Fiscal Year:	FY 2016	**Task Last Updated:**	FY 04/02/2016
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:	1	**No. of PhD Degrees:**	0
No. of PhD Candidates:	9	**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)		
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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 makes 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. In the past year, our efforts have included numerical and analytic modeling of the CAL lab magnetic field capabilities, and of predicted cold-atom dynamics in those fields. We looked at several different basic experimental strategies, including “delta-kick cooling” and adiabatic expansion. We presented these results at a Scientific Concept Review at JPL (Jet Propulsion Laboratory) in February of 2015. The bottom line result of these efforts is that everything is looking good for a precise measurement of two generations of Efimov states in Potassium-39. While preparing for experiments in space, we have been doing a number of related experiments in our ground-based laboratories. These experiments are interesting in their own right but they also lay the groundwork for future generation space-based experiments. The most notable result we achieved was the first-ever measurement of the energy and lifetime of a Bose polariton in the strongly interacting regime. Although in our Earth-based project we are not able to reach temperatures as low as those we anticipate reaching in space, we were able to get cold enough to cause individual potassium atom impurities to become entrained in a Bose condensate made of rubidium atoms. The resulting “snow-ball” is a sort of quasi-particle, so-called because it hangs together long enough for us to be able to measure a distinct spectrum for it, much as we could if it were a real particle. In other experimental developments, we found preliminary evidence for the existence of three-body Efimov states in rubidium Bose gas even as the interactions between the atoms become so strong that, at least mathematically, they are “infinite.” Our experimental work, the preparation for the upcoming ISS measurement, and our ground-based experiments, were complemented by an extensive theoretical efforts. These efforts including work on quantum quenching, quantum turbulence, and the quantum Hall effect. All three topics are candidate projects for future CAL flights. 1. Quantum quenching: we have been studying the quantum quenching in low dimensional systems where it is possible to obtain exact results. We have also noticed that the problem of quantum quenching can be viewed as a process of “inflation,” where the metric of space is rapidly increasing. We have worked out the evolution of density profile and momentum distribution for two and three particle systems, and are trying to the so-called Bethe Ansatz solution to study similar properties of many-particle systems. 2. Quantum turbulence: Recently, the Cambridge experimental group led by Zoran Hadzibabic has performed an experiment to shake a Bose condensate in a box trap vigorously. They found that after some period of shaking, the momentum distribution of the gas develops a power law over a wide range of momentum. (This experiment is currently under review and has not been posted on the preprint archive. We learned about it through communications with the authors.) Turbulence is one of the longest standing problems in physics. It remains unsolved after a century of studies. Once again, cold atom experiments offer a new and flexible platform to study a longstanding problem. Moreover, cold atom experiments also raise new questions. Traditional studies of turbulence have been focusing on velocity-velocity correlation functions, whereas cold atoms experiments force one to consider momentum distributions, which is a more fundamental quantity. We have recently completed a study of the analog of the Cambridge experiment for an ideal gas.

The results turn out to be surprisingly rich. We have found the emergence of power law behavior at long times, which is generated by the energy cascade processes driven by the external potential. We are in the process of writing up our results.

3. Quantum Hall states: There are two classes of quantum Hall states, abelian and non-abelian. They are distinguished by the statistics of their quasi particles under exchange. For abelian quantum Hall states, the system acquires a phase factor after the exchange, whereas for non-abelian states, the quasi particles states have internal structures and the exchange process will lead to a change of these internal structures rather than the appearance of a phase factor. In solid-state systems, the descriptions of these quasi-particles are very complicated. Recently, we have found a simple way to describe the wavefunction of the quasi-particles. We are currently trying to design experimental protocols for the exchange processes of these non-abelian quasi-particles so as to reveal their properties.

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