Symposium Quantum meets gravity and metrology (SYQG)

jointly organized by
the Quantum Optics and Photonics Division (Q) and
the Atomic Physics Division (A)

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Overview of Invited Talks and Sessions

(lecture room E 415)

Invited Talks

SYQG 1.1	Tue	11:00–11:30	E 415	**Does time exist in quantum gravity?** — •Claus Kiefer
SYQG 1.2	Tue	11:30–12:00	E 415	**How Attractive is the Moon for Relativity?** — •Jürgen Müller, Liliane Biskupek, Enrico Mai, Franz Hofmann
SYQG 1.3	Tue	12:00–12:30	E 415	**Interferometry with Bose-Einstein condensates in microgravity** — •Ernst Rasel
SYQG 1.4	Tue	12:30–13:00	E 415	**Relativistic effects in atom and neutron interferometry** — •Wolfgang Schleich

Sessions

SYQG 1.1–1.4	Tue	11:00–13:00	E 415	**Quantum meets gravity and metrology I**
SYQG 2.1–2.5	Tue	14:30–16:00	E 415	**Quantum meets gravity and metrology II**

SYQG 1: Quantum meets gravity and metrology I

Time: Tuesday 11:00–13:00 Location: E 415

Invited Talk SYQG 1.1 Tue 11:00 E 415

Does time exist in quantum gravity? — •Claus Kiefer — Universität zu Köln

Time is absolute in standard quantum theory and dynamical in general relativity. The combination of both theories into a theory of quantum gravity thus leads to a 'problem of time'. In my talk, I shall investigate those consequences for the concept of time that can be drawn without a detailed knowledge of quantum gravity. The only assumptions are the experimentally supported universality of the linear structure of quantum theory and the recovery of general relativity in the classical limit. Among the consequences are the fundamental timelessness of quantum gravity, the approximate nature of a semiclassical time, and the correlation of entropy with the size of the Universe.

Ref.: C. Kiefer, arXiv:0909.3767 [gr-qc].

Invited Talk SYQG 1.2 Tue 11:30 E 415

How Attractive is the Moon for Relativity? — •Jürgen Müller[1,2], Liliane Biskupek[1], Enrico Mai[1], and Franz Hofmann[1] — [1]Institut für Erdmessung (IfE), Leibniz Universität Hannover, Schneiderberg 50, 30167 Hannover, Germany — [2]QUEST – Centre for Quantum Engineering and Space-Time Research, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

In 1969, a new era for studying relativity has started. With the first returns of laser pulses sent from observatories on Earth to reflector arrays on the Moon, a new space technique – Lunar Laser Ranging (LLR) – has been providing an ongoing time series of highly accurate Earth-Moon distance measurements. To enable data analysis at the mm level of accuracy, all elements of the tracking process have to be modeled at appropriate (relativistic) approximation, i.e. the orbits of the major bodies of the solar system, the rotation of Earth and Moon, the signal propagation, but also the involved reference and time systems.

We will show where relativity enters the LLR analysis and how the whole measurement process is modeled, including the major classical (Newtonian) effects like gravity field of Earth and Moon, tidal effects, ocean loading, lunar tidal acceleration (that causes the increase of the Earth-Moon distance by about 3.8 cm/year), etc.

By analysing the 43-year record of range data, LLR is one of the best tools to test General Relativity in the solar system. It allows for constraining gravitational physics parameters related to the strong equivalence principle, geodetic precession, preferred-frame effects, or the time variability of the gravitational constant. We will present recent results for the various relativistic parameters.

[1] Hofmann, F., Müller, J., Biskupek, L.: Lunar laser ranging test of the Nordtvedt parameter and a possible variation of the gravitational constant. Astronomy and Astrophysics, Vol. 522, No. L5, 2010, doi: 10.1051/0004-6361/201015659.

[2] Müller, J., Hofmann, F., Biskupek, L.: Testing various facets of the equivalence principle using Lunar Laser Ranging. Classical and quantum gravity, Vol. 29, 184006 (9pp), 2012, doi:10.1088/0264-9381/29/18/184006.

[3] Müller, J., Murphy, T., Schreiber, U., Shelus, P., Torre, J., Williams, J., Boggs, D., Bouquillon, S. Francou, G.: Lunar Laser Ranging – A Tool for General Relativity, Lunar Geophysics and Earth Science. ILRS JoG special issue, submitted 2012.

Invited Talk SYQG 1.3 Tue 12:00 E 415

Interferometry with Bose-Einstein condensates in microgravity — •Ernst Rasel — QUEST, Institut für Quantenoptik-Leibniz Universität, Hannover, Germany

A new field in matter wave optics is emerging, which is based on very long baseline atom interferometry (VLBAI). These interferometers strive to increase the sensitivity by coherently spitting and separating wave packets over macroscopic spatial and temporal scales. Bose-Einstein condensates (BECs), representing a textbook example for a macroscopic wave packet, are the ideal source for performing this kind of interferometry and were exploited for the first time in the extended free fall with a chip-based atom laser for Rubidium ^{87}Rb. Combining delta kick cooling with BEC we can produce ensembles with energies equal to temperatures falling below one nK. Employing an asymmetric Mach-Zehnder type interferometer we could study over hundreds of milliseconds the coherent evolution of a wave-packet and analyse delta kick cooling with the help of the observed interference fringes. This experiment can be considered as a gigantic double slit experiment in microgravity. A novel generation of atom chips allows to improve the performance of these flexible devices. We could demonstrate loading of the chip with far more than 10^9 atoms in roughly a second and generate large condensates of more than 100000 atoms, up to now only achievable in room filling devices, in a shoebox sized setup. We discuss as a possible spin-off a chip based quantum gravimeter for ground based applications, recently demonstrated with our device. The design will be employed for a rocket based test of such an interferometer, which will demonstrate the feasibility of satellite based tests of Einsteins principle of equivalence as pursued by the STE-QUEST mission.

The QUANTUS cooperation comprises the group of C. Lämmerzahl (Univ. Bremen), A. Peters (Humboldt Univ. Berlin), T. Hänsch/J.Reichel (MPQ/ENS), K. Sengstock (Univ. Hamburg), R. Walser (TU Darmstadt), and W.P. Schleich (Univ. Ulm).

This project is supported by the German Space Agency Deutsches Zentrum für Luft- und Raumfahrt (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWI) under grant number DLR 50 WM 0346. We thank the German Research Foundation for funding the Cluster of Excellence QUEST Centre for Quantum Engineering and Space-Time Research

Invited Talk SYQG 1.4 Tue 12:30 E 415

Relativistic effects in atom and neutron interferometry — •Wolfgang Schleich — Institut für Quantenphysik, Universität Ulm, Albert-Einstein-Allee 11, D-89081 Ulm

Motivated by the recent debate if the Kasevich-Chu atom interferometer can measure the gravitational redshift, we show [1, 2, 3] that the physical origin of the observed phase shift depends on the representation of quantum mechanics chosen for the calculation. We illustrate this phenomenon using the position and the momentum representations and demonstrate that the decomposition of the total phase shift into three dynamical phases, which emerges in the Feynman path integral approach and is at the very heart of the redshift controversy, does not appear in position space. This feature stands out most clearly in a representation-free analysis of the Kasevich-Chu interferometer where two rather than three phases contribute to the phase shift. We also compare and contrast atom and neutron interferometry.

[1] W.P. Schleich, D.M. Greenberger, and E.M. Rasel, A representation-free description of the Kasevich-Chu interferometer: A resolution of the redshift controversy, New J. Phys. 15, 013007 (2013)

[2] W.P. Schleich, D.M. Greenberger, and E.M. Rasel, The redshift controversy in atom interferometry: Representation dependence of origin of phase shift, Phys. Rev. Lett. 110, 010401 (2013)

[3] D.M. Greenberger, W.P. Schleich, and E.M. Rasel, Relativistic effects in atom and neutron interferometry and the differences between them, Phys. Rev. A 86, 063622 (2012)

SYQG 2: Quantum meets gravity and metrology II

Time: Tuesday 14:30–16:00 Location: E 415

SYQG 2.1 Tue 14:30 E 415

Differences between neutron and atom interferometry — •Enno Giese[1], Daniel M. Greenberger[2], Ernst M. Rasel[3], and Wolfgang P. Schleich[1] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ$^{\text{ST}}$), Universität Ulm, D-89069 Ulm, Germany. — [2]The City College of New York, 160 Convent Ave, New York, NY 10031, USA. — [3]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover, Germany.

Triggered by the controversy whether atom interferometers are sensitive to relativistic effects such as the red shift, the difference between neutron and atom interferometers drew our attention. In contrast to a the first naive guess, subtle distinctions can be found. In general, the difference between these two types of interferometers can be traced back to the different scattering processes. A conventional neutron interferometer uses crystals as beam splitters and mirrors. This scattering mechanism can be understood in terms of conventional Bragg diffraction.

In contrast to that, a variety of scattering mechanisms can be applied to atom interferometers. In this talk, we focus on atomic Bragg scattering, where the atoms interact with a standing light wave and change just their external degree of freedom. We show that by a careful arrangement and tuning of the lasers this diffraction process can be changed so that a neutron interferometer is mimicked. The phases accumulated along both paths are different in comparison to the usual atom interferometer which leads to a measurable phase shift.

Group Report SYQG 2.2 Tue 14:45 E 415

A miniaturized, high flux BEC source for precision interferometry — •Waldemar Herr[1], Ernst Maria Rasel[1], and The QUANTUS Team[1,2,3,4,5,6,7,8,9] — [1]Institut für Quantenoptik, Leibniz Universität Hannover — [2]ZARM, Universität Bremen — [3]Institut für Physik, HU Berlin — [4]Institut für Laser-Physik, Universität Hamburg — [5]Institut für Quantenphysik, Universität Ulm — [6]Institut für angewandte Physik, TU Darmstadt — [7]MUARC, University of Birmingham — [8]FBH, Berlin — [9]MPQ, Garching

Atom chips have proven to be excellent sources for the fast production of ultra-cold gases due to their outstanding performance in evaporative cooling. However, the total number of atoms has previously been limited by the small volume of their magnetic traps. To overcome this restriction, we have developed a novel loading scheme that allows us to produce Bose-Einstein condensates of a few 10^5 ^{87}Rb atoms every two seconds. The apparatus is designed to be operated in microgravity at the drop tower in Bremen, where even higher numbers of atoms can be achieved in the absence of any gravitational sag.

Using the drop tower's catapult mode, our setup will perform atom interferometry during nine seconds in free fall. Thus, the fast loading scheme allows for interferometer sequences of up to seven seconds – interrogation times which are inaccessible for ground based devices.

The QUANTUS project is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number DLR 50WM1131.

SYQG 2.3 Tue 15:15 E 415

Sensing single remote nuclear spins in Nitrogen-Vacancy centers — •Jan Honert[1], Nan Zhao[1], Bernhard Schmid[1], Michael Klas[1], Junichi Isoya[2], Matthew Markham[3], Daniel Twitchen[3], Fedor Jelezko[4], Ren-Bao Liu[5], Helmut Fedder[1], and Jörg Wrachtrup[1] — [1]3. Physikalisches Institut, University Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany — [2]Graduate School of Library, Information and Media Studies, University of Tsukuba, 1-2 Kasuga, Tsukuba, Ibaraki 305-8550, Japan — [3]Element Six Ltd, Ascot SL5 8BP, Berks, England — [4]Institut für Quantenoptik, Universität Ulm, 89081 Ulm, Germany — [5]Department of Physics and Centre for Quantum Coherence, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China

The detection of single nuclear spins would be useful for fields ranging from basic science to quantum information technology. In addition, the ability to address weakly coupled nuclear spins in the solid state expands the number of addressable qubits surrounding the detector spin significantly. Here, we present the detection and identification of single and remote ^{13}C nuclear spins embedded in nuclear spin baths surrounding a single electron spin of a nitrogen-vacancy centre in diamond. We are able to amplify and detect the weak magnetic field noise ($\sim$10 nT) from a single nuclear spin located about 3 nm from the centre using dynamical decoupling control, and achieve a detectable hyperfine coupling strength as weak as $\sim$300 Hz. We also confirm the quantum nature of the coupling present the first steps and results towards manipulating those spins.

SYQG 2.4 Tue 15:30 E 415

A satellite based quantum test of Einstein's equivalence principle — •Christian Schubert[1] and the STE-QUEST ATI team[2] — [1]Institut für Quantenoptik, LU Hannover — [2]European Consortium

STE-QUEST [1] aims for performing a quantum test of Einstein's Equivalence principle by verifying the universality of the free propagation of matter waves on a satellite. A dual species atom interferometer will measure the differential acceleration of Bose-Einstein condensates of ^{87}Rb and ^{85}Rb. This is assumed to be zero if the inertial mass coincides with the gravitational mass. The Eötvös ratio derived from the differential signal will be determined with an accuracy of parts in 10^{15} beyond state-of-the-art precision of 10^{-13} established by lunar laser ranging and torsion balances.

The matter waves will be simultaneously prepared and interrogated with a free evolution time of 10 s enabled by the weightlessness conditions in space. Within a single cycle of 20 s a shot noise limited sensitivity to accelerations of $3 \cdot 10^{-12}$ m/s^2 is anticipated. The simultaneous interferometry is carried out in a double diffraction Mach-Zehnder geometry and allows for high suppression ratios of noise and bias terms.

In the talk the measurement principle will presented, an overview of the preliminary payload design will be given, and the estimated error budget will be discussed.

STE-QUEST is a proposal for an M3 mission in the frame of the Cosmic Vision program of ESA.

[1] http://sci.esa.int/ste-quest

SYQG 2.5 Tue 15:45 E 415

General relativistic effects in quantum interference of "clocks" — •Magdalena Zych[1], Fabio Costa[1], Igor Pikovski[1], Caslav Brukner[1], and Timothy C. Ralph[2] — [1]Universität Wien — [2]University of Queensland

Quantum mechanics and general relativity have been extensively and independently confirmed in many experiments. However, all experiments that measured the influence of gravity on quantum systems are still fully consistent with non-relativistic, Newtonian gravity. Here we discuss a novel effect in quantum interference experiments that can probe the interplay between quantum mechanics and general relativity.

We consider interference of a "clock" – a particle with some evolving degrees of freedom - placed in a superposition of two different gravitational potentials. According to general relativity each amplitude of the superposition will experience a different gravitational time dilation. Due to quantum complementarity the visibility of quantum interference will thus drop to the extent to which the information about the location becomes available from the "clock". The clock can be implemented in an internal degree of freedom of a massive particle or in the position of a photon. The proposed experiment would thus provide the first test of quantum mechanics in curved background.