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Perspective

Overcoming Challenges in Space-based Experiments with Ultracold Quantum Gases

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DESCRIPTION

Ultracold quantum gases have become important tools for studying fundamental physical phenomena at very low energy scales. These gases are ideal for high-precision space-borne sensing, which is critical for applications such as Earth observation, relativistic geodesy, and tests of fundamental physical laws [1]. Additionally, the study of new phenomena in many-body physics during extended free fall is possible with ultracold quantum gases. However, the full potential of these gases can only be realized by observing them for extended periods of time, during which they evolve freely and are probed for quantum sensing.

In recent experiments, researchers were able to precisely control the quantum state of individual 87Rb Bose-Einstein condensates in the Cold Atom Lab on the International Space Station. By employing fast transport protocols with sub-micrometer accuracy, they significantly reduced the total expansion energy to below 100 pK using matter-wave lensing techniques [2]. This precise control will enable numerous research applications, such as the study of quantum bubbles, space atom lasers, few-body physics, quantum reflection from material surfaces, and entangled state preparation.

One of the key challenges of space-based experiments with ultracold quantum gases is controlling the kinematics and expansion of the gas. In atom interferometric experiments, the uncertainty regarding the initial position and velocity can result in systematic effects, such as gravity-gradient-induced ones or Coriolis effects, which can impede modern experiments, such as Einstein equivalence principle tests [3]. Additionally, to detect free drift after a few seconds, the atomic ensemble's expansion rate needs to be drastically slowed down to kinetic temperatures below 100 pK. This is necessary to make space quantum sensors more sensitive than their Earth-bound counterparts.

To overcome these challenges, researchers have made significant advancements in three areas of quantum state engineering: controlling the quantum gas's position, release velocity, and expansion rate. They have used ab-initio recipes for atom chip-based quantum engineering and the microgravity environment to simplify quantum control protocols [4]. They have also used a non-custom multi-user facility to generate a robust, stable, and tunable atomic source for the metrological exploitation of a cold quantum gas space-platform. These advancements will allow researchers to face the most challenging requirements for space-based experiments in fundamental physics, geodesy, and gravitational wave detection [5].

Ultracold quantum gases have a wide range of applications, including: 1) studying fundamental physics: Ultracold quantum gases allow scientists to study and understand the behavior of matter at extremely low temperatures and in conditions that cannot be easily replicated in nature. This has led to breakthroughs in fields such as atomic physics, condensed matter physics, and quantum information science. 2) Precision measurements: The precise control over ultracold quantum gases has enabled the development of highly sensitive sensors for measuring magnetic and gravitational fields, as well as for detecting tiny variations in time and space. 3) Quantum computing: Ultracold quantum gases can be used as building blocks for quantum computers, which are expected to revolutionize computing by enabling the processing of vast amounts of data in parallel. 4) Material science: Ultracold quantum gases can be used to simulate the behavior of complex materials and condensed matter systems, allowing scientists to study and understand their properties in a controlled laboratory setting. 5) Chemistry: Ultracold quantum gases can be used to study chemical reactions and the behavior of molecules at the quantum level, leading to new insights into the fundamental processes that underpin chemistry.

In conclusion, ultracold quantum gases have become important tools for studying fundamental physical phenomena at very low energy scales, and space-based experiments with these gases have the potential to significantly advance our understanding of these phenomena. Through precise control of the quantum state of individual Bose-Einstein condensates, researchers have been able to significantly reduce the total expansion energy and enable numerous research applications. However, the full potential of these gases can only be realized by overcoming the challenges of controlling their kinematics and expansion in space-based

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experiments. Advancements in quantum state engineering have made significant progress in this area, enabling researchers to face the most challenging requirements for space-based experiments in fundamental physics, geodesy, and gravitational wave detection.

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