

Fiscal Year:	FY 2017	Task Last Updated: FY 02/10/2017	
PI Name:	Williams, Jason Ph.D.		
Project Title:	Fundamental Interactions for Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment		
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:	91109-8001	Congressional District:	27
Comments:			
Project Type:	FLIGHT	Solicitation / Funding Source:	2013 Fundamental Physics NNH13ZTT002N (Cold Atom Laboratory--CAL)
Start Date:	04/01/2014	End Date:	05/03/2019
No. of Post Docs:	0	No. of PhD Degrees:	0
No. of PhD Candidates:	0	No. of Master' Degrees:	0
No. of Master's Candidates:	0	No. of Bachelor's Degrees:	0
No. of Bachelor's Candidates:	0	Monitoring Center:	NASA JPL
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Flight Program:	ISS		
Flight Assignment:			
Key Personnel Changes/Previous PI:	February 2017 report: Dr. Ethan Elliott, Jet Propulsion Laboratory, is a world expert in the development of leading edge quantum gas facilities for ground and space-based fundamental physics experiments. Notably, he continues to play a leading role in the development, integrating, and testing of numerous subsystems of NASA's multiuser Cold Atom Lab facility. Dr. Elliott joins the project as a Co-Investigator to provide expertise to essentially all aspects of the project. His specific efforts will include leading the planned ground testbed studies, cooperating in the experimental sequence development, and analysis and dissemination of the results to the scientific community.		
COI Name (Institution):	D'Incao, Jose Ph.D. (University of Colorado) Elliott, Ethan Ph.D. (Jet Propulsion Lab)		
Grant/Contract No.:	Internal Project		
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Performance Goal Text:			

Task Description:

Precision atom interferometers (AI) in space promise exciting technical capabilities with diverse applications of interest to NASA. These quantum sensors are particularly relevant for fundamental physics research, with proposals including unprecedented tests of the validity of the weak equivalence principle, precision measurements of the fine structure and gravitational constants, and detection of gravity waves and dark matter/dark energy. Our studies will utilize the capabilities of NASA's multi-user Cold Atom Laboratory (CAL), in the microgravity environment onboard the International Space Station (ISS), to study mitigation schemes for the leading-order systematics expected to limit future high-precision measurements of fundamental physics with AIs in microgravity. The flight experiments, supported by theoretical investigations and ground studies at our facilities at Jet Propulsion Laboratory (JPL), will concentrate on the physics of pairwise interactions and molecular dynamics in ultracold quantum gases as a means to overcome uncontrolled AI shifts associated with the gravity gradient and few-particle collisions. We will further utilize the dual-species AI for proof-of-principle tests of systematic mitigations and phase-readout techniques for use in the next-generation of precision metrology experiments based on AIs in microgravity. Our proposed studies require the effective position invariance, long free fall times, and extremely low temperature samples uniquely available with the CAL apparatus. It is anticipated that our studies can lead to the unprecedented level of control and accuracy necessary for AIs to explore some of the most fundamental physical concepts in nature.

Rationale for HRP Directed Research:**Research Impact/Earth Benefits:**

Our studies are designed to achieve technological advances in precision metrology that can only be realized in the microgravity environment of the Cold Atom Laboratory. We utilize the tools of ultracold atomic and molecular physics (namely Feshbach resonances) for exquisite control of the differential center-of-mass distributions of the dual-species quantum gases and on methods to use the fundamentals of few-body interactions to maintain coherence in atomic ensembles for enhanced precision sensor capabilities. Subsequent proof-of-principle studies with the dual-species atom interferometer on CAL will further advance the state of the art for precision interferometry with ultracold matter waves. The impact of such research to the field of metrology can be seen through its potential to increase precision for atom-interferometry and also the possibility of engineering highly efficient system-specific devices based on the fundamental nature of few-body interactions. The microgravity environment of the CAL facility will strongly favor such explorations and allow for the possibility of uncovering novel effects and quantum phases of matter, a major goal in ultracold quantum gases and other disciplines of fundamental physics. These studies can benefit life on Earth by providing both fundamental understanding of nature in previously inaccessible environments and energy regimes, and by enhancing the tools available for scientific exploration at the highest precision.

Precision atom interferometers (AI) in space promise exciting technical capabilities with diverse applications of interest to NASA. These quantum sensors are particularly relevant for fundamental physics research, with proposals including unprecedented tests of the validity of the weak equivalence principle, precision measurements of the fine structure and gravitational constants, and detection of gravity waves and dark matter/dark energy. Our studies will utilize NASA's Cold Atom Laboratory (CAL), in the microgravity environment onboard the International Space Station, to study the leading-order systematics expected to limit future high-precision measurements of Einstein's weak equivalence principle with dual atomic-species AIs in microgravity.

The flight experiments, supported by theoretical investigations and measurements using the ground test bed facilities at JPL, will concentrate on the physics of pairwise interactions and low-energy s-wave Feshbach molecules in ultracold quantum gases as a means to overcome uncontrolled AI shifts associated with the differential center of mass of two atomic species influenced by gravity gradients and rotations. We will further utilize the dual-species AI, expected to be integrated into CAL, for proof-of-principle demonstrations of unprecedented atom-photon coherence times, phase-readout techniques, and characterizations of the rotational noise on the ISS for use in the next-generation of precision metrology experiments based on AIs in microgravity. Our proposed experiments require the effective position invariance, long free fall times, and extremely low temperature samples uniquely available with the CAL apparatus. It is anticipated that these studies can lead to the unprecedented level of control and accuracy necessary for future space missions, based on precision AIs, to test some of the most fundamental questions of modern physics.

In the third year of this project, we have finished the analysis of the conditions for efficient molecular association and dissociation, crucial for our goal of producing a dual specie ultracold quantum gas that mitigates systematic errors in differential AI related to the center-of-mass displacement of the two clouds. These studies were accepted for publication in Physical Review A. Our findings indicate that the microgravity environment of CAL provides an ideal scenario for such studies.

Task Progress:

We also initiated a theoretical study relevant for molecular delta-kick cooling, a possible cooling technique that can allow us to obtain much colder molecular samples for our interferometry studies as well as enable optimized collimation for two, initially co-trapped, atomic species. The differential ballistic expansion for two species is a limitation for achieving ultra-low temperatures for these dual-species gas studies in microgravity. In applying delta-kick cooling for molecules we found that the molecular internal degree of freedom can generate torques during the cooling process, depending on the strength and duration of the delta-kick pulse. Such effects, although interesting from the fundamental point of view, are detrimental to our precision interferometry studies. Our analyses, therefore, focus on determining the parameter regime in which such effects can be mitigated. We have developed a novel theoretical approach that accounts for the effects of the center-of-mass and relative motion of the molecules and additional studies are currently being performed in order to determine the final cooling efficiency.

Still during this period of performance, we have also developed other numerical techniques in which molecular association and dissociation can be studied, e.g., during magnetic field ramps. We are also moving towards the elaboration of novel numerical techniques in which we will be able to study, in more detail, the effects of atomic and molecular losses during the association and dissociation processes. These studies, therefore, partially define our goals for the next funding year.

Recent and ongoing work on this project has also concentrated on working with the CAL Ground Test Bed (GTB) and Science teams in maturing the GTB to a) validate the flight hardware and b) provide all of the functionality of CAL in a ground-based lab system for proof of principle and characterization studies to support the flight science projects. Due to the technical innovations required in our project and the sensitivity to numerous experimental/environmental parameters, access to the GTB has and will be enabling to mature our studies and to optimize our utilization of CAL. This work will progress through the remaining two months of this third-year effort.

Bibliography Type:	Description: (Last Updated: 12/15/2022)
Abstracts for Journals and Proceedings	D'Incao JP, Williams JR. "Association and dissociation of Feshbach molecules in a microgravity environment." Presented at the 47th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics (DAMOP), Providence, Rhode Island, May 23–27, 2016. Bulletin of the American Physical Society. 2016;61(8):abstract D1.00183. http://meetings.aps.org/Meeting/DAMOP16/Session/D1.183 , May-2016
Abstracts for Journals and Proceedings	Williams J, D'Incao J. "Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment." Presented at the 2016 NASA Fundamental Physics Workshop, Dana Point, CA, April 2016. 2016 NASA Fundamental Physics Workshop, Dana Point, CA, April 2016. , Apr-2016
Abstracts for Journals and Proceedings	Williams J. "Utilizing NASA's Cold Atom Lab for Technology Maturation of Precision Atom Interferometry in Space." Presented at the Workshop on Atom Interferometry, General Relativity and Space Technologies at the Occasion of Claus Lammerzahl's 60th Birthday, Hannover, Germany, August 08, 2016. Workshop on Atom Interferometry, General Relativity and Space Technologies at the Occasion of Claus Lammerzahl's 60th Birthday, Hannover, Germany, August 08, 2016. , Aug-2016
Abstracts for Journals and Proceedings	Williams J. "Opportunities for Maturing Precision Metrology with Ultracold Gas Studies Aboard the ISS." Presented at the US-German Programmatic Meeting for the NASA/DLR collaboration on the Bose-Einstein Condensate/Cold Atom Laboratory (BECAL), Bremen, Germany, December 15, 2016. US-German Programmatic Meeting for the NASA/DLR collaboration on the Bose-Einstein Condensate/Cold Atom Laboratory (BECAL), Bremen, Germany, December 15, 2016. , Dec-2016
Articles in Peer-reviewed Journals	D'Incao JP, Krutzik M, Elliott E, Williams JR. "Enhanced association and dissociation of heteronuclear Feshbach molecules in a microgravity environment." Physical Review A. 2017 Jan;95:012701. https://doi.org/10.1103/PhysRevA.95.012701 , Jan-2017