Fiscal Year:	FY 2017	**Task Last Updated:**	FY 05/24/2017
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		
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Zip Code:	80309-0440	**Congressional District:**	2
Comments:			
Project Type:	FLIGHT	**Solicitation / Funding Source:**	2013 Fundamental Physics NNH13ZTT002N (Cold Atom Laboratory--CAL)
Start Date:	04/01/2014	**End Date:**	04/30/2019
No. of Post Docs:	2	**No. of PhD Degrees:**	1
No. of PhD Candidates:	8	**No. of Master' Degrees:**	1
No. of Master's Candidates:		**No. of Bachelor's Degrees:**	1
No. of Bachelor's Candidates:	1	**Monitoring Center:**	NASA JPL
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Flight Program:	ISS		
Flight Assignment:			
Key Personnel Changes/Previous PI:	May 2017 report: During the reporting period, one of our co-investigators, Deborah Jin, died. Her duties in running the project have been assumed by Eric Cornell, the Principal Investigator. Prof. Jin's laboratory equipment is still in working condition and the supervision of her graduate students is now done by Cornell.		
COI Name (Institution):	Engels, Peter Ph.D. (Washington State University, Pullman) 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. While CAL is being prepared for flight, 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.
Task Progress:	We will be investigating exotic few-body physics, exploiting the specific strengths of NASA's Cold Atom Laboratory (CAL) onboard the International Space Station (ISS). CAL is a unique experimental platform that utilizes the near-weightlessness onboard the ISS and will make it possible to create atomic clouds that are both very dilute and extremely cold. These clouds are governed by intricate quantum mechanical effects. While Earth-based experiments with quantum gases have led to many revolutionary experiments over the past few years, the microgravity environment in which CAL is placed will allow us to push the boundaries significantly further. One recent and exciting venture in experiments with ultracold quantum gases is the three-body problem. In 1970, theoretical physicist Vitaly Efimov predicted that, under certain conditions, three atoms can form a bound state even if the attractions between just two atoms are too weak to cause binding. It was not until 2005 that this was first demonstrated in an experiment by a group at the University of Innsbruck. This initiated significant research efforts worldwide both in theoretical and in experimental research. Despite these efforts, further experimental input is needed to assist in theoretical predictions. CAL provides a unique new environment for testing few-body systems in previously inaccessible regimes that are prerequisite for the next generation of Efimov experiments. In preparation for CAL's launch, our collaboration has modeled actual Efimov experiments to be conducted with CAL. This past year, we have worked diligently to prepare for initial tests at the Ground Test Bed (GTB) and to prepare our cold atom apparatus at Washington State University (WSU) for corroborative tests with ultracold Potassium-39 clouds. To this goal, we have outlined an experimental plan for work at the GTB that will allow us to test and optimize our planned experimental strategies. This experimental plan will also provide benchmark results that will later be used to verify the proper operation of the CAL apparatus onboard the ISS. At the same time we have made great progress towards the generation of ultracold Potassium-39 clouds at WSU. The motivation behind these experimental efforts at WSU is twofold: First, we try to identify experimental steps that are specific to K-39 and that need to be optimized for the generation of ultracold Potassium-39 clouds with CAL. We have found a number of technical aspects that can affect the operation of a Potassium-39 experiment, and have discussed these aspects with members of the CAL team. A second motivation is the acquisition of control data that will later be needed to interpret the data taken with CAL. Meanwhile, in the experimental effort at JILA, we have been performing ground-based few-body studies using ultracold atoms. These experiments are meant to compliment the results we anticipate harvesting from the ISS-based Cold Atom Lab in the next two years. We have explored the properties of a potassium/rubidium bose polaron, which is a tiny "snowball" of two or three ultacold atoms right at the conceptual boundary between few- and many-body physics. This work appeared in press in the elite physics journal, Physical Review Letters. We also completed and submitted for publication a ground-based experiment on efimov molecules in Rubidium-85. These efimov molecules were in the first excited state, quite analogous to the efimov molecules we will eventually examine in space, in Potassium-39. Because we were working in the influence of Earth's gravity, we were unable to access the extreme low-temperature, low-density regime we will achieve in space, and thus we were not able to do the precise comparison we will do next year in space. Finally, we made progress towards completing a precision study on the ground-state efimov trimer in Potassium-39. This will be a control for a similar study done in space. At the same time, our theoretical wing at Ohio State made progress on few- and many-body calculations of the properties of ultracold gases, with an emphasis on rotating gases, in anticipation of a possible second-generation Cold Atom Laboratory experiment. Our team focuses on "strongly Interacting Bose gas" and "Quantum Hall states of Bose gases." Bosons are identical particles that tend to occupy the same quantum state. As a result, the ground state of a Bose gas will consist of atoms condensing in the same state, forming a "Bose-Einstein condensate," thereby magnifying quantum phenomena to a macroscopic scale. It is highly unusual for a Bose system not to have a condensed ground state. Yet an uncondensed ground state can emerge under special circumstances. One example is the strongly interacting Bose gas in low dimensions, where bosons will effectively turn into spinless fermions to avoid interacting with each other. The other example is the fast rotating Bose gas, where the system has many single particle states of the same energy competing for condensation. As a result, the bosons fail to condense into a single state, but form a highly correlated wavefunction (called quantum Hall state) with many novel properties. Our NASA projects are to study the property of a three dimensional Bose gas in the strongly interacting limit, and to realize the quantum Hall state in the

fast rotating limit. During last year, we have explored different ways to realize the bosonic quantum Hall states, and to identify their signatures. Achieving bosonic quantum Hall state turns out to be a very challenging task, as this state is strongly competed against by the usual condensed ground state. We noted that it is easier to the create a quantum Hall state of fermions, as their exchange properties (or "Fermi statistics") favors formation of quantum Hall state. On the other hand, by varying the interactions between fermions, one can associate two fermions of opposite spin into a bosonic molecule, (as demonstrated by Deborah Jin's group at JILA in 2003 and 2004). In this process, a fermionic quantum Hall state can turn into a bosonic one. The result of this work has been submitted to PRX for publication and is currently under review. This work has led to a number of invited talks at international conferences including the 90th year Cebebration of Fermi's paper on Fermi statistics at the Galileo Institute for Theoretical Physics in June 2016.

As for identifying the signature with the bosonic quantum Hall state, we have worked out the properties of quantum Hall states in rotating traps with different ellipticity. Due to the intrinsic correlation of that quantum Hall state, the surface contour of the quantum Hall droplet does not follow the equip-potential of the anisotropic trap. Rather, it is an ellipse with a different ellipticity. We are currently writing up this work. Walyon Chen will be giving a talk of this result at the upcoming American Physical Society (APS) March Meeting.

For strongly interacting Bose gas, the experiment of our team is to study the properties of the Bose gas after the interaction between bosons is increased suddenly, a process now referred to as quantum quenching. One key question is how the populations of bosons in different momentum states evolve in time. In order to obtain results that are free from uncontrolled approximations, we have been studying the quantum quenching of one dimensional Bose gas for which exact results can be obtained. The work is in progress.

Bibliography Type:	Description: (Last Updated: 01/17/2024)
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Articles in Other Journals or Periodicals	Ho T-L. "Fusing quantum Hall states in cold atoms." Cornell University Library. 30 Jul 2016. arXiv:1608.00074 [cond-mat.quant-gas]. Submitted to Physical Review X; see https://arxiv.org/abs/1608.00074 , Jul-2016
Articles in Peer-reviewed Journals	Hu MG, Van de Graaf MJ, Kedar D, Corson JP, Cornell EA, Jin DS. "Bose polarons in the strongly interacting regime." Phys Rev Lett. 2016 Jul;117(5):055301. https://doi.org/10.1103/PhysRevLett.117.055301 , Jul-2016