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The Bose-Einstein Condensate and Cold Atom Laboratory

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Abstract

Abstract: Cold and ultracold quantum gases enable the study of a wide range of interesting phenomena and applications including Bose-Einstein condensation, superfluidity, matter-wave optics, and quantum sensing. Under microgravity conditions these effects can be studied in a much cleaner environment and for longer interogation times boosting the experimental precision. Adapting the complex experimental apparatus to the requirements of a microgravity platform in space is a main challenge nowadays. In this paper we present the Bose Einstein Condensate - Cold Atom Laboratory (BECCAL), which is planned for deployment on the International Space Station (ISS) and outline areas for future investigations with cold atoms and Bose-Einstein condensates (BECs).

Keywords: Bose-Einstein Condensate; Quantum Optics; Atom Optics; Atom Interferometry; Microgravity; International Space Station

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1 Introduction

Cold atomic ensembles offer the possibilities to study fundamental aspects of quantum mechanics, such as the evolution of matter waves [1], the transition from quantum statistic to classical thermodynamics [2], the impact of the dimensionality and topology of the gases [3] and may also probe the interface between quantum mechanics and general relativity [4, 5, 6].

In a typical laboratory environment gravity deforms the trapping potentials and, in the absence of magnetic or optical fields, the atoms will simply fall towards the edge of the experimental chamber limiting the available free evolution times. Levitation techniques [7, 8] can compensate gravity, but can lead to unwanted systematic shifts in experiments, for example, additional phase shifts in atom interferometers, and they become technically more complex for multiple species with different atomic masses or internal states.

In microgravity, however, the atoms stay stationary with respect to the apparatus without the need for any external holding forces, thus enabling trap potentials without gravitational sag, long pulse separation times in atom interferometry [1] as well as probing of surfaces with atoms over long times [9] and the realization of cloud geometries that are inaccessible in ground-based setups [3, 10].

Therefore, ultracold atoms in microgravity are ideal candidates to probe fundamental physics, such as testing the Einstein equivalence principle [4, 5], investigating the validity of quantum mechanics on macroscopic scales [11], and probing dark energy [12] and dark matter [13, 14, 15]. Quantum sensors based on atom interferometry are considered for Earth observation with satellite gravimetry [16], satellite gradiometry, and navigation in space [17]. Furthermore, a flexible, microgravity cold atom system is a critical pathfinder for the demonstration of other space borne atomic physics systems, such as highly-accurate optical frequency standards. While these applications inherently require space-borne operation, the conditions of microgravity also boost the potential performance of the integrated atom sensors.

2 Cold Atoms in Microgravity

Ultracold atom instruments have been studied in microgravity using drop towers [18, 19, 20, 21] and sounding rockets [22] as well as with thermal atoms on board of aircrafts in parabolic flights [23, 24]. Their availability, however, is limited. The drop tower is limited to 2 to 3 drops per day, while sounding rockets and aircrafts require extensive preparation, infrastructure, and manpower for no more than six minutes in microgravity per launch. A novel facility, the Einstein Elevator in Hanover [25], is currently in the commissioning phase and will offer up to 100 shots per day, but with a limited free-fall time of approximately 4 s.

The ISS, on the other hand, provides a permanent microgravity environment. In May 2018 NASA launched the Cold Atom Laboratory (CAL) to the ISS [26, 27]. This apparatus is designed to produce ultracold degenerate quantum gases of rubidium and potassium and to perform a vast range of experiments proposed by various researchers. Foreseen studies include studies on few-body dynamics, magnetic-lensing techniques [28], bubble-geometry traps [3, 29], alternative rf-outcoupling mechanisms [30], and quantum coherence for longer than 5 s.

3 BECCAL

3.1 Overview

The Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL), presented in this paper, is a collaboration of NASA and DLR that will serve as a multi-user and -purpose apparatus on the ISS. It is built upon the heritage of previous and ongoing activities to offer higher atom numbers, an increased cycle rate, more complex optical and magnetic trapping strategies and improved atom-interferometry capabilities compared to the predecessor experiments. The apparatus is designed to create BECs of ^{87}Rb (^{41}K) with more than 1×10^6 (1×10^5) atoms. The creation of quantum degenerate gases of ^{40}K will also be possible. Hence, BECCAL will enable the study of scalar and spinor BECs as well as of mixtures of Bose-Bose and Bose-Fermi gases. To detect these quantum gases after several seconds of free expansion, delta-kick collimation [28] will be employed to lower the expansion velocities of the atomic clouds. The apparatus will support the coherent splitting of matter waves separated by several centimeters and free evolution times of several seconds, including well-established compensation methods for rotations [31, 32] and gravity gradients [33, 34]. The atoms can be exposed to blue- and red-detuned optical fields for trapping. These fields will be spatially controllable and it will be possible to create arbitrarily-shaped potentials, which allow for versatile trapping and anti-trapping configurations.

3.2 Scientific Envelope

BECCAL is dedicated to serve multiple scientific goals. The definition of these goals was performed by a team of eight researchers. The definition was not only driven by scientific merit, but also by necessity for the microgravity environment and feasibility within the proposed mission. The result is summarized in Frye *et al.* [35].

In total six dedicated scientific areas were identified:

1. Atom Interferometry
   Atom interferometry in microgravity yields the advantage of prolonged interrogation times. In microgravity, no additional fields are required to levitate the atom cloud, leading to the opportunity of executing more precise atom interferometry experiments. With the different species of atoms present in BECCAL, experiments such as tests of the universality of free fall [4, 36, 37, 5], as well as studies of Earth's gravitational field [38, 39], and measurements of the gravitational constant [40] are possible.
2. Coherent Atom Optics
   BECCAL will include a variety of trapping and manipulation potentials to study the produced BEC. One example are the Feshbach resonances [41] that can be addressed by applying magnetic fields. Another prominent example is the blue-detuned optical trap allowing for novel and flexible trapping geometries which in microgravity enable, for instance, the study of homogeneous quantum gases in greater detail.
3. Scalar Bose-Einstein Condensates
   Without the gravitational pull and consequently absence of additional levitation fields, shallow traps can be employed to direct the atomic cloud, leading to possible lower critical temperatures. In consequence, atomic ensembles with reduced entropy can be produced, enabling many-body studies, and increase the quality of quantum reflection experiments. Additionally, microgravity enables the study of closed 3D shells structures of BECs [10].
4. Spinor Bose-Einstein Condensates and quantum Gas Mixtures
   If the spin of atoms within an optically trapped BECs can be addressed without loosing the confinement, the system is called a spinor BEC [42]. This leads to the opportunity of studying effects of super-fluididy and the interaction with the available magnetic fields. In addition, quantum droplets based on spin mixtures have never been investigated under microgravity, which enables the study of the evolution of these systems over long time scales.

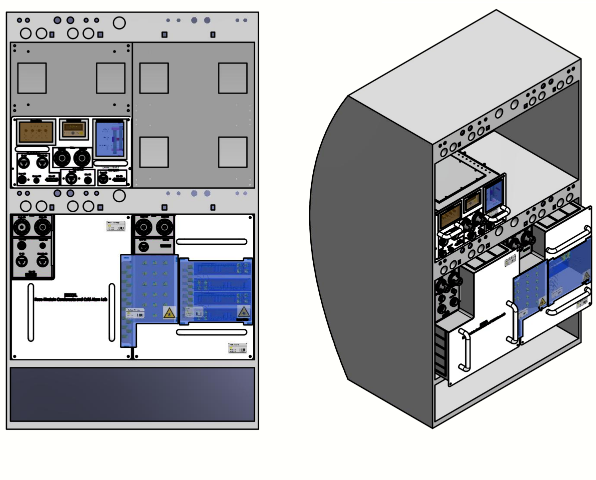

Figure 1 The available space for BECCAL in the EXPRESS rack is shown. Cables and fibers are omitted for clarity. One single locker contains the control electronics, one double locker the laser system, and another double locker the physics package. The front panels will have handles for the astronauts to hold on and to ease the installation. The light produced by the laser system is guided via optical fibers to the physics package. The fibers are protected by an interlocked cover. This figure is taken from [35] license CC-BY 4.0.

5. Strongly interacting gases and Molecules
   In microgravity, more dilute atomic gases can be produced, in which different species can be set to inherit the same physical space inside the vacuum chamber. In combination with changes of the scattering rate through magnetic fields, this enables the investigation of new regimes for three-body collisions and molecule formation.
6. Quantum Information
   With optical accesses and BECs being produced in orbit, BECCAL can serve as a pathfinder for quantum optics with cold atom ensembles in space. This paves the way for quantum memories and slow-light experiments.

3.3 Overall Design

BECCAL will be housed in the Destiny module on the ISS. The space station provides a standardized rack system to house payloads of different size and purpose, the so-called EXPRESS racks (EXpedite the Processing of Experiments to Space Station). Each EXPRESS rack offers eight standardized compartments and NASA allocates five of eight lockers for BECCAL (fig. 1). For implementation and due to launch restrictions, these five lockers will be separated into one single and two double lockers.

The remaining locker spaces of the EXPRESS rack are occupied by other payloads. The accommodation in an EXPRESS rack therefore sets stringent requirements on volume, mass, external power, thermal management, emitted radiation, and safety.

The payload is divided into three subsystems – the physics package, the laser system, and the control electronics. The physics package, which contains the ultra-high vacuum system, where all the experiments on the atoms are carried out, is located in one double locker. The other double locker contains the laser system and the laser electronics. The single locker will house parts of the control electronics and the on-board computer. The computer will run the experiment control software and will have additional hard drives for experimental data storage.

Compared to conventional quantum-optics-laboratory experiments, volume, mass, and power consumption of the apparatus are significantly reduced. The single locker has a size of 66 L and the two double lockers take 164 L each. The total mass is limited by the EXPRESS rack specifications to 328 kg.

4 Future Ideas

CAL [26] and BECCAL pave the way towards new experimental avenues for research and technology applications using cold atoms and BECs. Novel investigations of quantum states, unprecedented control of ultracold atom gases, the investigation of atom-surface interaction, the search for dark matter and dark energy, and the application of quantum technologies. All of these areas benefit strongly from cold atoms and BECs in a microgravity environment, allowing for more precise experiments.

Moreover, with the current advances in atom optics in orbit, other experiments come in reach. Those experiments are described in greater detail in various white papers submitted to this survey. Here, an incomplete list of possible improvements on the existing facilities or successors to those will be listed:

- Ultrahigh-Precision Atom Interferometry
  Both, BECCAL and CAL are multi-purpose laboratories, enabling a broad range of experiments. With a sole focus on atom interferometry additional precision in the experiments could be achieved, leading to improved tests of the universality of free fall, Earth observation, and cosmology studies.
- Source Masses
  Moveable source masses have been employed in ground based atomic fountains to measure the Newtonian gravitational constant [40]. With additional source masses in orbit, similar experiments in microgravity can be envisioned.
- Squeezed States
  By using squeezed states, the accuracy of an atom interferometer can be improved by enhancing the phase-resolution scaling ith the number of atoms and number of shots. A future experiment could be set up to include the possibility of squeezed atomic states to further improve the experimental performance.
- Other Species
  Both BECCAL and CAL employ rubidium and potassium as the atomic species for experimentation. As outlined by [15], other atomic species, such as ytterbium or strontium could be of use for future gravitational wave detection.
- Quantum Memories
  With cold and condensed atoms in orbit, relay stations for long-range Bell tests using cold atoms appear feasible. A pathfinder mission, with dedicated access and detection ports to a cold atom ensemble would be the next step towards those tests at the limits of quantum mechanics.

5 Conclusion

BECCAL is the next step in advancing research with ultracold atoms and BECs in space. Its capabilities render it an important facility for scientific research, operated in an unique environment. Six dedicated scientific areas were identified that are the basis for the overall design, which is in compliance with the ISS regulations.

With the successful efforts in miniaturization, automation, and adaption to the challenging environment, BECCAL is a pathfinder for future scientific and applied missions. If successful, more complex and challenging setups, targeting specific questions or broad applications, can be considered.

6 Remark

Sections III A of this paper is taken from Frye et. al [35] under license CC-BY 4.0. Sections III B and C are modified extracts from Frye et. al [35] under license CC-BY 4.0.

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For a complete list of the BECCAL collaborators, please regard the authors list of Frye et. al [35].

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