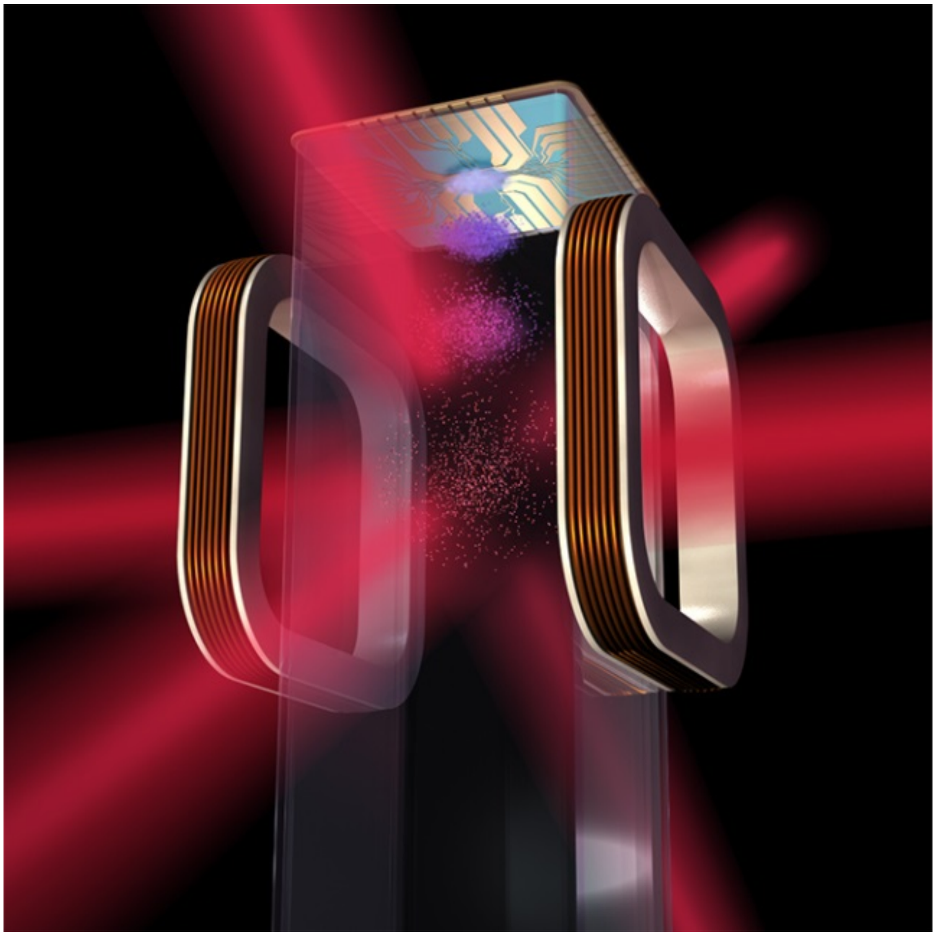
NASA
Fundamental Physics
PI Workshop

Abstracts



Pasadena Hilton Hotel, Pasadena, California

November 17-18, 2014

Fundamental Physics with Atomic Sensors in Space

Luigi Cacciapuoti, luigi.cacciapuoti@esa.int
ESA/ESTEC, Noordwijk, Netherlands

Atomic clocks and atom interferometers are precise instruments for the measurements of tiny variations in time and distance and for the detection of faint forces. As such, they can be used to test Einstein's theory of general relativity to high accuracy. Space offers the additional advantage of long free-propagation distances, large velocities and velocity variations, large variations of the gravitational potential (space-to-ground), thus providing unique experimental conditions, not accessible in a ground-based laboratory, to exploit the potential of these instruments. High-performance clocks and atom interferometers are being developed by ESA for testing fundamental physics in space.

Operated on-board the International Space Station, the ACES (Atomic clock Ensemble in Space) payload will distribute a clock signal with fractional frequency instability and inaccuracy of 1·10-16. Space-to-ground and ground-to-ground comparisons of atomic frequency standards will be used to test Einstein's theory of general relativity including a precision measurement of the gravitational red-shift, a search for time variations of fundamental constants, and tests of the Standard Model Extension. ACES is scheduled for a launch to the ISS in mid-2016.

As follow-on mission, SOC (Space Optical Clocks) is developing an optical clock improving the ACES performance by a factor 10.

Finally, atom interferometry instruments are being studied for tests of the Weak Equivalence Principle on the ISS.

This paper will report on the progress recently achieved in the development of atomic sensors for testing fundamental physics in space.

Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment.

Jason Williams[1], Jose D'Incao[2], Sheng-wey Chiow[1], Holger Mueller[3], and Nan Yu[1]. [1]Jet Propulsion Laboratory, California Institute of Technology, CA; [2]JILA, University of Colorado and NIST, Boulder, CO; [3]University of California, Berkley, CA.

Precision atom interferometers in space promise exciting technical capabilities with diverse applications of interest to NASA. These quantum sensors are particularly relevant for fundamental physics research, with proposals including unprecedented tests of the validity of the weak equivalence principle, precision measurements of the fine structure and gravitational constants, and detection of gravity waves and dark energy. Recent advances in the science of portable and high precision atom interferometers, and prospects of realization of ultracold quantum gases in microgravity, have brought the interferometry technology to a tipping point. Consequently, multiple atom interferometer-based missions have been proposed to NASA, including a dual-atomic-species interferometer that is to be integrated into the Cold Atom Laboratory (CAL) onboard the International Space Station. In this talk, I will discuss our plans and preparation at JPL for the flight experiment, funded by NASA's Physical Sciences Research Program, to use the CAL facility to study the leading-order systematics expected to corrupt future high-precision measurements of fundamental physics with atom interferometers in microgravity. The project concentrates on the physics of pairwise interactions and molecular dynamics in these quantum systems as a means to overcome uncontrolled shifts associated with the gravity gradient and few-particle collisions. We will further utilize the CAL atom interferometer for proof-of-principle tests of systematic mitigation and phase-readout techniques for use in the next-generation of precision metrology experiments based on AIs in microgravity.

Chip Based Atom Interferometry for Ground and Space

John Burke & Jim Stickney (AFRL) and Cass Sackett (UVa)

We will discuss ongoing efforts at AFRL and UVa to build an atom interferometer gyroscope using light pulses in a harmonic, isotropic, magnetic trap. In particular, we will discuss our atom trap modeling tool in conjunction with tuning the harmonicity of an atomic trap from an AFRL produced atom chip. We will also discuss efforts to characterize the transfer of trapped atoms to free flight atoms, which will be of particular interest to the CAL.

Ultracold atoms as quantum simulators for new materials –synthetic magnetic fields and topological phases

Wolfgang Ketterle
MIT-Harvard Center for Ultracold Atoms, and Department of Physics
Massachusetts Institute of Technology, Room 26-243
77 Massachusetts Ave., Cambridge, MA 02139-4307, USA
Massachusetts Institute of Technology

When atoms are cooled to nanokelvin temperatures, they can easily be confined and manipulated with laser beams. Their interactions can be tuned with the help of magnetic fields, making them strongly or weakly interacting, repulsive or attractive. Crystalline materials are simulated by placing the atoms into an optical lattice, a periodic interference pattern of laser beams. Recently, synthetic magnetic fields have been realized. With the help of laser beams, neutral atoms move around in the same way as charged particles subject to the magnetic Lorentz force. These developments should allow the realization of quantum Hall systems and topological insulators with ultracold atoms.

Precision physics with atom interferometry in space

Holger Mueller
University of California, Berkeley

The Cold Atom Lab (CAL) will be a pathfinder for using atom interferometry in space, which has applications from precision measurements of fundamental constants such as the fine structure constant and realization of a quantum mass standard for the international system of units to testing the equivalence principle, and maybe even detection of gravitational waves. The talk will focus on using CAL as an atom interferometer, ground-based experiments providing auxiliary data, and on the design of a dedicated, high-performance, follow-up mission.

Rydberg-atom spectroscopy in modulated optical lattices

G. Raithel, University of Michigan
Ann Arbor, MI 48109

Optically trapped, cold atoms are important in high-precision measurement, atomic clocks, field sensing and quantum information processing. In the work presented, Rydberg atoms are trapped in one-dimensional optical lattices of 1064nm laser light. Amplitude modulation is used to drive microwave transitions between Rydberg levels. The advantages of lattice-modulation spectroscopy of Rydberg-atom transitions include small trap-induced shifts, micron-scale spatial addressability, and freedom from typical selection rules. I will explain the method's background, which engages the A^2-term, not the usual $\mathbf{A}\cdot\mathbf{p}$-term. Here, we probe $nS_{1/2}$ to $(n+k)S_{1/2}$ Rydberg transitions in rubidium, with k=1, 2 or 3 and several selected values of n. The transitions occur primarily at odd harmonics of the lattice modulation frequency; in current experiments the 1st, 3rd and 5th harmonic have been demonstrated successfully. The highest transition frequency demonstrated to date being close to 100GHz. One of the transitions probed satisfies a "magic" condition, in which the trapping potentials of the lower and upper Rydberg states coupled by the modulated lattice have the same trapping potential. These results set the stage for using lattice modulation spectroscopy of Rydberg atoms in high-precision measurement. High-precision lattice-modulation spectroscopy will be most promising with circular, Bohr-like Rydberg states. These have long lifetimes and low electric polarizabilities, among other features. Towards this long-term goal, we have also recently produced and trapped cold, circular Rydberg atoms with an adiabatic "crossed-fields" state-switching method.

Coherent atom optics with magnons in a dense superfluid

Dan Stamper-Kurn
University of California, Berkeley

I will discuss the propagation of spin excitations within an atomic superfluid. These spin excitations, akin to magnons in magnetically ordered solid-state materials, propagate even within dense, trapped superfluids in a manner that is remarkably similar to free atoms propagating in a potential-free vacuum. We have realized an interferometer based on the coherent propagation of magnon waves in order to measure the magnon recoil energy. I will also discuss how magnon excitations can be used to measure and further reduce the temperature of a highly degenerate quantum gas.

Tailored geometries for BEC physics: radiofrequency-dressed optical lattices and microgravity bubble-geometry condensates

Nathan Lundblad
Department of Physics and Astronomy
Bates College

Notions of geometry, topology, and dimensionality have directed the historical development of quantum-gas physics. With a toolbox of forces for confinement, guiding, and excitation, physicists have used quantum gases to test fundamental ideas in quantum theory, statistical mechanics, and in recent years notions of strongly-correlated many-body physics from the condensed-matter world. We review a planned microgravity program which will explore a trapping geometry for quantum gases that is both theoretically tantalizing and difficult to attain terrestrially: a trap forming a spherical or ellipsoidal shell. This trap could confine a Bose-Einstein condensate to the surface of an experimentally-controlled topologically-connected "bubble." We also review recent terrestrial BEC work (at Bates College) studying the creation of tailored periodic geometries using radiofrequency dressing of spin-dependent optical lattices.

Time and frequency transfer from an almost freely-falling satellite

Neil Ashby, Steven Jefferts, Biju Patla
NIST - Time and Frequency Division
Boulder, CO 80302

We discuss the metric of general relativity in a falling reference frame that has small non-gravitational acceleration and rotation. The Principle of Equivalence implies that linear terms in the gravitational potential of external masses can have no observable effect in a freely-falling reference frame. Thus in a local, freely falling reference frame of a satellite carrying an atomic clock, the only significant effects arise from quadratic terms--tidal terms. However a satellite such as the ISS is not in free fall since it is generally rotating and suffers from non-gravitational forces. We discuss transformations of the metric tensor and of photon wave-vectors between the ECEF frame of reference, the ECI frame, the "almost" freely falling" frame, and the body-fixed frame of reference of a satellite carrying an atomic clock. Requirements for precision measurement leading to an improved test of the gravitational part of the total frequency shift of the orbiting clock will be discussed.

Accuracy Evaluation of the PHARAO Cesium Space Clock and Precision Measurements of Scattering Phase Shifts

P. Peterman, A. Bennett, K. Gibble, P. Laurent, and C. Salomon
Pennsylvania State University and Laboratoire Kastler Brossel, Ecole Normale Supérieure

The PHARAO accuracy evaluation is a significant goal of the ACES mission. The three largest sources of systematic uncertainty for PHARAO are the collisional frequency shift, a first-order Doppler shift, known as the distributed cavity phase shift (DCP), and the frequency shift due to the microwave lensing of the atomic wavepackets by the exciting microwave field in the clock. We have constructed large densely-meshed three-

dimensional finite element models of the microwave fields in the clock and state preparation cavities to evaluate these. We will present analysis of the DCP and Microwave Lensing frequency shifts. We will also discuss our recent precision measurements of cesium s-wave scattering phase shifts, which are expected to clarify the very low-energy cold-collision shift of PHARAO.

Laser Links for Optical Space Time Reference

L. Hollberg, and P. Berceau
Department of Physics, HEPL and SCPNT, Stanford University, Stanford, CA, USA
leoh@stanford.edu

We are exploring methods for precisely transferring “Time” and frequency references on the ground to future clocks in space. As a result of advances in laser technology and in laser-cooling and –trapping of atoms the past two decades have seen tremendous improvements in the performance of atomic frequency standards (both microwave and optical). Lasers also have great advantages over alternate methods for time and frequency transfer when fiber links are available or free-space line of site is feasible. If we can develop precise optical methods for transferring Time/frequency signals to space we can leave the best clocks at labs on the ground and transfer the Time/frequency signals to “flywheel clocks in space”. At Stanford we are studying both the fundamental and practical limits to optical time transfer between ground and space. Our laboratory experiments are based on a “self-referenced” fs optical frequency comb and a 4 km fiber link plus a short free-space link. Femtosecond timing is possible over these links, but more modest performance, at the 1 ps level, my have the greatest utility for most applications.

Recent results of turbidity measurements near the liquid-gas critical point of SF_6 fluid in microgravity

Inseob Hahn, Jet Propulsion Laboratory, California Institute of Technology, CA, USA.

Local turbidity measurements in an optical cell, filled with SF_6 fluid sample near the critical point, were performed in weightless conditions on board the International Space Station DECLIC (Dispositif pour l'Etude de la Croissance et des LIquides Critiques) facility. The turbidity was measured by using both a He-Ne laser source and a quasi-monochromatic light source (LED) with a photo detector and a CCD camera. The calculated turbidity using a recent crossover equation-of-state model is in good agreement with the experimental data. The two-dimensional turbidity data map shows a small density inhomogeneity inside the fluid near the critical temperature. We will describe the flight experiment and future plan to utilize the DECLIC facility.

The University of Iowa’s Dusty Plasma Projects for PK-4

John Goree
Dept. of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242

PK-4 is a European Space Agency instrument that was launched to ISS on October 29, 2014. It is dedicated to the study of the physics of dusty plasmas, which are also known as complex plasmas. A dusty plasma is a partially ionized gas containing micron-size particles of solid matter. These solid particles are called "dust particles" according to the terminology of astrophysics because dusty plasmas occur naturally in the planetary system and in interstellar space. Dust particles in a plasma gain a large negative electric charge, typically 5,000 elementary charges, so that they all repel one another. In ground-based experiments the dust particles rapidly sediment to the bottom of a chamber so that experiments allow the study of two-dimensional physics. Microgravity conditions avoid this sedimentation so the three-dimensional physics can be studied in a way that is not possible on the ground. Microgravity also prevents gravity from obscuring weak forces such as the ion drag force that act on dust particles in a plasma. One phenomenon in such a dusty plasma is crystallization, after which the instrument (Plasma Kristall 4) was named. The University of Iowa's projects for PK-4 include dedicated experiments as well as tangential analysis of experiments that other scientists have planned. In this talk I will review some of these projects, including synchronization of nonlinear waves and detection of non-Gaussian fluctuations in a nonequilibrium system. This work is done in collaboration with Dr. Bin Liu at The University of Iowa and the PK-4 Science Team, and it is supported by NASA-JPL Research Support Agreements 1471978 and 1485137.

Investigating ion drag effects in ground and microgravity complex plasma experiments

E. Thomas, Jr., T. Hall, B. Lynch, and U. Konopka,
Physics Department, Auburn University, Auburn, AL USA
etjr@ auburn.edu

Complex or dusty plasmas are four-component plasma systems consisting of ions, electrons, neutral atoms, and charged, micron-sized particles (i.e., "dust"). Because the microparticles are charged, they fully interact with the background plasma. This gives rise to phenomena where the presence of the microparticles can modify the background plasma as well as leading to new, dust-driven phenomena. Under ground-based laboratory conditions, the microparticles in a complex plasma must be suspended against gravity – which lead to a compression of the system.

However, under microgravity conditions, the microparticles can expand to fill the entire plasma volume allowing detailed investigations of the inter-particle forces as well as helping to reveal the interactions between the particles and the background plasma.

Over the last decade, understanding the interaction of the charged dust particles with the plasma ions via the "ion wind" or "ion drag" force has been a topic of intense study. Ion-dust interactions are believed to be responsible for the string alignment self-organization, the generation of instabilities, and introduction of thermal effects in complex plasmas. Many of these effects can be more easily studies under microgravity conditions when the particles are no long suppressed or restricted by gravitational effects such as sedimentation.

Our recent ground-based studies have focused on an asymmetric response of a complex plasma cloud due to applied perturbations. It is believed that the asymmetry arises due to the competition between electric and ion drag forces during the perturbation. To perform these studies, we have been developing time-resolved particle image velocimetry (PIV) and real-time particle tracking techniques to measure the transport of the microparticles. This presentation will report on the status of ground-based studies, the development of the PIV and tracking diagnostics, and prospects for current and upcoming microgravity studies of complex plasmas.

Precision Inertial Sensing Using Atom Interferometry

Mark Kasevich
Dept. of Physics and Applied Physics
Stanford University, Stanford, CA 94305
kasevich@stanford.edu

Recent advances in atom optics and atom interferometry have enabled observation of atomic de Broglie wave interference when atomic wavepackets are separated by distances approaching 10 cm and times of nearly 3 seconds. With further refinements, these methods may lead to meter-scale superpositions. In addition to providing new tests of quantum mechanics, these methods allow inertial force sensors of unprecedented sensitivity. We will describe methods demonstrated and results obtained in a 10 m atomic fountain configuration, their implications for technological applications in inertial navigation and their relevance to fundamental studies in gravitational physics, including tests of the Equivalence Principle. We will describe supporting techniques used to cool atoms to effective temperatures below 50 pK in two dimensions and novel atom optics configurations which have achieved greater than 5 sec of quasi-inertial free fall. We will describe an ultracold dual Rb85 and Rb87 atomic source.

Optical atomic clock - progresses and future outlook

Jun Ye
University of Colorado, JILA

I will present our recent progress on the JILA Sr optical lattice clock. The second evaluation of the clock systematics has pushed its overall uncertainty from 6.4x10^{-18} to the low 10^{-18}. I will discuss the next steps in our research of further advancing the clock performance using collective quantum effects.

A Yb Lattice Clock for Space-Based Research

C. W. Oates, A. D. Ludlow, J. A. Sherman, K. Beloy, N. B. Phillips, M. Schioppo, N. Hinkley, and W. F. McGrew
Time and Frequency Division
National Institute of Standards and Technology
Boulder, CO 80305

As a new type of atomic clock, one based on optical rather than microwave transitions, continues to push time/frequency metrology toward the 18th digit of precision/accuracy

and beyond, a new range of applications is coming to the forefront. As a result, the possibility of sending such clocks to space is appealing for (at least) three reasons. First, the precision of terrestrially-based clocks is now reaching a level where unpredictable gravitational noise may begin to compromise their performance via the clocks' sensitivity to the gravitational redshift. Second, the prospect of having a high-performance optical clock in a low- or medium-earth orbit would enable comparisons between widely spaced earth clocks at a level simply not possible today (assuming some formidable time transfer challenges are overcome). Finally, and perhaps most importantly, due to the fact that time can be measured so much more precisely than any other physical quantity, clocks in space may prove indispensible as we more stringently test our most fundamental theories in our search for new physics. Indeed such space-based clocks have been considered for testing the Weak Equivalence Principle, gravitational redshifts, and Local Lorentz Invariance, and even in searches for gravitational waves. In our lab, we are pushing the development of high performance optical clocks based on thousands of Yb atoms confined to an optical lattice. Due to its having favorable laser systems for space qualification, Yb is one of the candidate atoms for the European Space Agency's Space Optical Clock program. Our NASA research has focused on supporting the ESA goal of demonstrating lattice clock performance with an uncertainty below 1 part in 10^{17}. We are currently reducing the most relevant clock shifts and will present latest results and prospects for space-based applications.

Frequency metrology and optical clocks with microresonator combs

Scott Diddams[1], Scott Papp[1], and Kerry Vahala[2]

[1]*Time & Frequency Division, National Institute of Standards and Technology, Boulder, CO 80305, USA.*

[2]*T. J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA 91125, USA.*

A new class of optical frequency combs has recently emerged based on optical microresonators, and they provide a chip-scale platform to realize a variety of precise time and frequency measurements. Here we describe experiments in which we generate phase-locked frequency combs around 1550 nm using high-Q silica resonators. The phase-locking mechanisms and intrinsic noise processes are studied, and techniques have been developed to stabilize the comb spectrum to optical and microwave references. These advances have allowed us to realize a micro-resonator frequency comb optical clock that accurately divides terahertz frequencies associated with atomic transitions to the microwave domain. Efforts aimed at generating octave-spanning combs and their frequency control will also be discussed.

Theoretical tools and new approaches in atom interferometry

Wolfgang P. Schleich
Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST),
Universität Ulm, D-89069 Ulm, Germany;
Department of Physics and Astronomy and Institute for Quantum Science and Engineering (IQSE), Texas A&M University, College Station, TX 77843, USA

In the present talk we summarize the theoretical activities of the Ulm node in the QUANTUS project and focus on a few subjects such as: (i) a description of atom interferometry using Wigner phase space distribution functions [1], (ii) mirrors and beam splitters based on double Bragg diffraction [2] as realized by two experiments [3, 4], and (iii) interferometers testing and taking advantage of the cubic term in time appearing in the propagator of a particle in a linear potential.

BEC interferometry in extended free fall

Ernst Rasel
Leibniz Universität Hannover
Institut für Quantenoptik

Matter wave interferometers employing Bose-Einstein condensates and Delta-Kick cooling open a new avenue of precision tests of gravity with quantum objects. Novel robust and compact sources for generating ultracold atoms will allow to enhance the precision of these devices by extending the time of free fall and operating them in microgravity environment. We will report on the progress of the QUANTUS cooperation, which develops concepts for atom interferometry in space. One important motivation is the test of the principle of equivalence with quantum matter in the drop tower, on sounding rocket missions and on the International Space Station.

The QUANTUS cooperation is supported by the DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) due to an enactment of the German Bundestag under grant numbers DLR 50 1131-1137 (QUANTUS-III).

A Feasibility Investigation of QTEST

Nan Yu
Jet Propulsion Laboratory

QTEST is a proposed ISS mission for testing Einstein's Equivalence Principle (EEP) and exploring space-time using atom interferometers in the micro gravity environment. We will report on findings of a recent science feasibility investigation of the QTEST mission. The mission concept utilizes a number of innovative approaches to reduce systematics including Bragg diffraction beam splitting, gravity gradient fringe compensation, and gravity and k-vector reversal measurements, enabling QTEST to achieve its primary science objective of EEP test at a precision better than one part per 10^{15} level.

ABSTRACTS FOR POSTER PRESENTATIONS

Fundamental Interactions for Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment

Jose D'Incao[1] and Jason Williams[2]. [1]JILA, University of Colorado and NIST, Boulder, CO, USA; [2]Jet Propulsion Laboratory, California Institute of Technology, CA, USA.

Precision atom interferometers (AI) in space are a key element for several applications of interest to NASA. Our proposal for participating in the Cold Atom Laboratory (CAL) onboard the International Space Station is dedicated to mitigating the leading-order systematics expected to corrupt future high-precision AI-based measurements of fundamental physics in microgravity. Our project has two primary focuses, the first of which aims to enhance initial state preparation for dual-species AIs. Our proposed filtering scheme uses Feshbach molecular states to create highly correlated mixtures of heteronuclear atomic gases in both their position and momentum distributions. We will detail our filtering scheme along with the main factors that determine its efficiency. We also show that the atomic and molecular heating and loss rates can be mitigated at the unique temperature and density regimes accessible on CAL. The second focus of our project is to utilize the dual-species ^{39}K-^{87}Rb AI, recently integrated into CAL, for proof-of-principle tests of systematic mitigation and phase-readout techniques. We will review our planed investigations with the CAL-AI, including: optimization for long atom-photon coherence times, enhanced AI-contrast and phase-readout in dilute clouds, and control of inter- and intra-particle interaction shifts in heteronuclear gases. We will discuss the impact of the proposed studies to enhance the quests of NASA's fundamental physical sciences research program, focusing on potential tests of Einstein's General Relativity theory and the search for violations of the Weak Equivalence Principle with these quantum gases in space.

Chip-based BEC machines for mobile atom interferometry

Naceur Gaaloul & Ernst Rasel for the Quantus/Maius consortium
QUEST, Institute of Quantum Optics - Leibniz University, Hanover, Germany

In this poster, we present three experimental projects where atom interferometers are realized in compact and autonomous apparatus suited to operate in μ-gravity environments. At the heart of the three experiments, atom chips are the key ingredient that allows for an unprecedented miniaturization of BEC machines. Atom chips have proven to be excellent sources for the fast production of ultra-cold gases due to their outstanding performance in fast evaporative cooling. The first generation of experiments consists in a Bragg-type interferometer on a chip operated with ^{87}Rb atoms in the thermal or Bose-Einstein condensed regime [1]. With the help of delta-kick cooling [2, 3], implemented via the atom chip, we can further slow the expansion of the atoms down. With this toolbox we could extend the observation of a BEC of only 10^4 atoms up to two seconds. Benefiting from the extended free fall in the ZARM drop-tower in Bremen, we could operate an asymmetric Mach-Zehnder interferometer over hundreds of milliseconds (over 700 ms) to study the coherence and to analyze the delta-kick cooling with the help of the observed interference fringes [4]. A novel generation of atom chips allows improving the performance of these flexible devices. We have developed a novel loading scheme that allowed us to produce Bose-Einstein condensates of a few 10^5 ^{87}Rb atoms in less than 1.5 s. The apparatus is also 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.

As a next step towards the transfer of such systems in space, either on board the ISS or as a dedicated satellite mission, a chip-based atom interferometer operating on a sounding rocket is currently being built. The success of this project would mark a major advancement towards precision tests of fundamental laws in space.

References:
[1] T. van Zoest et al., Science **328**, 1540 (2010).
[2] S. Chu, J. E. Bjorkholm, A. Ashkin, J. P. Gordon, and L.W. Hollberg, Opt. Lett. **11**, 73 (1986).
[3] H. Amman and N. Christensen, Phys. Rev. Lett. **78**, 2088 (1997).
[4] H. Müntinga et al., Phys. Rev. Lett. **110**, 093602 (2013).

Complex Plasma under Microgravity Conditions

U. Konopka[1] , E. Thomas, Jr.[1], B. Lynch[1], C. A. Knapek[2], H.M. Thomas[2]
[1] *Auburn University, Auburn, AL, USA*
[2] *Deutsches Zentrum für Luft- und Raumfahrt, FGR Komplexe Plasmen, Wessling, Germany*

A complex or dusty plasma consists of electrons, ions and micron-sized particles. Due to the different mobilities of ions and electrons the dust particle typically acquires a negative equilibrium charge. Confined in the plasma volume by strong sheath electric fields, the micro-particles can form regular, ordered structures or show a fluid like behavior as a result of their mutual interaction. Their special features make complex plasmas interesting beyond their fundamental properties, as they show behavior found in other physical disciplines such as condensed matter systems. Because of particle sedimentation, only particles with sizes of one micron or smaller can built a substantial three dimensional system under gravitational influence. Studying the full potential of complex plasmas require experiments to be performed in a microgravity environment. Initially designed and tested during parabolic flights, complex plasma experiments were have been operated on board the International Space Station (ISS) for several years. After the first, DLR financed, experiment in this series, PKE-Nefedov in 2001 and its successor experiment PK-3plus, a more advanced complex plasma experiment facility called PK-4 has been built and will be launched to the ISS in 2014. This, ESA operated experimental facility will be utilized by an international researcher team with US contribution.

We will show an overview of the complex plasma microgravity developments from their beginning to the actual PK-4 facility and discuss the advanced developments for the next generation microgravity experiment facilities.

Rydberg-atom spectroscopy in modulated optical lattices

G. Raithel, University of Michigan
Ann Arbor, MI 48109

Optically trapped, cold atoms are important in high-precision measurement, atomic clocks, field sensing and quantum information processing. In the work presented, Rydberg atoms are trapped in one-dimensional optical lattices of 1064nm laser light. Amplitude modulation is used to drive microwave transitions between Rydberg levels. The advantages of lattice-modulation spectroscopy of Rydberg-atom transitions include small trap-induced shifts, micron-scale spatial addressability, and freedom from typical selection rules. I will explain the method's background, which engages the A^2-term, not the usual $\mathbf{A}\cdot\mathbf{p}$-term. Here, we probe $nS_{1/2}$ to $(n+k)S_{1/2}$ Rydberg transitions in rubidium, with k=1, 2 or 3 and several selected values of n. The transitions occur primarily at odd harmonics of the lattice modulation frequency; in current experiments the 1st, 3rd and 5th harmonic have been demonstrated successfully. The highest transition frequency demonstrated to date being close to 100GHz. One of the transitions probed satisfies a "magic" condition, in which the trapping potentials of the lower and upper Rydberg states coupled by the modulated lattice have the same trapping potential. These results set the stage for using lattice modulation spectroscopy of Rydberg atoms in high-precision measurement. High-precision lattice-modulation spectroscopy will be most promising with circular, Bohr-like Rydberg states. These have long lifetimes and low electric polarizabilities, among other features. Towards this long-term goal, we have also recently produced and trapped cold, circular Rydberg atoms with an adiabatic "crossed-fields" state-switching method.

The Physics Package for the CAL Mission

Jaime Ramirez-Serrano, ColdQuanta, Inc.

ColdQuanta's Physics Package lies at the heart of the Cold Atom Laboratory (CAL) that will be launched on 2016. The package, which is based on ColdQuanta's RuBECI system, has been designed to meet all the technical, engineering and scientific requirements for the CAL mission. We present a general overview of the features of the system, together with an overview of the possible experiments that can be performed with it.

STE-QUEST: Testing the Equivalence Principle using cold atom interferometry

Thilo Schuldt[1,2] for the STE-QUEST atom interferometer team
[1]DLR-Institute of Space Systems, 28359 Bremen, Germany
[2]ZARM, University Bremen, 28359 Bremen, Germany
thilo.schuldt@dlr.de

The proposed SpaceTime Explorer and Quantum Equivalence Space Test (STE-QUEST) satellite mission will perform a Weak Equivalence Principle (WEP) test based on a differential measurement between two atom interferometers, operating with Rb85 and Rb87, respectively, where the accelerations of the two atom clouds under the influence of the Earth's gravity field are compared simultaneously. As both atom interferometers are operated at the same time, also using the same optical components, a high common-mode rejection is achieved. The instrument design is based on the expertise of a European consortium, which includes the German DLR-funded cold atom experiments QUANTUS (QUANTengase Unter Schwerelosigkeit) and MAIUS (Materiewelleninterferometrie Unter Schwerelosigkeit), both operated in drop-tower experiments, and the French CNES-funded experiment I.C.E. (Interférométrie Cohérente pour l'Espace) operated in zero-g parabola flights. For STE-QUEST, Bose-Einstein-Condensates (BECs) are prepared on an atom chip, which is beneficial with respect to power, mass and dimensions. The key specifications of the system are the 10^6 atoms in each of the two BECs, a free evolution time between the atom interferometer beam splitter pulses of 5 s, and a total repetition rate of 20 s. With these parameters, the target Eötvös ratio test at 10^{-15} is expected to be reached in less than 5 years integration time.

Phase A studies of the STE-QUEST mission and payload were carried out during the last two years within the ESA Cosmic Vision plan. A preliminary design resulted where for the atom interferometer a total mass budget of 265 kg, an average power of 680 W, a peak power of 900 W and a telemetry budget of 110 kbps was allocated (numbers include 20% component contingency and 20% system margin).

Cold Atom Laboratory Mission.

A. Sengupta[1], R. Thompson[2], D. Aveline [3], and P. Yates[4]. [1-4]NASA Jet Propulsion Laboratory, California Institute of Technology, CA, USA.

The Cold Atom Laboratory (CAL) is a multi-user facility for the study of ultra-cold quantum gases in the microgravity environment of the International Space Station (ISS). The CAL payload is being developed by the Jet Propulsion laboratory (JPL) for NASA's Human Exploration Mission Directorate, and is scheduled to launch in early 2016. The instrument uses the techniques of laser, adiabatic, and evaporative cooling to create a Bose-Einstein Condensate (BEC). In the microgravity environment of the ISS, temperatures on the order of less than 100 picoKelvin can be achieved with interaction times in excess of five seconds, a marked improvement over Earth-Based laboratories. CAL will provide new scientific insight into the properties of Bose-Einstein Condensates and Degenerate Fermi gases, in microgravity. The CAL mission objectives are derived from the microgravity decadal survey. CAL utilizes the microgravity environment of the International Space Station (ISS) to form, create, and study ultra-cold quantum gases. CAL will be a technology and science pathfinder mission with the first ever demonstration of laser cooling, BEC, and atom interferometry in a space environment. As CAL is a multi-used facility, it will allow the scientific community to propose experiments using the instrument with the unique quantum physics capabilities. It will be launched on a Dragon Pressurized Cargo vehicle in late 2016 and operated remotely from the Jet Propulsion Laboratory. A presentation of science investigations, mission architecture, instrument technology, and development status will be given.

Supported by NASA Johnson Space Center and NASA Space, Life and Physical Sciences.