Physics

VIEWPOINT

Spin Gyroscope is Ready to Look for New Physics

An enhanced version of a magnetometer based on atomic spins could be used to search for theoretically predicted exotic fields with ultrahigh sensitivity.

by Derek F. Jackson Kimball*

Why is gravity so much weaker than the other fundamental forces? What are dark matter and dark energy? And why is there vastly more matter than antimatter in the Universe? Physicists have proposed a wide variety of theories to solve these mysteries. It turns out that a ubiquitous prediction of these theories is the existence of exotic fields that generate tiny torques on the spins of atoms. Numerous experiments are actively searching for such effects [1, 2], though none have been observed so far. Michael Romalis and co-workers from Princeton University, New Jersey, have perfected an atomic spin "gyroscope" that stands to greatly contribute to these searches [3]. The device detects torques on atomic spins with exquisite accuracy, and it will enable new, more sensitive searches for fields predicted by an assortment of theories.

Atoms are supremely accurate measurement devices. A good example is the atomic clock, which is the primary standard for the unit of time and is the heart of the global positioning system (GPS). In an atomic clock, the frequency of a periodic signal—the number of "ticks" per second of the clock—is referenced to the energy difference between two quantum states. The fact that this energy difference depends solely on the internal interactions among the atom's electrons and nucleus is why an atomic clock is so accurate. Indeed, as far as we can tell, the clock's frequency is a constant of nature.

The "built in" accuracy means that atoms can do more than just keep time: they can also detect external fields with high sensitivity. That's precisely the idea behind atomic magnetometry [4]—the basis for the technique that Romalis and colleagues use. Atomic magnetometry entails using, for example, laser light to optically detect a shift in the relative energy between various atomic states caused by an external magnetic field. Alternatively, one can understand the principle behind atomic magnetometry by thinking of the field-sensing atom as a gyroscope. Recall that a spinning

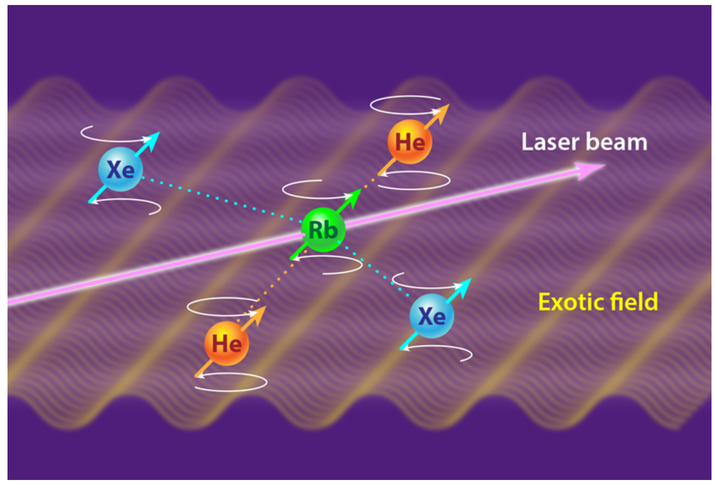

Figure 1: Romalis and colleagues [3] have greatly enhanced the sensitivity of an atom-based magnetometer, which can be used not only to detect magnetic fields, but also to search for exotic fields predicted by certain theories. Their device is called a comagnetometer because it uses two types of atoms—in this case, helium (orange) and xenon (blue)—to detect a field. The field torques the spins on the atoms, causing them to precess at well-defined frequencies. The Romalis team measures the precession frequencies of the helium and xenon atoms via the precessing atoms' effect on the spin precession of a third species, rubidium (green), which they detect with a laser. (APS/Alan Stonebraker)

top on Earth will "wobble," or precess, because of the torque from gravity. Similarly, the magnetic dipole associated with an atomic spin will precess at a well-defined frequency (the Larmor frequency) if it experiences a torque from a magnetic field. Exotic fields could also exert a torque on the atomic spins, but because the effects are expected to be so small, researchers must eliminate any "prosaic" external perturbations to see them.

The Princeton team tackles these perturbative effects by enhancing an existing scheme for an atomic spin gyroscope with several ingenious techniques. To start, the researchers use a form of atom magnetometry, known as comagnetometry [5], which makes it easier to disentangle the effects of

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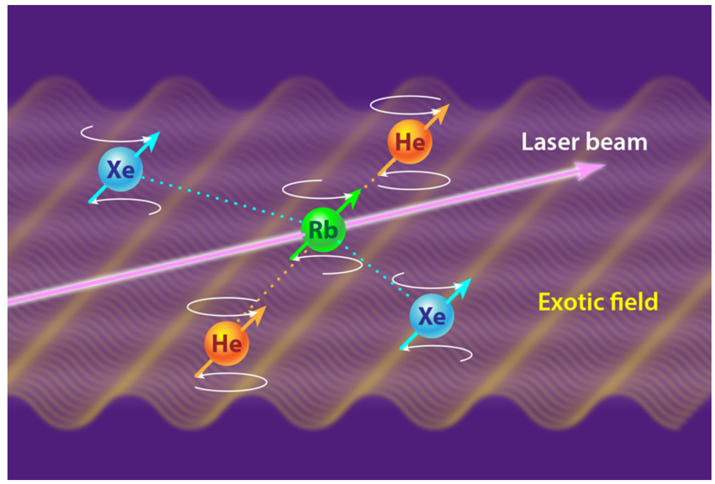

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an exotic field from those caused by other sources, such as a change in the local magnetic field, an accidental rotation of the experiment, or light from the probe laser. In comagnetometry, the same field, magnetic or otherwise, is measured using two different, but overlapping, gases of atoms. In this case, the gases are isotopes of helium and xenon with nonzero spin, and they are contained in a marble-sized glass vapor cell. The ratio between the precession frequencies of the two types of atoms is generally expected to be different, depending on whether the atoms' precession is caused by exotic fields or any of the sources listed above. This allows the relative contributions of the different sources (any of which could be zero) to be disentangled by varying certain experimental parameters.

Previous comagnetometry experiments typically measured the helium and xenon precession frequencies using a sensor that was placed outside the vapor cell [6, 7]. Romalis and co-workers instead follow a practice known to offer greater sensitivity, which is to measure these frequencies via their effect on a third species, rubidium, which is added to the cell in gaseous form (Fig. 1). The team then uses a laser to monitor the rubidium atoms' precession in response to the precession of the helium and xenon magnetic dipoles.

Although these methods have been used before, the Princeton team achieves a new level of sensitivity by following several steps. First, they reduce the deleterious effects of collisions between rubidium atoms by keeping the rubidium spins aligned with one another, which requires applying a synchronized series of laser-light pulses and magnetic-field pulses. Second, they minimize the perturbation to the helium and xenon spins caused by collisions with the rubidium atoms. To do so, they apply a complicated series of magnetic field pulses to the sample that "averages away" the effects of both the rubidium spins and the pulses themselves. However, this second set of pulses, which optimizes accuracy, is incompatible with the first series of pulses, which optimizes sensitivity. To get the best of both worlds, the team therefore probes the helium and xenon spins under the first pulse sequence, but only before and after the spins have been allowed to precess "in the dark" for a roughly 200 second period. During this time, the researchers block the laser light and apply the second pulse sequence.

This combination of techniques results in an atomic spin gyroscope with properties that are among the best in the world for such a device: a precession-frequency stability of better than 7 nHz and an absolute accuracy (in the measured precession frequency) at the sub-ppm level [3]. The first number, for example, means that the Princeton team's atomic spin gyroscope can sense torques so small that, in the absence of other effects, they would cause atomic spins to precess with periods of longer than four years. This opens the possibility of probing subtle exotic-field effects that may have evaded detection in past experiments.

Startling discoveries are sometimes hiding just beyond the horizon of our measurement accuracy. In this sense, the Princeton group's atomic spin gyroscope promises to open new vistas in the hunt for exotic physics. Some of the many possibilities include the search for dark matter fields [8], new long-range forces [9], and permanent electric dipole moments, whose hypothetical existence has been tied to the source of the Universe's matter-antimatter asymmetry [10]. Eventually, the tool is poised to be the most sensitive means of searching for gravitationally induced torques on spins that aren't expected in our current theory of gravity [11].

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