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COMPILATION OF ABSTRACTS

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Session 1

Single photon measurements, radiometry with entangled sources, superconducting particle detectors

Chair: Maria Luisa Rastello, INRIM (Italy)

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ORAL / Session 1

Quantum optical metrology by photons

Author and Speaker: Maria Luisa Rastello, INRIM, Italy

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Abstract: The present Photonic era is based on rapidly developing optical technology and photon devices, with special impact on the fields of quantum communication, quantum computing, quantum enhanced measurements beyond the standard quantum limit, and optical radiometry.

These applications require quantum optical metrology based on new standards and calibration chains, together with new metrics. In particular, standards are required which operate in the single-photon regime and are embedded in quantum optical technologies.

Moreover, quantum enhanced optical measurements e.g. the exploitation of quantum phenomena such as entanglement and other non-classical state correlations, are among the challenges to yield sensitivity and accuracy better than purely classical approaches. The goal is to develop theoretical and technological capabilities for operating optical systems (e.g. sub-shot noise imaging, ghost imaging, phase measurement) or opto-mechanical systems (micro-cavities), in the quantum regime, beyond the Standard Quantum Limit.

A single-emitter sub-shot noise quantum light source: press a button and get one photon

Author and Speaker: Stephan Götzinger, Max Planck Institute for Light, Germany

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Abstract: In this talk I will discuss our recent progress towards a deterministic single-photon source. By embedding a single molecule into a metallo-dielectric antenna we obtained the most regulated stream of single photons reported to date. Such a source might have potential applications in the calibration of photodetectors and could lead to the redefinition of the candela.

Quantum imaging: challenges and perspectives in radiometry and biophotonics

Author and Speaker: Ivano Ruo-Berchera, INRIM, Italy

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Abstract: Non-classical correlations in optical beams offer unprecedented opportunity of reducing the uncertainty of measurements especially when a low photon flux, down to the single photon level, is used. We review the principles and the state-of-the-art of quantum imaging and sensing techniques with emphasis on the applications to radiometry and biophotonics. In particular, non-classical correlations could represent a cutting-edge tool for investigating phototransduction processes at the fundamental level, such as the one responsible of human vision.

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Predictable single photon source with variable photon flux

Authors: Erkki Ikonen[1,2], Aigar Vaigu[1,2], Geiland Porrovecchio[3], Xiao-Liu Chu[4,5], Sarah Lindner[6], Marek Smid[3], Albert Manninen[1], Christoph Becher[6], Vahid Sandoghdar[4], and Stephan Götzinger[4,5]

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Speaker: Erkki Ikonen

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Abstract: This paper describes a method that allows us to realise an SI traceable single-photon source (SPS) based on a silicon vacancy centre in nanodiamond, which is optically excited by a pulsed laser. Our method takes advantage of a very sensitive analog-mode photodetector comprising of a low-noise 3 × 3 mm silicon photodiode in conjunction with a custom made switched integrator amplifier. At the excitation rate of 70 MHz, the source delivers a photon flux large enough to be measured by the low optical flux detector. The directly measured photon flux constitutes an absolute reference. A measurement of the SPS's absolute optical power with this detector eliminates the need for a precise knowledge of the SPS characteristics.

By changing the pump laser repetition rate, the photon flux of the SPS can be tuned in a controlled way. This gives us a direct way of linking conventional optical power levels, measurable with specifically designed analog-mode detectors, down to low photon flux levels needed for single-photon detectors. The advantage of our method of changing the pump laser repetition rate is that it does not require precise knowledge of the source efficiency, as long as it remains the same for all the used pump frequencies. The source is calibrated by the analog-mode detector and can then be used at the reduced repetition rate for detector responsivity characterizations at the few-photon level.

POSTER / Session 1

S1-1: Embedded Mass, Force and Laser Power Standard Using a Resonant Optical Cavity

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Affiliation of authors: NIST, USA

Speaker: Gordon A. Shaw

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Abstract: The relationship between optical power and force provides an emerging frontier in metrology. Photon pressure forces result from the scattering, absorption and reflection of light, providing an alternative to calorimetry for laser power measurement, and an alternative to mass standards for force measurement. Because the forces generated from photon pressure are so small (1 Watt of laser power provides about 7 nN of force), this phenomenon is ideal for the small force metrology standards used in nanometer-scale materials properties measurement. It is impractical in many cases to incorporate a Watt-scale laser into small force measuring instrumentation, however. In this work we create a resonant optical cavity with a finesse of approximately 1000 that effectively multiplies the optical power available for force measurement. One of the cavity mirrors is mounted on a miniature fused silica parallelogram flexure that acts as a spring balance, permitting the direct measurement of the cavity circulating optical power. A preliminary model allows us to assess the agreement between the circulating optical power inferred from the mirror and cavity properties with the direct measurement. The result is a NIST-on-a-chip type standard that incorporates the measurement of mass force and laser power in a miniature device.

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S1-2: The effect of turbulence in free-space synchronization, using second-order quantum interference.

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Speaker: Filippus S. Roux

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Abstract: Recently, the Hong-Ou-Mandel (HOM) effect, which incorporates second-order quantum interference, has been used for remote synchronization of clocks with a synchronization stability of less than a picosecond [R. Quan, et al., Sci. Rep. 6, 30453 (2016)]. However, this implementation has only been demonstrated over a few kilometers. When such a synchronization protocol is implemented over longer distances, the effect of the channel may start to deteriorate the second-order quantum interference in the HOM effect. For instance, if the channel is the atmosphere (see for instance [J.-D. Deschenes, et al., Phys. Rev. X 6, 021016 (2016)]), turbulence may affect the quantum interference observed in the HOM effect.

Here we investigate the effect of turbulence on the HOM effect. In our experiment, turbulence is simulated for weak scintillation conditions by a single phase screen and the input state is prepared with spontaneous parametric down-conversion. We consider various scenarios allowing for different variations of the synchronization protocol. The experimental results, which agree with our theoretical calculations, show that for symmetric input states under particular conditions (in a one-sided turbulence channel) the HOM effect is independent of the scintillation strength. This result follows from a combination of the fact that the HOM dip is only observed if the input state is symmetric and the fact that a one-sided turbulent channel does not convert a symmetric state into an anti-symmetric state. In view of these results, it should be possible to use second-order quantum interference to synchronize remote clocks over longer distances.

S1-3: Directly realizing the becquerel with quantum thermal sensors

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Affiliation of authors: ^NIST and *LANL, USA

Speaker: Dan Schmidt

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Abstract: The SI derived unit of radioactivity is the becquerel. A becquerel simply corresponds to one decay per second of a particular nuclide. However, realizing the becquerel is quite complex. Essentially, all methods currently employed operate by detecting the decay products from radioactivity events. Radioactivity produces decay products with a four order of magnitude energy span and multiple particle types. A large suite of measurement methods must be maintained to measure and standardize the vast set of radionuclides of interest to metrology. Unknown impurities, in-grown daughter products, and short half-lives make standardization particularly difficult. Separate absolute and spectrometry techniques must be combined to extract absolute activity and impurity content. Even under the best of circumstances, current methods only indirectly realize the becquerel. NIST and other groups have produced micro-fabricated calorimeters sensitive enough when operated at ultra-low temperatures to detect individual decay events (femtojoules to picojoules). The total absolute activity of radioactive material embedded in the calorimeter is directly measured. At the same time, the calorimeter measures the energy of each decay event with resolving power greater than 1000. This high resolution spectral signature provides the nuclide content. One measurement produces both absolute activity and spectrometry. Several groups have conducted small scale demonstrations. NIST has, together with Los Alamos National Laboratory, measured the energy spectra of alpha particle decay events for the analysis of mixed actinide samples [Anal. Chem. 2015, 87, 3996−4000]. For metrology, we will need to invent robust protocols to embed a wide range radioactive materials into the calorimeter and develop gravimetrically traceable techniques for delivering the radioactive material to the micro-fabricated calorimeters. The goal is a universal metrological method for measurement and standardization of radioactivity that would directly realize the becquerel.

S1-4: Nano-SQUIDs based on Niobium nanobridges for the inductive calorimeter

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Speaker: Wang Xueshen

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Abstract: Superconducting quantum interference devices (SQUIDs) have been used to measure kinds of physical parameters with high accuracy. Nanoscale SQUIDs (NanoSQUIDs) show lower noise spectrum to 170 $n\Phi_0/Hz^{1/2}$ and lower energy sensitivity because of the lower inductance and capacitance, and play an important role in nanometrology such as measuring single spin, single photon. We have fabricated nanoSQUIDs based on monolayer niobium (Nb) film weak-link nanobridge junctions by focus ion beam (FIB) milling. The dimension of the nanobridge was less than 60 nm and the loop scale is 20×20 μm^2. The device was characterized in a cryostat with external self-made excitation coils. The working temperature range for this device was ～1 K which will be improved by the addition of the shunt resistor layer. The voltage-flux transfer properties were measured at different working temperatures. The maximum of the voltage ΔV_Φ across the nanosquid device by a flux quantum Φ_0 is 180 µV and the transfer function expressed by $dV/d\Phi_0$ is 0.9 mV/Φ_0 at 6.5 K, and the values were only 180 µV and 0.043 mV/Φ_0 at 7.0 K. This kind of nanoSQUID will be used for inductive calorimeter with one layer of designed Nb film as the absorber film located in the loop.

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S1-5: Photon-based radiometry at KRISS

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Speaker: Kee Suk Hong

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Abstract: We present the research activities in the field of photon-based radiometry at the Center for Photometry and Radiometry of KRISS. The most urgent task is to provide the calibration service for the single photon counting detectors. We are preparing the detection efficiency calibration of single photon counting detectors based on Si and InGaAs avalanche photodiodes as a function of wavelength from 250 nm to 1600 nm, which should be traceable to the "classical" spectral responsivity scale. The validity of this calibration measurement is additionally tested by comparison with the "quantum" method based on a correlated photon source at one fixed wavelength. The second issue is to develop a well-characterized test source for single photon detectors. For this purpose, we are developing a single photon source based on the single Silicon-vacancy center in nano-diamonds. To make the single photon source more useful for applications such as quantum communication, we also realize the wavelength conversion device that can convert the single photons at 738 nm to the fiber communication wavelength of 1310 nm. The ultimate goal of our activities is to realize a radiometric standard source of single photons, which provides only one single photon in a defined region of time and space with an accurately measurable probability.

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S1-6: High performance Silicon Single Photon Avalanche Diodes (SPAD): a valuable tool for quantum metrology.

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Speaker: Angelo Gulinatti

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Abstract: The capability of detecting single photons with high efficiency, low noise and extremely low temporal jitter is a prerequisite for a successful implementation of many quantum-based approaches in metrology.

Luckily, a few radically different technologies are available today for detecting single photons. Each of them has advantages and limitations that determine their specific field of application. One of these options is to exploit the junction breakdown in semiconductor materials in order to attain a macroscopic current-pulse from the absorption of a single photon. Devices based on this working principle are usually called Single Photon Avalanche Diodes (SPADs). The combination of excellent performance in terms of photon detection efficiency, noise, active area diameter and temporal response provided by these detectors, makes them suitable for a wide range of applications. In addition, they present all the advantages that are typical of the semiconductor devices, i.e. ruggedness, compactness and suitability for the integration on the same chip of many devices. Finally, they are usually operated at room temperature or moderately cooled by means of a Peltier stage with great advantages in terms of easiness of operation, reduced system costs and power consumption.

In this talk we will present some recent developments in SPAD detectors, and in particular a technology we developed to improve the Photon Detection Efficiency (PDE) in the red/near infrared region of the spectrum, while maintaining a good temporal response. Detectors developed by adopting this technology attained for example a remarkable 40% PDE at a wavelength of 800 nm with a detection jitter lower than 100 ps FWHM, thus overcoming the classical trade-off between these two parameters. We will discuss also the use of this technology for the fabrication of arrays of detectors and future developments.

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S1-7: Determination of x-ray fundamental parameters using quantum sensors

Authors: J. N. Ullom, J. W. Fowler, B. K. Alpert, D. A. Bennett, W. B. Doriese, J. D. Gard, G. C. Hilton, L. T. Hudson, Y.-I. Joe, K. Morgan, G. C. O'Neil, C. D. Reintsema, D. R. Schmidt, D. S. Swetz, C. I. Szabo

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Abstract: Quantum sensors operating at sub-Kelvin temperatures show promise for the determination of x-ray energies, line-shapes, and fluorescence yields, components of a body of knowledge known as x-ray fundamental parameters. X-ray fundamental parameters are of practical significance because they facilitate compositional analysis of complex materials. They are also a useful test of atomic theory because they are related to electronic transitions between quantized, element-specific orbitals. We have recently undertaken a reassessment of the absolute energies of the x-ray L lines of several newly important rare earth elements. The measurements were performed using an array of calorimetric sensors consisting of metal films electrically biased in the superconducting-to-normal transition. These Transition-Edge Sensors (TESs) provide exquisite spectral resolving power, high collecting efficiency, and broadband response, in part because of the sharpness of the resistive transition and the suppression of thermal noise at sub-Kelvin operating temperatures. Previous measurements of absolute line energies have relied on diffraction by well-characterized crystalline materials. In our technique, we perform a simultaneous measurement of multiple x-ray lines determined to great accuracy through the diffraction method, as well as other lines whose spectral features are of interest but are poorly known. The well-known lines are used to estimate the calibration curve of the TESs, which then establishes the energies of the unknown features. We present results for 22 x-ray L lines in the range 4.5 keV to 7. 5 keV and show numerous instances in which our energy measurements improve on existing tabulations. The same measurements provide information on x-ray line shapes and widths, data that is presently not systematically tabulated. We describe upcoming measurement campaigns and planned improvements to the TES technology that will reduce the energy uncertainty of our measurement technique below present ~0.4 eV levels. Finally, we describe efforts to add energy calibration features using traditional diffractive methods.

S1-8: Single Photon Metrology at NRC

Authors: Angela Gamouras and Andrew D. W. Todd

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Speaker: Angela Gamouras

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Abstract: At the National Research Council of Canada, we are working to establish a quantum metrology capability for optical radiometry. As applications of few-photon methods have now extended beyond quantum information science (*e.g.* quantum computing, quantum key distribution, random number generation, *etc*.) to several other areas including spectroscopy, particle detection, and medical point-of-care diagnostics, the development of measurement infrastructure is crucial for future implementations of these technologies. With SI traceability to the NRC cryogenic radiometer, initial efforts in detector efficiency measurements of silicon single-photon avalanche photodiodes will be made using a substitution configuration with a calibrated silicon transfer radiometer and 840 nm fiber laser source. This first step towards the establishment of few-photon metrology at NRC will lead to advanced measurement capabilities which will be extended to the telecom band and with an eye to the characterization of on-chip single-photon sources.

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S1-9: Traceable calibration of single-photon detectors and sources

Authors: B. Rodiek, M. López, H. Hofer and S. Kück

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Speaker: B. Rodiek

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Abstract: Quantum metrology requires high efficient single-photon detectors and single-photon sources for its proper operation. To achieve that, they also need an appropriate metrological support that guarantees the traceability of their measurements to primary standards. The calibration of single-photon detectors with respect to its detection efficiency is frequently carried out by the double attenuator technique, described in detail in [1]. Alternatively, the detection efficiency can be determined by a direct comparison against a traceable low optical flux detector (LOFD) [2]. Both measurement procedures were recently compared for determining the Si-SPAD quantum detection efficiency [3]. The comparison was carried out at a wavelength of 770 nm and at optical power levels from 90 fW to 1300 fW, with mean relative deviations < 1 %.

Besides the calibration of single-photon detectors, pure and reliable single-photon sources that provide high single photon fluxes and a negligible background are needed for instance in quantum computing and cryptography as well as for radiometric applications, e.g. single-photon detector calibration [4]. The source under investigation here is based on a nitrogen-vacancy (NV) center in a nanodiamond. It was absolutely characterized in terms of its absolute optical radiant flux and spectral power distribution [5]. The photon flux is adjustable between 190 000 photons per second and 260 000 photons per second (corresponding to 55 fW and 75 fW, respectively. The purity of the single-photon emission, the $g^{(2)}$-value, is between 0.10 and 0.23. This result is considered being the first step towards the realization of a standard single-photon source.

Details of the setups and the calibration procedures as well as recent progress will be discussed at the conference.

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S1-10: Traceability for single photon radiometry

Authors: Ingmar Müller, Jörg Hollandt, Janin Lubeck, Roman Klein, Mathias Richter, Rainer Thornagel, Gerhard Ulm, Lutz Werner

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Speaker: Ingmar Müller

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Abstract: Within the emerging field of quantum radiometry several methods have been established to calibrate single-photon detectors (SPDs) traceable to the International System of Units [1-7]. In recent years, the traceability and accuracy for the determination of the detection efficiency of SPDs has been improved and the relative standard uncertainties were determined according to the GUM. For free-space detectors uncertainties as low as 0.16 % have been reported by exploiting the properties of synchrotron radiation and by means of the so-called double attenuator technique. In addition, fiber-coupled SPDs have been calibrated with a relative standard uncertainty of approximately 2 % by means of the synchrotron radiation based calibration method. This method provides an independent calibration chain, in addition to the existing chain, leading to the primary detector standard, — the cryogenic radiometer —, that achieved the lowest uncertainties for SPDs thus far. Moreover, synchrotron radiation is a helpful tool to provide traceability under the aspect of a possible photon based definition of the SI unit Candela. The synchrotron radiation based calibration method has been successfully validated for fiber-coupled measurements by a bilateral comparison between the National Institute of Standards and Technology and the Physikalisch-Technische Bundesanstalt (PTB) at the electron storage ring of PTB [8,9], the Metrology Light Source. The unique radiometric properties of synchrotron radiation are ideal to bridge the radiometric gap between classical radiometry and quantum radiometry. In addition, a few-photon detector based on a photodiode with an internal quantum efficiency close to unity, as they are used in Predictable Quantum Efficient Detectors (PQEDs), is under development. The device is equipped with an interchangeable pinhole that can be used to match the effective sensitive detector area to that of the device under test. This reduces a major uncertainty contribution associated with the different sizes of the sensitive areas of classical SPDs. In the presentation, the synchrotron radiation based calibration method as well as the few-photon detector are described.

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S1-11: Towards measurement and control of single-photon microwave radiation on chip

Authors: A.J. Manninen[(1)], A. Kemppinen[(1)], J. Lehtinen[(1)], E. Mykkänen[(1)], G. Amato[(2)], E. Enrico[(2)], V. Lacquaniti[(2)], M. Kataoka[(3)], T. Lindström[(3)], S.E. de Graaf[(3)], R. Dolata[(4)], M. Khabipov[(4)], B. Jalali Jafari[(4)], S.V. Lotkhov[(4)], A.B. Zorin[(4)], J. Govenius[(5)], R.E. Lake[(5)], M. Möttönen[(5)], J.P. Pekola[(5)], O.-P. Saira[(5)], J. Senior[(5)], K.Y. Tan[(5)], R. George[(6)], Yu.A. Pashkin[(6)], J. Prance[(6)], O. Astafiev[(7)], P.J. Meeson[(7)], and K. Porsch[(7)]

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Speaker: Antti Manninen

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Abstract: Detection and generation of single microwave photons would be important in many quantum technology applications. In a joint research project MICROPHOTON of the European Metrology Research Programme EMRP, we have studied several solutions for both microwave detectors and sources and advanced the technologies towards single-photon level. All devices operate at cryogenic temperatures, most of them below 100 mK. Another topic of the project was to study effects of microwave background radiation on cryoelectronic quantum devices and to develop methods for eliminating the detrimental effects.

Highlights of the project in microwave photon generation include development of two types of on-demand single-photon sources based on a superconducting quantum bit (qubit). One of them is a tuneable source based on a tuneable gap flux qubit. With that device, on-demand generation of microwave photons has been demonstrated with efficiency of about 65–80% in a wide frequency range from 7.75 to 10.5 GHz. The other version is based on the so-called transmon qubit, and single photon sourcing with that system has also been realized.

For microwave detection, a thermal detector based on a superconductor - normal metal - superconductor nanostructure has been developed, and detection of 1.1 zJ energy packet corresponding to 200 photons at 8.4 GHz has been demonstrated. Also, a new type of a bifurcation amplifier, a period-doubling bifurcation amplifier, has been developed for ultrasensitive microwave detection. With detectors based on single-electron effects, events caused by single microwave photons generated by an on-chip microwave source have been detected. A similar detector has also been used to characterize on-chip microwave filters.

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S1-12: Single photon detection without lose the count

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Speaker: M. Rajteri

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Abstract: Photonics is becoming a key enabling technology for the 21st century and single photons are the fundamental elements for such development. The capability to generate and manipulate single photons must be complemented by the possibility to detect them without losing any information. In particular, the possibility to discriminate the number of photons in a light pulse is a fundamental tool in many different fields of optical science and technology, including quantum metrology, foundations of quantum mechanics, and quantum information. One of the best photon number resolving (PNR) detector available nowadays is the Transition-Edge Sensor (TES): it is a detector based on the sharp transition between the superconducting and the normal state of a thin film. In the visible-NIR region, the film itself acts as absorber and the TES is so sensitive to detect single photons with intrinsic energy resolution, or at fixed wavelength with PNR capability, and negligible dark counts.

In this talk recent results on TESs fabricated and characterized at INRIM will be presented. AuTi-based TESs, with an active area of 100 μm^2, have demonstrated to reach high energy resolution (ΔE=0.11 eV) at telecom wavelength, while Ti-based TESs, with a smaller active area (1 μm^2 and 4 μm^2), have shown the best optimization between energy resolution and count speed, that could reach up to 1 MHz.

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S1-13: Single photon interference in x-ray interferometry and the lattice parameter of silicon

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Speaker: Ulrich Kuetgens

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Abstract: The lattice parameter of silicon can be regarded as a reproducible quantity of nature [1]. This sub-nm length is measured in the SI-unit of length by comparison with an optical wavelength in combined optical and x-ray interferometers [2]. The applied laboratory x-ray sources limit the photon flux at the detectors in practical set-ups to about 10000 cps and therefore the scanning speed of few nm/s with continuously smoothed intensity. A thermal x-ray source however produces single x-ray quanta incoherently, so that single photon interference becomes detectable, if all photons are detected separately in short time channels [3]. The correlation in this time series allows the off-line evaluation of the x-ray interference fringes and the scanning speed can be increased up to some µm/s. The single photon method is applied to the estimation of the lattice parameter of silicon.

The lattice parameter of Si can be applied as a naturally quantized standard of length in nanometrology [4] and especially in the case of isotopically enriched silicon-28 it is the link between the macroscopic 1 kg mass of silicon spheres and the microscopic atomic mass quantum m_{Si} for the determination of the Avogadro constant N_A in the framework of the new definition of the SI-unit of mass [5].

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Session 2

Quantum standards for mass, pressure, vacuum, temperature, acoustics and vibration

Chair: Carl Williams, NIST/JQI (USA)

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ORAL / Session 2

The next generation of metrology - NIST Quantum SI

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Abstract: With the new definition of the SI currently scheduled to be internationally accepted in 2018, the new SI definition will replace the classical SI [artifact based SI traceability (*e.g.,* kilogram)] with the quantum SI based on quantum phenomena and fundamental and atomic constants. NIST is positioning itself to develop quantum-based standards and sensors to disseminate the quantum SI. These new devices will potentially enable zero-chain SI traceability be enabling NIST to deliver dual standards and sensors to the factory floor. The NIST vision is that these quantum-based innovations will improve the SI dissemination through dual standards and sensors to the point where routine exchange of artifacts for measurement quality assurance is no longer needed. Quantum and photonic based rugged small-scale devices open new horizons in measurement science and represent a disruptive technological shift in how metrology is done. These quantum SI devices draw upon a range of technologies not previously exploited for these applications, such as nanofabrication, photonics, and atomic physics. The NIST next-generation, quantum-metrology programs will be discussed in terms of the larger programmatic view of how quantum-based, chip scale technologies will disrupt the dissemination of the SI through the NIST quantum SI.

Coherent caloritronics in superconducting circuits: from heat interferometers to 0-π controllable thermal Josephson junctions

Author and Speaker: Francesco Giazotto, NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore di Pisa, Italy

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Abstract: The Josephson effect [1] represents perhaps the prototype of macroscopic phase coherence and is at the basis of the most widespread interferometer, i.e., the superconducting quantum interference device (SQUID). Yet, in analogy to electric interference, Maki and Griffin [2] predicted in 1965 that thermal current flowing through a temperature-biased Josephson tunnel junction is a stationary periodic function of the quantum phase difference between the superconductors. In this scenario, a temperature-biased SQUID would allow heat currents to interfere thus implementing the thermal version of the electric Josephson interferometer.

In this talk I will initially report the first experimental realization of such a heat interferometer [3]. We investigate heat exchange between two normal metal electrodes kept at different temperatures and tunnel-coupled to each other through a thermal device in the form of a DC-SQUID. Heat transport in the system is found to be phase dependent, in agreement with the original prediction. After this initial demonstration, we have extended the concept of heat interferometry to various other devices, implementing the first quantum `*diffractor'* for thermal flux [4, 5], realizing the first

balanced Josephson heat modulator [6], and an ultra-efficient low-temperature hybrid `*heat current rectifier*' [7, 8], thermal counterpart of the well-known electric diode [9]. The latter structure offers a remarkable heat rectification ratio up to about 140 which allows its implementation in solid-state thermal nanocircuits and general-purpose electronic applications requiring energy harvesting and isolation at the nanoscale. Finally, I will conclude by showing the realization of a fully superconducting heat modulator based on the first tunable „0-π“ *thermal* Josephson junction [10], and I will describe the principle for a microwave quantum cooler based on the Josephson effect [11].

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Putting the quantum into mechanics: Quantum standards for mass and force

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Abstract: The Planck constant plays an important role in quantum mechanics, but is not relevant for classical mechanics. It seems therefore surprising that the Planck constant expressed in SI base units is a number times kgm^2s^{-1}. Contemplating the fact that the unit of mass, the kilogram, is contained in the Planck constant, leads to the conclusion that the most precise determination of the Planck constant must involve a test mass with a mass of 1 kilogram. Because at this cardinal point, the smallest relative uncertainty in mass metrology can be achieved.

One link between the Planck constant and the unit of mass is the Kibble balance, formerly known as watt balance. This balance establishes a connection between virtual mechanical power and virtual electrical power, which can be measured using the Josephson Effect and the quantum Hall effect as a product of the Planck constant and two frequencies. In the planned revision of the international systems of units (SI), the Planck constant will be fixed and the Kibble balance can be used to realize the unit of mass. The Kibble balance is not limited to mass metrology at 1 kg, but can be used effectively for smaller mass ranges and even to realize forces down to the mN level. For forces well below the mN, the electrostatic balance can be used.

Quantum absolute sensors for gravity measurements

Authors: R. Karcher, R. Caldani, M. Langlois, A. Trimeche, A. Imanaliev, S. Merlet and F. Pereira Dos Santos

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Speaker: Sébastien Merlet

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Abstract: The measurement of gravity, gravimetry, or its gradients, gradiometry, allows for static and dynamical studies of mass distributions, from local to global scales. Applications of gravimetry cover many disciplinary fields, such as geophysics, natural resources exploration, hydrology, geodesy, inertial navigation, fundamental physics and fundamental metrology. Gravity measurements are performed with two different classes of instruments: gravimeters, most widely used, measure the gravity acceleration *g* and its variations, whereas gradiometers measure its gradient.

Quantum gravity sensors, based on cold atom interferometry technique, can offer higher sensitivities and accuracies than current technologies. Moreover gravity acceleration and gradient measurements can be realized in a single quantum device, which offers the possibility to resolve, by combining these two signals, the ambiguities in the determination of the positions and masses of the sources.

I will first present our Cold Atom Gravimeter used for Planck constant determination with Watt Balance. It performs continuously 3 gravity measurements per second with an accuracy better 1 nano-*g* and with a demonstrated long term stability of 0.06 nano-*g* in 40 000 s of measurement. Then I will describe a « dual sensor » under development which will perform measurements of *g* and its gradient. It will combine ultra-cold atomic sources produced by magnetic traps on a chip and multiphotonic beam splitters based on the transfer of hundreds of photon momentum. With these two key elements, the gradiometer will perform measurements in the sub-E sensitivity range in 1 s measurement time on the ground (1 E = 1 Eötvös = 10^{-9} s^{-2}). Such a level of performances opens new prospects for on field and on board gravity mapping, for navigation with the retracking of inertial units, for geophysics and for fundamental physics, with the measurement of *G*.

POSTER / Session 2

S2-1: New technologies for a cold-atom vacuum standard

Authors: Stephen Eckel, Daniel Barker, James Fedchak, Nikolai Klimov, Julia Scherschligt, Greg Strouse

Affiliation of authors: National Institute of Standards and Technology, NIST, USA

Speaker: Julia Scherschligt (or Stephen Eckel)

Speaker email: Julia.s(at)nist.gov (or stephen.eckel(at)nist.gov)

Abstract: As part of NIST's transition to the quantum SI, the Thermodynamic Metrology Group at NIST is pushing several efforts to realize temperature and pressure. In this talk, I will discuss the Cold-Atom Vacuum Standard (CAVS) which uses ultra-cold trapped atoms as a direct means of counting background molecules in a vacuum system. Researchers in atomic physics have long known that the lifetime of the ultra-cold cloud in magnetic or optical traps is limited by the background gas pressure. We invert this relationship and exploit the fact that the measured loss-rate of ultra-cold atoms from the trap depends on a fundamental atomic property (the loss-rate coefficient or thermalized cross section) to make an absolute sensor and primary vacuum standard. In a parallel effort, we are developing technologies that will be useful in realizing miniaturized cold-atom technologies. We anticipate that these miniaturized technologies would allow us to make the CAVS robust and deployable with zero-chain traceability, thus enabling the realization and dissemination of the quantum pascal in the extreme-high-vacuum (XHV) and ultra-high-vacuum (UHV) regimes.

S2-2: The Quantum Pascal

Authors: Julia Scherschligt, James Fedchak, Stephen Eckel, Daniel Barker, Nikolai Klimov, Jay Hendricks, Jacob Ricker, Patrick Egan, Jack Stone, Greg Scace, Greg Strouse

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Speaker: Julia Scherschligt

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Abstract: NIST is actively developing a new paradigm in the methodology of pressure and vacuum measurement and primary standards. To drive the transition from classical to quantum metrology, we have recently launched research efforts into realizing the quantum pascal in terms of the Boltzmann constant ($k_B T$) over a wide range of pressures, with plans to cover the entire range of pressure from megapascals to the XHV. This talk will highlight progress made in the barometric range, and at the lowest end of the pressure scale. In part 1, we discuss the new quantum-based, photonic technique that utilizes ultra-precise measurement of refractive index of gases to determine gas pressure in the barometric range. The new standard is based on the fundamental physics of light interacting with a gas, and when the gas is helium, the refractive index of the gas is based upon first principle quantum chemistry calculations and is realized as a primary standard. In part 2, we discuss the Cold-Atom Vacuum Standard (CAVS) which uses ultra-cold trapped atoms as a direct means of counting background molecules in a vacuum system. Researchers in atomic physics have long known that the lifetime of the ultra-cold cloud in magnetic or optical traps is limited by the background gas pressure. We invert this relationship and exploit the fact that the measured loss-rate of ultra-cold atoms from the trap depends on a fundamental atomic property (the loss-rate coefficient or thermalized cross section) to make an absolute sensor and primary vacuum standard. Both of these efforts, the optical standard and the atomic standard, will result in devices that function as both standards and sensors. They will be robust and deployable with zero-chain traceability, thus enabling the realization and dissemination of the quantum pascal.

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S2-3: Realization and Dissemination of Small Mass with an Electrostatic Force Balance

Authors: Gordon A. Shaw, Julian Stirling, Patrick Abbott, Zeina J. Kubarych

Affiliation of authors: National Institute of Standards and Technology, NIST, USA

Speaker: Gordon A. Shaw

Speaker email: gshaw(at)nist.gov

Abstract: The accurate measurement of small mass (1 gram or less) is essential in a variety of endeavors; the chemical and pharmaceutical industry, precision measurement instrumentation, federal, state, and private calibration labs, fundamental research labs, and more recently laser machining operations all require small mass standards to maximize their effectiveness. Concurrently, the kilogram redefinition planned for the International System of Units (SI) in 2018 affords an opportunity to improve the scaling of mass calibrations. Recently, we have shown that an Electrostatic Force Balance (EFB) can provide mass realization from quantum electrical metrology that is consistent with that provided by the conventional method of kilogram subdivision. Because mass is realized directly at the milligram scale, the additional accrual of uncertainty from repeated subdivision of larger masses is avoided. This work demonstrates the realization of mass between 50 micrograms and 20 milligrams consistent with the current and redefined SI, but with uncertainty reduced by up to two orders of magnitude from other methods. A process for efficient dissemination of this calibration method will also be discussed.

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S2-4: Photonic Thermometry: A new Hope

Authors: Zeeshan Ahmed, Nikolai Klimov and Kevin Douglass

Affiliation of authors: National Institute of Standards and Technology, NIST, USA

Speaker: Zeeshan Ahmed

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Abstract: For the past century, industrial temperature measurements have relied on resistance measurement of a thin metal wire or filament whose resistance varies with temperature. Though resistance thermometers can routinely measure industrial temperatures with uncertainties of 10 mK, they are sensitive to mechanical shock which causes the sensor resistance to drift over time requiring frequent off-line, expensive, and time consuming calibrations. These fundamental limitations of resistance thermometry have produced considerable interest in developing photonic temperature sensors to leverage advances in frequency metrology and to achieve greater mechanical and environmental stability. The thermo-optic effect of silicon presents an inviting oppertunity for developing novel, high sensitivity temperature sensors. We are developing a suite of photonic devices that leverage advances in mid-IR light sources to fabricate cost-effective photonic temperature sensors. Our work to date indicates that photonic sensors can match the performance of a wide variety of legacy thermometers and in the short-term will out-compete all legacy technology. Our on-going work in opto-mechanic thermometry raises the possibility of putting thermodynamic temperature standards on a chip that can deployed in the field.

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S2-5: An action quantum on a scale – dissemination of the quantum based kilogram

Authors: D. Knopf, Th. Wiedenhöfer, K. Bauer, F. Härtig

Affiliation of authors: Physikalisch-Technische Bundesanstalt, PTB, Germany

Speaker: Dorothea Knopf

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Abstract: The Meter Convention exists more than hundred years. The units hosted by the Metre convention base on ideas born within the French Revolution. Thus, the meter and the kilogram were defined by natural constants of that time, the circumference of earth and the mass of water at a specific temperature. Even at that time metrologists try to find stable realisations of the definitions. One of the resulting artefacts is still defining the Kilogram. Just now we are facing the change to a system of international units defined via natural quantum based constants. Even the Kilogram will be defined by a natural constant, the Planck-Constant.

The "new Kilogram" will by its link to the Planck-Constant offer theoretically unlimited ways for its realisation. Just now only a few seem to be achievable. The experiments required for a new definition – the Kibble-Balance and the Avogadro-Sphere – are expected to be the two most prominent realisations. But, are these tremendously expensive experiments that are probably difficult in operation as well suitable in the sense of disseminating the Kilogram?

The presentation would like to develop the idea of silicon spheres of different qualities for the dissemination of the quantum based kilogram to the macroscopic world. Beside metrological aims even the availability of realisations is an important aspect within such a dissemination chain. The developed tools and procedures for using the spheres as mass standards and the respective investigations will be presented. Aspects like the connection to the "old" system as an important aspect for practise or the current state of the activities to proof the expected long term characteristics of silicon spheres in use will be highlighted as well.

S2-6: Towards a quantum standard for absolute pressure measurements in the range 200 Pa to 20 kPa based on a superconducting microwave cavity

Authors: L. Pitre [1,3], R. M. Gavioso [2,3], F. Sparasci [1,3],M.D. Plimer[1], D. Madonna Ripa [2,3]

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Speaker: Laurent Pitre

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Permission to post the abstract not granted.

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S2-7: The progress of Joule balance at NIM

Authors: Zhengkun Li, Zhonghua Zhang, Yunfeng Lu, Pengcheng Hu, Yongmeng Liu, Shisong Li, Jinxin Xu, Yang Bai, Tao Zeng, Gang Wang, Qiang You, Qing He, Jiubin Tan

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Speaker: Zhengkun Li

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Abstract: To precisely measure the Planck's constant for the redefinition of the mass unit kilogram, different approaches are anticipated to give at least three independent results with uncertainties lower than 5×10^{-8}. Inspired by the Kibble balance method, the National Institute of Metrology (NIM, China) proposed a joule balance method in 2006. The main difference of Kibble balance and joule balance is that the induced voltage and velocity measurement in the Kibble balance is replaced by the mutual inductance measurement in the joule balance to avoid the trouble from the dynamic measurement. NIM built its first prototype NIM-1 to verify the principle of the joule balance with a relative uncertainty of 8.9×10^{-6} by 2013. The main uncertainties are from the self heating of the coils, force measurement, length measurement and air buoyancy. To get a better result, since 2013, the new joule balance NIM-2 has been designed with a series of new approaches. An electromagnet has been built to decrease the self heating problem. However, the nonlinearity of the soft iron in the electromagnet makes it difficult to measure the mutual inductance with an accuracy of 10^{-8} level. A flux linkage difference measurement method is proposed to solve this problem. At the same time, this approach keeps the advantage of joule balance method, i.e., the accuracy of the flux linkage difference mainly depends on two static positions z_1 and z_2. A mass comparator is used to lower the uncertainty of force measurement. A laser based position locking system is built to decrease the swing and vibration of the suspended coil. Thus the uncertainty of length is reduced. Finally, the main part of the joule balance is put in a vacuum chamber to avoid the problem from the air refractive index and air buoyancy. At present, the joule balance NIM-2 has been constructed and a series of measurements have been carried out. The uncertainty under 5 parts in 10^7 can be expected by the Jul. 2017.
Further improvement approaches are still in consideration to get an uncertainty of 10^{-8} level finally.

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S2-8: Calculated atomic and molecular interactions for thermophysical standards

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Speaker: R. M. Gavioso

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Abstract: Future metrology standards will increasingly be based on physical quantities computed from first principles rather than measured. For example, progress made in the calculation of the thermophysical properties of helium reduced their uncertainty well below that of the corresponding experimental determinations, leading to novel metrological applications such as primary standards of pressure and temperature. Extending the computational capability previously developed for He to a broader class of more complex systems, like heavier monatomic gases and even molecules, will greatly improve our understanding of the fundamental physics of the studied systems with a deep positive impact on the metrology of fluids. We review the current capabilities of theory and experiment to achieve an accurate determination of the polarizability and thermophysical properties of different substances and systems and discuss the perspectives of advancing the state-of-the-art and how this progress may finally lead to improved - or even novel – measurement methods and standards of temperature, pressure, humidity, flow and gas transport properties. These new methods, being theoretically grounded, will be more simple to operate, robust and accurate, resolving many practical issues which afflict traditional metrological techniques.

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S2-9: Precise determination of the fine structure constant: impact on the new International System of Units

Authors: S. Bade1, P. Cladé[(1)], F. Firaben[(1)] and S. Guellati-Khélifa[(1),(2)]

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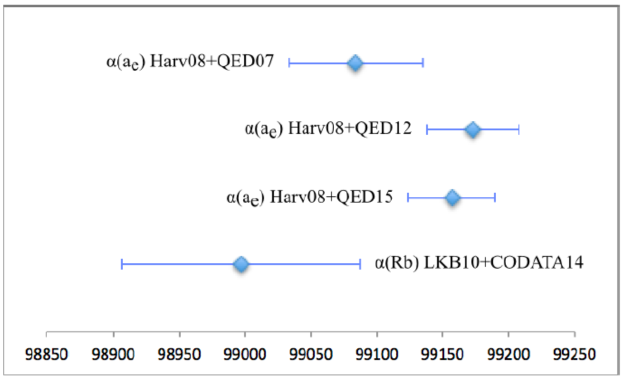
Abstract: Because it is dimensionless, the fine structure constant α has a particular role among fundamental constants. This constant is a cornerstone of the future International System of Units as it links the two approaches proposed for the redefinition of the kilogram, foreseen in 2018: the watt balance experiment and the silicon sphere. Moreover, in the proposed new SI, many physical constants that will have a fixed value depend strongly on its knowledge (such as the vacuum permeability μ_0 and atomic mass unit m_u). The reliability of the determination of the fine structure constant is therefore, essential for the redefinition of the SI.

Nowadays the CODATA value, α_{CODATA}, is derived mainly from two experiments: First, Harvard's experiment that consists on the measurement of the anomaly of the gyromagnetic factor of the electron (a_e). The value $\alpha(a_e)$ is then deduced from complex and sophisticated quantum electrodynamics (QED) calculations. Second, Paris's experiment where the value $\alpha(h/m)$ is directly deduced from the measurement of the ratio h/m between Planck constant and the rubidium atomic mass.

In 2010, the two values $\alpha(a_e)$ and $\alpha(h/m)$ were in good agreement but in 2015, new QED calculations have been performed which shifted the value of $\alpha(a_e)$, there is no more overlap between error bars especially if one considers the new value of the relative electron mass and the latest adjustments of the Rydberg constant and the rubidium mass (see Figure). Using the value of the Rydberg constant derived from muonic hydrogen and 1S-2S transition experiments results in an even larger discrepancy. This makes the CODATA adjustment less reliable.



We are currently carrying out a new measurement campaign. In this talk we will present our last results.

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S2-10: Thermodynamic temperature measurement with traceability to quantum electrical standards

Authors: Jifeng Qu[1], Samuel P Benz[2], Kevin Coakley[2], Horst Rogalla[2], Weston L Tew[3], Rod White[4], Kunli Zhou[1] and Zhenyu Zhou[1]

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Speaker: Jifeng Qu

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Abstract: Johnson noise thermometer (JNT) infers thermodynamic temperature through measuring the thermally-induced voltage or current noise that occurs in all electrical conductors, which offers an appealing alternative to other forms of primary gas based thermometry and has attracted increasing interest. However, because the noise signal is extremely small, random, and distributed over very wide bandwidths, it is very difficult to enable measurements with accuracies comparable to the other primary methods. In this presentation, we will introduce the foundation of Johnson noise thermometry and the technological breakthroughs, including the cross correlator, frequency-domain signal processing, and most recently, the quantum-accurate pseudo-random noise source developed by NIST, that have enabled the application of JNT to absolutely measure the thermodynamic temperature with traceability to the quantum electrical standards. Through comparing the thermal noise across a 200 ohm sense resistor immersed in a triple point of water cell to the synthesized quantum accurate pseudo-random voltage noise, we determined the Boltzmann constant k_B with a relative uncertainty of 3.9×10^{-6}. Recent experiments implicate further improvement on k_B determination with a relative uncertainty less than 3.0×10^{-6}, which could contribute to the redefinition of the kelvin in 2018.

S2-11: Quantum-based Johnson noise thermometry at NIST

Authors: Nathan E. Flowers-Jacobs, Alessio Pollarolo, Horst Rogalla, Anna E. Fox, Kevin J. Coakley, Weston L. Tew, Samuel P. Benz

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Speaker: Nathan E. Flowers-Jacobs

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Abstract: Johnson noise thermometry utilizes the direct theoretical link between noise fluctuations and dissipation, where the power spectral density of the voltage fluctuations across a resistor are proportional to the temperature of the resistor and the resistance, with a proportionality constant equal to four times the Boltzmann constant. Measuring these small voltage fluctuations is challenging and is accomplished using custom, low-noise electronics which are calibrated over a 1 MHz bandwidth using a quantum-based Josephson arbitrary waveform synthesizer (JAWS), also known as a quantum voltage noise source (QVNS).

I will summarize the state of Johnson noise thermometry at NIST. We are currently focused on measuring the Boltzmann constant with a few parts in 10^6 uncertainty using a resistor held at the triple point of water. After the redefinition of the SI in 2018, this project will pivot towards development of a compact primary thermometer and use the newly-defined Boltzmann constant to make precise temperature measurements over a wide range of temperatures. The redefinition will unlink the Kelvin from the triple point of water. However, a programmable and scalable primary thermometer will have the potential to revolutionize thermometry by reducing dependence of practical thermometry on the remaining fixed points of the ITS-90 temperature scale. A QVNS-JNT primary thermometer will increase understanding of the temperature scale and possibly reduce the uncertainty of temperature measurements at arbitrary temperatures, especially at temperatures away from these fixed points.

S2-12: Optomechanical accelerometers for low-uncertainty calibration in the field

Authors: Y. Bao, A.J. Fleisher, J. Gorman, J. Lawall, D. Long, J. Taylor, F. Zhou, and T. LeBrun

Affiliation of authors: National Institute of Standards and Technology , NIST, USA

Speaker: T. LeBrun

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Abstract: We will describe the development of optomechanical reference accelerometers fabricated on silicon chips and designed to provide uncertainties in the field that rival an NMI calibration service. Based on Fabry-Perot cavities, the readout is directly traceable to the SI using the wavelength of light, requiring only an internally performed calibration of a resonant frequency. The sensitivity is expected to be limited principally by thermomechanical noise in the mechanical resonator, which increases in small damped oscillators. However, MEMS resonators can easily achieve thermal noise below the level required to allow acceleration measurement with a relative uncertainty of 10^{-3} for accelerations down to 1 m/s^2 (approximately 0.1 standard gravity). We will also present optical frequency comb measurements of the noise equivalent acceleration that demonstrate the high stability of the cavities, and discuss applications to quantum sensing and standards.

S2-13: Perspective on Metrology of Thermophysical Quantities Based on Quantum Electrodynamic Calculations

Authors: Jintao Zhang, Xiaojuan Feng, Hong Lin, Yuning Duan,

Affiliation of authors: National Institute of Metrology, NIM, China

Speaker: Jintao Zhang

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Abstract: In classical metrology, thermophysical quantities are generally scaled in macroscope on the base of thermodynamic laws and thermal properties of practical materials. On the other hand, the advanced quantum electrodynamics calculations result in the thermophysical and electromagnetic properties, and the virial coefficients of helium in high accuracy in temperatures from 1 K to 10^4 K. The thermodynamic relations of helium are well characterized over such wide temperatures. The accurate calculations are transferring to the heavier monoatomic gases, such as argon, xenon, and krypton. The new primary procedures are emerging according to the state of the art of the calculations. For instance, the temperature is calculated out by knowing the Boltzmann constant and the measure of refractivity or kinetic energy of helium or a reference monoatomic gas; the pressure by knowing the relative electric permittivity of such a monoatomic gases; the flowrate by knowing the pressure difference, the calculable viscosity and the pvt relation of such a monoatomic gas. The new procedures exploit the exceeding stability of the properties of helium and other monoatomic gases. Relative primary procedures are perspective to be developed accordingly, which will be of the advantages of operational convenience with high stability of measurements in wide temperatures and pressures. The trains for the SI traceability of thermophysical quantities may be largely squeezed and the ranges largely extended.

Session 3

Highly entangled systems for metrology, entangled optical clocks

Chair: Patrick Gill, NPL (UK)

ORAL / Session 3

Atomic clocks, Superpositions and Entanglement

Author and Speaker: Patrick Gill, NPL, UK

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Abstract: Progress in atomic clocks has taken advantage from quantum techniques even from the original caesium clock developments using Ramsey's technique of separated field interrogations generating state superpositions. The advent of laser cooling of ions and atoms over four decades ago led to many new quantum operations such as quantum jump detection, cooling to motional ground states in traps, microwave fountain clocks and optical clocks based on single trapped ions or neutral atoms held in optical lattice traps. More recent developments include the dual ion quantum logic clock, and the use of entanglement to achieve frequency instabilities below the standard quantum limit or to measure clock systematic frequency shifts. I will briefly address some of these quantum techniques in atomic clock metrology.

Optical clocks with single ions

Author and Speaker: Ekkehard Peik, PTB, Germany

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Abstract: Following Dehmelt's seminal ideas of using a single trapped ion, laser cooling and the observation of quantum jumps as a spectroscopic signal, optical clocks have now been realized with a systematic uncertainty in the 10^{-18} range. Different elements (Yb, Sr, Al) and different types of reference transitions are investigated. Frequency ratios between these clocks can be measured at an uncertainty that is smaller than in the realization of the SI Hertz with caesium clocks, permitting reliable consistency checks of the new clocks and also searches for new physics like violations of Einstein's equivalence principle.

Optical clock protocols for Heisenberg-limited stability

Author and Speaker: David R. Leibrandt, NIST, USA

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Abstract: With the systematic uncertainties of optical atomic clocks fast approaching 10^{-18}, and with new applications in metrology, geodesy, and fundamental physics on the horizon, it is enticing to consider using quantum entanglement to enhance the stability of state-of-the-art optical clocks. Typically, one of the barriers to the use of entangled states is that their decoherence with respect to the local oscillator is more rapid than unentangled states, forcing the use of shorter interrogation times and at least partially nullifying the stability enhancement. This talk presents a brief summary of recent progress on the NIST Al+ quantum-logic clock, and discusses a new protocol for optical clock comparisons that circumvents the local oscillator decoherence limit and that reaches the Heisenberg stability limit for maximally-entangled GHz input states.

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Non-destructive detection for strontium optical lattice clocks: towards a lattice clock in the quantum regime

Authors: Grégoire Vallet, Eva Bookjans, Sl·awomir Bilicki, Rodolphe Le Targat, Jérôme Lodewyck

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Abstract: Optical lattice clocks with record frequency stability and systematic uncertainties have now been demonstrated. However, their stability still does not reach the fundamental quantum projection noise (QPN) limit. In this paper, we propose and experimentally demonstrate a detection scheme for the transition probability in a strontium optical lattice clock, based on the measurement of the phase shift induced by the lattice trapped atoms on a weak probe laser. This measurement is enhanced by a high finesse optical cavity, and features a robust heterodyne signal extraction, in order to reach a resolution of a few atoms for a few tens of scattered photons. This detection therefore demonstrates "classical" non-destructivity (the atoms are kept trapped after probing), while its signal-to-noise ratio is compatible with "quantum" non-destructivity (the atomic coherent is preserve after probing). The former will enable us to reach the QPN by reducing the Dick effect, and the latter will enable us to demonstrate entanglement between atoms in order to overcome the QPN.

POSTER / Session 3

S3-1: The Quantum Allan Variance

Authors: K. Chabuda, I. D. Leroux, R. Demkowicz-Dobrzanski

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Abstract: The instability of an atomic clock is characterized by the Allan variance, a measure widely used to describe the noise of frequency standards. We provide an explicit method to find the ultimate bound on the Allan variance of an atomic clock in the most general scenario where N atoms are prepared in an arbitrarily entangled state and arbitrary measurement and feedback are allowed, including those exploiting coherences between succeeding interrogation steps.

K. Chabuda, I. Leroux, R. Demkowicz-Dobrzanski, New J. Phys. 18, 083035 (2016)

S3-2: Towards creation of the nuclear clock and frequency reference point: search for the optimal parameters today, working instruments of the future

Authors: F.F.Karpeshin[1], M.B.Trzhaskovskaya[2] and L.F.Vitushkin[1]

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Speakers: F.F.Karpeshin

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Abstract: Creation of nuclear reference for the frequency, and nuclear clock on this basis, is a very topical problem at the contemporary research metrology. Simple estimates show that nuclear transitions are characterized with higher stability and narrower line widths. Basing on these principles, it is possible to create nuclear clock e.g. on the basis of ^{229}Th nuclide with relative uncertainty at the level of 10^{-19}. Such precision will allow one to solve a number of problems of fundamental research including the determination of gravity field, as well as applied engineering. Thus, differences of the gravitation potential in various space points, or stability of the fundamental constants will be measured with higher resolution. For comparison, best facilities have the uncertainties at the level of 10^{-17} at the time being.

The idea of a new standard is based on the cooperative atomic-nuclear transitions. Internal conversion transitions comprise a conventional class of the transitions of this type. They underlie nuclear spectroscopy, being used for decades. For the purpose of creation the nuclear clock, subthreshold, or bound internal conversion (BIC) [1-3] becomes indispensable means. It is in the resonance exchange with energy between electron shells and the nuclei. We discuss the principles which underlie the BIC phenomenon and related cooperative atomic-nuclear transitions. Specifically, the principle of the frequency stabilization is discussed, has its basis on the resonance two-photon absorption of laser quanta [4]. To this end, the widths of the hyperfine atomic transitions accompanied with change of the nuclear state are considered under the accent of their stability against the ambient parameters.

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S3-3: Heisenberg limited Rabi spectroscopy

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Speaker: Ravid Shaniv

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Abstract: The most precise clocks in the world measure time by performing spectroscopy on narrow dipole-forbidden optical atomic transitions [1]. Through the use of N identical particles the uncertainty of the spectroscopic measurement can classically be decreased, scaling as $1/\sqrt{N}$. However, by quantum-mechanically entangling the particles, one can improve the uncertainty scaling to $1/N$, fundamentally limited by the Heisenberg energy-time uncertainty relation [2]. In this work we generate an entangling Ising $\sigma_x\sigma_x + \delta\Sigma\sigma_z$ Hamiltonian acting on two ion-qubits trapped in an effective harmonic trap. The Hamiltonian detuning δ is scanned through the transition resonance creating a correlated Rabi spectroscopy measurement. We observe a spectral peak which is twice as narrow as the one given in a single-ion spectroscopy, demonstrating the Heisenberg-limited nature of the measurement. This is the first demonstration of a Rabi-type Heisenberg-limited spectroscopy. Furthermore, we show that the Ising Hamiltonian acts independently on two separate subspaces of the two-ion system. We show that one subspace is susceptible to changes in the mean transition frequency between the ions while being invariant to changes in the difference between the ions' frequency, and vice versa for the other subspace. Each of these subspaces can therefore be addressed and probed individually, with the Ising interaction providing a correlated spin-flip rotation term. Hence, we can perform Heisenberg-limited spectroscopy of the difference frequency in one subspace while remaining invariant to mean frequency noise and vice versa in the other sub-space.

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Bureau International des Poids et Mesures

S3-4: Developing optical frequency standard in India

Authors: S. De, S. Panja, V. N. Ojha and D. K. Aswal

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Speaker: S. De

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Abstract: Accurate timing system is the basis for many sophisticated technologies such as high speed communication, positioning of satellites, navigation, weather prediction and so on. Measuring temporal constancy of fundamental constants, violation of Lorentz symmetry and many more scientific research relies on ultra-precise time. Thus, worldwide there is a continuous effort for upgradation of the atomic clocks since these are the backbone for generation and maintenance of accurate time and frequency. The caesium (Cs) based SI definition of second has served last five decades and it is expected that it will be redefined based on an optical transition in the coming years. Keeping that in mind, after successful demonstration of Cs-fountain reaching to a fractional accuracy of 2×10^{-15}, we being National Metrology Institute (NMI) of India have started developing an optical frequency standard based on the $4f^{14}6s\ ^2S_{1/2}$ - $4f^{13}6s^2\ ^2F_{7/2}$ transition of ytterbium-ion ($^{171}Yb^+$) which is a potential candidate for the next generation SI definition of second.

At present we are developing subcomponents associated to the experiment such as the precision ion trap and its ultra-high vacuum (UHV) container, optical systems associated to the photoionization, laser cooling of $^{171}Yb^+$, imaging system and electronic hardware in order to produce the trapped and laser cooled ions. Further parts for building the frequency standards, *e.g.*, clock laser, ultra-stable reference cavity and associated system are in the pipeline.

We have designed an end-cap type Paul trap where the trap induced systematics will be reduced. This will produce nearly ideal quadrupole potential for confining the ion. The trap design is complete and a prototype has already been fabricated which we are testing at present. The UHV system has been assembled and the atomic oven is ready to use. We are currently emphasizing on developing the optical subsystem for the ion production and laser cooling $^{171}Yb^+$. Overall progress of this activity will be presented in the meeting.

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S3-5: Optical-clock local-oscillator universal interrogation protocol for zero probe-field-induced frequency-shifts

Authors: T. Zanon-Willette, R. Lefevre, A.V. Taichenachev and V.I. Yudin

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Speaker: Thomas Zanon-Willette

Speaker email: thomas.zanon(at)upmc.fr

Abstract: Optical clock interrogation protocols, based on laser-pulse spectroscopy, are suffering from probe-induced frequency-shifts and their variations induced by laser power.

Original Hyper-Ramsey probing scheme, which was proposed to alleviate those issues, does not apply below fractional frequency changes of 10^{-18} when decoherence and relaxation by spontaneous emission or collisions are present.

We present a universal interrogation protocol based on composite laser-pulses spectroscopy with phase-modulation for both fermionic and bosonic optical clocks, eliminating probe-induced frequency-shifts at all orders even in presence of various dissipative processes.

Our scheme, using a magic combination of $\pm\pi/4$ and $\pm3\pi/4$ phase-modulated generalized Hyper-Ramsey resonances, extremely robust to errors in laser parameters, can be implemented in two flavours: either by inverting clock state initialization or by pulse order reversal.

It can be designed using magic-wave induced transitions, two-photon excitation and magnetically-induced spectroscopy for atomic, molecular and nuclear frequency metrology, mass spectrometry and precision spectroscopy. It might even be implemented with quantum logic gate circuit and qubit entanglement.

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S3-6: BBR-induced shifts and broadening of states in atoms and ions of alkaline-earth elements and thermometry for optical clocks

Authors: Vitali D. Ovsiannikov[1], Vitaly Palchikov[2], and Igor Blinov[2]

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Speaker: Vitaly Palchikov

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Abstract: The development of the highest-precision ion and neutral-atom clocks [1] requires accurate account for the influence of surrounding environmental fields on the clock uncertainties. Significant perturbations of clock frequency come from the field of the ubiquitous blackbody radiation (BBR). The BBR cannot disappear unless the absolute temperature *T* of environment is zero. Consequently, the energy of a state $|nl\rangle$ in an atom (neutral or ionized) in really existing laboratory conditions is shifted and broadened by the BBR due to the dynamic Stark effect. The corresponding energy of the BBR-atom interaction includes both real (shift) and imaginary (broadening) parts: $\delta\varepsilon_{nl}(T) = \delta E_{nl}^{BBR}(T) - i\Gamma_{nl}^{BBR}(T)/2$.

In this communication we present detailed calculations of the shift $\delta E_{nl}^{BBR}(T)$ and broadening $\Gamma_{nl}^{BBR}(T)$ of the clock levels in ions of the group IIa (Be^+, Mg^+, Ca^+, Sr^+, Ba^+) and IIb (Zn^+, Cd^+, Hg^+) elements, calculated on the basis of the Fues' Model Potential (FMP) [1] approach and in the Quantum Defect Method (QDM) for determining the single-electron radiation transition amplitudes. Asymptotic equations are derived for estimating $\delta E_{nl}^{BBR}(T)$ and $\Gamma_{nl}^{BBR}(T)$ of Rydberg states, which may be useful for determining the BBR temperature and corresponding uncertainties in high-accuracy measurements of the clock frequency.

In our previous paper [1] we have shown that optical spectroscopy of Rydberg states can provide accurate *in situ* thermometry at room temperature. We demonstrated that magic wavelength lattices exist for both Strontium and Ytterbium transitions between the metastable and Rydberg states. Frequency measurements of Rydberg transitions with 10^{-16} accuracy provide 10mK resolution and yield a blackbody uncertainty for the clock transition of 10^{-18}. Therefore, Rydberg thermometry may be particularly useful for clock applications where cryogens are prohibitive, including optical- frequency space clocks.

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S3-7: Ion microtrap chips for atomic quantum technologies

Authors: Guido Wilpers, Kaushal Choonee, Mariam Akhtar and Alastair Sinclair

Affiliation of authors: National Physical Laboratory, NPL, UK

Speaker: Guido Wilpers or Alastair Sinclair

Speaker email: alastair.sinclair(at)npl.co.uk

Abstract: Ion microtraps are of significant interest for their applicability to quantum technologies such as information processing and metrology. We demonstrate parallel, wafer-scale MEMS fabrication of monolithic ion trap chips. The devices have a near-ideal, three-dimensional electrode geometry, and an ion-electrode distance of 240 μm. Each trap chip contains a remote loading zone and a linear array of 7 operation segments. The first 5 (of 6) fabrication stages are performed at wafer level; the mechanical form of the microstructured chips is fully intact and 90 % of chips are within ± 3 % of the geometric design targets. After dicing into individual chips, an automated die-attach process completes the electronic package in a modified ceramic chip carrier, which also serves as a UHV electrical feedthrough. RF tests result in surface breakdown voltages ranging up to 600 V amplitude. Tests with improved dicing methods indicate that > 500 V amplitude is feasible.

A first chip from the most recent batch has undergone trapping tests using a Doppler-cooled $^{88}Sr^{+}$ ion. Coherent optical spectroscopy on the S-D transition shows Lamb-Dicke confinement and initial measurements suggest an ion heating rate of < 50 quanta/s, a significant improvement over our earlier work. Notably, this is achieved in a scalable device operating at room temperature, in contrast to scalable microtraps with a 2D electrode geometry. More detailed heating rate measurements using a sideband-cooled ion are in progress and will be presented. Beyond this, the device will be used to prepare entangled ion strings. In parallel, we are investigating the use of an *in-situ* microplasma for selective sputtering of contaminants on the device electrodes, to further reduce electric field noise and the ion heating rate. This work aims to realise quantum metrology with entangled ions in a scalable device, free of motional decoherence.

Session 4

Advances in quantum electrical standards, single electron transistors and demonstrations of the “quantum metrology triangle”

Chair: Uwe Siegner, PTB (Germany)

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ORAL / Session 4

Electrical quantum standards: foundation of electrical units and measurements

Author and Speaker: Uwe Siegner, PTB, Germany

Speaker email: Uwe.Siegner(at)ptb.de

Abstract: Electrical quantum standards are the basis of electrical measurements in the present International System of Units, the SI. In the new SI they will also realize the electrical SI units. In this talk Josephson voltage metrology, quantum Hall resistance metrology, and single-charge transport will be reviewed. Their contributions to fundamental and applied metrology as well as their potential for innovation will be addressed.

Practical quantum current standard: performances and perspectives

Author and Speaker: Wilfrid Poirier, LNE, France

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Abstract: The ampere, as defined from *e* in the future SI, can be realized by applying directly Ohm's law to the quantum voltage and resistance standards. I will present a novel programmable quantum current generator (PQCG) able to generate currents in a wide range of values that are quantized in terms of ef_J (f_J is the Josephson frequency) within one part in 10^8. I will address its applications and perspectives, notably a compact quantum calibrator based on the graphene resistance standard.

GaAs based single electron pumps for electrical quantum metrology

Author and Speaker: Hans Werner Schumacher, PTB, Germany

Speaker email: hans.w.schumacher(at)ptb.de

Abstract: After the 2018 revision of the SI system of units a direct primary representation of the revised ampere could be realized by so-called single electron pumps. Single electron pumps are based on single electron transistors that are driven by an oscillating voltage with frequency *f*. During one oscillation cycle one electron is first captured from source and later ejected to drain thereby generating a quantized current $I = ef$, with *e* the charge of the electron.

In my talk I will review the present state of single electron pumps for the direct representation of the ampere. I will show that semiconductor-based single electron pumps are excellent candidates for this task allowing high currents in combination with excellent quantization accuracy. I will further discuss in-situ measurements of pump errors by single charge detection for the realization of a self-referenced quantized current source.

Stable and tunable carrier density control of epitaxial graphene for quantum metrology

Authors: Hans He[1], Samuel Lara[1], Tobias Bergsten[2], Andrey Danilov[1], Kyung Ho Kim[1, 3], Yung Woo Park[3] and Sergey Kubatkin[1]

Affiliation of authors: Chalmers University of Technology[1], RISE Research Institutes of Sweden[2], Seoul National University[3]

Speaker: Hans He

Speaker email: hanshe(at)chalmers.se

Abstract: The viability of graphene as a quantum resistance standard was first demonstrated in 2010[1]. The results has since been reproduced[2,3,4] and graphene seems to be a superior as a practical quantum resistance standard due to better performance, and usability, than conventional 2DEG systems such as GaAs. However some challenges still remain, and control over carrier concentration in graphene is one of the most important issues to tackle. This is especially difficult for epitaxial graphene due to high intrinsic doping and Fermi level pinning, both due to the interface layer. It is important because the optimal critical current for the operation of a quantum resistance standard depends on the carrier concentration. At a certain temperature and field there is a corresponding optimal zero-field carrier concentration which will maximize critical current[5]. Existing methods such as photochemical gating or corona discharge are useful but lack stability, tunability, or potency. In this work we present a new method of encapsulating and gating epitaxial graphene on SiC which changes carrier concentration on the order of 10^{13} cm^{-2}. We use a chemical gating method with a strong electron acceptor and polymer encapsulation of graphene in order to bring the intrinsic doping down to low levels (as low as around $n<10^{10}$ cm^{-2} at 2K). The base doping of the graphene can be tuned by varying the polymer spacer thickness. Further control over carrier concentration can be exerted by using a top-gate if needed. This method is stable and preserves the quality of graphene with samples surviving over 6 months stored in ambient conditions/N_2-atmosphere (and through several thermal cycles) without appreciable degradation. Thus it can be used to bring highly doped samples down to practical carrier concentrations for quantum metrology.

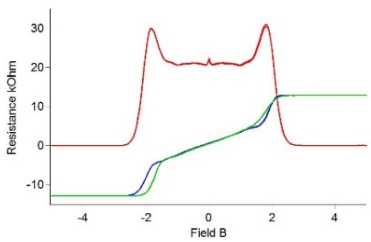

Figure 1. **A.** Sample gated using only chemical gating shows well-defined quantization at 2K. The polymer spacer thickness is such that the doping at 2K reaches $n=2\bullet10^{11}$ cm^{-2} electrons. Mobility exceeds 7000 cm^2/Vs.

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POSTER / Session 4

S4-1: Epitaxial Graphene QHR standards: Beyond GaAs

Authors: Randolph E. Elmquist and Yanfei Yang

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Abstract: Quantum standards in the new SI promise to provide “access for all” to primary units based on internationally recognized physical realizations. The laser, for example, has made standards of length inexpensive and accurate in terms of another easily accessed quantum standard, the GPS broadcast. Electrical standards based on the quantum Hall effect, on the other hand, have succeeded in yielding unprecedented consistency and accuracy, but have failed at reaching the broad user level of benchtop metrology. Thus, major NMIs are focused on creating graphene based quantized Hall resistance (QHR) standards that operate above 2.5 K, below 5 T, at a factor of 10 larger current than today’s typical GaAs QHR standards. This project addresses basic needs of the metrology community and will also provide aid to those studying graphene for other uses, by developing techniques to ensure long-term stability of graphene’s electronic characteristics. In high-quality EG standards produced at NIST, we have observed fully quantized magnetotransport in devices of millimeter-size, where the precise quantized Hall resistance of $R_{xy} = h/2e^2$ is maintained up to record levels of critical current (0.72 mA). These results exceed the highest critical currents reportedfor the QHR in graphene and allow resistance tracability based on commercial non-cryogenic bridge measurement techniques. Room temperature bridges are much less difficult to operate than cryogenic current comparators developed and used at many NMIs, and are also compatible with the higher vibration levels produced in cryogen-free superconducting magnet cryostats. The growth techniques, device architecture, and characterization methods used to develop suitable EG QHR standards will be described.

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S4-2: Digital Josephson Impedance Bridge

Authors: F. Overney, N. E. Flowers-Jacobs, B. Jeanneret, A. Rüfenacht, A. E. Fox, J. M. Underwood, A. D. Koffman and S. P. Benz

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Abstract: This paper describes a Digital Josephson Impedance Bridge (DJIB) capable of comparing two impedances at any arbitrary ratio and phase angle over a large frequency range from 1 kHz to 20 kHz [1]. At the heart of the bridge are two Josephson arbitrary waveform synthesizer systems that offer unprecedented flexibility in high-precision impedance calibration i.e. a full coverage of the complex impedance plane using a single bridge. In the near future, this new DJIB bridges will replace their transformer-based counterparts leading to great simplification in the establishment and maintenance of impedance scales across the world.

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Bureau International des Poids et Mesures

S4-3: Impact of the new generation of Josephson voltage standards in ac and dc electric metrology

Authors: Alain Rüfenacht, Paul D. Dresselhaus, Nathan E. Flowers-Jacobs, Anna E. Fox, Justus A. Brevik, Charles J. Burroughs, and Samuel P. Benz.

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Abstract: After the 2018 redefinition of the SI, Josephson voltage standards will no longer be a representation of the unit volt, but will become a powerful tool to directly realize the voltage. Innovations over the last two decades, including device fabrication and circuit design, have opened the way to two new types of quantum based voltage standard: programmable Josephson voltage standards (PJVS), and Josephson arbitrary waveform synthesizers (JAWS). More recent advances include the ability to operate these standards in non-liquid, dry cryogenic environments and enhanced automation, which eliminate liquid helium costs and enable operation and dissemination of quantum voltage metrology beyond the domain of the expert scientists at national metrology institutes. With its large current operating margins and larger noise immunity compared to conventional Josephson voltage standards, PJVS systems have established a broader range of dc voltage metrology applications and are a key instrument in electronic kilogram realization. PJVS stepwise waveforms provide a SI traceable voltage reference for electric power metrology at frequencies less than 1 kHz. Recent record increases in JAWS output voltage, combined with new bias techniques may potentially revolutionize the way ac voltage metrology is performed. JAWS will certainly replace long and cumbersome thermal converter based calibrations over large ranges of frequency and voltage. Accuracy and scalability of JAWS have also been exploited for impedance metrology, simplifying greatly the measurement of impedance ratios of any kind with the same bridge setup. Finally, JAWS devices containing only 8 Josephson junctions are used to synthesize noise-like arbitrary waveforms to calibrate low-noise electronics to make a primary thermometer based on measuring the Johnson noise of a resistor.

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S4-4: Error modelling of quantum Hall array resistance standards

Authors: M. Marzano[1,2], T. Oe[3], M. Ortolano[1,2], N.-H. Kaneko[3], L. Callegaro[1]

Affiliation of authors: [1]Istituto Nazionale di Ricerca Metrologica, [2]Politecnico di Torino, [3]National Metrology Institute of Japan

Speakers: Martina Marzano

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Abstract: Quantum Hall Resistance Standards (QHARS) are integrated circuits composed of interconnected Quantum Hall Effect (QHE) elements that allow the realization of virtually arbitrary resistance values. Indeed, the possibility of realizing decadic values like 100 Ω, 1 kΩ, 10 kΩ, etc. is of particular interest for electrical metrology. In recent years, techniques have been presented to efficiently design QHARS networks [1] and the National Metrology Institute of Japan (NMIJ) has developed a number of devices [2,3] at intermediate and high values.

An open problem is that of the evaluation of QHARS accuracy, which is affected by contact and wire resistances. In fact, QHARS can be composed of more than a hundred elements, with relatively long resistive interconnections. If so-called multiple series, parallel and bridge connections allow to reduce the effect of contact and wire resistances to possibly negligible levels, they make error modelling far from straightforward. In this work, we present a general and systematic procedure for the error modelling of QHARS, which is based on modern circuit analysis techniques [4] and Monte Carlo evaluation of the uncertainty.

As a practical example, this method of analysis is applied to the characterization of a 1 MΩ QHARS developed by NMIJ [3]. Software tools are provided to apply the procedure to other arrays.

[1] M. Ortolano, M. Abrate, and L. Callegaro, “On the synthesis of quantum Hall array resistance standards,” *Metrologia*, vol. 52, pp. 31–39, 2015.

[2] T. Oe, K. Matsuhiro, C. Urano, H. Fujino, H. Ishii, T. Itatani, G. Sucheta, M. Maezawa, S. Kiryu, and N.-H. Kaneko, “Development of 10 kΩ quantum Hall array resistance standards at NMIJ,” in 2010 *Conference on Precision Electromagnetic Measurements Digest*, 2010, pp. 619–620.

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S4-5: The NMIA Calculable Capacitor: a unique opportunity for investigating quantum realizations of electrical quantities

Authors: H L Johnson, G W Small and J R Fiander

Affiliation of authors: National Measurement Institute, Australia

Speaker: H L Johnson

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Abstract: A new calculable capacitor and associated impedance measurement chain is being built at the NMIA. The new system is intended to reduce the uncertainty of the Farad as realized by a calculable capacitor by an order of magnitude. A calculable capacitor of this accuracy provides unique opportunities for investigating quantum realizations of electrical quantities.

The calculable capacitor measurement system is based on a sophisticated implementation of a ratio transformer bridge, with significant provision for measurement automation. Components are configured as four-port devices and measured at ten frequencies from 199 Hz to 1990 Hz. To meet the target uncertainty, all aspects of the design have been carefully controlled to introduce an uncertainty of not more than one part in 10^9. Measurements on the newly assembled calculable capacitor confirm that this target is met for the uncertainties arising from geometrical errors, and from the frequency correction. Ratio errors of the main transformer are expected to be of the order of one part in 10^8, and will be characterized to 1 part in 10^{10} using Thompson's method. Other components, including the suite of capacitors with associated precision air bath, the programmable injector/detectors and balancing IVD, and the active coaxers, all meet the required specifications for the target uncertainty.

The target uncertainty of few parts in 10^9 will allow the comparison of traditional impedance standards with quantum-based standards at an unprecedented level of precision. Options include comparison with the dc quantum Hall resistance (QHR) via a quadrature bridge and resistance scaling, or with the ac QHR with capacitance scaling and a quadrature bridge.

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S4-6: Josephson voltage standard circuit design improvements for AC and DC metrology

Authors: Anna E. Fox, Evan B. Golden, Alain Rüfenacht, Paul D. Dresselhaus, and Samuel P. Benz

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Speaker: Anna E. Fox

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Abstract: As Josephson voltage standards assume a prominent role in the quantum-based realization of the new SI, advances in circuit design and fabrication have enabled systems such as programmable Josephson voltage standards (PJVS) and Josephson arbitrary waveform synthesizer (JAWS) to operate with higher output voltages and larger operating margins. These improvements have allowed for 10 V PJVS systems with operating margins on the order of 2 mA, and JAWS systems with operating margins over 1 mA at amplitudes up to 1 V and synthesis frequencies up to 1 MHz. Both systems currently operate on a cryogen-free compact cryocooler. Large operating margins are a crucial element of Josephson circuit designs for metrology because they enable that the Voltage Standards to continuously operate in quantized states.

To achieve high output voltages and higher synthesis frequencies while maintaining large operating margins, we optimized the Josephson junction electrical characteristics as well the microwave circuits and thermal designs of both PJVS and JAWS chips, and cryopackages. Junction optimizations include maximizing the number of Josephson elements in each microwave array, narrow targeting of the junction critical currents and resistivity of the niobium/silicon junctions used, and improving the fabrication process to yield uniform barriers. Optimized microwave design includes an impedance tapered coplanar waveguide to maintain a uniform microwave current over nearly 13,000 dissipative junctions, and widening the bandwidth and targeting the center frequency of microwave splitters. To operate on a cryogen-free compact cryocooler, devices were fabricated on a series of different substrates to determine an optimal material for heat transfer. Additionally, circuit designs with longer arrays and fewer splitter layers were examined to better utilize the input microwave power. These optimizations have resulted in more thermally efficient and more user friendly PJVS and JAWS systems.

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S4-7: Arbitrary waveform generation of current with single-electron pump

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Abstract: Generation of electric current based on a single-electron pumps is one of the promising candidates for direct primary representation of the revised SI ampere. In contrast to dc current generation with which the uncertainty is as low as sub-ppm level had already been demonstrated, generation of finite-frequency current based on a single-electron pump is still challenging. Here we have demonstrated arbitrary waveform generation of current at a sub MHz frequency range using a GaAs-based single-electron pump. In our experiment, the pump operation is digitally controlled to generate a density-modulated single-electron stream, by which arbitrary waveforms of current including sinusoidal, square, and triangular waves have been generated. Our result can open new avenues for precision measurement of electric impedance and current noise as well as demonstration of a quantum metrology triangle experiment at a finite frequency range.

S4-8: Distinction between electromagnetically induced transparency and Autler-Townes splitting: a conceptual approach

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Abstract: There is a constant push nowadays to make all the measurements traceable to either physical constants or basic SI units. For the development of a system to measure Electric-Field accurately and traceable to Planck's constant a thorough understanding of two identical phenomena as per their results with different concept is required: Electromagnetically Induced Transparency and Autler-Townes splitting. NIST, USA [1] has reported the quantum E-field measurement and as being NMI, NPLI has also started working towards quantum E field standards. Though both phenomena gives transparency window one should be able to distinguish between the two. While EIT occurs due to the interference effects between different transition pathways, Autler-Townes splitting occurs due to the degeneracy and splitting of the atomic energy levels and has nothing to do with interference effect. In this work different schemes of 3-level system are considered and compared to analyse the distinction between the two effects. Each scheme is studied in both the cases i.e. weak coupling and strong coupling strength and results are reported. Two resonances for density matrix element responsible for transitions due to probe field in each case are studied. Figure 1 shows the reduction in absorption as a function of coupling Rabi frequency in a 3-level lambda system with strong coupling strength.

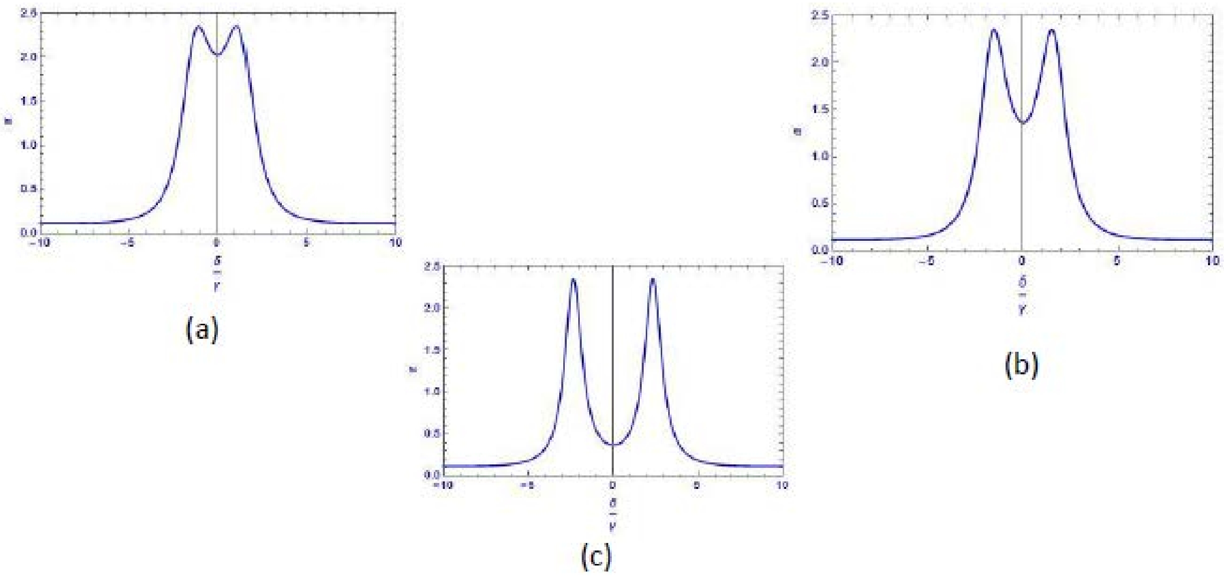

Figure 1 Dip in the absorption spectrum of probe field as a function of coupling Rabi frequency.

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S4-9: Dependence of maximum pumping frequency on the profile of the quantum-dot potential in quantum dot-based single electron pumps

Authors: Ye-Hwan Ahn[1,2], Changki Hong[3], Young-Seok Ghee[1,4], Yunchul Chung[3], Myung-Ho Bae[1], and Nam Kim[1]

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Abstract: Our quantum-dot (QD) electron pump has uniqueness in design that the QD potential shape can be manipulated, especially its potential depth can be controlled by a plunger gate [1]. We find that there exist strong correlations between the potential depth of the QD and the maximum pumping frequency, f_m when the modulating microwave power is fixed. As the depth of the QD potential was deepened, f_m showed decreasing characteristics while the flatness of the 1st current plateau was increased. We confirmed the same trend for five different devices. We quantitatively analyzed these correlations by using the notion of so called 'non-adiabatic Coulomb blockade gap energy', ΔE_{LU} [2]. We found that ΔE_{LU} parameters being under control by a plunger gate is proportional to the pumping frequency f. The flatness parameter of 1st current plateau, δ_2 is also found to be proportional to ΔE_{LU}. Our numerical calculations based on master equations reproduced qualitatively the frequency dependence of ΔE_{LU}, which is consistent with the decay cascade model [3]. Based on its frequency dependence, we could estimate semi-quantitatively the maximum operation frequency f_m at a fixed modulating microwave power. Consequently, we arrive at provisional conclusions that the f_m observed in our experiments is due to the deficiency of the modulating power and in order to get higher pumping frequency we should decrease ΔE_{LU} by sacrificing the flatness parameter δ_2. For more quantitative analysis we need further study.

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S4-10: A new measured value of von Klitzing constant through Calculable Capacitor experiment at NIM

Authors: Yan Yang, Lu Huang, Zuliang Lu, Wei Wang, Yunfeng Lu, Jing Qian, Lu Wenjun, Jianbo Wang, Qing He

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Abstract: The von Klitzing constant has important application to build quantum resistance standard as well as to deduce the fine structure constant. The experiment linking the calculable capacitor and the quantized Hall resistance is an indispensable input data source to determine the value of von Klitzing constant in term of the SI unit. However the input datas of this experiment were not updated in almost 20 years [1, 2].

The original calculable capacitor of National Institute of Metrology NIM , P.R. China is horizontal one built in 1970s with the standard uncertainty of 1.0×10^{-7}. And a new calculable capacitor with movable guard electrode has been built at NIM in 2013. It is a vertical one on basis of the original design of NMIA and BIPM. As an initial result, the standard uncertainty to reproduce the capacitance unit of 1 pF was 2.0×10^{-8} [3].

Since 2014, some improvements have been further performed, including replacement and re-adjustment of some mechanical parts of the calculable capacitor body and laser interferometer, repeatedly calibration and inspection of the two port capacitance bridge [4, 5]. The type A uncertainty to reproduce the capacitance unit has improved to 5.0×10^{-9} in 2016 than that of 1.0×10^{-8} in 2013.

At NIM, the national standard of QHR was built in 2003. And a new set was constructed at NIM's Changping campus in 2014. The resistance unit can be transferred from QHR to 10 kΩ by CCC. After AC-DC transfer, it can be compared with 10 nF using the four port quadrature bridge at 1592Hz.

Under this foundation, an experiment to determine the value of the von Klitzing constant is carried out and presented. This value, as an update one of NIM, will make contribution to the coming redefinition of the basic unit of the SI. The characteristics of experimental system are described, included its each part such as the calculable capacitor, the bridges, and the measuring chain. The value of the von Klitzing constant and its uncertainty are reported.

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S4-11: KRISS potential-profile-tunable electron pump for future current standard

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Abstract: A single-parameter electron pump based on a quantum dot (QD) fabricated in a GaAs heterostructure is a promising candidate for a future quantum current standard. Here, we present precision measurement results and robustness tests of the potential-profile-tunable electron pump, where the shape of the QD is manipulated by multiple top gates. With a driving rf frequency, f = 0.95 GHz at B = 11 T and T = 0.5 K, we obtained the relative deviation of the pumped current from ef, $\Delta I_p \equiv (I_p\text{-}ef)/ef = (-0.92 \pm 1.37)$ ppm at a output current level of I_p = 152.19 pA. For the robustness test, the pump current was evaluated within 2 ppm uncertainty while changing various parameters such as gate voltage, B-field (12.9 - 14 T) and temperature (0.3 - 1.3 K). The evaluation of the pumped current with an ultrastable low-noise current amplifier (ULCA) will be also presented.

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S4-12: Progress of the quantum Hall (array) devices and Josephson junction array devices for the quantum electrical standards at NIM

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Abstract: The talk will cover the current development of the quantum Hall (array) devices for the quantum resistant standard and the Josephson junction array devices for the quantum voltage standards. Single quantum Hall devices which can be used in the quantum Hall resistance standard system with either high or low work magnetic field have been achieved. The 10 kΩ and 1 kΩ quantum Hall array devices have been designed and fabricated. We use the direct current comparator (DCC) to calibrate the device. For the 10 kΩ device, the difference between the measured and its nominated value as well as the standard deviation are in the level of 1E-8**,** which is already at the resolution limit of DCC. In the furture we are going to make large quantized Hall resistor on the 100 kΩ level which have may have application in the quantum triangle study. For the Josephson junction array, 20 thousand junction arrays (without transmission line) with good dc V-I curves have been achieved. Small scale PJVS (programmable Josephson voltage standard) chip, chip for the quantum micro-volt application, and chip for the noise thermometry have been made. We expect to realize the functional chip for the 1V dc quantum voltage standard and chip for the ac quantum voltage application in near future.

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S4-13: Accurate operation of single-electron pumps beyond 1 GHz

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Abstract: Semiconductor-based single-electron pumps are promising candidates to be used as primary standards for the revised ampere. These nanoscale devices transfer electrons one per cycle, generating a quantised current $I = ef$, where e is the elementary charge and f is the pump operating frequency. Current quantisation accuracy as good as 1.6 parts in 10^7 has been demonstrated [1]. One of the remaining important challenges is to increase the pump current in order to reduce the measurement integration time. For this purpose, it is desirable to operate pumps at frequencies above 1 GHz, but it has been shown that the current quantisation accuracy tends to degrade rapidly in the high-frequency range. This means that a current plateau for a certain parameter sweep shows a finite slope, i.e., a varying current level, which contributes to the uncertainty in determining the value of current quantisation. To date, the uncertainty (in the flatness of the current plateau) achieved for ~1 GHz operation is ~1 part in 10^6 [1-5], which has been the limiting factor in achieving the current quantisation accuracy at the level of 1 part in 10^7 or better. Here, we will discuss the scope for improving the performance of single-electron pumps beyond 1 GHz, based on the recent results on GaAs and Si-based devices and a pump-error-reduction technique using arbitrary waveform generators.

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S4-14: The robustness and universality of tunable-barrier electron pumps

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Abstract: Semiconductor tunable-barrier electron pumps have emerged as a strong candidate for a primary current standard, offering a practically useful combination of accuracy and high output current. We focus on two attributes of pumps which are key to their adoption as primary standards: robustness and universality.

Robustness refers to the property of the pump whereby the current remains constant if any of the control or environmental parameters (gate voltages, RF drive amplitude, temperature etc) are detuned from their optimal settings. In other words, the current exhibits a flat plateau if any control parameter is adjusted. We present measurements showing robust operation of one design of GaAs pump [1], and we compare different statistical approaches to evaluating plateau flatness.

Universality requires that the pump current be insensitive to details of the device material or geometry as long as it implements the tunable-barrier pumping mechanism. To date, we have measured pumps with four widely varying designs fabricated using gallium arsenide [1,2] and silicon [3,4], against the same reference current source. We find in all cases that the pump current is equal to the expected quantized value of ef (e is the elementary charge and f the pumping frequency) to within measurement uncertainties between 1.2×10^{-6} and 0.27×10^{-6}. Very encouragingly, two of these four pump designs [1,3] were operated at a temperature of 1.3 K, accessible with relatively simple refrigeration. Combined with ultra-high precision measurements on a fifth design of pump at PTB [5], the overall data set presents a strong argument that the tunable-barrier pump mechanism can be implemented universally in any suitable semiconductor structure.

Finally, we argue that electron pumps are becoming competitive with more conventional reference small current sources for currents below 150 pA, and we consider what work remains to be done before electron pumps can be regarded as primary current standards.

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S4-15: Optically driven Quantum Josephson Voltage standard

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Abstract: Voltage on Josephson junction (JJ) directly depends on frequencies of bias signal. Existing Josephson voltage standards (JVS) usually use irradiation frequencies for biasing JJ arrays in the range from 10 GHz to 100 GHz. In consequence, value of the electric voltage that reproduced on the single JJ in the range from 20 µV to 200 µV. For increasing voltage on JJ it is required to use bias irradiation of higher frequency. The highest possible bias frequency for the Josephson junction is limited for low temperature superconductor (LTS) at about 1 THz, for High temperature superconductor (HTS) JJ order up to 10 THz. It is difficult to develop high stability THz – range generator or synthesizer with enough power and phase locked to quantum time and frequency standard. It would be easier to use the optical range of the frequency for the JJ bias signal, because modern standards of time and frequencies work in optical range, but in fact, them are outside of the limited possible frequencies range of the JJ bias signal. However, if using the irradiation JJ by two optical signal sources, having between themselves a difference on frequency from possible GHz or THz range, on the high nonlinearity of the Josephson junction and its ability to lock the phase, on the junction can appear the signal of différence frequency that sufficient for biasing of the JJ. This characteristic of the JJ can be used for increasing of the voltage on single junction, and development of realization of DC, AC, and Pulse Josephson voltage standards, as well as for development of the new classes of the converters, frequency and phase detectors with carrying from optical effect into the electric voltage signals. As HTS Josephson junction has maximum irradiation bias frequency higher than LTS JJ, it's possible to produce mV level output voltage on the small several junctions arrays. Liquid Nitrogen cooling level is not required complicated thermal insulation, it's possible build bi-optically driven JJ converter in greatly short tract and in this way provide a good connecting features with precision level of the reproducible Voltage for calibration oscilloscopes, AD Converters, high-speed voltmeters.

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S4-16: Quantum capacitances and inductances in the Quantum Hall Effect regime

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Abstract: In a two dimensional electron gas, low energy transport in presence of a magnetic field occurs in chiral 1D channels located on the edges of the sample. In the Buttiker's description of a.c. quantum transport [1], the density of states of the 1D channels -which contains the drift velocity- scales the quantum capacitance and determines the amplitude of the imaginary part of the admittance. The topology determines the sign: in the case of an Hall bar, the emittance is an inductance. While it is a capacitance in the case of a corbino. Quantum capacitances and inductances are what finally limits the access time of quantum devices [2].

We performed low frequency a.c. electrical measurements (typically in the range1kHz-100kHz) to obtain the ac admittance of quantum Hall samples in both topology, Hall bar and Corbino ring. Our samples have no gate, to exhibit only their inner electrochemical capacitance or inductance. I will discuss our measurement configuration, by the use of an impedancemeter, and what is the impact of the cables on the measurements [3]. Based on the Buttiker's theory, I will explain what are the physical quantities accessible to our measurements.

I will present our results on the quantum capacitance obtained on Corbino rings and on the kinetic inductance of multiterminals Hall bars. Both quantities are related to the density of states of the chiral edge states, and allows to measure the drift velocity of carriers along these 1D conductors. In other words, the determination of the capacitance/inductance gives access to the transit time of electrons through the device.

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Session 5

Emerging ideas in quantum metrology:
“Beyond quantum metrology”

Chair: Sang-Kyung Choi, KRISS (Republic of Korea)

From Quantum Interference to Human Perception

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Abstract: Superconducting quantum interference devices (SQUID) have widely been used for state-of-the-art precision measurements in various scientific research areas in range of metrology to basic physics. Beyond the fundamental applications, magnetoencephalography (MEG) based on the SQUID technology is the most developed non-invasive brain research tool for studying neuronal dynamics. Measuring and exploring human perception with MEG could give us neurophysiologic guidelines in standardization and quantification of human sensory and cognitive functions. We introduce SQUID-based brain measurement technologies such as MEG and Ultra-low field MRI, and our trials for cognitive measurements.

New approaches for sensitivity and spectral resolution improvement in diamond quantum metrology

Author and Speaker: Fedor Jelezko, Ulm University, Germany

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Abstract: In quantum metrology, where the phase of a qubit is used to detect external fields, the clock stability is defined by the qubit coherence time, and therefore determines the spectral linewidth and frequency precision. Here we demonstrate a quantum sensing protocol where the spectral precision goes beyond the sensor coherence time and is limited by the stability of a classical clock. We also discuss the sensitivity improvement of diamond sensors by quantum error correction and show applications of magnetometry enabled by NV defects in diamond.

Nanomechanical oscillators in the single-phonon regime

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Abstract: Nanomechanical oscillators have been employed as precision sensors in a diverse range of physical measurements. These versatile mechanical sensors reached the single-phonon regime recently as they demonstrate operations near quantum ground states. I will review the current progress in the field and discuss KRISS's approach in applying the nanomechanical oscillators for quantum metrology.

Quantum optical explorations of the nanoscale metrology frontier

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Abstract: I will describe emerging efforts to build and control small systems using quantum optics techniques. This includes magnetometry using individual color centers in diamond, but also transducer systems in which a force is converted into a dimensional change for mechanical systems near their quantum ground state. I examine how these new efforts are changing the paradigm of small-scale metrology.

NanoSQUIDs for Quantum Metrology

Authors: Ling Hao, David Cox and John Gallop.

Affiliation of authors: NPL

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Abstract: Super conducting quantum interference devices (SQUIDs) have played a prominent role in electrical and thermal metrology for more than 50 years. Over the recent decades nanoscale SQUIDs have emerged and developed to provide another important tool with applications to quantum metrology across another set of applications. SQUIDs themselves can act as quantum objects, realizing various forms of quantum bits for QIP applications, including their widespread use in various QIP developments. However nanoSQUIDs can be used as single particle detectors and extremely sensitive sensors for femtometre displacement measurements. The presentation summarises recent work at NPL, demonstrating the fabrication techniques required to produce near quantum-limited nanoSQUIDs. Existing and future applications are described including energy resolving photon detection, nano-electromechanical systems (NEMS) resonator readout and nanomagnetic particle detection. State of art nanoSQUIDs are already capable of detecting single spin flips, opening up a range of spin-based quantum engineering applications. Prospects for extending to arrays of nanoSQUID detectors are explored, together with discussion of future applications to metrology.

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POSTER / Session 5

S5-1: Self-calibrating photodiodes for measuring fundamental constants

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Abstract: Predictable Quantum Efficient Detectors (PQEDs) have a responsivity linked to fundamental constants and have proven to be stable devices with internal quantum deficiency (IQD) below 100 ppm. The simple structure of these devices makes them well suited for high accuracy modelling with device simulation software. The 3D models have proven to predict the responsivity to current state-of-the-art accuracy represented by the cryogenic radiometer (CR). Recently, a successful realization of a self-calibrating photodiode as an “NMI-on-a-chip” for optical power measurements at room temperature was developed. The device is realized as a PQED photodiode and a CR on one chip and enables the operation of two independent primary standard methods in one device with a heating non-equivalence estimated to be 50 ppm based on COMSOL simulations. The room temperature prototype of the self-calibrating detector is capable of calibrating the photodiode response to better than 0.04 % at 1 mW and approaches the uncertainty of the liquid He operated CR. Combining simulation models and self-calibration photodiodes enables the predicted response over a wide spectral range based on the measurement at one wavelength only.

Photocurrent simulations predict that the IQD of the PQED photodiodes should be reduced between one and two orders of magnitude when cooled from room temperature to cryogenic temperatures below 77 K. In addition, material properties for electrical substitution operation is also improving with orders of magnitude when cooling the self-calibrating detector. Therefore, operating the self-calibrating photodiode at cryogenic temperatures is expected to improve both electrical substitution and photocurrent mode of the self-calibrating photodiodes. An ultimate comparison of the two independent standards on one chip can link radiometric quantities to the new SI by measuring the fundamental constants ratio e/h to accuracies around 1 ppm. The photon to electron conversion ratio and the quantum transport simulation is supporting the philosophy and realization of improved quantum standards in a coherent and consistent new SI system.

S5-2: Electrical measurements of the dimensions of nanostructures

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Abstract: The electrical conductance of nanostructures within the atomic size is changed stepwise as a function of the cross section area of a nanostructure at its narrowest point [1]. The effect of quantization of electrical conductance (resistance) with the quantum $G_0 = 2e^2/h = (12.9\text{k}\Omega)^{-1}$ occurs for nano-structures under the conditions given by Landauer in his new definition of conductance [2]: that the nanostructure is made of electrical conductor; that the nanostructure (sample) has a constriction (narrow throat) between two wide terminals; that the thickness of the nanostructure is comparable with the Fermi wavelength λ_F; and that the length of the constriction is smaller than the mean free path l_e in sample material. This effect can be used to measure the width W of nanostructures (samples), or rather to estimate it - see Fig. 1. Electrical measurements of geometric sizes of nanostructures are potentially very important for nanotechnology, where other methods of measurement are very complex. One such possible method is STM microscopy. The new method here proposed is based on electrical measurements. Therefore, the measurements are relatively simple and the results of measurement are more accurate when nanostructures is smaller.

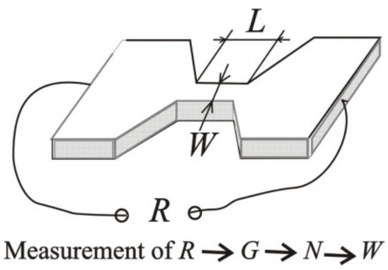

Fig. 1 Estimations of the width of a nanostructure by electrical measurements (R – resistance, G- conductance, N – number of transmission channels, W – width).

[1] W. Nawrocki, Introduction to Quantum Metrology, Springer, 2015.

[2] R. Landauer, *Journ. Physics: Condensed Matter* **1** 8099-8110 (1989).

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S5-3: Thermoelectricity measurements at QHE regime with Corbino structures

Authors: Real, Mariano[1]; Giudici, Paula[2]; Dietsche, Werner[3]; Tonina, Alejandra[1]; Arrachea, Liliana[4]

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Abstract: The aim of this project is to measure thermoelectric properties in GaAs systems at quantum Hall effect regimes, with the purpose to study charge and thermal transport. Our main motivation is the experimental measurement of the quantum of thermal conductance, which is of interest in metrology because it could be used as a standard of temperature or energy. We started to do experiments where the charge transport is compared with the thermal one, given that heat can be transported both with and without simultaneously charge flow and yields therefore different information. To this end, we are studying conventional Corbino devices with three contact-rings.
A central NiCr heater is used to produce a radial temperature gradient. Preliminary results will be presented at the time of the presentation.

This project requires advanced epitaxy and nanostructuring technologies as well as precision experiments at extremely low temperatures and high magnetic fields. The required technologies are developed in collaboration between scientists of INTI, CNEA and ICAS-UnSam and the Max-Planck-Institut für Festkörperforschung. They are mainly based at INTI. GaAs heterostructures that are needed for this project are available from the stock at MPI–FKF and PTB. Sample-preparation technologies like e-beam-lithography are already available at INTI. An important problem is the availability of low-temperature equipment at INTI´s laboratory. Because of the liquid helium price is excessively high in Argentina, we are working to obtain a dry system instead of our earlier wet one.

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S5-4: Searching for an invariant of the sample composition in the measurement of the amount of substance

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Abstract: The measurement of the amount of substance implies the determination of the number of elementary entities of a sample at the microscope scale. The determination of a sample composition means the measurement of the amount of chemical elements. A central question for the measurement of the chemical composition is to search for the true value of a sample composition in the chemical measurement process at both the microscopic and macroscopic scales. The true value of the analyte element composition of a sample is the ratio of the number of atoms of the analyte element to the total number of atoms of all elements.

We found that the true value of a sample composition exists in any subsample of a homogeneous molecular population of the sample. We defined the homogeneity of a sample composition at the molecular level, i.e. the "homogeneity of the sample molecular population" is defined as "the closeness of agreement between a sample molecular population and the homogeneous molecular population of a sample". We proposed the Central Law of Measurement of the Amount of Substance: "The homogeneity of a sample molecular population represents the measurement accuracy of the sample composition in an analytical procedure".

In fact, the true value of the amount-of-substance fraction of an element exists in the entire molecular population of the sample as well as in any homogeneous molecular population of the sample. The true value of a sample composition is an invariant for the homogeneous molecular population.

S5-5: Measuring a mole of photons: optical power traceable to the kilogram

Authors: John Lehman, Aly Artusio Glimpse, Ivan Ryger, Paul Williams

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Abstract: Laser-based manufacturing represents an area of industrial importance and commercial growth. Welding, cutting, and additive manufacturing are examples where manufacturers have seized the advantages of low maintenance and high efficiency of fiber and disk lasers. NIST has provided high-power laser measurements since the 1970s by means of thermal detectors that are relatively slow and massive. Recently we have demonstrated that it is possible to achieve fast and accurate measurements ranging from 10 W to 100 kW by means of photon momentum and radiation pressure. This provides us with an entirely new route for traceability. Rather than relying on the Volt and standard resistors, we now can rely on mass measurements and traceability to the kilogram. Above approximately 1 W, mass measurements provide lower uncertainties for optical power measurements, while below 1 W (less than 1 µg) radiation pressure provides lower uncertainty for mass measurements. Our techniques and instrumentation for photon momentum are unprecedented and provide a means to completely rethink classical radiometry.

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S5-6: Challenges for radionuclide metrology in the SI

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Abstract: This paper will present an overview of the quantum basis for various measurands related to radioactivity, and present the problem of multiple paths to the SI for realizing either the becquerel or mole for radionuclides. Examples will be given for radiochronometry, which can rely on a combination of mass spectrometry and radioactivity measurements to infer the date of origin for a material. Hidden correlations and measurement biases can have detrimental effects on the measurement and uncertainty, yet may be overlooked. Combining these methods requires invoking radionuclide half-lives, which themselves have been measured by some combination of the same methods.

Quantifying the activity of a radionuclide (Bq) can involve traceability to the SI through (e.g.) calorimetry, defined solid angle counting, coincidence counting, or isotope dilution mass spectrometry, depending on the application. Atom counting in particular is only comparable with activity measurements by invoking the radioactive decay law, dependent upon assumptions of stochasticity, and on independent measurement of relevant half-lives. This trinity - activity, number of atoms and half-life of a radionuclide - presents a challenge to contemporary metrology. Related problems arise in nuclear medicine, where complex radionuclide decay schemes are gaining interest for new precision treatments, but pose serious measurement challenges to traditional methods to quantify dose to a patient.

The field is ripe for new techniques, preferably with direct links to the SI base units, as well as more accurate quantum-mechanical calculations of atomic and nuclear transitions that are used in measurement models of increasing complexity for realizing the becquerel. A few promising candidates will be discussed.

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S5-7: Novel source of multimode squeezed light for quantum enhanced space-time positioning

Authors: Syamsundar De, Luca La-Volpe, Valentina Parigi, Claude Fabre, Nicolas Treps

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Abstract: To find out the position in space (by ranging to a reference) or time (by synchronizing the local clock with a reference) using pulsed light, one can measure either the arrival time of the maximum of the pulse envelop (time-of-flight measurement) or the phase of the electric field using interferometric method (phase measurement). A modal description of the field leads to the fact that the space-time positioning information is attached to both the mean-field and the time-of-flight mode [1]. Therefore, a measurement that combines the information of both phase and time-of-flight can achieve better sensitivity. It has been found that a homodyne detection whose local oscillator projects the measurement on an appropriate mode (timing mode; combination of phase and time-of-flight mode) can indeed reach Cramer-Rao bound of ultimate sensitivity. The quantum limit for such space-time position measurement is proportional to $1/2\sqrt{(\Delta\omega^2 + {\omega_0}^2)}\sqrt{N}$ for a coherent light pulse with N number of photons at central frequency ω_0 and spectral bandwidth $\Delta\omega$ [1]. In this measurement scheme, the sensitivity can be further improved to overcome the standard quantum limit by using an input beam, whose mean-field mode is squeezed in phase and the time-of-flight vacuum mode is squeezed in amplitude. We propose a novel quantum source to produce such a multi-mode squeezed light. Our source is based on type-I non-collinear parametric amplification process in a second order nonlinear crystal placed inside a synchronous cavity for pump enhancement. A proper choice of pump spectrum and phase matching condition provides the desired quantum light with appropriate squeezing of the phase of the mean-field mode as well as the amplitude of the time-of flight mode.

[1] B. Lamine, C. Fabre, and N. Treps, PRL **101**, 123601 (2008).

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S5-8: Real-time state estimation and feedback control of an oscillating qubit via weak measurements and weak measurement reversal.

Authors: Pieter du Toit[1,2], Shaun Burd[3], Thomas Konrad[4], Hermann Uys[5,6]

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Abstract: We present a scheme for the estimation and feedback control of an oscillating qubit in the presence of noise through monitoring of the system by periodic weak measurements. Weak measurement reversal is investigated as a means to suppress measurement noise and improve estimation and control of the quantum system in real-time. We show numerical results demonstrating the viability of the scheme.

Periodic Positive Operator Value Measure (POVM) measurements are made to gain information of the system in real-time. Weak POVM measurements only disturb the system weakly without collapsing the quantum state. It has previously been shown that they can be used to estimate the state of the system from the information obtained, with high fidelity, using a Bayesian estimation approach. Estimation of a dynamical parameter, which in our model is the Rabi oscillation frequency of the qubit, is also possible.

Here we show through simulation that by applying a unitary reversal of the weak measurement, the effect of measurement back action on the system can be reduced, thereby decreasing measurement noise, which leads to improved stability of the system. The effect of dephasing and amplitude noise on the system is also investigated.

Classical proportional-integral-derivative (PID) feedback control is used to steer the system to oscillate at different target frequencies and its effectiveness is characterized through analyzes of step responses to changes in the target frequency.

It is envisioned that this scheme could be used in metrology for the operation of more accurate and controlled quantum clocks based on single ion traps.

S5-9: Entanglement generation through non-linear spin dynamics in atomic magnetometers

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Abstract: Atomic magnetometers are a versatile platform for magnetic field measurement with applications ranging from fundamental physics, navigation, and chemical analysis to security and medical screening. Their operation is based on monitoring the evolution of ground state coherences of alkali-metal atoms located within the external magnetic field, and hence the performance relies on both high signal to noise and long coherence lifetime. Significant progress has been achieved in magnetometry through the design and implementation of various protocols that prolong this lifetime.

It is generally accepted that either an optical probe or spin-exchange collisions, through so-called quantum back-action and decoherence respectively, will introduce perturbations to the atomic system. Usually these have a detrimental effect on the performance of the quantum measurement. We show that non-linearities introduced by an optical probe (i.e. the tensor light shift) or by spin-exchange collisions generate novel non-linear atomic spin dynamics that can lead to the generation of entanglement. In the case of an optical probe we will demonstrated this in the context of the so-called spin maser. Non-linear dynamics induced by an optical probe can also lead to increased coherence times, making them particularly interesting for magnetometry applications. We will discuss the case of non-linear spin dynamics mediated by spin exchange collisions in context of the Bell-Bloom pumping process – where the atomic coherences are created by a train of optical excitation pulses.

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S5-10: Microvolt Josephson voltage standard based on a double channel Josephson array

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Speaker: Honghui Li

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Abstract: According to Josephson effect, the programmable Josephson voltage standard (PJVS) generates a dc voltage V_M at the quantized values $V_M = Mf / K_{J\text{-}90}$, where M, the junction number, is an integer. f is the microwave frequency applied to the Josephson array. $K_{J\text{-}90}$ = 483 597.9 GHz/V. However, the voltage resolution of the PJVS is limited by the quantized voltages depending on the frequency. For example, if f is 15 GHz, the voltage resolution is 31 µV.

We present an idea to improve the voltage resolution by setting a differential Josephson voltage standard. That means when a PJVS, applied the frequency f_1, is compensated by the other PJVS, applied the frequency f_2, the differential value of them is equal to $V_{diff} = M\Delta f / K_{J\text{-}90}$, where $\Delta f = f_1\text{-}f_2$. For example, for M=1, if Δf is 483.6 MHz, V_{diff} is 1µV. Therefore the voltage resolution of the PJVS is improved to 1 µV.

The disadvantage of this kind of the differential PJVS is the complication of two PJVSs. To simplify it, we also present a design of a double channel Josephson array. That means a chip consists of double channels of series Josephson junctions. Each channel has its independent path for microwave injection. When the chip is applied by two microwave sources with f_1 and f_2, the double channel of series junctions can be driven independently to generate the different voltages. Thus the differential voltage could be obtained from one chip, which is mounted at the bottom of one cryoprobe, to produce a dc voltage at microvolt level.

When combined with a normal 10 V PJVS, this kind of the microvolt Josephson voltage standard based on a double channel Josephson array could be used as a fine-resolution 10 V Josephson voltage standard. Different from the previous, when Δf is fixed, it could produce quantized voltages with very fine resolution just by changing the junction number instead of changing frequency. In addition, it also could produce very low voltage level, even to 10 nV. Therefore, it could be set as an ideal quantum voltmeter which covers all voltage ranges from 0 to 10 V.

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S5-11: How to optimize the shape of quantum light for quantum metrology?

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Abstract: Because of the $1/N^x$ scaling of quantum limits in optical measurements (x=0,5 for standard quantum noise and 1 for Heisenberg limited measurements), the best strategy for maximum sensitivity is to use states of light with very high photon number N. In this respect, multimode Gaussian states of light, encompassing intense coherent states, squeezed states and EPR entangled states, are the best practical choice. This strategy has indeed been successfully implemented to reduce the quantum noise floor in the gravitational wave interferometer, which uses a coherent state from an ultra-intense laser and a squeezed vacuum.

We have generalized this approach to any parameter estimation by optical means, and found the expression of the quantum Cramer Rao limit when one uses multimode non-classical Gaussian states, with the possibility of optimizing not only the multimode quantum state, but also the shape of the modes in which the state “lives”. We have identified in particular a “noise mode”, the quantum fluctuations of which are responsible for the noise in the estimation, and shown how to reach the quantum Cramer-Rao limit by an appropriate homodyne detection method.

We will finally give examples of improvement of parameter estimation beyond the standard limit in the case of frequency shifts and beam displacements.

[1] O. Pinel, J. Fade, D. Braun, Pu Jian, N. Treps, C. Fabre, « *Ultimate sensitivity of precision measurements with intense Gaussian quantum light: a multi-modal approach* », Phys. Rev A Rapid Com.**85,** 010101 (2012)

[2] V. Thiel, Pu Jian, C. Fabre, N. Treps, J. Roslund, “*Absolute measurement of quantum-limited interferometric displacements*”, arXiv :1602.02581 (2016)

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S5-12: Tracking the evolving spin of an ensemble, unbothered by the uncertainty principle

Authors: Giorgio Colangelo, Ferran Martin, Lorena Bianchet, Robert Sewell, and Morgan W. Mitchell

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Speaker: Morgan W. Mitchell

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Abstract: We study the use of continuous quantum non-demolition measurements to "track" the evolution of a precessing atomic spin ensemble. Our results disagree rather completely with the "common wisdom" in quantum optics, which says that simultaneous measurement of multiple, non-commuting observables can give at best the standard quantum limit of sensitivity for each variable. Instead, we find that the algebra of spin observables permits simultaneous tracking two spin degrees of freedom, for example the two dynamical components of a precessing spin, with sensitivity to each exceeding the standard quantum limit. In this scenario the third, unmeasured spin component is an uninteresting constant of the motion, so that the tracking is almost completely free of measurement-induced quantum noise. We demonstrate the physics of this scenario using Faraday rotation QND measurements of cold rubidium ensembles precessing in response to a magnetic field.[1]

[1] Simultaneous tracking of spin angle and amplitude beyond classical limits, G. Colangelo, F. Martin Ciurana, L. C. Bianchet, R. J. Sewell, M. W. Mitchell, Nature 543, 525-528 (2017)

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S5-13: Optical magnetometry beyond the shot noise limit

Authors: Ricardo Jimenez-Martinez, Vito Giovanni Lucivero, Jia Kong, Janek Kolodynski, Charikleia Troullinou, and Morgan W. Mitchell

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Abstract: Atomic sensors, such as atomic clocks and magnetometers, are of practical and scientific interest, finding applications ranging from navigation to the imaging of the human brain. Recently their sensitivity has reached the limits of classical techniques. Overcoming such limits is an active area of interest, as increasing sensitivity promises to create a new class of ultra-sensitive instruments. A promising approach to achieve this goal relies on techniques to reduce shot noise and to generate entanglement such as squeezed-light and quantum-non-demolition (QND) measurements. These techniques have allowed ultra-sensitive measurements and the enhancement of physical systems beyond their classical limits. To date, in a proof-of-principle way, QND measurements and squeezed light have been used to improve the performance of atomic sensors independently but not within the same device. Their simultaneous use in a best-in-class device remains an open challenge. Here I describe our recent work and results aimed at achieving this challenging goal in alkali-based magnetometers. I will describe versatile instrumentation to optically prepare and detect alkali vapors using QND measurements with squeezed light and optimal estimation techniques[1]. As a first step we have experimentally studied[2] the quantum limits in the optimal estimation of system properties of atomic ensembles in thermal equilibrium via spin noise spectroscopy. We are currently extending these techniques to the time domain as required for real-time sensing and control applications, for example in magnetometry[3], we will report our progress.

1. V. G. Lucivero, et al. "Squeezed-light spin noise spectroscopy," Physical Review A 93. 053802 (2016).

2. V. G. Lucivero, et al. “Sensitivity, quantum limits, and quantum enhancement of noise spectroscopies,” arXiv: 1610.02356.

3. R. Jimenez-Martinez and S. Knappe, “Microfabricated optically-pumped magnetometers”, in “High Sensitivity Magnetometers”, Springer-Verlag 523-551 (2017).

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S5-14: Chip-scale atomic instrumentation for metrology

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Abstract: We discuss recent work at NIST to develop chip-scale quantum-based instrumentation based on alkali vapor cells for accurate, low-cost, deployable calibration that could be built directly into instruments and systems. We have demonstrated microfabricated alkali vapor cells integrated with single-mode photonic waveguides and diffractive output couplers and shown that we can successfully lock a distributed feedback laser to a saturated absorption resonance in this vapor cell. We achieve a short-term instability of $2\times10^{-11}/\sqrt{\tau}$ and a long-term instability near 10^{-11} out to 10^{4} seconds. Such a device could be fabricated in large numbers using planar, lithographically patterned photonics and micromachining processes and may be suitable for compact, low-cost wavelength references that could be integrated directly into instruments to provide in-situ length calibration. We are also developing a microfabricated platform for the generation of laser-cooled atomic samples. We have demonstrated the cooling and trapping of 10^{6} cold atoms in a microfabricated alkali vapor cell 4 mm thick pumped with a small ion pump. We also have identified and tested glasses with low helium diffusion that can be used to make microfabricated cells with the potential to be passively pumped using getters. Finally, we discuss future opportunities for a broader range of instruments that could measure temperature, voltage and current with SI traceability.