QUANTUM PHYSICS

Feel the force

An approach based on quantum sensing, in which controlled quantum systems serve as precision sensors, has enabled measurement of the weak magnetic interaction between two electrons bound to two separate ions. See Letter p.376

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That electrons have negative charge and repel each other are concepts familiar to most readers. Less well known is that they also possess a magnetic moment associated with their spin, and therefore exert magnetic forces on one another. However, interactions between individual electron spins have hitherto not been measured. This is mainly because they are dwarfed by other effects: for small, atomic-scale separation between electrons, the Pauli exclusion principle, which states that two electrons cannot occupy the same quantum state, and the Coulomb electric interaction dominate; and for large separation, the strength of the magnetic interaction is vastly reduced and typically fully masked by the force that an electron's magnetic moment experiences in an ambient fluctuating magnetic field. On page 376 of this issue, Kotler *et al.*[1] report how they have succeeded in detecting the minuscule magnetic interaction between two electrons bound to two ions separated by about 2 micrometres, using ideas from the emerging field of quantum sensing.

The quantum states of single photons, atoms and ions, and of impurity ions in crystals, can be controlled almost perfectly in the laboratory. Initially, the development of experimental techniques to control and manipulate such quantum states was motivated by an interest in testing the fundamental principles of quantum physics. Nowadays, advances in quantum-state manipulation are also targeted towards applications such as quantum computing, quantum simulation and quantum sensing. Whereas quantum computing and simulation require exquisite control of interactions between large numbers of quantum particles, sensing applications, in which quantum systems serve as sensing devices, are much less demanding in that regard.

In their study, Kotler *et al.* control and manipulate the valence electrons of two strontium ions confined in an electrical device known as a Paul trap. To understand their work, think of the spin of a strontium ion's valence electron as a tiny magnet with a north and a south pole — like the needle of a magnetic compass — that aligns with external magnetic fields. But imagine what happens if two such compass needles are placed close to each other. Now, one needle may interact with the other and rotate slightly, depending on the orientation of the other needle. It is exactly this small effect — the magnetic interaction of two single spins — that Kotler and colleagues measured in their experiment.

To perform their measurements, the researchers first used laser pulses to cool the ions and initialize them such that the magnetic moments of the valence electrons pointed in opposite directions. Returning to the magnetic-compass analogy, both south poles are now facing and repelling each other (Fig. 1a). In addition, the interactions of the two electrons with a uniform external magnetic field — which should be eliminated in order to measure the tiny spin–spin interaction strength — are balanced out, because they are of the same magnitude but opposite sign.

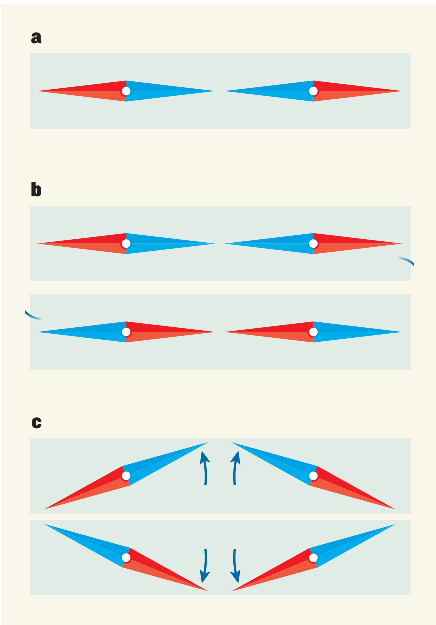

Figure 1 | Measuring magnetic forces. Kotler *et al.*[1] have measured the tiny interaction between two electron spins bound to two strontium ions about 2 micrometres apart. **a**, The electron spins of both ions can be illustrated by magnetic-compass needles, here aligned opposite to each other; blue indicates a south pole and red a north pole. **b**, By repeatedly flipping the needles' directions rapidly and simultaneously, the authors could cancel out the interactions of the ions with a fluctuating external magnetic field (not shown). **c**, This allowed them to measure the magnetic interaction between both needles from the rotation that they undergo in the previous configurations.

Next, the directions of both compass needles were rapidly and continuously flipped simultaneously (Fig. 1b). This step helped to compensate for fluctuations of the external magnetic field, which are different in strength at the two ion locations. On average, any interactions of the ions with the fluctuating external magnetic field essentially vanished, and Kotler and co-workers were set to measure the spin–spin interaction strength.

In the two configurations described above (south poles or north poles facing one another), the spin–spin interaction causes the magnetic moments to repel each other and start turning (Fig. 1c). In the experiment, the magnetic moments turn but do so in a 'coherent quantum superposition'. This is a neat quantum trick, in which the electrons' magnetic moments are forced to align with each other and eventually become quantum entangled. By measuring the properties of this carefully designed state, which is immune to magnetic noise and has a lifetime of almost 1 minute, the authors could measure the rotation of the moments and thus the spin–spin interaction strength. Owing to the extremely small strength of the interaction and associated rotation rate (only 0.0009 hertz), the authors had to wait 15 seconds before they could determine the rotation.

Kotler and colleagues' study has broad ramifications for quantum sensing. The experimental sequence adopted by the authors may be readily applied to other atomic systems, as well as to molecular, optical and solid-state systems, with the prospect of using them as sensitive magnetic probes. The approach may be relevant for developing clocks based on trapped ions or atoms[2] and for sensing small interactions in hybrid systems, such as mixtures of cold ions and atoms[3,4]. Applying the technique to solid-state systems will be particularly interesting, because these systems offer prospects for commercial applications such as magnetic sensors operating in 'noisy' environments. Magnetic sensors based on single-nitrogen-atom impurities in diamond have already been produced[5,6] and are close to reaching the sensitivity needed to detect a single nuclear spin. Physicists await further advances in quantum sensing with great interest. ■

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