National Aeronautics and Space Administration

Spaceborne quantum sensors based on magnetically insensitive atomic gases

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Program: FY22 R&TD Topics
Strategic Focus Area: Origin, evolution, and structure of the universe

Objectives

The objective was to develop novel techniques to produce, trap and control ultracold neutral atoms in magnetically insensitive Zeeman states (magnetic quantum number, mf = 0), in order to improve the capabilities of spaceborne quantum sensors. The primary goal is to develop a novel source of ultracold atoms with magnetic quantum number of zero, making them insensitive to weak magnetic fields. A second goal is to utilize these atoms and magnetic techniques for atom interferometer designs. Novel trap shapes can be tailored to achieve 3D geometries ideally suited for inertial and force gradient sensing, while remaining immune to stray magnetic fields and residual fields from the apparatus.

Background

The Cold Atom Lab (CAL), in operation aboard the ISS for over 4 years, has demonstrated routine production of Bose-Einstein condensates at nanoKelvin temperatures. The next generations of quantum systems promise to further revolutionize fundamental physics experiments, position, timing, and navigation technologies. All such quantum sensors applications could benefit from large atom numbers prepared at ultracold temperatures specifically in the *magnetically insensitive state.*

Approach and Results

A prime example of such a system is the Cold Atom Lab (CAL), in which the atom chip's (Fig. 1) current-carrying wires produce very strong magnetic field gradients near the surface so the trap confinement is strong [1]. Atoms in a magnetically insensitive state are immune to smaller perturbations of magnetic fields due to imperfections in the wires and fluctuations in the external environment. They are, however, strongly guided and trapped spatially by quartic-scaling walls of the trap potential. In a spaceborne sensor, microgravity makes trapping of insensitive states is readily achievable. These novel traps can be demonstrated on the ground by trapping atoms above the chip wires. The closer atoms "sag" towards the chip, the stronger the magnetic field and gradient. In this manner, the spin zero cloud can be levitated instead of falling.

Significance

NASA continues to show a strong interest to perform microgravity experiments with ultracold atoms aboard the International Space Station (ISS), as well as the Lunar Gateway. JPL-built Cold Atom Lab (CAL) has now been routinely operating in space for over 4 years. Independent from on-going CAL activities, this research project will allow us to prepare for future funding opportunities for space-based quantum sensors with NASA SMD, while at the same time demonstrate the suitability of this technology for a number of scientific investigations. It will directly benefit microgravity-based science studies such as follow-on missions to CAL, including the potential investigations with the Bose-Einstein Condensate Cold Atom Lab (BECCAL), a joint NASA-DLR mission currently planned for 2024-2025 deployment on ISS. Additionally, there is a fourth Science Module ("SM-3B") for a CAL upgrade that could be deployed over the next 1-3 years. This work could develop techniques that would benefit future planetary missions for gravity mapping and inertial sensing.

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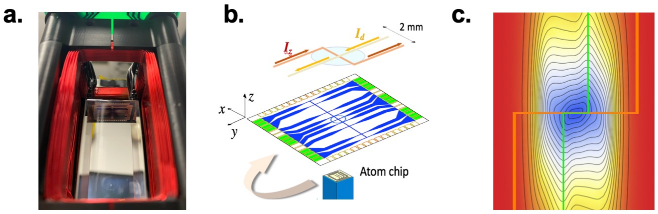
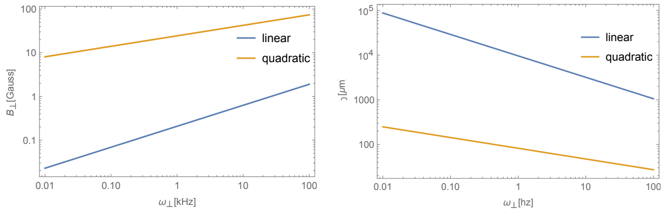
Clearance Number: CL#312186
Poster Number: RPC#223



An atom chip located at the top of a dual-celled vacuum chamber (a.) is capable of forming a trap for neutral atoms by running currents through micro-wires on the semiconductor chip. The "z-d" planar geometry (b.) produces a [1.0 , 1.0 , 0.2] kHz trap for Rb atoms in the mf=2 state. A simulated atom chip trap shown here (c.) uses a BECCAL-like chip design.



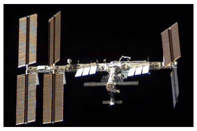
Plots comparing the magnetic field, B, and trap position, r_0, of spin-zero (quadratic Zeeman) traps compared to the typical (linear Zeeman) magnetic traps. In microgravity, one of the primary goals is to reach low densities and extremely low temperatures by use of weak traps (extremely low trap frequencies <10 Hz), but these tend to be foiled (overpowered) by residual magnetic fields and gradients. The quadratic Zeeman (spin-zero) traps, however, can achieve <10 Hz trap frequency with substantial fields and at modest ranges of the atom chip surface. This makes the spin-zero traps less susceptible to uncontrolled external field perturbations.

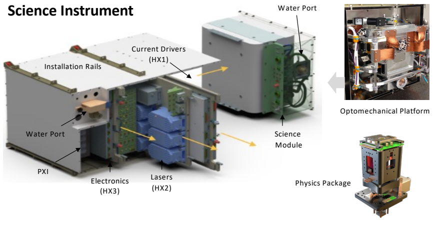
NASA's Cold Atom Lab Facility (CAL)


Antares rocket launch, 4:44am, May 21, 2018


OA-9 minutes before launch, Wallops Island, VA


CAL Install by Astronaut Ricky Arnold





Aveline, Williams, Elliott, *et al.*
Nature **582,** 193–197 (2020)

- Multi-user facility on the International Space Station for atomic physics research
- A microgravity environment circumvents the gravitational limits of terrestrial quantum experiments
- The instrument produces and holds a cold quantum gas using laser light, RF radiation, and magnetic fields

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