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Optical control stabilizes cold-atom comagnetometry

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The use of tailored laser fields improves the coherence times of two co-trapped ytterbium isotopes, resulting in the rejection of magnetic-field noise by more than thirty-thousand-fold, opening the way to improved comagnetometry.

Theorists considering extensions to the standard model of physics have proposed the existence of a variety of small exotic spin couplings[1]. The challenge is that these coupling effects are difficult to distinguish from small changes in magnetic field. The experimental tests to confirm their existence thus require extreme absolute sensitivity and controlling the magnetic field to a sufficient level over long periods of time is not practically possible, even with high-performance magnetic shielding.

One solution to this problem is to use comagnetometry, where two spin species or transitions having resolvable coupling strengths to magnetic fields are co-located. Comagnetometry allows researchers to distinguish magnetic fields imparted on the system from other spin couplings or physical rotations of the apparatus (quantum gyroscopy). There are many hypothesized exotic interactions that are solutions to outstanding problems in physics, which would be groundbreaking if discovered experimentally, such as a permanent electric dipole moment[2], or a coupling to axion-like dark matter[3]. When the experiments to search for such interactions are performed, long coherence times of the spin states translate directly to higher performance; for example, researchers continue to push warm vapour-cell comagnetometers to remarkable energy resolution by leveraging the long spin lifetimes (minutes to days) of noble gas nuclear spin states[4].

While the current highest absolute sensitivity using spins is provided by warm vapour cell systems, they come with the disadvantage of macroscopic sensing volumes, that are on the scale of millimetres to centimetres in size. The use of laser-cooled atoms has the potential to remove these constraints, since the atom cloud can be compressed to the length scale of the interaction, and test masses can in principle be brought inside the same vacuum chamber. However, difficulties in stability and coherence can arise from the act of spatially trapping atoms using light. Notably, this comes with light shifts, where the intense light needed to spatially constrain cold atoms can shift the energy sublevels being interrogated in a way that mimics magnetic field drift and noise, and often does so unevenly across the trapping region. Prior cold-atom comagnetometers, whether built from two hyperfine states of ^{87}Rb (ref. 5) or from a paramagnetic–diamagnetic ^{87}Rb–^{87}Sr mixture[6], have been limited to millisecond spin coherence times, much shorter than the minutes to days of nuclear spin coherence that are achieved in noble gas comagnetometer vapour cells.

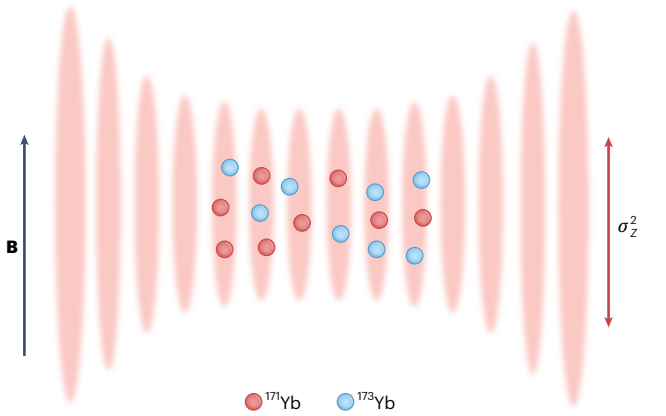


Fig. 1 | Long spin coherence in a pair of co-trapped ytterbium isotopes. Two ytterbium isotopes, spin-1/2 ^{171}Yb and spin-3/2 ^{173}Yb share an optical lattice, prepared by a detuned laser into a ^{73}Yb superposition such that the state becomes insensitive to the tensor shift that causes fast spin relaxation. Comagnetometry using simultaneous Ramsey interferometry of both isotopes leverages the minute-long nuclear spin coherence times, and yields a frequency ratio insensitive to magnetic-field noise and drifts. The red arrow indicates the polarization axis and the black arrow the bias field **B**. Adapted from ref. 7, Springer Nature Ltd.

Now, writing in *Nature Photonics*, Zhang and co-authors report a cold-atom comagnetometer that shows significant improvements in the spin coherence time[7]. By engineering the optical fields so that the dominant light shifts do not affect the overall measurement, they achieve 60 s of spin coherence in a pair of co-trapped (see Fig. 1) ytterbium isotopes (^{171}Yb and ^{173}Yb), suppress magnetic noise by a factor exceeding 30,000, and as a first demonstration, determine a ratio of ^{171}Yb and ^{173}Yb nuclear magnetic moments to four parts per million.

To achieve these results, both ^{171}Yb (nuclear spin 1/2) and ^{173}Yb (nuclear spin 5/2) are used in the $^1S_0$ ground state, where the overall electronic angular momentum is null and the spin character is nuclear. The access to pure nuclear spin states can be advantageous for precision measurements in several ways. Firstly, nuclear spin states are often well-isolated systems from their environment with inherently long coherence times that allow for low overall measurement error. Secondly, nuclear spins couple roughly a thousand times more weakly to magnetic fields than electronic spins. Here, the two ytterbium isotopes are cooled and trapped together, with on the order of 10^4 atoms loaded into a one-dimensional optical lattice, forming about 160 pancakes of diameter 40 μm that are separated by 0.5 μm.

The developments by Zhang et al. build upon their previous implementation and control of light shifts that affect the m_F nuclear spin state energy levels in ^{173}Yb. While light shifts are well-understood theoretically, taming them experimentally to a level required for precision

measurements can be difficult. Their theoretical treatment expands the light–atom interaction to many terms, where a vector term behaves as a fictitious magnetic field along the light's path. The vector shift on the optical lattice is minimized by imparting light as close to linearly polarized as the optics allow, with the residual circular component tuned below a Stokes parameter of 0.1%. What remains is an effective vector light-shift field under 100 μG and a fractional error on the ^{171}Yb and ^{173}Yb frequency ratio below 3×10^{-7}.

A higher-order tensor light shift is absent by symmetry in the spin-1/2 ^{171}Yb ground state, but in spin-5/2 ^{173}Yb it is the dominant decoherence channel in a cold-atom lattice. Here the researchers encode the ^{173}Yb spins in a dubbed Schrödinger cat state, a coherent superposition of the two stretched sublevels at $m_F = +5/2$ and $-5/2$, so the tensor shift does not affect the optical lattice. To create the cat state, Zhang and colleagues use their previous work that leverages the nonlinear nature of the tensor light shift[8] to enhance coherence times in ^{173}Yb. In addition, as this cat state accumulates phase five times faster than an ordinary single-quantum coherence, this provides an enhancement akin to a NOON state in optical interferometry.

After state preparation, a Ramsey sequence (detect–evolve–detect) is performed on both isotopes using careful pulse timing and control. Here, if the lattice polarization axis and the bias magnetic field are slightly misaligned, the transverse field component mixes the stretched sublevel with its neighbour at second order and twists the cat state, shifting its frequency. The authors show that by careful tuning of the tensor light shift on ^{173}Yb, and in turn the relevant frequency ratio, they are able to null this bias field orientation effect on their system. The overall result is a cold-atom comagnetometer that is quite tolerant to magnetic field drifts, where one can conceivably put a test mass a distance of micrometres from the spins, inside the same vacuum, with the ensemble compressed to the scale of the interaction being sought. We anticipate further extensions to this work will enable unique regimes for precision measurements.

Challenges remain, such as a coherence time limited at 60 seconds by collisions between the two isotopes rather than by light shifts, which is an inherent difficulty when colocation is at the heart of the comagnetometry technique. Lower densities in a larger trap volume, or sparse tweezer arrays that keep the species near one another without overlapping them, may extend that collisional limit. In addition, the Ramsey sequence imposes dead time, so a faster non-destructive readout could help if higher measurement bandwidths are desired. Finally, improvement in raw sensitivity is always a goal for precision measurements, where trapping larger atom numbers may have advantages in longer-term exotic physics searches.

By considering optical tweezers positioning atoms a few micrometres from a dense source mass and a month of integration, the authors posit a three-order-of-magnitude improvement on micrometre-range monopole–dipole couplings, the parity- and time-violating interactions that would signal an axion-like particle (the axion theoretically solves the strong CP problem). We anticipate that many interesting systematics and rich physics will be uncovered in the study of the long-term stability of such a system for these longer time frames. The authors also note that the electric dipole moment search in ^{171}Yb is currently limited by Johnson noise from nearby electrodes[9], which in principle is the type of noise that comagnetometry should suppress. For the broader photonics and quantum communities, this work is a demonstration of using quantum advantaged states to overcome a dominant constraint rather than attempting to beat the standard quantum limit.

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Competing interests

The author declares no competing interests.