ATOMIC PHYSICS

Collisions give sense of direction

The ability to measure small or slow rotations relative to an inertial frame is valuable in navigation as well as in fundamental physics. A device that exploits techniques developed in atomic physics could lead to sensitive and compact rotation sensors.

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Could techniques used in fundamental tests of physics[1] and in compact atomic clocks soon find broad application in navigation? Writing in *Physical Review Letters*[2], Tom Kornack and collaborators from Princeton University report on the application of novel atomic physics techniques to realize a 'two-species spin gyroscope'. First results show promising sensitivity to inertial rotation — with hope that similar miniaturization and robustness can be achieved for spin gyroscopes, as has been for 'chip scale' atomic clocks that use similar techniques.

The idea of using spins for sensing rotation is not new. The device built by the Princeton group, led by Michael Romalis, uses electron-spin-polarized potassium vapour as the inertial rotation sensor. The potassium atoms are co-located in a glass chamber with nuclear-spin-polarized helium-3 gas, which serves as a 'co-magnetometer' to eliminate the effects of magnetic fields on the potassium electron spins, and also to enhance the signature of inertial rotation. Figure 1 illustrates the basic functional principle of the co-magnetometer. A 'pump' laser beam polarizes the potassium electron spins ($\mathbf{S}_K$) along its direction. The linear optical polarization of a 'probe' laser beam, which passes through the atomic mixture orthogonal to the pump beam, is sensitive to the component of potassium electron-spin polarization along the probe beam. Rotation of the device relative to an inertial frame is determined by measuring rotation of the optical polarization of the probe beam.

To achieve excellent sensitivity to inertial rotation, Kornack *et al.* had to confront the effects of thermally driven atomic collisions, which usually limit spin gyroscopes by restricting operation to relatively low spin densities. In general, thermal effects — such as the so-called Johnson noise in electrical conductors or random lattice vibrations in solids — degrade the performance of precision-measurement devices. The Princeton team instead exploits quantum mechanical properties of 'spin exchange' collisions to improve measurements of inertial rotation. In collisions between alkali atoms, there is significant overlap of the wavefunctions of the unpaired outer electron of each atom. This leads — through a process known as the exchange interaction — to a relative rotation of the electron spins. In most cases studied to date, spin-exchange is a source of relaxation of electron-spin polarization, and has thereby limited the density of alkali vapour that can be used in experiments. Kornack *et al.* however, have overcome the limitations by building on ideas pioneered by William Happer and colleagues[3] in the 1970s. The two-species spin gyroscope operates in a regime of relatively high potassium density and near-zero magnetic field, such that the spin-exchange collision rate and the resultant

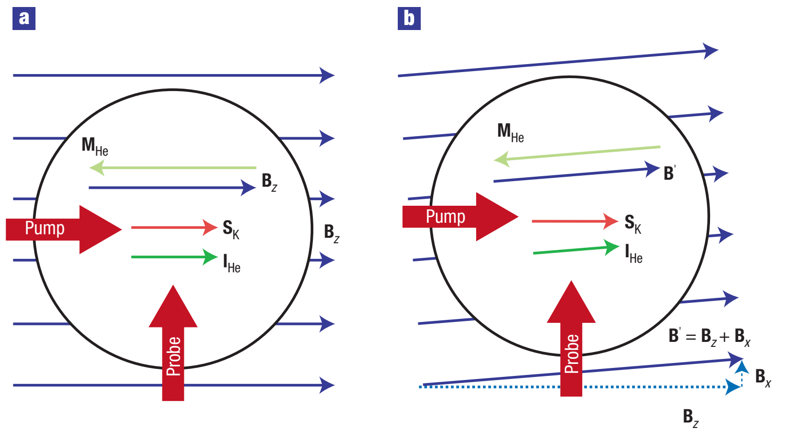

Figure 1 The two-species spin gyroscope developed at Princeton University uses a self-compensating helium-3 co-magnetometer to shield the co-located potassium atoms from external magnetic fields. **a**, An optical pumping laser beam polarizes the potassium electron spins ($\mathbf{S}_K$), which then polarize the helium-3 nuclear spins ($\mathbf{I}_{He}$) through spin-exchange collisions. The strength and direction of the externally applied magnetic field ($\mathbf{B}_z$) is adjusted to be equal and opposite to the helium-3 magnetization ($\mathbf{M}_{He}$), so that the potassium atoms experience no net field. Rotation of the gyroscope (including the glass chamber, laser beams, and source of applied magnetic field) relative to an inertial frame is sensed by changes in the component of $\mathbf{S}_K$ along the probe laser beam. **b**, The helium-3 magnetization adiabatically follows slow changes in the external magnetic field ($\mathbf{B}_z \rightarrow \mathbf{B}'$). Thus, the magnetic field experienced by the potassium atoms remains zero, to leading order. Reprinted with permission from ref. 8, copyright 2004, American Institute of Physics.

rate of relative rotation of the colliding atoms' electron spins dominates over the rate of magnetic Larmor precession of the spins about the local magnetic field. Operation with such high potassium density and rapid spin-exchange greatly suppresses relaxation of the electron-spin polarization[4], while also providing a large signal for inertial rotation of the apparatus as measured by optical polarization rotation.

To isolate the potassium electron spins from external magnetic fields, Kornack *et al.* use a high-density helium-3 gas co-magnetometer, co-located in the same glass chamber. Some of the potassium electron-spin polarization is transferred to the helium-3 nuclear spins ($\mathbf{I}_{He}$) through a different form of spin-exchange collision, involving the transient hyperfine interaction between the potassium electron spin and the helium-3 nuclear spin that exists during a collision. The spin-polarized helium-3 ensemble provides a large effective magnetic field (proportional to the helium magnetization $\mathbf{M}_{He}$) that is enhanced by the quantum mechanical properties of potassium–helium-3 spin-exchange collisions, and effectively screens the potassium spin ensemble from external magnetic fields ($\mathbf{B}_z$) and gradients, even if they change during the experiment. But elimination of magnetic fields on the potassium electron spins is only one asset brought along by the admixed helium-3 gas. In addition, the use of two spin species — with magnetic moments that differ by approximately three orders of magnitude — enhances the component of potassium electron-spin polarization that rotates into the probe beam direction as the device rotates[5]. And this component, of course, is exactly the signature of inertial rotation.

In navigation applications, the rotation frequency sensed by a gyroscope is integrated over time to obtain the rotation angle. To date, Kornack *et al.* have realized rotation-angle sensitivity of 5×10^{-7} rad s^{-1} Hz$^{-1/2}$ and low-frequency angle drift of 0.0007 rad h^{-1} using a table-top laboratory version of the potassium–helium-3 spin gyroscope. The team estimates that by replacing helium-3 with neon-21, and with extensive further development, rotation-angle sensitivity of 2×10^{-10} rad s^{-1} Hz$^{-1/2}$ may be possible in a compact two-species spin gyroscope with a measurement volume as small as 10 cm^3. For comparison, compact fibre-optic gyroscopes have achieved rotation angle sensitivity of 2×10^{-8} rad s^{-1} Hz$^{-1/2}$ (ref. 6), with good prospects for further improvement. Already, however, the potassium–helium-3 spin gyroscope provides sensitivity to new physics, such as violations of Lorentz symmetry, that is comparable to the best previous tests[7]. Thus the work of Kornack *et al.* continues the fruitful practice in atomic physics of synergy between fundamental and applied science.

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