| | | | |
|---|---|---|---|
| **Fiscal Year:** | FY 2020 | **Task Last Updated:** | FY 05/18/2020 |
| **PI Name:** | Cornell, Eric Ph.D. | | |
| **Project Title:** | Zero-G Studies of Few-Body and Many-Body Physics | | |
| **Division Name:** | Physical Sciences | | |
| **Program/Discipline:** | | | |
| **Program/Discipline--Element/Subdiscipline:** | FUNDAMENTAL PHYSICS--Fundamental physics | | |
| **Joint Agency Name:** | | **TechPort:** | No |
| **Human Research Program Elements:** | None | | |
| **Human Research Program Risks:** | None | | |
| **Space Biology Element:** | None | | |
| **Space Biology Cross-Element Discipline:** | None | | |
| **Space Biology Special Category:** | None | | |
| **PI Email:** | Cornell@jila.colorado.edu | **Fax:** | FY |
| **PI Organization Type:** | UNIVERSITY | **Phone:** | 303-492-6281 |
| **Organization Name:** | University of Colorado | | |
| **PI Address 1:** | JILA | | |
| **PI Address 2:** | 440 UCB | | |
| **PI Web Page:** | | | |
| **City:** | Boulder | **State:** | CO |
| **Zip Code:** | 80309-0440 | **Congressional District:** | 2 |
| **Comments:** | | | |
| **Project Type:** | FLIGHT | **Solicitation:** | 2013 Fundamental Physics NNH13ZTT002N (Cold Atom Laboratory--CAL) |
| **Start Date:** | 04/01/2014 | **End Date:** | 08/31/2021 |
| **No. of Post Docs:** | 1 | **No. of PhD Degrees:** | 3 |
| **No. of PhD Candidates:** | 5 | **No. of Master' Degrees:** | 0 |
| **No. of Master's Candidates:** | | **No. of Bachelor's Degrees:** | 1 |
| **No. of Bachelor's Candidates:** | 1 | **Monitoring Center:** | NASA JPL |
| **Contact Monitor:** | Israelsson, Ulf | **Contact Phone:** | |
| **Contact Email:** | ulf.e.israelsson@jpl.nasa.gov | | |
| **Flight Program:** | ISS | | |
| **Flight Assignment:** | NOTE: End date changed to 8/31/2021 per U. Israelsson/JPL (Ed., 5/12/2020)<br>NOTE: End date changed to 4/30/2020 per PI (Ed., 5/1/19) | | |
| **Key Personnel Changes/Previous PI:** | | | |
| **COI Name (Institution):** | Engels, Peter Ph.D. ( Washington State University, Pullman )<br>Ho, Tin-Lun Ph.D. ( Ohio State University ) | | |
| **Grant/Contract No.:** | JPL 1502690 | | |
| **Performance Goal No.:** | | | |
| **Performance Goal Text:** | | | |

| | |
|---|---|
| **Task Description:** | Future advances in both technology and fundamental science will hinge on a better understanding of the weird effects of quantum mechanics on collections of electrons, atoms, molecules, and so on. In some cases, experiments probing this so-called "quantum few-body and many-body physics" can be more readily accomplished in the weightless environment found in an orbiting laboratory. We propose a staged series of experiments, including (1) "first science" experiment, to be performed in the Cold Atom Laboratory (CAL) flying in the International Space Station (ISS) first-generation, to answer a question in few-body quantum physics that can't be performed in a ground-based laboratory: how universal are the weakly bound clusters of three atoms known as Efimov trimers? In a weightless environment, experiments can be performed at very low densities and temperatures, the perfect conditions for these exotic but fragile quantum states to form. (2) Bose gases with "infinite" interactions. As interactions between atoms become stronger, there is a crossover between gas-phase and liquid behavior. In ultra-cold atoms, the crossover is between a quantum liquid and a quantum gas. (3) Highly rotating quantum gases. Many of the most exotic and unexplored predicted states of matter occur in the presence of very strong magnetic fields, for electrons, or high rates of rotation, for neutral particles. We will explore Quantum Hall physics in highly rotating Bose and Fermi gases. Experiments (2) and (3) will benefit significantly from the longer expansion times and weaker traps possible in weightlessness. Preliminary versions of both experiments will be done in a ground-based laboratory in order to establish the foundation for future flight-based experiments. |
| **Rationale for HRP Directed Research:** | |
| **Research Impact/Earth Benefits:** | Physics is the discipline that provides understanding of biology and chemistry at the most microscopic level, and the area within physics most relevant to chemistry and biology is "few-body physics." It is an often neglected portion of physics, because it is so difficult to do! An important way to make progress is to simplify, simplify, simplify: to come up with model systems in which we can make progress that can later be applied to human-centric disciplines like biology, and develop exotic and useful new materials. A promising way to simplify is to study matter at lower temperature, and lower densities. The Cold-Atom Lab (CAL) flying in the International Space Station (ISS) is where we will reach the lowest possible temperatures, and low densities, to do our studies of simple, yet intricate (think "snowflakes") clusters of three or four atoms. We have been doing prefatory experiments and calculations here on Earth. Not at as low temperature, but still cold enough to help us learn things we will need to know to do the space experiments. While CAL is now in flight, we have been participating in the effort to remotely tune it up for maximum performance. |
| **Task Progress:** | Our collaboration has actively contributed to CAL through three different lines of work: through calibration measurements performed with CAL and accompanying numerical modeling, through ongoing discussions with the Jet Propulsion Laboratory (JPL) team about the operational performance of the CAL instrument onboard the ISS, and through performing ground based measurements at both JILA and Washington State University (WSU) that optimize experimental procedures for the planned few-body measurements.<br>In 2019 CAL's operations on board the ISS continued with Science Module 2 (SM2) until December 2019, when Science Module 3 (SM3) was launched to the ISS as an AI-enabled replacement of SM2. With SM2, we successfully used Rb-87 to test the traps needed to perform our planned few-body studies with potassium, confirming that our model replicated the trapping frequencies found for a trap with the necessary magnetic field characteristics. At the end of 2019, SM3 was launched to the ISS and installed at the start of 2020. The new science module has required a new numerical model and new calibrations. We have updated our calculations accordingly, both with basic Mathematica and with a new software package. We are currently developing strategies with the JPL team to calibrate the bias fields of SM3 to ensure accurate models. Along those lines, we have discovered a clear discrepancy with the manufacturer's specification of one of the magnetic coil pairs (the Fast Feshbach coils), which we believe is due to an error in the manufacturer's calibration routine. We plan to resolve this soon together with the JPL team. A deep understanding of CAL's performance and magnetic field stability is key for the optimization of the planned few-body experiments.<br>During the operation of SM2 it became clear that a microwave generator used to effect state changes in Rb is malfunctioning. Pinpointing the exact cause of the malfunctioning was challenging due to the limited telemetry available. To help analyze this problem, members of our team, including Eric Cornell, Peter Engels, and Maren Mossman, traveled to JPL in October 2019 to serve as independent advisors. In discussions with JPL scientists and engineers, we were able to suggest a series of tests that in the end were able to pinpoint the most likely problem. Ground based tests performed by JPL have been able to duplicate this error and plans for correcting this problem are currently being discussed at JPL. Correcting this problem is an important step not only for facilitating experiments for potassium, but also for specific Rb experiments that require the flexibility of changing hyperfine states between different manifolds.<br>Furthermore, our collaboration has continued to perform extensive accompanying studies on the ground in the Cornell lab at JILA and the Engels lab at WSU. While JILA has focused on experiments with 39K, the Engels lab at WSU has continued to work towards the formation of a quantum degenerate 41K gas. The variety of experimental approaches used in the ground-based studies at JILA and WSU allows us to validate a broad variety of aspect relevant for CAL. These studies not only serve to optimize the experimental procedures of our few-body experiments with CAL but have also produced a surprising science result. At JILA, our team has performed precision measurements with 39K that have resulted in an unprecedented calibration of the Feshbach resonance and knowledge of the exact scattering length at which the first Efimov trimer crosses the free-atom threshold. The experiments have been accompanied by theoretical investigations performed by Jose D'Incao. Compared to the previously known results, the new results are more precise by two orders of magnitude. This has enabled us to perform a precision measurement of the first Efimov resonance, leading to the surprising finding that a previously assumed "van-der-Waals universality" in the system is unambiguously broken. A theoretical analysis by Jose D'Incao has confirmed this surprising result. Furthermore, we have explored the temperature and density limits that constrain the observation of the first Efimov state in ground-based experiments. This work was published in Physical Review Letters in 2019https:// . These studies have direct consequences for the planned measurement of the second, next higher Efimov state with CAL -- that can only been done with the flight module onboard the ISS -- by informing us about the required parameter regimes and optimal procedures.<br>Results of our research activities were presented at several conferences. In April 2019, we presented a poster at the NASA Fundamental Physics Workshop held in Washington DC. In December 2019, members of our team, Peter Engels and Maren Mossman, attended the BECCAL meeting in Ulm, Germany where we presented our planned Efimov studies with CAL and proposed future studies creating quantum droplets in microgravity. In addition to this, Peter Engels presented two talks on our work with CAL: one during the Physics Slam event at WSU's Conference for Undergraduate Women in Physics (CUWiP) and the other at the WSU-hosted Northwest Quantum Nexus workshop for Quantum |

Computing, Sensing and Simulation with Cold Atoms.

Professor Jason Ho and his team at Ohio State University have been looking forward, both towards future more elaborate Cold-Atom work, and towards applications of related concepts to important topics like materials design and quantum information. Recent work focused in particular on how quantum simulation can be used to solve computationally difficult problems such as how to find find the ground state and the excitations of a doped antiferromagnet. Other results explained the properties of one of the most exotic new material currently under exploration, twisted bilayer graphene. This system has recently been shown to be a superconductor and could have interesting technological applications.

In summary, our continued experiments at JILA and at WSU are providing important benchmarks for the CAL apparatus, while our work with the CAL flight module onboard the ISS is contributing to a full characterization of the instrument in preparation for the planned Efimov measurements. As SM3 continues to be calibrated, we will optimize our model and procedures accordingly. Regarding the technical aspects of the CAL instrument, we will continue to work with JPL researchers on the microwave slice development before a potential launch of a new microwave module later this year.

| | |
|---|---|
| **Bibliography Type:** | Description: (Last Updated: 05/19/2020) |
| **Articles in Peer-reviewed Journals** | Chapurin R, Xie X, Van de Graaff MJ, Popowski JS, D'Incao JP, Julienne PS, Ye J, Cornell EA. "Precision test of the limits to universality in few-body physics." Phys Rev.Lett. 2019 Dec 6;123:233402. https:// , Dec-2019 |
| **Dissertations and Theses** | Xie X. "Precise Calibrations of Few-Body Physics in Potassium-39: Experiment and Theory." University of Colorado, Boulder, April 2020. , Apr-2020 |