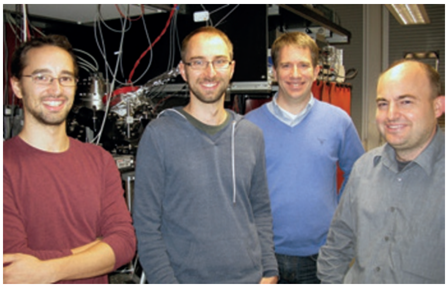
Maximum nonlinearity, minimum light

Arno Rauschenbeutel explains to *Nature Photonics* how atoms help induce a nonlinear π phase shift at the single photon level.



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From left to right: Michael Scheucher, Christian Junge, Arno Rauschenbeutel and Jürgen Volz from the Vienna University of Technology have exploited the coupling between a resonator and a single rubidium atom to induce an optical π phase shift that is nonlinear at the single-photon level.

What is the role of the atom?

The experiment is about making photons interact. As photons in free space don't interact, a nonlinear medium is necessary to create the interaction. As it turns out, a single atom is an absorber that interacts with light in a nonlinear way. When a second photon arrives after a first one has already excited the two-level atom, the second photon cannot be absorbed. When two photons arrive simultaneously, the atom can only scatter one. The atom is therefore a nonlinear absorber that doesn't absorb two photons as well as one.

What are the principles behind your experiment?

We can drastically enhance the atom–light interaction by placing the atom into an optical microresonator with small mode volume and long photon lifetime. This coupled system is interfaced with an optical fibre through which the photons enter and exit the resonator. Due to wave–particle duality, part of the photon enters the resonator and then exits through the fibre.

The part of the photon that comes back from the resonator acquires a phase shift of π and then interferes with the part that stays in the fibre without entering. Because the atom is coupled to the resonator, only a small part of the photon can enter the resonator as its resonance frequency is now detuned. Therefore, the interference is dominated by the part that remains in the fibre and the overall phase is zero as most of the photon didn't enter.

When two photons arrive simultaneously at the resonator in that same configuration, they see a more transparent atom. The amplitude of the part of the two-photon wavefunction that enters is now larger than in the one-photon case and even larger than the part that remains in the fibre. So even though we have partially destructive interference between the two parts, the remaining wavefunction has a phase of π, which therefore amounts to a nonlinear phase shift.

What are the main results?

Before interacting with the resonator the two photons are uncorrelated as they come from a greatly attenuated laser beam. After their interaction with the atom–resonator system, we measure coincidences of the two photons in three different non-orthogonal polarization bases, which allows us to reconstruct the density matrix that contains all information regarding the two-photon polarization state. Our results show that the polarization correlations cannot be explained classically and that the photons are now entangled. This ability to generate entanglement between initially uncorrelated photons is relevant for many applications and can, for example, be used to distinguish between the four Bell states — the maximally entangled states of two qubits. This renders our work important for quantum teleportation, which is at the heart of many quantum communication schemes.

What was your motivation?

Realizing nonlinearities at the single-photon level is the key for processing photons; even in the simplest kind of two-bit operation. Our experiment is an important step towards this goal. At the same time, this was a really cool experiment: we observed the strongest possible nonlinearity with the smallest possible amount of light. A π phase shift is as large as it gets as it doesn't differ from a 2001π phase shift, because any multiple of a 2π phase shift equates to nothing. At the same time, there is no smaller quantity than a single photon.

Can you realize a quantum gate with your scheme?

At first glance it seems plausible: the polarization of one photon flips depending on the state of another. However, we only work with post-selected photons, having chosen those events where the two photons were present in the resonator at the same time. Without this post selection, there would be a trade-off, however, between control over the arrival times of the photons and their spectral properties. This would require short laser pulses. On the other hand, the photons must have a narrow spectral linewidth to ensure interaction with a resonator of finite bandwidth. Both these requirements cannot be completely fulfilled simultaneously.

Is there room for improvement?

For the current experiments the atom is the nonlinear medium, but it wasn't deterministically inserted in the resonator. It was actually free falling: a cloud of laser cooled atoms below the resonator was launched upwards. When the cloud and the resonator overlapped, a few of the several millions of atoms entered the resonator field at random times. Detecting the presence of atoms in the resonator was thus the trigger for the rest of the experiment, rendering the interaction probabilistic. However, a scalable configuration must rely on deterministic schemes. Our plans for improvement include optical tweezers for trapping and pulling the atom in the vicinity of the resonator where it can remain for an extended period of time.

What was the most crucial element?

Our whispering-gallery-mode resonator, because it performed better than we hoped. There are usually two degenerate modes that coexist, propagating in opposite directions for symmetry reasons. However, although this second mode is there, the atoms do not interact with it due to its polarization properties — a result that was not predicted theoretically. We interpret this as a manifestation of anti-Murphy's law: although something could go wrong, it didn't and in fact it worked better than we could have hoped.

INTERVIEW BY MARIA MARAGKOU

Arno Rauschenbeutel and co-authors have an Article on two photons acquiring a nonlinear π phase shift on page 965 of this issue.