Two-color cavity QED makes its debut

In a tunable, doubly resonant optical cavity, two distinguishable photons can strongly couple to the same atom and thus to each other.

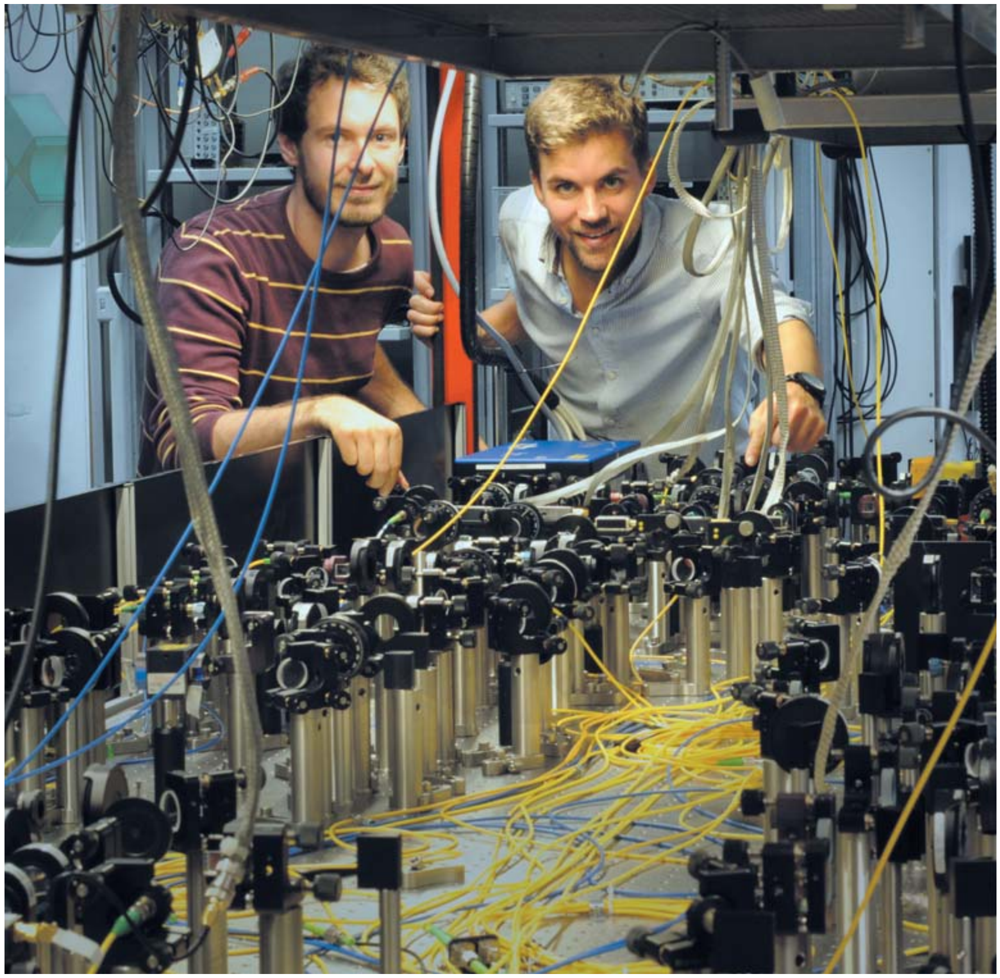

FIGURE 1. CAVITY QED at the Max Planck Institute of Quantum Optics. Nicolas Tolazzi (left) and Christoph Hamsen peer over a table packed with mirrors, lenses, and fiber-optic cables (yellow) that route several laser beams to an adjacent table (not shown), where the optical cavity and a trapped rubidium atom reside in a vacuum chamber. On the left side are several acousto-optic modulators fed by a high-power laser diode (blue box). Hamsen points to a λ/2 plate that rotates the polarization of the beams into specific, well-defined states. (Photo courtesy of Nicolas Tolazzi.)

Photons are superb carriers of information, but they rarely exchange it with one another. In some extreme astrophysical settings, photons interact via electron–positron pairs. But the powers needed to produce the pairs from a vacuum—on the scale of 10^{29} W/cm^2—have never been achieved in a terrestrial lab. So researchers turn instead to atoms as intermediaries.

The conceptually simplest approach is to store one photon's state in a single atom—or a collection of them—whose response affects the state of another photon. In the past few years, researchers have used, for instance, highly excited (Rydberg) atoms to entangle pairs of photons and build single-photon transistors. In the latter case, a single photon can control the destiny of many, with the optical medium—a cloud of excited atoms—being quickly switched on or off under the control of a gate photon.[1] The presence of multiple atoms, however, can be a source of decoherence.

Besides simplicity, an advantage of using single atoms is that they behave like a highly nonlinear medium: Often, the absorption of a single photon raises the atom to an excited state and thus completely alters its optical behavior. To boost the photon–atom interaction, researchers confine both particles between the mirrors of an optical cavity—an approach known as cavity quantum electrodynamics (cavity QED). As the photon bounces back and forth repeatedly in a resonant cavity, the absorption probability approaches unity. And if the mirror spacing is tuned so that the cavity's resonant frequency also matches that of an electronic transition in the atom, the photon and atom can become strongly coupled. That's the condition in which the coherent rate of interaction between the atom and photon is higher than both the rate at which photons leak through the mirrors and the rate of the atom's spontaneous decay (see PHYSICS TODAY, November 2004, page 25).

Christoph Hamsen, Nicolas Tolazzi (both pictured in figure 1), their PhD adviser Gerhard Rempe, and Tatjana Wilk—all at the Max Planck Institute of Quantum Optics in Garching, Germany—now report a cavity QED experiment in which photons at two different wavelengths are each simultaneously resonant with the cavity and with one of two electronic transitions of the same atom.[2] Because the two photons are each strongly coupled to the same atom—rubidium in this case—they can also be strongly coupled to each other. Residing in the cavity in different optical modes, the photons are also distinguishable, a feature that may ameliorate efforts to create complex optical links in quantum networks.

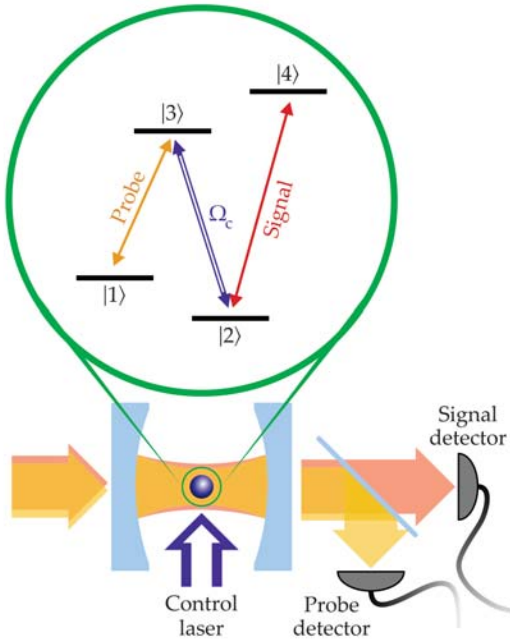

FIGURE 2. STRONG COUPLING OF LIGHT FIELDS. Two weak laser beams, probe (yellow) and signal (red), are resonant with different modes of an optical cavity and populate the cavity with photons that couple strongly to two transitions of a four-level atom. As illustrated in the atom's energy-level diagram (top), the photons also couple to each other through a control field of strength Ω_c. Via interactions with that field, the number of photons in one cavity mode can affect the number of photons in the other. (Adapted from ref. 2.)

Modes and nodes

Strong coupling of optical fields with an atom requires a tiny cavity, on the scale of microns, to generate a high energy density. But the smaller the cavity, the more widely separated in frequency are the modes. Hamsen and colleagues built a novel cavity resonator whose mirrors are adjustable over centimeters using piezoelectric crystals that offer nanometer-scale precision. The researchers found a cavity length, around 295 μm, that could simultaneously support two light fields at wavelengths that nearly matched two hyperfine lines in Rb—one at 780 nm, the other at 795 nm.

"We were lucky," says Rempe. The length had to be an integer multiple of the different photons' half wavelengths, but achieving that condition might have required larger mirror spacing, in which case the energy density would drop and strong coupling might have been lost. Even so, the resonance match wasn't exact. To fine-tune it, the researchers used a light field to subtly alter the atom's energy levels via the Stark effect.

Even after matching the level spacing to cavity modes, Hamsen and his colleagues still had to adjust the spatial position of the Rb atom itself. Photons reside in the cavity as standing waves, with nodes at the two mirrors. But between the mirrors, the nodes of the two different wavelengths occur at different intervals along the cavity axis. The group therefore used their atom-trapping lasers to nudge the atom into a spot between the mirrors where the antinodes for the two modes coincide.

Coupled photons

In the team's setup, two cavity modes, at 795 nm and 780 nm, are pumped using weak laser beams called the probe and the signal. The separate beams drive electronic transitions in Rb between states |1⟩ and |3⟩ and between |2⟩ and |4⟩, as depicted in figure 2. To couple the photons, the researchers added a control laser beam with strength Ω_c to drive the |2⟩ to |3⟩ transition. The additional field connects the ground states |1⟩ and |2⟩ via the excited state |3⟩.

Because the modes are linked by the control field, the number of photons in one mode can have a dramatic effect on the number of photons in the other. In the researchers' current implementation, however, the average number of photons in each mode is far less than 1, and their coincidence probability is a mere 0.04%.

Even so, the control beam exerts an important influence on cavity dynamics in another way. With no signal photon in the cavity, the control and probe beams together create a coherent superposition of the two ground states |1⟩ and |2⟩. That produces an interference effect known as electromagnetically induced transparency (EIT) on the |1⟩ to |3⟩

transition. Thus, with the control field on, the probe photon passes through to the detector unabsorbed. (For more on EIT, see PHYSICS TODAY, November 2011, page 14.)

Conversely, without a probe photon present, any signal photons entering the cavity are also fully transmitted. That's because the control beam has the effect of pumping the atom from state |2⟩ into |1⟩, which prevents it from absorbing the signal tuned to the |2⟩ to |4⟩ transition.

When probe and signal photons enter the cavity together, either the signal perturbs the fragile EIT state and thus prevents the transmission of the probe photon, or the probe pumps the atom to state |2⟩, where it reflects a signal photon. Either way, only one photon can make it through—not both.

Indeed, the energy-level configuration gives rise to an optical-switching effect: The presence of a signal photon in the cavity blocks the transmission of a probe photon, and vice versa. Yet each photon, probe or signal, passes directly through in cases when a Rb atom exists in the cavity and the other type of photon is absent. If the light fields are detuned from atomic frequencies, the dynamics are richer still, and the transmission and blocking scenarios can be reversed.

The two-color cavity QED experiment opens new possibilities for quantum nondemolition photon detection—that is, the indirect detection of one photon's presence using another—for frequency conversion of photons, and for quantum logic. One of the next steps, says Rempe, is to prepare the photons as qubits. The experiment can easily be adapted to include polarization as one of the photons' degrees of freedom.

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References

1. See D. Tiarks et al., *Phys. Rev. Lett.* **113**, 053602 (2014); H. Gorniaczyk et al., *Phys. Rev. Lett.* **113**, 053601 (2014).
2. C. Hamsen et al., *Nat. Phys.* (2018), doi:10.1038/s41567-018-0181-1.

Diamond-defect magnetometry gets ready for the field

A frequency-locking scheme endows the sensors with the necessary robustness to make practical measurements.

When diamond is bombarded with nitrogen ions accelerated to a few thousand electron volts, its formerly pristine crystal lattice is imbued with point-like defects. Most prized and intriguing of those defects is the negatively charged nitrogen–vacancy (NV) center, shown in figure 1, which consists of a nitrogen atom adjacent to a vacant lattice site.

The unpaired electrons in the dangling bonds surrounding the vacancy together behave like a spin-1 atom, with a trio of electron-spin quantum states that can be externally manipulated. Shielded from their surroundings by the diamond lattice, NV centers have a long spin coherence time that makes them appealing as building blocks for a quantum computer. And because the spin states shift in energy in response to an external magnetic field, the defects also serve as tiny magnetometers that can pick up magnetic signals in single living cells or picoliter-sized samples. (See PHYSICS TODAY, May 2018, page 21.)

Of course, the need for magnetic field measurements isn't confined to the microscopic world. Archaeologists, for example, use magnetic mapping as a nondestructive tool for surveying sites; it can reveal the presence of not just magnetic metals but also brick, burned soil, and other materials (see PHYSICS TODAY, March 2014, page 24). And all-magnetic navigation, based on maps of anomalies in Earth's magnetic field, is valuable in military settings where GPS is vulnerable to disruption.[1] Plenty of technologies exist already for detecting macroscopic fields. But sensors based on ensembles of NV centers promise some distinct advantages, including small size, low power consumption, and the ability to detect all three components of the field vector with a single device.

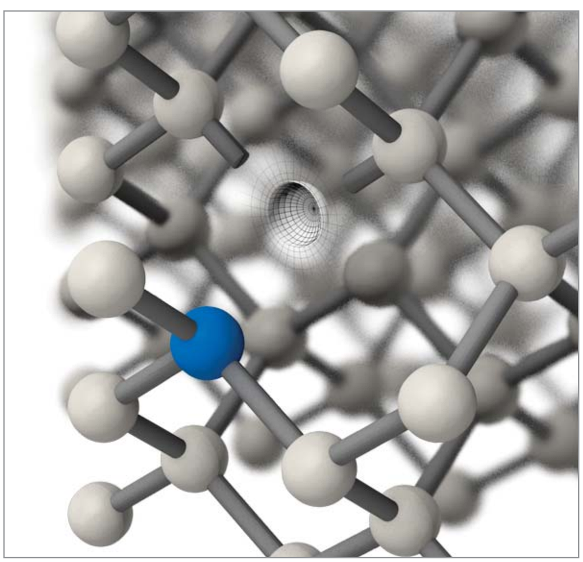

FIGURE 1. IN A NITROGEN–VACANCY (NV) center, a nitrogen atom (blue) replaces a carbon atom in the diamond crystal lattice, and an adjacent lattice site is vacant. The defect behaves like a spin-1 atom whose Zeeman sublevels can be shifted by an external magnetic field. (Image by James Hedberg, CC BY-NC-SA 3.0.)

Now Danielle Braje and her colleagues at MIT Lincoln Laboratory—including lead authors Hannah Clevenson, Linh Pham, and Carson Teale—have taken an important step toward creating an NV magnetometer that's suitable for use in real-world conditions.[2] Their detection scheme is robust to changes in temperature and other parameters that would otherwise necessitate frequent recalibration. And it provides fast and continuous measurements of the field vector for magnitudes up to at least 11 mT. For comparison, the magnitude of Earth's magnetic field at ground level is orders of magnitude smaller, ranging from 25 μT to 65 μT, and previous real-time NV magnetometry schemes are limited to dynamic ranges of just a few microteslas.

Microwave resonances

An NV center's ground-state sublevels are characterized by spin quantum numbers m_s of −1, 0, and +1. At room temper-