LV) may nevertheless be detectable via precision measurements at low energies. I will give an overview of such searches for new physics in atomic systems, present key results, and highlight select future proposals.

Testing the hypothesis of spatial α-variation with terrestrial laboratory atomic measurements requires at least $\dot{\alpha}/\alpha \sim 10^{-19}\,\mathrm{y}^{-1}$ sensitivity. We identified atomic systems for such a test that have all features of the best optical clock transitions leading to possibility of the frequency measurements with fractional accuracy on the level of 10^{-18} or better and have a factor of 100 extra enhancement of α-variation in comparison to experimental frequency ratio measurement accuracy.

I will report a systematic study of sensitivities to Lorentz violation in atomic systems that identified ytterbium ion as an ideal system with high sensitivity as well as excellent experimental controllability. By applying quantum information inspired technology to Yb^+, we expect tests of LV violating physics in the electron-photon sector to reach levels of 10^{-23}, five orders of magnitude more sensitive than the current best bounds. Similar sensitivities may be also reached with highly-charged ions.

Jan. 26th : Session 4

Presentation title	Searching for Dark Matter with Atoms, Molecules and Nuclei
Name	Yevgeny Stadnik
Affiliation	University of New South Wales

Abstract

We propose new schemes for the direct detection of low-mass dark matter in atomic and molecular experiments. Dark matter, which consists of low-mass bosons (axions, pseudoscalars or scalars), can readily form an oscillating classical field that survives to reside in the observed galactic dark matter haloes if these particles are sufficiently light and weakly interacting.

We have recently shown that the interaction of an oscillating classical dark matter field φ with Standard Model fields via quadratic-in-φ couplings produces both a 'slow' cosmological evolution and oscillating variations in the fundamental constants [1]. Oscillating variations in the fundamental constants produce oscillating shifts in the transition frequencies of atomic clocks, highly-charged ions, molecules and nuclear clocks – all of these systems can be used as high-precision probes to search for dark matter. Using the recent atomic dysprosium spectroscopy data of [2], we have derived limits on the quadratic interaction of φ with the photon that improve on existing constraints by up to 15 orders of magnitude [1]. We have also proposed the use of laser and maser interferometry, in which a photon wavelength is compared with the interferometer arm length, as another high-precision platform to search for dark matter via the effects of variation of fundamental constants [3,4].

Apart from the effects of the variation of the physical constants, an oscillating classical dark matter field can also give rise to a number of oscillatory spin-dependent effects, which can be sought for in atoms, molecules and nuclei. In particular, an oscillating dark matter field can induce oscillating electric dipole moments and other oscillating P,T-violating electromagnetic moments, while the motion of Earth through galactic dark matter can induce the precession of polarised spins in the laboratory about Earth's direction of motion [5-7].

Jan. 26th : Session 4

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Jan. 26th : Session 4

Presentation title	High-Precision Investigation of the Fundamental Properties of the Antiproton and the Proton
Name	Stefan Ulmer (on behalf of the BASE collaboration)
Affiliation	RIKEN, Ulmer IRU, Wako, Saitama, Japan

Abstract

The Standard Model (SM) is the theory that describes Nature's particles and fundamental interactions, although without gravitation. However, this model is known to be incomplete which inspires various searches for physics beyond the SM. Among them are tests of charge, parity, time (CPT) invariance that compare the fundamental properties of matter-to-antimatter conjugates at lowest energy and with greatest precision.

In this context, the BASE collaboration [1] at the antiproton decelerator of CERN targets high-precision comparisons of the fundamental properties of antiprotons and protons, namely, charge-to-mass ratios and magnetic moments. To perform these tests we developed a Penning trap based quantum jump spectrometer which enabled us to carry-out the most precise measurement of the proton magnetic moment with a fractional precision of 3.3 parts in a billion [2]. Application of the technique to the antiproton will provide a thousand-fold improved comparison of proton/antiproton g-factors. In addition we performed the most precise comparison of the proton-to-antiproton charge-to-mass ratio, with a fractional precision of 69 parts in a trillion [3]. To date, our measurement constitutes to most precise test of CPT invariance with baryons. Recent improvements in the stability of the apparatus demonstrate the feasibility to improve this test by another factor of 10. In the talk I will summarize our most recent results and the future perspectives of the BASE experiment program.

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Jan. 27^{th} : Session 5

Presentation title	Entanglement of 3000 atoms by one photon
Name	Vladan Vuletic
Affiliation	Massachusetts Institute of Technology

Abstract

Quantum-mechanically correlated (entangled) states of many particles are of interest in quantum information, quantum computing and quantum metrology. Metrologically useful entangled states of large atomic ensembles (spin squeezed states) have been experimentally realized, but these states display Gaussian spin distribution functions with a non-negative Wigner quasiprobability distribution function. Non-Gaussian entangled states have very recently been produced and characterized in atomic ensembles. Here we generate entanglement in a large atomic ensemble via an interaction with a very weak laser pulse; remarkably, the detection of a single photon prepares several thousand atoms in an entangled state. We reconstruct a negative-valued Wigner function, and verify an entanglement depth (the minimum number of mutually entangled atoms) of 2,900 out of 3,100 atoms. The achieved purity of the state is slightly below the threshold for entanglement-induced metrological gain, but further technical improvement should allow the generation of states that surpass this threshold. Furthermore we discuss how for an ensemble inside an optical resonator with very strong atom-cavity coupling almost any symmetric entangled many-atom state can be generated by the detection of one photon.

Jan. 27th : Session 5

Presentation title	Precise control and probe of ultracold ytterbium atoms in an optical lattice
Name	Yoshiro Takahashi
Affiliation	Kyoto University

Abstract

We report our recent experiments on precise control and probe of ultracold ytterbium(Yb) atoms in an optical lattice. In particular, precise control of multiple optical lattice potentials enables us to form a novel type of lattice configuration known as a Lieb lattice, and load a Bose-Einstein condensate of Yb atoms into a flat band of a Lieb lattice. In addition, a precise dynamical control of an optical super-lattice enables us to demonstrate a Thouless topological charge pumping. We will also report our development of a Yb quantum gas microscope, which can precisely probes a single atom with a single-site resolution.

Jan. 27th : Session 5

Presentation title	Linking Time to Ultracold Yb Physics
Name	Massimo Inguscio
Affiliation	1. INRIM Istituto Nazionale di Ricerca Metrologica, Torino 10135, Italy 2. LENS European Laboratory for Nonlinear Spectroscopy, Sesto Fiorentino 50019, Italy 3. Department of Physics and Astronomy, University of Florence, Sesto Fiorentino 50019, Italy

Abstract

Ytterbium is suitable for precise experiments in metrology and atomic physics, including quantum degenerate matter. Optical clocks based on Ytterbium give a contribution to the present debate on a possible redefinition of the second in the International System of units, whilst Ytterbium quantum gases offers unprecedented results on many body physics also towards an effective demonstration of quantum simulators. We report on the INRIM ^{171}Yb optical clock operation including the absolute frequency measurement of the clock transition using a primary Cs fountain as reference. At LENS (University of Florence) an ^{173}Yb degenerate Fermi gas is produced for quantum simulation. A coherent fibre link, 642 km long, remotely connects the two sides of the Ytterbium physics, joining metrology and atomic physics, using remote accurate and stable time and frequency standards to empower the experiments on many body physics and exploiting the properties of the Fermi gases to improve the measurements of forbidden transitions or to investigate symmetries of physics (SU(6), gauge fields …). In general we address the cross-fertilization of the different scientific attitudes for a more effective study of the Ytterbium physics using remote experiments.

Jan. 27th : Session 5

Presentation title	The Scattering of Coherent Superpositions of Clock States and Precision Measurements
Name	Kurt Gibble
Affiliation	The Pennsylvania State University, USA

Abstract

Atom-atom scattering is often detrimental to precision measurements that use atomic coherences. I'll discuss several topics related to the scattering of cold atomic coherences. One recent result is using atomic clock techniques to observe and precisely measure the microscopic quantum scattering phase shifts that atoms experience when they scatter. With mrad accuracy, we observe s-wave scattering phase shifts with variations that approach π through a series of Feshbach resonances of ultra-cold cesium atoms in a fountain clock. In optical lattice clocks, the forbidden s-wave collisions of identical fermions can in fact extend coherence times and produce novel collision shifts. I'll also discuss the scattering of clock coherences due to room-temperature background gas collisions. The universal behavior of this scattering provides useful limits on the associated frequency shift from measurements of trap loss rates, essentially independent of the background gas, in diverse cold atom clocks, fountains, lattice clocks, and quantum-logic ion clocks. I can also briefly discuss the recent controversy regarding the microwave lensing frequency shifts of fountain clocks – an atom-interferometric frequency shift which has a correspondence to photon recoils shifts.

Jan. 27th : Session 5

Presentation title	Interfacing ultra-cold atoms and solids
Name	József Fortágh
Affiliation	University of Tübingen

Abstract

Interfacing ultra-cold atoms and solids promises novel quantum interfaces where electronic, magnetic or mechanical degrees of freedoms may be transferred from one system to the other while preserving the quantum nature. I present experimental results on the coherent manipulation of atomic clouds on a superconducting chip and discuss the perspectives for coupling atoms to superconducting circuits. I also discuss the possibility of local detection of classical and quantum noise in electromechanical circuits through their coupling to an atomlaser.