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PI Name:	Williams, Jason Ph.D.		
Project Title:	Fundamental Interactions for Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment		
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PI Email:	Jason.R.Williams.Dr@jpl.nasa.gov	**Fax:**	FY
PI Organization Type:	NASA CENTER	**Phone:**	303-725-1580
Organization Name:	NASA Jet Propulsion Laboratory		
PI Address 1:	Quantum Sciences & Technology Group		
PI Address 2:	4800 Oak Grove Dr 298-103B		
PI Web Page:			
City:	Pasadena	**State:**	CA
Zip Code:	91109-8001	**Congressional District:**	27
Comments:			
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Contact Monitor:	Israelsson, Ulf	**Contact Phone:**	
Contact Email:	ulf.e.israelsson@jpl.nasa.gov		
Flight Program:	ISS		
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COI Name (Institution):	D'Incao, Jose Ph.D. (University of Colorado)		
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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 corrupt 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 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, recently integrated into CAL, 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 exploring a wide variety of nature at the highest precision.

During this first year of the project, we concentrated on further developing our science concepts and on design studies of the CAL facility, in addition to theoretical modeling of the physics of ultra-low energy Feshbach molecules in microgravity to better predict the outcomes of the study. The driving goals were to assist in maturing the flight projects, to understand the relevant design constraints of CAL, to predict the CAL performance and our science deliverables, and to understand the implications of the project for follow on precision-AI-based studies of fundamental physics in space. Our work during the year is summarized in the following.
The effects of low-frequency ISS vibrations on the performance of CAL and on our experiments requiring high-stability dual-species imaging capabilities were a significant concern at the beginning of the task. To address these issues, we developed a general algorithm to collect and analyze the raw accelerometer data from the Principal Investigator Microgravity Services (PIMS) website for the 121F04 SAMS sensor located nearest the projected CAL location. A representative acceleration record for the entire day of January 01, 2015 was analyzed, from which we determined that the displacements between the ultracold atoms in free fall and the CAL apparatus, from ISS vibrations, are on the order of 10s of microns, negligible in comparison to the distance from the atoms to the surfaces of the Science Chamber and also as compared to the diameter of the AI Bragg beam. Further, we considered the effects of ISS vibrations on the ability to determine the overlap of two clouds that are sequentially imaged. Assuming that the images of the two clouds are taken within 100 microseconds of each other, and assuming that vibrations at all frequencies above 200 Hz is negligible, the displacement extrapolates to a root-mean-square displacement between the two images on the order of 10 nanometers along all directions, well-below the camera resolution. Vibrations from hardware on the CAL apparatus and the related effects still need to be characterized and similar analyses will be required when that data becomes available.

Our main project explores a unique energy regime for studying the dynamics and adiabaticity in associating/dissociating long-lived, heteronuclear Feshbach molecules from low-density, dual-species gases at 100s of pK. During this year, we completed many of the theoretical investigations that were required to understand the lifetime and heating rates/mechanisms in these ultra-low energy gas studies on CAL. It is well known that at large scattering lengths (a), three-body collisions can lead to the formation of deeply bound states with large enough kinetic energy to make them escape from typical traps. Therefore, three-body losses set an important time scale within which our experiments have to be performed, i.e., before losses start drastically affecting the atomic and molecular densities. We used our previously calculated semi-analytical results and those from K. Helfrich et al., Phys. Rev. A 81, 042715 (2010) in order to estimate the importance of three-body losses for the experimental scenario described in our proposal.

The free-atom lifetimes are found to be long for small values of a, and they reach a minimum value for a << 1/(2uT)^(1/2), where u is the three-body reduced mass. As the temperature decreases [implying the decrease of the atomic densities for a given phase-space density and interparticle interaction strength], the lifetime increases for all values of a. Temperatures of about 100pK and densities of the order of 10^8 /cm^3 are expected to be accessible at CAL, which would allow for lifetimes greater than 1s for values of aOne other collisional effect that can lead to systematic errors in preparing our initial state for interferometry (two perfectly overlapping clouds of Rb and K) are elastic atom-molecule collisions. In this case, elastic collision can introduce additional momentum to the molecules, which in turn can affect the molecular dissociation rates. Therefore, we also estimated the typical collision time in which elastic atom-molecule collisions are important. We found that the collision times are considerably shorter than the lifetime corresponding to inelastic atom-molecule for large values of a, by an order of magnitude or greater. This indicates that some attention will be required to understand the effects of elastic atom-molecule collisions in our system. We note, however, that since elastic rates can vanish for some specific values of the scattering lengths, it is possible to minimize the atom-molecule collisional effects. The actual position of such zeros, however, can only be determined from ground experiments or through full numerical simulations.

The CAL AI is developed as a technology demonstration to perform experiments related to atom interferometry in microgravity on a “best effort” basis. The great majority of the work developing the dual-species AI and incorporating it into the already-mature CAL system design was carried out before the start of this NRA. However, on April 28, 2014, the atom interferometer was peer-reviewed as a delta PDR (preliminary design review) for this subsystem. I supported this review by developing the AI performance budget and as a consultant for required hardware developments for the AI upgrade. I was also a reviewer at the PMR2/TIM of ColdQuanta's chip trap and atom interferometer designs on November 3, 2014. My findings and recommendations for the CAL AI system are summarized below.

Task Progress:

The pointing of the Bragg beam must be constrained to (a) maintain the optical lattice-depth and (b) maintain overlap with the atomic clouds throughout the AI sequence. After delta-kick cooling, the 87Rb (39K) atoms have a Gaussian width on the order of 200 (400) microns, whereas the Bragg beam diameter is designed to be 1 mm. Lateral translations of the Bragg beam should be made as stable as possible to preserve contrast and to minimize wavefront-related systematic shifts for precision measurements; however, vibrations of the ISS, discussed previously, practically limit the overlap of the Bragg beam and the free-fall atoms to 10s of microns with no benefit for lateral pointing stability beyond this level. Further, if the atoms travel a maximum of two inches from the chip in the science cell, the mirror must be normal to the Bragg beam to within 2 mRad at all timescales! This level of pointing-accuracy is also required to assure that the atoms don't drift out of the Bragg beam during interferometry. This is a requirement on the overlap of the incident and reflected beams so absolute pointing accuracy is required.

The curvature of the coated chip surface and the mode of the beam out of the GRIN lens are also a concern, with different constraints for beam-overlap and for controlling systematic shifts for precision measurements. I proposed that the ColdQuanta team characterize the beam wavefront out of the GRIN lens and also after reflection from the entire AI beam path (including the coated chip during operation and through the vacuum cells). I recommend using a Shack-Hartmann wavefront sensor camera that will provide unambiguous pictures of the wavefronts for a quick measurement of the curvature.

The contrast of the CAL AI and the loss of atoms from the interferometer are calculated with a simple model that we developed, taking into account the temperature-dependent density profile of the atomic gases in freefall and the spatially dependent Rabi frequency for the two-photon Bragg pulses in a Mach-Zehnder AI. We find that there is a complicated tradeoff between the initial temperature, cloud size, and Bragg pulse-width for achieving the optimum contrast and population in the AI. These constraints arise due to the significant initial atom size in comparison to the Bragg beam waist for the coldest delta-kick-cooled samples (100 pK), the faster rate of ballistic expansion at higher (1 nK) temperatures, and the Doppler width of the transitions for the ultracold clouds. The model allows us to optimize the interferometer interrogation time, the time-dependent cloud density, and the temperature and pulse times depending on the sensitivity and temperature requirements of the AI experiments planned. Further, we calculated the noise requirements on the retro-reflecting mirror fluctuations and the Bragg laser noise to demonstrate that these effects will negligibly affect the performance of the CAL AI based on the known ISS vibration environment and the laser system performance already characterized for CAL.

In the final two months of our first-year effort, we will concentrate on preparing for the Science Concept Review (SCR) that is expected to be held sometime in May, 2015. It is expected that in March, a CAL performance package will be sent out to the NASA Research Announcement (NRA) PIs highlighting the expected CAL system performance and noise characteristics, and hopefully information about the imaging system, SNR, and software or PI interface. This information will then guide the following tasks that will be among the subjects reviewed at the SCR:

For the Feshbach molecule filtering study we anticipate to 1) Develop the specific sets of experimental sequences required to associate and dissociate the heteronuclear molecules with minimal heating and loss. 2) Characterize the expected efficiency for removing unpaired atoms while minimally perturbing the Feshbach molecules. 3) Develop the dual-species imaging routine and analyses for optimally measuring the differential density distributions for the dissociated clouds and estimate the total averaging time required to achieve ~nanometer level differential center-of-mass accuracy. 4) Identify the ground tests required to sufficiently characterize the atomic and molecular loss rates, heating rates, and all potential ground tests to optimally utilize the experimental time with the CAL apparatus on the ISS and 5) Identify potential shortfalls and mitigations for the study.

For the dual-species AI studies, our tasks over the next two months include: 1) Calculate the expected contrast and systematic shifts based on the measured Bragg-beam characteristics. 2) Develop the experimental sequences for demonstrating extended AI time by refocusing the 87Rb atomic clouds with a near-resonance dipole trap. 3) Develop the experimental sequences for observing rotational phase-fringes on the ISS. 4) Quantify the expected SNR and optimum sensitivity for the dual-species AI, leading to the required interrogation times and expected precision of each measurement. 5) Identify the possible AI-based ground tests to optimally utilize the experimental time with the CAL apparatus on the ISS. and 6) Identify potential shortfalls, mitigations, and applications of the CAL AI, including the feasibility of using the CAL AI during the anticipated down time as a high-precision sensor for local accelerations and rotations.

Bibliography Type:	Description: (Last Updated: 05/02/2019)
Abstracts for Journals and Proceedings	Williams J, D'Incao J, Chiow S-W, Botter T, Kellogg J, Yu N. "Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment." Presented at the 30th Annual Meeting of the American Society for Gravitational and Space Research, Pasadena, CA, October 22-26, 2014. 30th Annual Meeting of the American Society for Gravitational and Space Research, Pasadena, CA, October 22-26, 2014. https:// ; accessed 2/10/15. , Oct-2014
Abstracts for Journals and Proceedings	Williams J, D'Incao J, Chiow S-W, Mueller H, Yu N. "Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment." Presented at the NASA Fundamental Physics PI Workshop, Pasadena, CA, November 17-18, 2014. NASA Fundamental Physics PI Workshop, Pasadena, CA, November 17-18, 2014. https:// ; accessed 2/10/15. , Nov-2014
Abstracts for Journals and Proceedings	D'Incao J, Williams J. "Fundamental Interactions for Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment." Presented at the NASA Fundamental Physics PI Workshop, Pasadena, CA, November 17-18, 2014. NASA Fundamental Physics PI Workshop, Pasadena, CA, November 17-18, 2014. https:// ; accessed 2/10/15. , Nov-2014