Fiscal Year:	FY 2019	**Task Last Updated:**	FY 04/27/2019
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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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:**	04/30/2020
No. of Post Docs:	2	**No. of PhD Degrees:**	3
No. of PhD Candidates:	8	**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 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) 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:	The goal of this project is the investigation of exotic few-body physics and novel quantum states, 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. In 2018 CAL's operation on board the ISS has begun. We have been in constant discussions with the Jet Propulsion Laboratory (JPL) team to assist with and keep track of the calibration procedures that are being performed to evaluate the CAL instrument onboard the ISS. While science data runs with potassium are currently awaiting the optimization of potassium evaporation routines by the JPL team, the current calibrations performed using Rb in the CAL flight module already inform us about essential performance figures of CAL such as the vacuum limited lifetime, atom number stability, imaging capabilities, etc. A deep understanding of CAL's performance is key for the optimization of the planned Efimov experiments. Furthermore, our collaboration has performed extensive studies on the ground in the labs at JILA and Washington State University (WSU). These studies not only serve to optimize the experimental procedures of our Efimov experiments with CAL but have also produced a surprising science result. At JILA, we have 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 our collaborator 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. 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. While JILA has focused on experiments with 39K, efforts at WSU have been directed towards the formation of a quantum degenerate 41K cloud. This is the potassium isotope that will be used in later stages of CAL for extended Efimov studies and for atom interferometry experiments. 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. For example, laser cooling of the bosonic potassium isotopes poses particular difficulties related to the level structure of these atoms. We are developing optimized cooling strategies to address these difficulties and to provide an optimized starting point for the generation of quantum degenerate potassium clouds with CAL. In summary, our ground based experiments at JILA and at WSU provide important benchmark results for the CAL apparatus. As more and more calibration and machine characterization is performed with the CAL flight module, we continue to update our proposed experimental procedures for the planned Efimov measurements. Our experiments have also delivered important science results, such as the characterization of a Feshbach resonance with a record precision (improving previous results by a factor of 100) as well as the unambiguous confirmation of breaking of a "van-der-Waals universality" that in the past had been an important paradigm. In anticipation of the next-generation of CAL, we've been doing extensive theoretical work at Ohio State University, with a goal of understanding the exotic states of matter than can result when ultra-cold atoms rotate very rapidly. Generically known as "quantum Hall states," the various excitations of these states are generally regarded as examples for hardware components for fault tolerant quantum computers. Effort has been focused on (i) realizing quantum Hall states cold atoms in different platforms, (ii) the manipulation of the quasi-particles of the quantum Hall states, and (iii) quantum dynamics of multi-component quantum Hall states.

For Project (i),we study the feasibility of realizing quantum Hall states in rotating potentials generated by Digital Mirror Devices, while K.H. Chen studies the creation of quantum Hall states using photons, motivated by the recent experiments of Jon Simon's group at University of Chicago to create quantum Hall states with photons in cavities. The latter work has led to the discovery of a "super-degenerate" quantum Hall regime in photonic systems, where all the higher Landau levels (such as those in Simon's experiment) are made degenerate with the lowest one by simply adjusting the configurations of the laser beam. The degeneracy of "super-degenerate" manifold is considerably larger than those of the usual quantum Hall states, and is an exciting regime to study quantum many-body physics.

For Project (ii), we worked on the protocols to engineer singlet and triplet spin states of quasi-particles in a fully filled Landau levels with both spin up and spin down fermions. The creation and manipulation of these spin states with precision is crucial for the study of non-abelian exchanges processes in these systems, a process of key importance in quantum information processing.

For Project (iii), we have been studying the quantum evolution of ferromagnetic quantum Hall states in a quadrupolar field. The ferromagnetic quantum Hall state will emerge in a two-component fermions each in a half-filled lowest Landau level. The particular kind of quantum evolution we study will generate Skyrmion excitations in this ferromagnet. This work is in progress.

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