Topical White Paper: Gravity Probe Spin

Precessing magnet in space

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Gravity Probe B, a satellite containing four highly spherical niobium-coated fused quartz gyroscopes in a cryogenic environment, measured precession of angular momentum of the gyroscopes due to gravitational effects predicted by general relativity [1]. Electrons have angular momentum whose origin is of a different nature: intrinsic spin, which is a fundamentally quantum phenomenon. Experimentally, it is unknown if intrinsic spin precesses due to gravitational effects in the same way as the quartz gyroscopes precessed in Gravity Probe B.

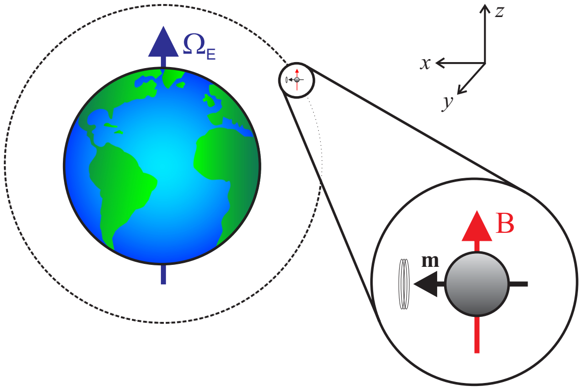

Figure 1: Conceptual schematic diagram of a "Gravity Probe Spin" experiment. A freely floating spherical ferromagnet located within a superconducting shield is in a circular polar orbit. The magnetic field B (from the frozen flux in the superconducting shields) is oriented parallel to the direction of Earth's rotation axis Ω_E, both designated to point along z. The insert shows the initial orientation of the magnetic moment of the ferromagnet and spin m along the x axis. The pick-up coil measures the ferromagnet's magnetization along x. This geometry is designed for the detection of the Lense-Thirring effect.

It is infeasible to test general relativistic precession of intrinsic spin using a single electron. However, an ensemble of 10^{20} electrons enables new possibilities. Such an amount of electrons is the main source of magnetization in a ferromagnet (e.g., compass needle). Recently we proposed a space mission similar to Gravity Probe B where instead of spherical quartz gyroscopes, millimeter-scale ferromagnets are used. In Figure 1 a schematic diagram of the setup is shown. Modelling the dynamics of such a setup and sensitivity estimates reveal possibilities to detect the Lense-Thirring effect or the de Sitter effect on intrinsic spin [2].

In order for a ferromagnet to behave like a gyroscope its angular momentum must be dominated by the electrons' intrinsic spin [3]. This condition demands that the ambient magnetic field should be low ($10^{-8} - 10^{-10}$ gauss). Efforts are ongoing to carry out a proof-of-principle experiment to observe precession of a ferromagnet in the laboratory [4, 5].

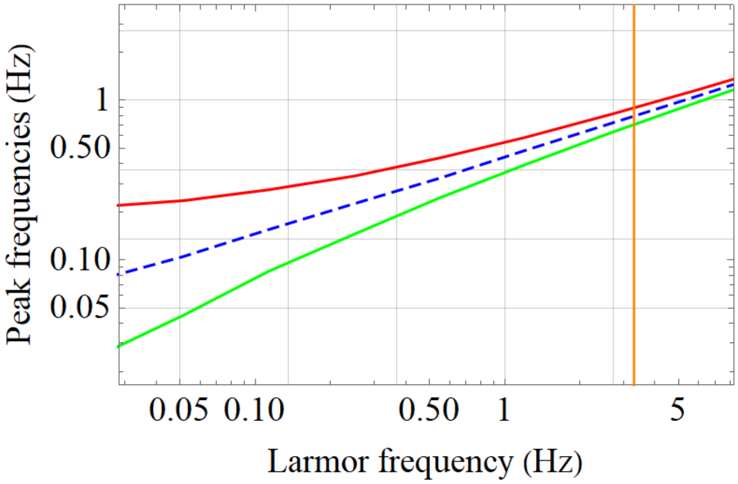

Figure 2: Modelling the dynamics of a ferromagnet. Presented are the frequencies of the maxima in the spectrum of ferromagnet dynamics as a function of the Larmor frequency (as can be measured with a SQUID pick-up loop). The Larmor frequency is proportional to the applied magnetic field. The middle line (dashed blue) is the sole frequency appearing in the spectrum to the right of the vertical line, and corresponds to the librational motion. The red and green curves are the frequencies corresponding respectively to nutation and precession frequencies. The orange vertical line is the threshold frequency, i.e. the frequency below which distinguishable precession and nutation motion appear.

One of the most serious obstacles to carrying out such a proof-of-principle experiment is the problem of how to levitate the ferromagnet and isolate it from the environment so that it is free to precess: this problem is far easier to solve if the experiment is performed in a microgravity environment, such as the International Space Station or a satellite orbiting the Earth. Three main ingredients are required: a mm- to μm-scale ferromagnet, magnetic shielding and field control coils, and a superconducting quantum interference device (SQUID) connected to a pick-up loop to measure the ferromagnet's dynamics.

With these ingredients in place, various types of motion of the ferromagnet can be recorded as changes in the flux through the SQUID pick-up loop. The flux changes can be measured in the frequency domain. In relatively large magnetic fields, the ferromagnet librates (wobbles), producing a characteristic frequency. This frequency has been observed in experiments [6]. In relatively low magnetic fields, we predict the libration frequency to effectively split into nutation and precession frequencies, red and green curves in the Figure 2, enabling a method to tune the magnetic field to values where precession can be observed.

In summary, experiments with levitated ferromagnets in a microgravity environment may open possibilities for new tests of fundamental physics [3, 4], including novel experiments testing the predictions of general relativity [2].

References

[1] C. W. F. Everitt, et. al., Gravity probe B: final results of a space experiment to test general relativity, Phys. Rev. Lett. **106**, 221101 (2011).

[2] Pavel Fadeev, Chris Timberlake, Tao Wang, Andrea Vinante, Yehuda Band, Dmitry Budker, Alexander Sushkov, Hendrik Ulbricht, and Derek F. Jackson Kimball, Ferromagnetic gyroscopes for tests of fundamental physics, Quantum Science and Technology (2021).

[3] D. F. Jackson Kimball, A. O. Sushkov, and D. Budker, Precessing ferromagnetic needle magnetometer, Phys. Rev. Lett. **116**, 190801 (2016).

[4] Pavel Fadeev, Tao Wang, Yehuda Band, Dmitry Budker, Peter W. Graham, Alexander O Sushkov, Derek F. Jackson Kimball, Gravity Probe Spin: Prospects for measuring general-relativistic precession of intrinsic spin using a ferromagnetic gyroscope, accepted to Physcial Review D (2021).

[5] T. Wang, S. Lourette, S. R. O'Kelley, M. Kayci, Y. B. Band, D. F. Jackson Kimball, A. O. Sushkov, and D. Budker, Dynamics of a ferromagnetic particle levitated over a superconductor, Phys. Rev. Appl. **11**, 044041 (2019).

[6] A. Vinante, P. Falferi, G. Gasbarri, A. Setter, C. Timberlake, and H. Ulbricht, Ultralow mechanical damping with Meissner-levitated ferromagnetic microparticles, Phys. Rev. Applied **13**, 064027 (2020).