Fiscal Year:	FY 2015	**Task Last Updated:**	FY 01/29/2015
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:**	2013 Fundamental Physics NNH13ZTT002N (Cold Atom Laboratory--CAL)
Start Date:	04/01/2014	**End Date:**	04/30/2019
No. of Post Docs:	0	**No. of PhD Degrees:**	0
No. of PhD Candidates:	6	**No. of Master' Degrees:**	0
No. of Master's Candidates:		**No. of Bachelor's Degrees:**	0
No. of Bachelor's Candidates:	1	**Monitoring Center:**	NASA JPL
Contact Monitor:	Israelsson, Ulf	**Contact Phone:**	
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Flight Program:	ISS		
Flight Assignment:			
Key Personnel Changes/Previous PI:			
COI Name (Institution):	Engels, Peter Ph.D. (Washington State University, Pullman) Ho, Tin-Lun Ph.D. (Ohio State University) Jin, Deborah Ph.D. (University of Colorado)		
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:	The goal of this project is the investigation of 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 because the near weightlessness onboard the ISS makes it possible to create atomic clouds that are, at the same time, 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 has been 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, which fluctuate widely. CAL provides a unique new environment for testing few-body systems in new and previously inaccessible regimes that are prerequisite for the next generation of Efimov experiments. In preparation for CAL's launch in 2016, our work-to-date for this project has involved analytic calculations and numerical modeling of actual Efimov experiments to be conducted with CAL. We are currently conducting numerical analyses addressing the question of how we can attain optimum data while keeping the complexity of the experiment low. To this goal, our numerical calculations simulate exactly what the cloud of atoms will act like in a micro-gravity environment by using actual design parameters of the CAL facility. The planned experiments begin with an ultracold cloud of atoms trapped by a suitably tailored magnetic field. This cloud is prepared using evaporative cooling techniques similar to those used in Earth based experiments. From there, different pathways can be followed to reach the extreme regimes required for next-generation Efimov experiments. First, one can slowly ramp down the trapping confinement, during which the cloud cools in process called adiabatic cooling. Alternatively, one can suddenly turn the trapping confinement off so that the cloud expands ballistically. A subsequent "magnetic field delta-kick," during which the trapping confinement is switched on again for a very brief period of time, then stops the ballistic expansion and leads to a super cooled cloud. A combination of these two techniques is also possible. In our thermodynamic calculations we are assessing the efficiencies of these methods and matching them to the experimental design parameters of CAL. The final cooling procedure establishes clouds that are very dilute and ultracold, with temperatures on the order of 100pK, the perfect regime for Efimov studies. After this, we plan to apply a homogeneous magnetic field for a set time. This homogeneous field determines how strongly atoms interact with each other, through an effect called Fano-Feshbach resonance. We then will observe how the cloud loses atoms over time as collisions in the cloud occur. When plotted as a function of the atomic interaction strength (determined by the applied homogeneous magnetic field), these losses contain signatures of the Efimov states under investigation. The research conducted in the frame of this project lays the groundwork for future investigations of few-body physics using NASA's planned CAL facility onboard the ISS. While CAL is currently under construction at JPL, our modeling, based on actual design parameters of CAL, paves the way for the next-generation Efimov experiments. We have identified successful pathways to generate atomic clouds with sufficiently low density and temperature and have determined realistic parameters to be used in these studies. To develop the intricate patterns of atoms we want to study, we need low temperatures, yes, but also we need to get the atoms to clump together in interesting ways. Towards this end, and in parallel with our work on Efimov resonances, we are spinning the cloud of atoms at ever higher rates. The individual atoms, like strands of wool being spun into yarn, become increasingly more entangled. This year we have succeeded in spinning atoms rapidly in a novel atomic trap, a sort of bowl for atoms constructed of laser beams. Our hope is to do a similar experiment in a second-generation Cold Atom Laboratory, on the ISS. In other progress this year, we have improved our ability to take pictures of the cold atoms. Going into this past year, if two clumps of atoms were closer together than about four ten thousandths of an inch, they would appear us a single blurry clump. Now we can see patterns of atoms that are two times smaller than before. This will help us better understand what's going on at extremely low temperatures. To interpret our results from CAL, both the Efimov state work and the high-rotation work, we will need to have

extensive theoretical understanding. We have been making progress in this area over the last year.

Together with Dr. Ran Qi (NIST), we have studied the quantum quenching of two and three particle systems in a trap. Specially, we study the time evolution of the system after the interaction between particles suddenly jumped from being weakly repulsive to being strongly repulsive. We have investigated this evolution for different kind of confining potential. We have completed the study for the two-particle case, and is in the process of studying the three particle case. The study of the two-particle case reveals a universal structure of the time evolution. The study of the three-particle case will illustrate the relative role between two- and three-particle contributions in quantum quenching. Our long term goal is to use the insight from a few body study to construct a general description (like that renormalization group) for systems with a large number of particles, which will form a solution of this class of long-standing non-equilibrium problems.

Theoretically, it is known that a rotating quantum gas will reach the so-called quantum Hall state when it gains sufficiently large angular momentum. A necessary condition to realize quantum Hall states is to reach the fast rotating regime where the energy levels of the particles are organized into almost degenerate levels (called Landau levels). This regime has been achieved by the lead P.I. (E. Cornell) of our team. The next step is to increase the angular momentum further to reach the quantum Hall state. For Bose gases, this turns out to be a difficult step as Bose-Einstein condensation competes strongly with the formation of quantum Hall states. In contrast, it is much easier for Fermi gases to go into quantum Hall states, since their formations are helped by Fermi statistics. On the other hand, another member of our team (D. Jin) has pioneered the technique of associating fermion pairs into bosons by changing the interaction of the system, which can be achieved by simply varying an external magnetic field. This then create a new path for us to achieve the bosonic quantum Hall states. One can first produce a fermionic quantum Hall state, and then associate the fermionic quantum Hall states into bosonic ones by changing the interaction between particles. At present, our theory group, led by T.-L. Ho, has been performing theoretical studies of this association process, as well as methods to identify the presence of quantum Hall states. We have demonstrated the success forming bosonic quantum Hall states in this association process. We are now trying to extend the study to systems with larger number of particles. Together with our students, we have also shown that the presence of quantum Hall states can be easily identified through their density profiles and local density fluctuations.

Bibliography Type:	Description: (Last Updated: 05/19/2020)