Fiscal Year:	FY 2023	**Task Last Updated:**	FY 07/07/2023
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:**	09/27/2024
No. of Post Docs:	0	**No. of PhD Degrees:**	0
No. of PhD Candidates:	2	**No. of Master' Degrees:**	0
No. of Master's Candidates:	0	**No. of Bachelor's Degrees:**	1
No. of Bachelor's Candidates:	2	**Monitoring Center:**	NASA JPL
Contact Monitor:	Callas, John	**Contact Phone:**	
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Flight Program:	ISS		
Flight Assignment:	NOTE: End date changed to 9/27/2024 per U. Israelsson/JPL (Ed., 10/20/21) NOTE: End date changed to 8/31/2021 per U. Israelsson/JPL (Ed., 5/12/2020) 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) Mossman, Maren Elizabeth Ph.D. (University of San Diego)		
Grant/Contract No.:	JPL 1502690		
Performance Goal No.:			
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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. 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. While CAL is now in flight, we have been participating in the effort to remotely tune it up for maximum performance.
Task Progress:	A major goal of our research program is the investigation of delicate few-body systems with the NASA Cold Atom Lab (CAL) aboard the International Space Station (ISS). These exotic few-body states are described by Efimov physics and can be created by manipulating the interaction strength between colliding atoms in an ultracold gas at temperatures near absolute zero. The ability to manipulate interatomic interactions is one of the outstanding properties of ultracold quantum gases. It distinguishes this field of research from most other areas of physics, where interaction strengths are fixed, given by immutable natural constants. This capability is also an important ingredient for quantum gas-based technologies. The CAL instrument operates with two different atomic elements, rubidium and potassium. Due to the particular energy level structure of the atoms, only potassium allows one to manipulate the interatomic interaction strength within experimentally accessible regimes. Our experiments to create and measure exotic few-body bound states require the potassium atoms in the sample to be at temperatures very near absolute zero. While rubidium can be cooled using standard laser cooling and evaporative cooling techniques, these methods are inefficient for cooling potassium. To circumvent this difficulty, potassium is cooled by bringing it in thermal contact with ultracold rubidium, using the latter as a "refrigerant". This requires simultaneous dual species operation of the CAL instrument, making the experiments more complex than single species experiments. However, the added complexity comes with a large payoff, as dual species operation and the ability to manipulate interatomic interactions are two essential ingredients for advanced current and future quantum gas experiments, including few-body measurements and differential atom interferometry, which strive to support the development of cutting-edge quantum devices. CAL first demonstrated the sympathetic cooling of potassium in 2022. These early demonstration experiments successfully generated ultracold clouds, but also displayed a number of issues in need of optimization, including the achieved atom number, ultimate temperature, and the stability and reproducibility of the procedure. Furthermore, the atoms need to be prepared in a specific internal state to access the tunable interatomic interactions, requiring the precise application of radiofrequency and microwave pulses to excite atomic resonances. The frequency of these pulses depends strongly on the magnetic field environment in which the atoms are held, which in turn requires a precise experimental characterization using the flight instrument. Our team, comprised of Principal Investigator (PI) Dr. Eric A. Cornell (JILA/University of Colorado), co-PI Dr. Peter Engels (Washington State University/WSU), co-I Dr. Maren Mossman (University of San Diego/USD) and Dr. Jose D'Incao (JILA/University of Colorado), has worked together with scientists and engineers at the NASA Jet Propulsion Lab (JPL) to conduct an extensive series of experimental runs characterizing the potassium performance and identifying the correct radiofrequency and microwave pulses. The investigations of radiofrequency resonances have provided our team with a precise calibration of the magnetic field environment, enabling us to devise a consistent theoretical model of the CAL apparatus. However, identifying the correct microwave resonances has been more difficult, despite our updated theoretical predictions. In an extensive series of investigations into this issue, we have concluded that the intensity of the applied microwave pulses delivered to the atoms is abnormally low. An unexpectedly low efficiency of the microwave transition was also detected in an independent measurement led by JPL. This triggered a major discussion with the CAL team at JPL to identify the root cause of this technical problem with the instrument, resulting in a change to the microwave setup and coil positioning for the upcoming replacement module SM3B. The ability to perform efficient microwave pulses is an important step for many applications and experimental procedures, so identifying this problem has been a critical step for the CAL project. To circumvent the problems with the current flight module, our team also developed an alternative scheme to prepare the atomic states that could work with significantly lower microwave powers. To sum up the flight related portion of our work, the experimental studies conducted with the CAL instrument anboard the ISS have successfully characterized the radiofrequency transitions needed for state preparation but have also identified unexpected difficulties connected to the microwave setup. However, the lessons learned and the mitigating strategies developed to compensate these deficiencies will be highly valuable for future steps and experiments with this instrument. Our findings have informed changes to upcoming hardware replacements and will be important in designs for future space-based cold atom missions, as they have pinpointed areas of potential problems that will require careful

	engineering. With the upcoming installation of the new flight module SM3B, planned for the second half of 2023, we expect that a successful completion of these hardware exchanges will allow us to achieve the necessary state preparations and progress towards our research goals to measure few-body Efimov physics. This project is a prime venue for the training of students. At WSU and USD, two graduate students, one post-bachelor student and one undergraduate student have contributed to the project. The students have been involved in all aspects of this project, including data handling and analysis, numerical modeling, discussing the results within our collaboration, and the presentation of the results at conferences. The results of our work have been presented at several conferences, including the 2023 NASA Fundamental Physics workshop in Santa Barbara and the 54th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics (DAMOP). Work within the frame of this project has also been highlighted in several invited talks at academic institutions. Co-I Engels has co-authored a publication describing CAL in the journal Quantum Science and Technology which appeared in December 2022, together with the JPL team and other PIs of the CAL project. Drs. Mossman, D'Incao, and Engels are also co-authors on a joint publication with the JPL team and other PIs describing the commissioning of quantum gas mixtures and dual-species atom interferometry in space, available on the arXiv preprint server. The theoretical work conducted in the frame of this project has contributed to two publications co-authored by Dr. Jose D'Incao. [Ed. Note: For complete citations, see Bibliography.]
Bibliography Type:	Description: (Last Updated: 02/29/2024)
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