AN OVERVIEW OF NASA’S PROGRAM FOR FUNDAMENTAL PHYSICS RESEARCH ON THE INTERNATIONAL SPACE STATION

Presentation to:

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NASA ISS Fundamental Physics Program

- Cold Atom Laboratory
  - CAL1
  - CAL2 and Beyond
    - FP community advice
    - FP NRA
    - International participation

- Atomic Clock Ensemble in Space

- DECLIC

- PK – 4/Dusty Plasma
  - NRA
  - Open Science
• **QWEP/QTEST**
  - *Pre-Phase A Study*
  - *NASA/ESA collaboration discussion*

• **SOC**
  - *Space to space*
  - *Space to ground*

• **Microscope**
  - *Reflectors*
“Research related to the Physics and Applications of Quantum Gases. Space Environment enables many investigations, not feasible on earth, of the remarkable unusual properties of quantum gases and degenerate fermi gases”

– Recapturing Future for Space Exploration Decadal Survey, Recommended Program Element 3: Research Related to the Physics and Applications of Quantum Gases (FP3), P261, 2011
CAL – Particle-Wave duality

All matter has both a wave aspect and a particle aspect.

At high temperatures atoms behave as particles.

At very cold temperatures the wave nature becomes more pronounced.

At the critical temperature and density, the wavelengths of the atoms overlap. Below this temperature, most of the atoms share the same wavefunction (for a gas of bosons).

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Technique</th>
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<tr>
<td>T~1K</td>
<td>Laser Cooling</td>
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<tr>
<td>T~1 microKelvin</td>
<td>Evaporative Cooling</td>
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<tr>
<td>T~10 nanoKelvin</td>
<td>Delta-kick cooling in Microgravity</td>
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<tr>
<td>T~1 picoKelvin</td>
<td>BEC production in CAL ground test bed</td>
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\[ \lambda \sim 1 \text{ mm} \]
Microgravity offers a wealth of advantages for ultracold atom experiments:

- Long **interrogation time** in **perturbation free** environment
- Very **weak trapping forces** result in **low temperatures**
- Absence of density stratification and separation of mixtures of different species

The International Space Station is the ideal location for studies of ultra-cold atoms in a regime that can not be accessed on Earth.
The CAL Facility: A Cutting Edge Ultra-cold Atom Laboratory in Space

- CAL offers Investigators a suite of precision tools to enable a wide variety of science
- 3 atomic species; microwave state selection and adiabatic rapid passage enables any of 24 different quantum states to prepared (with an infinite number of mixtures and super positions)
- Feshbach coil allows for the precise control of interactions between atoms in certain states
- Bragg beams enable atom interferometry; but are also a sensitive way to probe a variety of condensate properties
- High and low resolution imaging allow scientists to view atom clouds from 2 directions
- Delta-kick cooling allows scientists to access a previously unexplored range of effective temperature; but also enables precise focusing and shaping of atomic clouds
CAL Firsts

• 1st laser cooling of K and Rb in a space environment
• 1st dual species laser cooling in a space environment
• 1st demonstration of magnetic trapping in a space environment
• 1st demonstration of evaporative cooling in a space environment
• 1st observation of BEC in a space environment
• 1st observation of dual species degenerate gases in space
• 1st demonstration of Delta-kick Cooling to temperatures below 100 picoKelvin (goal 20 pK)
• 1st demonstration of interaction times longer than 5 seconds (goal 10 seconds)
• 1st Demonstration of Bragg splitting and atom interferometry in space
• 1st Multi-purpose ultra-cold atom laboratory in space
Cold Atom Laboratory Science

Science Timeline of Events

- CAL1 Science Workshop Dec 2012
- FP NRA – July 2013
  - Recruiting first line US researchers in cold atom research
  - Allowing minor CAL facility modifications to the extent feasible
  - Fundamental Physics community responded in force
- 5 Flight and 2 Ground PIs selected Jan 2014
  - 19 Funded PI’s and Co-I’s including 3 Nobel Laureates
  - SLPSRA CAL1 NRA funding augmentation
  - CAL1 facility modifications
  - Total CAL1 funding
- Science Before and After NRA Upscopes
  - Before: Repeat ground-based experiments in space and demonstrate microgravity advantages
  - After: Investigate at the frontier of physics and probe deep into the Planck-scale physics
- FP/CAL2 Science Workshop planned for Dec 2015
  - Define science goals for future science module upgrades
Zero-G Studies of Few and Many Body Physics (PI E. Cornell)
  - How complexity of the universe evolves from subatomic scale
  - Incorporation of Potassium 39 and a fast tuning magnetic field into CAL instrument

Atom interferometry will pave the way for definitive space-based tests of Einstein’s Theory of General Relativity (PI N. Bigelow, Co-PI W. Ketterle, Co-I W. Phillips)
  - Holy grail of theoretical physics probing deep into Planck-scale physics
  - Incorporation of Bragg scattering beam for two species atom interferometry

Microgravity dynamics of bubble-geometry Bose-Einstein condensates (PI Nathan Lundblad)

Fundamental Interactions for Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment (PI Jason Williams)

Development of Atom Interferometry Experiments for the International Space Station’s Cold Atom Laboratory (PI Cass Sackett)
CAL represents a real scientific opportunity, something that can't be replicated on the ground.

This unintentional confinement, this unwanted trapping potential, means that either one has to work with vanishingly small samples, or one has to reconcile to not being able to reach arbitrarily low temperatures. This is where I think CAL offers the most potential -- to be able to get to temperatures that are really too low to reach on earth.
Atom Interferometry on CAL

- CAL shall develop a “proof-of-concept atom interferometry capability”
- We have worked with PI’s to develop a simple but powerful AI capability incorporating Bragg pulses
- AI testing will begin after flight unit and spare are delivered (April 2015)
Atom chip based Bose-Einstein condensation at JPL

- Density plots showing the formation of a Rubidium 87 Bose-Einstein condensate (BEC) in the JPL Ground Testbed
- By means of laser- and evaporative cooling in an atomchip-based setup, the temperature $T$ of the atoms is reduced to less than a millionth of a degree above absolute zero (~ 200 nK)
- By surpassing a critical temperature $T_c$, the atoms coherently condense into a single quantum state
# Science and Applications of Cold Atoms in Space

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<th>Atomic Clocks</th>
<th>Atom Interferometers</th>
<th>Degenerate Quantum Gases</th>
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<td><strong>Fundamental Physics</strong></td>
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<tr>
<td>• Standard Model Extension tests</td>
<td>• Weak Equivalence Principle tests</td>
<td>• Macroscopic wavepackets</td>
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<tr>
<td>• Gravitational red-shift</td>
<td>• Measurement of fundamental constants</td>
<td>• Vortex formation and relaxation</td>
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<tr>
<td>• Time variations of fundamental constants</td>
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<td>• BEC coherence properties in microgravity</td>
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<tr>
<td>• Violation of Lorentz and CPT symmetry</td>
<td>• Tests of the Newton’s law at short distances</td>
<td>• Role of interactions in BEC: dipolar forces and short range interactions</td>
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### Applications

- Atomic time scales (TAI)
- Time & Frequency metrology
- Deep space navigation
- Improved GPS performance
- Doppler tracking
- VLBI
- Time & Frequency transfer
- Gravity mapping
- Planetary exploration

### Applications

- Inertial navigation
- Earth observation and monitoring
- Gravity and gravity-gradient mapping
- Planetary exploration

### Applications

- Atomic sources for atom interferometry
- High-resolution interferometric measurements with dilute coherent matter waves
- Atom Holography
- Quantum Computation

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CAL1 opens the door to a wide range of future cold atom missions.
Rubidium atoms trapped by laser beams could herald dawn of quantum supercomputers that can solve problems far, far quicker than today's hardware.

Read more:
http://www.itpro.co.uk/121086/trapped-atoms-could-advance-quantum-computing#ixzz39QoUqAY0
CAL Instrument

Power Electronics
(5th Locker)

Science Instrument
(Quad Locker)
• Strong FP Community Participation and Advocacy

• Marketing of Fundamental Physics Investigations on ISS

• International Collaborations

• 2024 and beyond
NASA Fundamental Physics Program
Current ISS International Collaborations

- DECLIC/CNES
- ACES/ESA-CNES
- PK-4/ESA-Roscosmos
- SOC-ESA
- QWEP-ESA
- QTEST-NASA Study
• DECLIC facility is a joint CNES/NASA project
  – Following ~10 years of development, the DECLIC multi-user/multi-discipline facility was launched in Aug, 2009.
  – CNES finances the development of the instrument. NASA covers the costs of launch and operations.

• Overall science objectives
  – Physical principles governing microstructure formation: Material Science (DSI insert)
  – Supercritical water property: Fluid Management (HTI insert)
  – Boiling phenomena, Critical Phenomena: Fundamental Physics (ALI insert)

• NASA portion of science
  – NASA support in Fundamental Physics
  – Scientific collaboration with CNES scientists
  – Re-flight of ALI insert refurbished by CNES planned for launch early 2015
  – Studying equation-of-state, phase transition phenomena and two-phase fluid behavior in microgravity
US Collaboration in the ESA ACES Mission

Atomic Clock Ensemble in Space (ACES) – an ESA ISS Experiment (2017 Launch)

Science Objectives:

- Demonstrate validate a new generation of atomic clocks in space \((10^{-16})\) stability and accuracy level
- Demonstrate the capability to compare ground clocks on a world-wide basis (stability better than \(10^{-16}\))
- Test fundamental laws of physics to high accuracy (gravitational Red-shift, drift of fine structure constant, and anisotropy of light.)
US Collaboration in the ESA ACES Mission

Ground link stations at leading US time and frequency metrology institutions for the critical global coverage

US ACES ground link station sites
JPL: PI, Dr. N. Yu
NIST: PI, Dr. T. O’Brien

US Collaboration Objectives:

♦ Contribute to ACES objectives to validate the cold atom space clock; to perform time and frequency transfer to the Earth at the same stability level; and to test general and special relativity to high precision

♦ To demonstrate US clock capabilities at NIST; validate and characterize the JPL trapped ion mercury clock technology

♦ Establish an ESA-NASA collaboration on Fundamental Physics in Space

Ground Research supporting ACES clock and time transfer sciences

ACES cold atom clock shift studies:
PI: Prof. K. Gibble, Penn State Univ.

ACES advanced optical frequency transfer and time synchronization:
PI: Prof. L. Hollberg, Stanford University

Fig. 3. a) Schematic of the PHARAO Ramsey cavity. Microwave power is supplied at the middle of the cavity along the z axis, flowing outward (red arrows). This power flow leads to travelling waves and large phase gradients along z. b) Cylindrical TE 011 cavity in fountain clocks. The phase gradients that the atoms experience in the PHARAO cavity are analogous to those in a fountain cavity if the microwave power was fed only from the top endcap. In fountains, the cavities are instead fed from the midplane to minimize longitudinal phase gradients. While the phase gradients are larger in the PHARAO cavity, the 10 times narrower linewidth that is possible in microgravity reduces this systematic frequency error.

The PHARAO cavity in Fig. 3a does not have the cylindrical symmetry of the cavities used in fountain clocks. Thus, the calculations will likely need to be 3D and these require vastly greater RAM than 2D calculations - the memory increases by the 3/2 power. To get converged fields, we expect that in 3D we will probably still need to solve sub-regions as in [2]. However, we now have access to a machine with 1 TB of RAM and 32 parallel processors for 3D calculations, as compared to 2 GB of RAM for 2D, as in the early 2000’s. With this capability, it may be possible to solve without decomposing into sub-regions, or at least with fewer sub-regions.

Our analytic DCP models have given a clear understanding of the DCP shifts that the sharp corners contribute. The limit of low microwave amplitude offers helpful insight. Here, the tipping angle is small and the effective phase [2] for a cavity traversal is:

Figure 3. Conceptual diagram of the integrated Multi-Link, Laser-Microwave-GPS Time Transfer system (LMG_TT) that takes advantage of, and optimally integrates, a two-way three-frequency microwave link, a high performance GPS timing system, and an ultrahigh performance laser-TT link based on a stabilized femtosecond mode-locked laser. The system transfers precise Time and Frequency between the ground station and the satellite (such as ACES on the ISS). The design of the multi-link LMG-TT system will be guided by analysis that takes into account the capabilities and limitations of all three links so that they can be optimally integrated to achieve the highest overall performance. Each link provides additional performance capabilities and will synergistically enhance the performance of the other links and the overall system. For example, adding the laser channels provides additional information about the static and dynamic characteristics of the atmosphere (dispersion, scintillation, etc.) that will reduce the errors and uncertainties in the microwave link atmospheric corrections.

The experimental effort in this project will focus entirely on designing, building and testing the Laser-TT link based on a femtosecond mode-lock fiber laser that will be reference-able to either a high performance optical atomic clock (described below) or, when an optical reference is not available, to a high performance microwave frequency standard (e.g. Cs atomic clock or H-maser).
PK-4 (Plasma Krystal -4 )
ESA-Roscosmos International Collaboration

- PK-4 instrument is an ESA-Roscosmos project
  - Following 9 years of development, the PK4 multi-user facility will launch in Oct, 2014. PK-4 is a very large Class-II ISS payload.
  - ESA has invited U.S. scientists and other nations to participate in PK-4 on an equal footing with European scientists

- Overall science objectives
  - Study of the liquid phase of complex plasma such as flow phenomena

- NASA portion of science
  - NASA support in Fundamental Physics
  - Science collaboration with ESA scientists
  - Studying mobility of a charged particle in a strongly coupled dusty plasma with gas

Photograph of the PK-4 instrument.

Photograph of the PK-4 Facility Ground Model, integrated into the European Physiology Module (EPM) rack. (source: J. Goree)
Potential European collaborations on Precision measurements in Fundamental Physics

ELIPS-4 Research Cornerstones in Physical Sciences

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<th>FUNDAMENTAL PHYSICS</th>
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<td>Cold Atom Clocks, Matter Waves, Bose-Einstein Condensates &amp; Quanta</td>
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- ACES mission now planned to launch on Space-X end of 2015; agreements with NASA, JAXA and Australia for the network of MWL ground terminals+clocks to be prepared until end of 2013;
- SOC pre-phase A successfully completed; target stability of $10^{-17}$ deemed feasible with a miniaturised Sr lattice; transportable model under tests in a 3-y project currently funded by the European Commission;
- QWEP on ISS currently subject of a feasibility study by ESA

Fundamental Physics and Precision measurement activities in ESA and European space agencies
Potential European collaborations on Precision measurements in Fundamental Physics

NASA and ESA and scientists have common science objectives, common interests in precision measurements for fundamental physics with high performance atomic clocks and quantum tests of Einstein equivalence Principle.

Quantum Tests of the Equivalence Principle and Space-Time (QTEST) – a CAL experiment exploring gravity’s influence on quantum and classical systems

Science Motivations

- **Improve the limit on violation of Einstein’s universality of free fall**
  - Indirect limits on hidden antimatter EEP
  - Opportunity for discovery: violations of EEP, dilatons, moduli

- **Test Space-Time dependence of quantum states**
  - Complementary to classical EEP tests
  - Test gravitational redshift for quantum states
  - Open fundamental questions of quantum mechanics, subject of recent discussion [1]
  - Quantum mechanics on macroscopic scales
  - Spin-gravity coupling

- **Achieve more precise photon recoil measurement**
  - Establish the most precise primary mass standard in the proposed SI
  - Most precise measurement of the fine structure constant
  - Most precise test of Quantum Electrodynamics
  - Opportunity for discovery: inner structure of electron at LHC energy scale

In response to NRC Decadal survey report [2]: two of the three high priority thrust areas:

- Precision measurements of the fundamental forces and symmetries
- Physics and Applications of Quantum Gases

In response to NRC Decadal survey report [2]: two of the three high priority thrust areas:

Opportunities to collaborate in ESA Space Optical Clock (SOC) and Quantum Weak Equivalence Principle (QWEP) experiments on ISS and Cosmic Vision mission.

International Collaboration on ESA’s Space Optical Clock study

**SOC Objectives**

- Demonstrate an optical clock on the ISS accurate to one part in $10^{17}$, measure the Earth’s gravitational redshift to two parts in $10^7$, and test relativistic effects in the frequency comparisons of moving clocks.
- Perform a null measurement of the Sun’s gravitational redshift to two parts in $10^7$.
- Perform differential geo potential measurements with 1 cm height resolution on the geoid; such measurements are based on the comparison of distant clocks on ground.
- Perform time synchronization and time transfer experiments (space-to-ground and ground-to-ground) and to allow comparison between ground clocks to a fractional frequency resolution of 1 part in $10^{18}$.
Potential International Collaboration on Microscope

- Microscope International cooperation explored
• Cold Atom Laboratory
  • CAL1
  • CAL2 and Beyond (2017)
    • FP community advice
    • FP NRA
    • International participation

• PK – 4/Dusty Plasma
  • NRA 2016/2017
  • Open Science