Fiscal Year:	FY 2018	**Task Last Updated:**	FY 03/15/2018
PI Name:	Bigelow, Nicholas Ph.D.		
Project Title:	Consortium for Ultracold Atoms in Space		
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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PI Organization Type:	UNIVERSITY	**Phone:**	585-275-8549
Organization Name:	University of Rochester		
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City:	Rochester	**State:**	NY
Zip Code:	14627-0171	**Congressional District:**	25
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:	8	**No. of PhD Degrees:**	0
No. of PhD Candidates:	16	**No. of Master' Degrees:**	0
No. of Master's Candidates:	0	**No. of Bachelor's Degrees:**	0
No. of Bachelor's Candidates:	2	**Monitoring Center:**	NASA JPL
Contact Monitor:	Callas, John	**Contact Phone:**	
Contact Email:	john.l.callas@jpl.nasa.gov		
Flight Program:	ISS		
Flight Assignment:	NOTE: End date changed to 9/27/2024 per U. Israelsson/JPL (Ed., 10/20/21) NOTE: Extended to 3/31/2023 per U. Israelsson/JPL (Ed., 7/10/19) NOTE: Extended to 4/30/2019 per U. Israelsson/JPL (Ed., 12/14/17)		
Key Personnel Changes/Previous PI:	March 2018 report: No changes since time of selection for funding.		
COI Name (Institution):	Pritchard, David Ph.D. (Massachusetts Institute of Technology) Stamper-Kurn, Dan Ph.D. (University of California, Berkeley) Vuletic, Vladan Ph.D. (Massachusetts Institute of Technology) Kasevich, Mark Ph.D. (Stanford University) Ketterle, Wolfgang Ph.D. (Massachusetts Institute of Technology) Lukin, Mikhail Ph.D. (Harvard) Mueller, Holger Ph.D. (University of California, Berkeley) Phillips, William Ph.D. (University of Maryland) Ye, Jun Ph.D. (University of Colorado)		
Grant/Contract No.:	JPL 1504801		

Performance Goal No.:	
Performance Goal Text:	
Task Description:	Consortium for Ultracold Atoms in Space (CUAS) We represent a research consortium of senior people, all pioneers in Bose-Einstein condensation, atom optics, atom interferometry, and related areas, with experience with NASA's program on fundamental research in microgravity. The Consortium's work is described in the context of four Tasks. Task 1: Advanced Clocks in Space and Time Transfer Task 2: Maturing and Advancing Atom Interferometer Technology for Space Task 3: Precision Atom Interferometric Measurement in Space Task 4: Strategies for the Frontier of Ultracold Atoms in Space. The Consortium is: N. P. Bigelow, M. Kasevick, W. Ketterle, M. Lukin, H. Müller, W. D. Phillips, D. Pritchard, D. Stamper-Kurn, V. Vuletic, and J. Ye. We have established a cooperation with German Scientists: C. Braxmaier, W. Ertmer, C. Lämmerzahl, A. Peters, E. M. Rasel, and W. P. Schleich. In forming this Consortium, we have several aims: (1) to, in one consolidated move, provide NASA with a community of talented and respected researchers who are committed to developing well thought out, highly impactful precision, quantum gas and atomic physics space experiments; (2) to support several first-class experimental efforts with significant potential to impact NASA interests and specifically to impact future flight experiments or indeed to become flight definition experiments; and (3) to provide intellectually compelling strategies that will impact future generations of flight experiments, aboard the International Space Station (ISS) and beyond. This consortium will provide NASA with a far larger return than could be expected from a series of individual projects. In part this is because of the natural synergies among the interests and expertise of the Consortium members. In part this is because the membership is meeting regularly in person and via teleconference in order to create and refine ideas beyond the work described at the formation of the consortium, challenging each other to advance only the most excellent projects to NASA. The interests and expertise of the Consortium represent two of the four Thrusts identified in a recent National Research Council (NRC) report and the current NASA Research Announcement: (1) Precision Measurement of Fundamental Forces and Symmetries and (2) Quantum Gasses. In the present proposal we choose to focus on two specific areas: ultra-performance clocks and clock networks and atom interferometers (including those using degenerate quantum gasses). We have developed a cooperation plan with leading German expert scientists involved with DLR (German Space Agency) sponsored work in Bremen who are collaborators on this proposal. Berkeley and Stanford lead Tasks 2 and 3. MIT, U.C./JILA, and Harvard lead Task 1. U. Md., Rochester, and MIT lead Task 4. Members of the Consortium can and often will contribute to all four tasks with priorities being set by the lead institutions.
Rationale for HRP Directed Research:	
Research Impact/Earth Benefits:	Research Impact / Earth Benefits Significant progress has been made on atomic interferometry and atomic clocks in terrestrial experiments. The work has long-term impact for fundamental science, navigation technologies, and global clock synchronization. Clocks are vital to navigation, communication, and security. ATOM INTERFEROMETRY We have pushed atom interferometry for space applications forward in many ways: 1. We have shown that atom interferometry can detect dark-energy scalar fields with unprecedented sensitivity. There is a chance to cover all the relevant parameter space so as to detect them or to rule them out once and for all. This work has been published in Science, Nature Physics, and Physical Review D. 2. We have demonstrated a theoretically predicted, but never observed, attractive force on atoms from blackbody radiation. It is an important limitation that has to be taken into account in the design of atomic-physics space missions. 3. We have pushed forward the accuracy of atom interferometry for measuring the fine structure constant, which has resulted in a measurement of this constant with an accuracy about three times better than the best previous one. The agreement of this measurement with others sets very strong constraints on hypothesized particles from the dark sector, such as dark photons. 4. We have developed atom interferometry with "lukewarm" lithium atoms, opening up the possibility to do interferometry with a much wider class of atoms than available previously. We will continue to develop atom interferometry for demonstrating the gravitational Aharonov-Bohm effect, and measuring fundamental constants very precisely. We will also work with the Bose-Einstein Condensate Cold Atom Laboratory (BECCAL) science definition team and other teams to identify future targets for spaceborne fundamental physics. The interferometry work has several main thrusts. In the first thrust, we have been investigating how spaceborne atom interferometry can probe models for dark matter and dark energy. This has resulted in experimental demonstrations of such tests for so-called chameleon and symmetron models, and theoretical studies on how to make detailed predictions of the putative signals. In the second thrust, we have developed strategies to overcome systematic effects in atom interferometers that use Bragg diffraction, as the one planned for the Cold Atom lab. In the third, we have developed specific plans for spaceborne atom interferometry. We have collaborated with the German team Document

for atom interferometry on the Cold Atom Lab and BECCAL. Plans include demonstrating long coherence times thanks to microgravity, tests of the equivalence principle, and searches for dark-energy candidates. They have also collaborated with Nan Yu (Jet Propulsion Laboratory-JPL) on a concept study QTEST (Quantum test of the Equivalence Principle and Spacer-Time) for testing the equivalence principle in space.

CLOCKS AND QUANTUM SENSORS & TECHNOLOGIES

We have demonstrated the first direct optical cooling to Bose-Einstein condensation, without any evaporative cooling. This has promising impact of simplifying spaceborne experiments. The Bose-Einstein condensation by direct optical cooling was achieved for small ensembles of ~1000 atom. We will attempt to make substantially larger condensates with the same method by using a more powerful trapping laser.

We have been working on spin squeezing in the optical-transition clock with trapped ytterbium atoms. By implementing both frequency and intensity feedback loops for the magical wavelength trap inside an optical cavity, we have now lengthened the trap lifetime for the Yb sample from 200 ms to 2 seconds. We have also started non-destructive state-dependent measurements for spin squeezing by observing the light transmitted through the cavity, and we can already more than resolve the shot-noise limit.

In the Rb experiment, we are working towards using Rydberg states for increasing the light-atom interaction in cavity QED. We have frequency-stabilized the control laser coupling the P state to high-lying Rydberg states.

We have demonstrated a new optical lattice clock configuration using a three-dimensional optical lattice, leading to measurement precision in the 19th decimal place. We have also demonstrated another record-breaking performance on stable lasers, with the narrowest laser linewidth at 10 mHz. We will perform a clock comparison between this JILA Sr clock and the NIST (National Institute of Standards & Technology) Yb clock and Search for ultralight dark matter by comparing the Sr transition frequency with the resonance frequency of a crystalline cavity.

As of December 2017
ATOM INTERFEROMETRY

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1. We have shown that atom interferometry can detect dark-energy scalar fields with unprecedented sensitivity. There is a chance to cover all the relevant parameter space so as to detect them or to rule them out once and for all. This work has been published in Science, Nature Physics, and Physical Review D.

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NEW DIRECTIONS

Task Progress:	We have developed techniques for printing complex topological states on a spinor condensate that include the realization of skyrmions, spin-monopoles, alice states, and non-abelian spin textures that are particle-like excitations of the BEC matter wave field. We will investigate the realization of these and other phase/amplitude printing in space, where long interaction times will be possible. The following paper is under review: Azure Hansen, Justin T. Schultz, and Nicholas P. Bigelow "Generation of Monopole Spin Textures and Synthetic Fields in 87Rb Bose-Einstein Condensates" , in review (2017). Task Progress As of December 2015: ATOM INTERFEROMETRY Demonstrate 50 pK kinetic temperatures and 30 photon recoil, 50% contrast, 1.1 s interrogation time atom interferometry (18 cm wavepacket separation). First demonstration of a cavity-based atom interferometer. The cavity provides power enhancement, spatial filtering, and a precise beam geometry, enabling new techniques such as low power beamsplitters (<100 μW), large momentum transfer beamsplitters with modest power, or new self-aligned interferometer geometries. A manuscript has been accepted by Physical Review Letters and will be featured in an upcoming viewpoint article by Alex Cronin in Physics Today. We have applied this novel technology to set limits on fifth forces that are undetectable in previous experiment by a "screening" mechanism which suppresses the forces in the vicinity of massive objects. Such theories have been studied in the context of dark matter and dark energy. Using atoms as test particles avoids triggering the screening and allows us to rule out a broad range of theories that could explain the observed cosmic acceleration. This work has been submitted for publication. Clock Networks Tested a novel quantum, cooperative protocol for operating a network of geographically remote optical atomic clocks. Theoretically showed that such a network can be operated near the fundamental precision limit set by quantum theory. Furthermore, the internal structure of the network, combined with quantum communication techniques, guarantees security both from internal and external threats. Realization of such a global quantum network of clocks will allow construction of a real-time single international time scale (world clock) with unprecedented stability and accuracy. We have initiated proof-of-concept experiments aimed at exploring key elements of such a network. We have recently finished evaluation of our Sr II clock's total accuracy, and we have now reached 2.1 x 10^-18, an improvement of a factor of three over the previous world record. We have started designing an optical cavity for collective measurement of Sr atoms in a cavity QED setting, in preparation for spin squeezing and connection between two clocks. A goal is to demonstrate an entangled network of clocks. We have taken two steps towards this goal: (1) In our work towards an optical transition clock with Yb atoms that operates below the standard quantum limit, we have finished the assembly of an optical resonator operating in the strong coupling regime (peak cooperativity of 40), and are ready to install the system inside the vacuum chamber. (2) We have achieve a magneto-optical trap for Yb both on the wide singlet transition, and on the narrow triplet transition that yields much lower atomic temperatures. The remote entanglement between clocks will be achieved by communication via photonic quantum bits. We have shown that a single photon can create a strongly entangled state of a large atomic ensemble containing 3000 Rb atoms. We demonstrate that the atomic state upon detection of a single photon is characterized by a negative Wigner function, which represents the first observation of a negative Wigner function for a system containing more than a few atoms. Moreover, we also verify an entanglement depth (minimum number of mutually entangled atoms) comprising 90% of the ensemble.
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