Fiscal Year:	FY 2018	**Task Last Updated:**	FY 04/27/2018
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:**	04/30/2019
No. of Post Docs:	3	**No. of PhD Degrees:**	1
No. of PhD Candidates:	6	**No. of Master' Degrees:**	0
No. of Master's Candidates:		**No. of Bachelor's Degrees:**	1
No. of Bachelor's Candidates:	2	**Monitoring Center:**	NASA JPL
Contact Monitor:	Israelsson, Ulf	**Contact Phone:**	
Contact Email:	ulf.e.israelsson@jpl.nasa.gov		
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)		
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. Our initial work has focused on the study of exotic three-body states. 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. CAL will provide a unique new environment for testing few-body systems in previously inaccessible regimes that are prerequisite for the next generation of Efimov experiments. We have worked diligently to prepare an experimental plan for research both at the ground test bed and with the CAL apparatus on board the ISS. Over the past year, we have also extended the scope of our work to investigate quantum droplets using the CAL apparatus. Quantum droplets are an intriguing state of quantum matter that can be created out of a dilute-gas BEC. Quantum droplets are fluids, rather than gases, which means that they are characterized by a constant density and exhibit pronounced surface effects. They have a sparse excitation spectrum, making them essentially zero-temperature objects. Furthermore, they are self-bound, implying that they are stable, non-dispersing objects even in the absence of a trap. Their self-bound nature makes them ideal candidates for studies in microgravity: only in microgravity is it possible to investigate these droplets in the absence of any confinement, and thus in their purest form. Our goal is to measure basic properties of these systems, including their excitation spectrum, surface effects, and lifetime in microgravity, using the existing technology of CAL. In the meantime, we have been working on some ground-based measurements that are complementary to our planned CAL-based measurements. We have made very precise studies of how ultracold gases (in particular, Potassium-39) collide as one changes the ambient magnetic field. In particular, we have determined the value of magnetic field at which an Efimov resonance occurs. We are in the midst of extensive calculations that predict the difference in magnetic field between this Efimov and the next highest up. That next resonance can not be accurately studied in a ground-based experiment, because temperatures on Earth, although very cold, are not cold enough. In the much colder temperature accessible on CAL, below one nanokelvin, we anticipate making the second, critical half of the comparison. These combined measurements will yield the most precise ever study of resonant three-body quantum mechanics. In addition to our experimental work on Efimov physics, we have been doing some more purely theoretical investigations into rapidly rotating ultracold gases. Our hope is that these studies will provide the ground work for a more advanced set of ISS-based cold-atom experiments early in the next decade. These future experiments, combined with the Efimov studies planned for next year, will yield insight and understanding into the nature of the quantum mechanics of interacting particles. Quantum mechanics is the science of the very, very small, and if the trends of technology tell us anything, it is that the future of technology lies in the direction of the very small. One component our project is to study methods to realize quantum Hall states in cold atoms systems. Quantum Hall states are remarkable quantum states with fractionally charge quasi-particles and fractional statistics. They can also be divided into two classes, those with the so-called "Abelian" statistics, and those with "non-Abelian" statistics. All of them are useful for quantum information storage, and the "non-Abelian" ones are found theoretically to be a robust hardware component for quantum computation – the so-called "fault' tolerant qubits. The reason that these quasi-particles are so robust in holding quantum information is because of the strongly correlated nature of the quantum Hall state that prevents their decay, unlike the excitations in all other quantum systems. This correlated nature originates from the unique correlated mechanism of particles that rotate relative to one-another with fixed angular momentum, hence giving rise to usual exchange properties of the quasi-particle excitations. In our proposal, we plan to realize quantum Hall states with bosonic and fermionic atoms using rotating quantum gases. The realization of these states is not to reproduce that known states in condensed matter, but to (i) find ways to locate

and manipulate quasi-particles that are necessary for quantum information processing but have so far elude all solid-state experiments, (ii) to realize quantum Hall states (such as those of high spin particles) that are inaccessible to solid-state systems, (iii) to resolve long standing problems in quantum Hall effect such as whether the nu=1/2 and 5/2 fractional quantum Hall state is indeed the Pfaffian state that hosts non-Abelian excitations.

Recently, it is also realized that quantum Hall states can also be realized in a number of other cold atom systems, such as 2D optical lattices and optical ladders with artificial magnetic fluxes. Moreover, recent experiments at the National Institute of Standards and Technology (NIST) by Spielman's group on the so-called Yang Monopole also suggest the possibility of realizing 4D quantum Hall systems. The fact that experiments in low dimensional space can access the physics in higher dimensional ones is an exciting possibility, and may even be a new avenue for quantum information processing.

In this cycle of NASA-funded research, we have looked into a number other topological matters that are closely related to quantum Hall systems, new physics settings to realize quantum Hall states, as well as mechanisms and protocols to locate and manipulate quasi-particles. The first is to realize the Majorana edge modes in 1D chains with fermions near p-wave resonance. The Majorana edge modes in 1D chains obey non-Abelian statistics like those in the Pfaffian states in quantum Hall systems. The system we considered is a generalization of the Kitaev model with the "p-wave superconductivity" replaced by the fluctuating closed channel bosons. This scheme is much simpler than other schemes to realize Majorana edge modes currently proposed for cold atom systems. We have performed exact calculations to prove that the Majorana edge modes indeed exist in these systems.

Bibliography Type:	Description: (Last Updated: 05/19/2020)
Abstracts for Journals and Proceedings	Mossman ME, Engels P, D'Incao J, Cornell E. "Microgravity Studies of Few-Body Physics." Presented by Maren Mossman at the 33rd Annual Meeting of the American Society for Gravitational and Space Research, Seattle, WA, October 25-28, 2017. 33rd Annual Meeting of the American Society for Gravitational and Space Research, Seattle, WA, October 25-28, 2017. , Oct-2017
Articles in Other Journals or Periodicals	Yin XY, Ho TL, Cui X. "Majorana edge state in a number-conserving Fermi gas with tunable p-wave interaction." Cornell University Library. 23 Nov 2017. arXiv:1711.08765 [cond-mat.quant-gas]. Submitted to Physical Review X; see https:// , Nov-2017
Articles in Other Journals or Periodicals	Zhang J, Ho TL. "Potential scattering on a spherical surface." Cornell University Library. Submitted on 29 Jul 2017 (v1), last revised 5 Mar 2018 (v2) [cond-mat.quant-gas]. arXiv:1707.09460 [cond-mat.quant-gas] (or arXiv:1707.09460v2 [cond-mat.quant-gas] for this version). Submitted to Journal of Physics B; see https:// , Jul-2017
Articles in Other Journals or Periodicals	Ho TL, Li C. "The Chern Numbers of Interaction-stretched Monopoles in Spinor Bose Condensates." Cornell University Library. 12 Apr 2017. arXiv:1704.03833 [cond-mat.quant-gas]. Submitted to Physical Review Letters; see https:// , Apr-2017
Articles in Other Journals or Periodicals	Wu J, Ho TL, Lu YM. "Symmetry-enforced quantum spin Hall insulators in pi-flux models." Cornell University Library. 14 Mar 2017. arXiv:1703.04776 [cond-mat.quant-gas]. Submitted to Physical Review Letters; see https:// , Mar-2017
Articles in Peer-reviewed Journals	Klauss CE, Xie X, Lopez-Abadia C, D'Incao JP, Hadzibabic Z, Jin DS, Cornell EA. "Observation of Efimov molecules created from a resonantly interacting Bose gas." Phys Rev Lett. 2017 Oct 6;119(14):143401. https:// ; PubMed PMID: 29053296 , Oct-2017