toward the bottom. Leaving that effect uncorrected would obliterate all other resolution-improving advances. To compensate for gravity's influence, the researchers introduce a thermal gradient such that the bottom of the analyzer is 10 K cooler than the top.

To test the energy resolution, the researchers made some proof-of-concept measurements, including the hyperfine spectrum of cobalt. But the new spectrometer isn't ready for users yet. The analyzers constructed so far represent just 3% of the area of a fully furbished instrument. And there's still some room for improvement in resolution: The theoretical limit for an ideal GaAs(200) crystal is just 13 neV.

Johanna Miller

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Spin excitations in a cavity hop coherently over long distances

Virtual photons mediate nonlocal interactions between cold atoms.

Quantum mechanics is as counterintuitive as it is in large part because of its nonlocality. Particles can be entangled with other particles, no matter how far away (see PHYSICS TODAY, August 2017, page 14), with information stored not in the state of one particle or the other but in their correlations. A measurement on one particle instantly changes the state of its distant entangled partner. That spooky action at a distance isn't technically an interaction between the particles. But it looks enough like one that it's difficult to reconcile with physical intuition.

Stanford University's Monika Schleier-Smith (shown in her lab in figure 1) and colleagues are using a cloud of cold rubidium atoms in an optical cavity to engineer and study nonlocal interactions. They've now induced a collective spin excitation to act at a distance on a far-away part of the cloud by having it hop more than a quarter millimeter, skipping over all the identical atoms in between.[1] With the combination of nonlocal interactions and local control and imaging, they hope to create a new platform for exploring the limits of how quantum systems can behave.

Driving a spin exchange

The experimental setup is shown schematically in figure 2a. A cloud of some 10^5 spin-1 atoms is held in a one-dimensional array of optical traps created by the standing wave in the optical cavity. An applied magnetic field **B** produces Zeeman splitting of the atoms' $m = +1$, 0, and -1 spin states.

DAWN HARMER

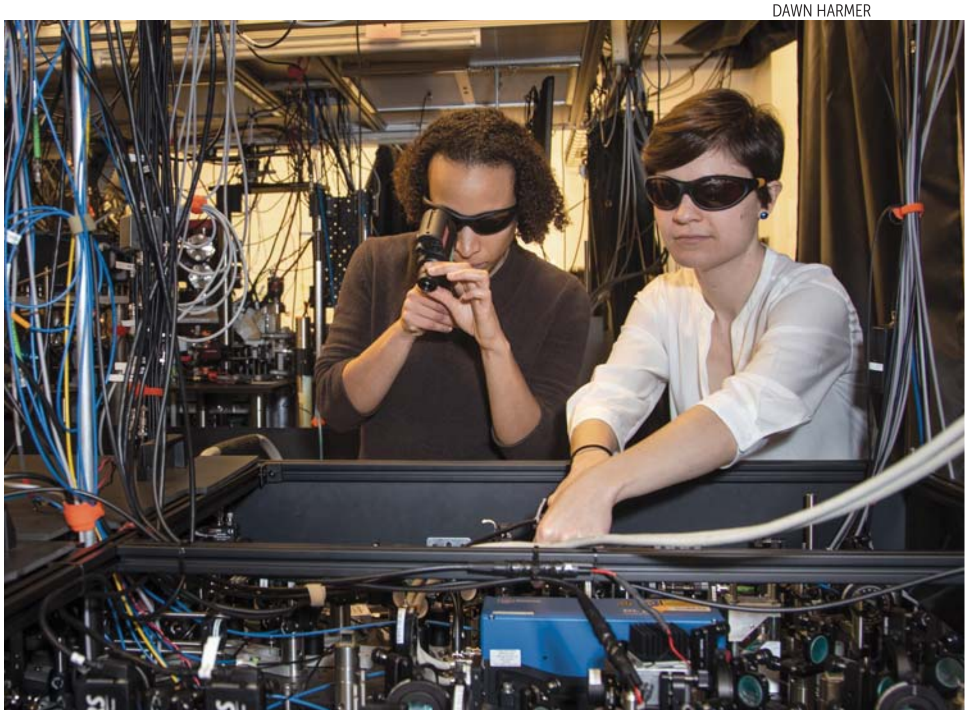

FIGURE 1. MONIKA SCHLEIER-SMITH (left) observes with an IR viewer as her student Emily Davis adjusts a pair of mirror mounts. In the background is a second table where the researchers cool and trap a cloud of rubidium atoms. Optical fibers carry light between the two parts of the experimental setup.

By driving the cavity with a laser pulse of a suitably chosen wavelength, the researchers set off a flip-flop process like the one shown in figure 2b. When a drive-pulse photon inelastically scatters off an atom, it changes the atom's spin state and creates a virtual photon of a different wavelength. The virtual photon then induces a change of spin of equal and opposite energy elsewhere in the cavity, and the photon returns to the original wavelength.

The drive-pulse wavelength is chosen so that the virtual photons are almost, but not quite, resonant with a cavity mode. If they were exactly on resonance, they would be able to exit the cavity without ever completing the spin flip-flop. The slight detuning ensures that the virtual photons have nowhere to go but to scatter off another atom.

Several recent experiments have used similar setups to produce collective spin interactions among atoms in cavities.[2] But until now they've focused on controlling and probing the atoms through global degrees of freedom, such as the total magnetization or the intensity of the light exiting the cavity. Schleier-Smith and colleagues introduced the new capability to manipulate and measure the spin states locally so they can directly see where in the cloud the spin excitations are located.

State-sensitive imaging is a standard technique in cold-atom physics: The spin states are mapped by driving them, one at a time, through a closed-cycle excitation loop that produces detectable fluorescence. But it's challenging to implement in the context of an optical cavity. Traditionally, when researchers use an optical resonator to concentrate light in a small space, they make the whole resonator small. Schleier-Smith and colleagues used a different setup, a so-called concentric configuration, with curved mirrors separated by nearly twice their radius of curvature, a distance of several centimeters. A concentric cavity is extremely sensitive to misalignment of its mirrors. But it concentrates light tightly at its center while leaving plenty of room to introduce imaging laser beams from the side.

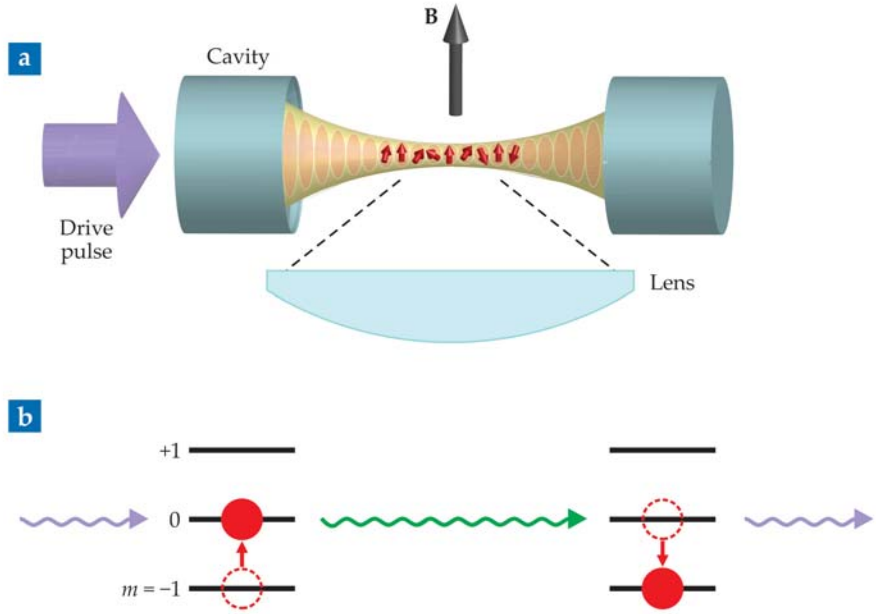

FIGURE 2. SPIN-EXCHANGE INTERACTIONS among atoms in an optical cavity. **(a)** A cloud of atoms (red) is held in a one-dimensional array of optical traps (orange). A magnetic field **B** induces Zeeman splitting, and the lens enables imaging of the cloud from the side. **(b)** When a photon (purple) from a drive pulse scatters inelastically off an atom, it changes the atom's spin state and creates a virtual photon (green) of a different energy. The virtual photon then induces a spin change of equal and opposite energy elsewhere in the cloud. (Adapted from ref. 1.)

Toward spatial control

Figure 3 shows the results of one experiment. After initializing the cloud in the $m = -1$ state, the researchers locally excite atoms at position A. When the drive pulse is introduced to turn on the spin-exchange interactions, the excitation quickly hops to position B, 250 μm away. It slides back to A, and then it hops to B again.

The hop destination is always position B because that's the part of the cloud nearest the cavity center, where the light intensity and thus the light–atom coupling is strongest. The subsequent sliding is a more complicated effect, but it too is explained by the inhomogeneity of cavity light. Over the course of the experiment, the overall excitation density goes up; that's because the experimental conditions aren't quite perfect for ensuring that the flip-flops are complete. The virtual photons are close enough to resonant that some of them do leak out of the cavity, so some spin excitations are not matched with de-excitations elsewhere.

Despite those complications, the results are reproducible. The data in figure 3 weren't collected in real time during a single trial—the nature of the imaging method makes that impossible. Rather, the figure is a patchwork of time slices from many trials with the same initial state prepared each time. Experiment and theory agree well.

The researchers are working on ways to control where the hopping spin excitations end up. For example, by making the applied magnetic field (and thus the Zeeman splitting) spatially inhomogeneous, they could restrict which pairs of atoms can mutually interact to participate in a flip-flop. Another possibility is to replace the end-on drive pulse with drive lasers incident from the side of the cavity to target specific regions of the atom cloud. Between those two approaches, it should eventually be possible to engineer any desired pattern of interactions between pairs of atoms.

Excitation hopping is at its heart a classical phenomenon: Although the atoms interact nonlocally, no nonlocal correlations are involved. But the same physics of the spin flip-flop can also be used to generate and manipulate entangled states. For example, when the cloud is initialized in the $m = 0$ state, the drive pulse creates correlated pairs of +1 and −1 spins: The number of atoms in both states must be the same, but it's not known which atom is in which state. The long-term goal is to combine pair creation, spin exchange, and spatial control to engineer arbitrarily complicated quantum states in large numbers of atoms.

Black hole connections

Schleier-Smith's inspiration for her experiment came from her background in quantum control: creating entangled states for specific practical purposes.[3] For example, squeezed states, in which quantum fluctuations in one variable are reduced at the expense of increasing them in another variable, have applications in metrology. (See the Quick Study by Sheila Dwyer, PHYSICS TODAY, November 2014, page 72.) That's still an area of interest. "But as we were setting up the lab," she says, "we learned about another possible application that could potentially take things in a totally new direction"—the black hole information paradox, an unsolved problem in quantum gravity. (See the article by Steve Giddings, PHYSICS TODAY, April 2013, page 30.)

What happens to quantum information when it falls into a black hole? It can't just disappear without violating the unitarity of time evolution, a fundamental property of quantum mechanics: Any quantum state can be uniquely propagated forward or backward in time. In the absence of a wavefunction collapse

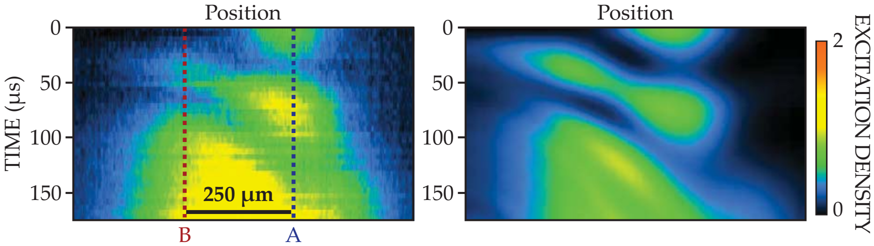

FIGURE 3. NONLOCAL HOPPING of a spin excitation as captured by experimental data (left) and a theoretical model (right). The excitation was prepared at position A at time 0. Turning on the drive pulse causes the excitation to quickly hop to position B, closer to the cavity's center. It then slides back to A, and at time 100 μs hops again. (Adapted from ref. 1.)

associated with an observation, information can't be created or destroyed.

Nor can the information stay inside the black hole's event horizon forever—at least, not necessarily. If a black hole doesn't take in enough new mass to balance out the energy it loses to Hawking radiation, it will eventually evaporate away to nothingness. Where will the information go?

Some mechanism must seemingly exist to allow information to leak out past the event horizon. Figuring out how that mechanism works is a daunting theoretical challenge. But experiments may be able to help, thanks to the duality, or mathematical correspondence, between gravitational systems and quantum many-body systems. (See the article by Igor Klebanov and Juan Maldacena, PHYSICS TODAY, January 2009, page 28.) Experimenters can't build a black hole in the lab, but they may be able to construct its dual.

Which physically realizable quantum systems are the duals of black holes is itself an open theoretical question. But Schleier-Smith is hopeful that her cold-atom spin-exchange experiment could provide the answer.[4] Theoretical models that attempt to solve the black hole information problem often do so by bending the familiar rules of physical locality. "They can look very strange," she says, "because they include all these nonlocal hopping effects," reminiscent of the hopping of spin excitations induced by nonlocal atomic interactions. "In the future, maybe we can build something in the lab that processes information like a black hole."

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Measurements of elusive mineral could explain mantle discontinuity

A predicted phase transition shows up in high-pressure experiments.

As Earth's tectonic plates shift and collide, slabs of cold, dense oceanic crust get pushed down into the mantle. The subduction process carries volatile compounds and water into the mantle along with crustal material that has a different isotopic signature from primitive mantle material. Heat and pressure in Earth's interior can transform the subducted crust into different minerals and may eventually return it to the surface in the magma that upwells and forms new crust. However, the depth to which crust material descends during that cycling is still a subject of debate among geophysicists and is key to understanding heterogeneities in the mantle structure.

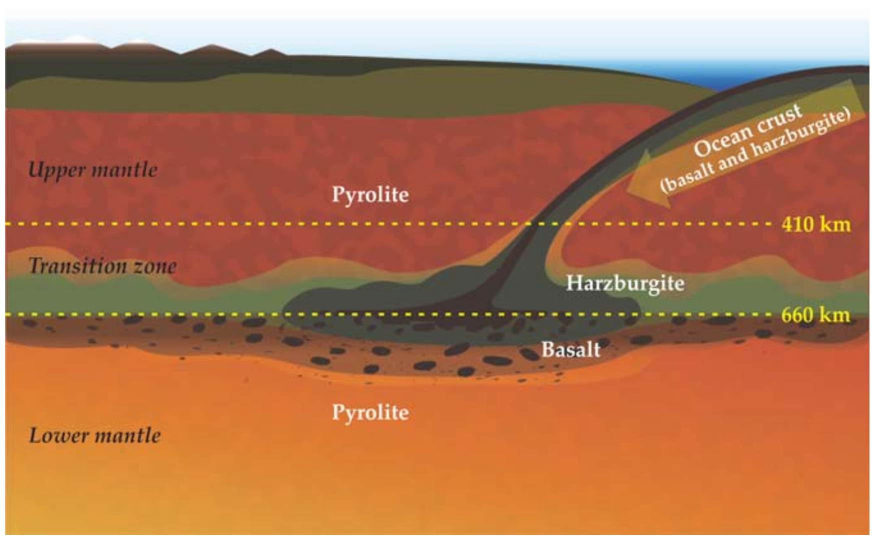

FIGURE 1. SLABS OF BASALTIC OCEANIC CRUST and underlying mantle rocks of harzburgite sink into Earth's mantle during tectonic processes. The boundary between upper and lower mantle is marked by sudden slowing in seismic-wave velocities at depths of around 660 km. New sound-velocity measurements of high-pressure minerals believed to exist in subducted ocean crust suggest that the crust accumulates at the bottom of the mantle transition zone. (Image by Steeve Gréaux.)

Knowledge of Earth's interior structure is based on inferences of how seismic waves travel at different depths. The boundary between the upper and lower mantle is marked by a sharp change in density, and therefore of seismic-wave velocities, at a depth of 660 km. Toward the bottom of the upper mantle, at a depth of 410 km, is another density change that