Invited talk

Cold atom interferometry in space

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Atom interferometry has been expected to exhibit unique advantages in space due to the microgravity and ultra-low-noise environment, enabling breakthroughs in precision and sensitivity. These advantages position space-based cold atom interferometers as transformative tools for quantum sensing, navigation, and frontier physics. Explicitly, the key benefits from space include longer interrogation time (microgravity allows atoms to free-fall continuously in a few seconds to tens of seconds, increasing the interferometer's baseline and boosting sensitivity by orders of magnitude), suppressed environmental noise (isolation from ground vibrations, thermal fluctuations, and electromagnetic interference), enhanced sensitivity for fundamental physics (tests of general relativity (e.g., frame-dragging, equivalence principle) achieve unprecedented precision) and for applications in planetary exploration and deep space navigation. However, due to complexity of the technology and the high time and capital cost, experiments of space atomic interference have only started recently.

At the end of 2022, we successfully developed the dual-species ^{85}Rb - ^{87}Rb cold atom interferometer and loaded it on the microgravity cabinet of the Tianhe core module of the Chinese Space Station (CSS) with the Tianzhou-5 cargo spacecraft. Microgravity atomic interference experiments have been conducted for more than two years. The two-component atomic interferometer was realized successively, by which the space cold atom gyro and acceleration sensing were performed, and the preliminary experiment of the equivalence principle test was carried out.

One example is the realization of a cold atom gyroscope[1] (as shown in Fig.1), which was demonstrated by the atom interferometer installed in CSS as a payload. By compensating for the CSS's high dynamic rotation rate using a built-in piezoelectric mirror, spatial interference fringes in the interferometer were successfully obtained. Then, the optimized ratio of the Raman laser's angles was derived, the coefficients of the piezoelectric mirror are self-calibrated in orbit, and various systemic effects were corrected. A rotation measurement resolution of 50 μrad/s for a single shot and 17 μrad/s for an average number of 32 was achieved. The measured rotation is $-1142 \pm 29\,\mu$rad/s and is compatible with that recorded by the classical gyroscope of the CSS.

The successful application of cold atom interferometers in space inertial sensing marks the transition of quantum technologies from labs to engineering. Future integration with quantum entanglement and miniaturized designs will further push the boundaries of deep-space exploration and fundamental physics.

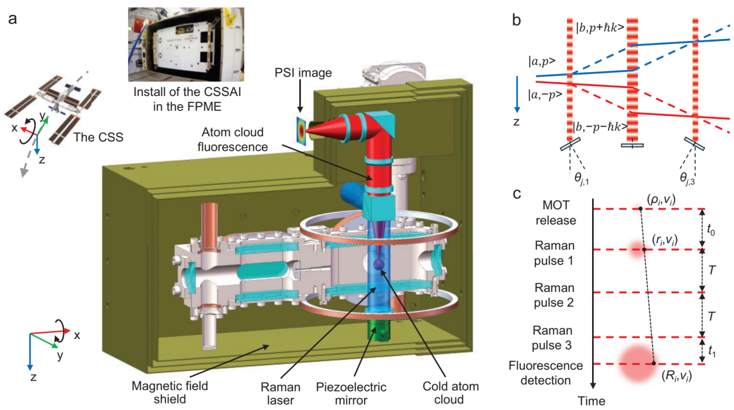

Figure 1: (from Fig.1 in Ref.[1]) The working principle of the China Space Station Atom Interferometer (CSSAI). (a) The installed CSSAI in the Free-floating Platform for Microgravity Experiment (FPME), and the CSSAI's physical system profile. The Raman laser for the point source interferometry (PSI) and the imaging of the fluorescence of the cold atom cloud are also illustrated in the physical system. (b) The double single diffraction Raman transition and Raman interference loop scheme for the ^{85}Rb atom. (c) Atom position changes over time during the interference experiment.

[1] J.T. Li, X. Chen, D.F. Zhang, W.Z. Wang, Y. Zhou, M. He, J. Fang, L. Zhou, C. He, J.J. Jiang, H.Y. Sun, Q.F. Chen, L. Qin, X. Li, Y.B. Wang, X.W. Zhang, J.Q. Zhong, R.B. Li, M.Z. An, L. Zhang, S.Q. Wang, Z.F. Li, J. Wang, and M.S. Zhan, *Nat. Sci. Rev.* **12**, nwaf012(2025).