Demonstrating slow light in rubidium vapor using single photons from a trapped ion

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Experimental schematic of photon production from a 138Ba+ ion, QFC, and photonic slowing in a warm neutral 87Rb vapor. (A) The energy levels of 138Ba+ and schematic showing the ion confined in a segmented blade trap. A TTL pulse-activated AOM controls a 650-nm excitation light. (B) The QFC setup including a PPLN waveguide. Converted light, ?0, is at the difference frequency between photons emitted from the ion at ?ion and pump photons at ?pump. The output of the PPLN is fiber coupled to a polarization maintaining single-mode fiber (PM-SMF). A series of filters and a Bragg grating filter out pump light and unconverted 493-nm light, which reduces the amount of anti-Stokes noise. (C) A 87Rb energy level diagram and a vapor cell housed inside a heater through which converted single photons pass. (D) Photons are detected on an APD, and a TCSPC collects the arrival time of the photons with respect to the TTL sent to the AOM. As an example, single-photon temporal shapes at 493 nm (blue circles) and frequency-converted photons after passing through the cell at room temperature (red circles) are shown. Credit: Science Advances, doi: 10.1126/sciadv.aav4651

Quantum networks can be practically implemented to interface with different quantum systems. In order to photonic link hybrid systems with combined unique properties of each constituent system, scientists must integrate sources with the same photon emission wavelength. For instance, trapped ions and neutral atoms can both have compelling properties as nodes and memories within quantum networks but without photonic linking due to their vastly different operating wavelengths. In a recent report on Science Advances, J.D. Siverns and colleagues at the Joint Quantum Institute, Department of Physics and the Army Research Laboratory in the U.S. demonstrated the first interaction between neutral atoms and photons emitted from a single trapped ion.

To accomplish this, they used Rubidium ($^{87}$Rb) vapor to delay the origin of photons from a trapped Barium ($^{138}$Ba$^+$) ion by up to 13.5 ± 0.5 nanoseconds (ns). The researchers used quantum frequency conversion (QFC) to overcome the frequency difference between the ion and neutral atoms during the process. They tuned the delay and preserved the temporal profile of the photons and delivered the results as a hybrid photonic interface with applications as a synchronization tool critical for large-scale quantum networks in the future.

To establish scalable quantum networks, physicists must integrate disparate quantum components. Researchers had previously linked photonic quantum systems to form hybrid platforms with single atoms, Bose-Einstein condensates, solid-state systems, atomic vapors and atomic ensembles. Progress in hybrid networking is typically focused on cases where the native photon wavelength of each system is the same by definition, or via direct engineering of the photon source itself. In a practical network, such strict requirements are unlikely to be achieved, since photons emitted from existing devices in quantum communication technologies vary across a wide photon spectrum. To avoid spectral mismatch, researchers can introduce quantum frequency conversion (QFC) to convert a photon's frequency to another frequency while preserving its quantum properties. A hybrid system that combines the desirable features of different components can help realize a viable quantum networking tool.
Trapped ions are strong candidates for communication nodes due to their long qubit lifetime as well as high-fidelity ion-photon entanglement. Neutral atoms are versatile quantum systems useful as memories, photon storage media or for tunable photon delay by slowing light. Investing in the design, control and development of trapped ion and neutral quantum technologies have yielded remarkable progress in quantum networking, computing, metrology and simulation. Researchers commonly use neutral atom vapors and magneto-optically trapped atoms as slow-light media for pulses of light or for single photons. Slowing light for tunable photonic delays is useful for photon synchronization to implement network protocols using photonic interference. In the present work, Siverns et al. demonstrated the first interaction between neutral atoms and photons emitted by an ion by slowing the photons generated from a single trapped ion within a neutral atom vapor.

To create a medium with low group velocity for slow light propagation within atomic vapors, the research team used photons with a frequency between two absorption resonances of a medium. They investigated the two absorption resonances using electromagnetically induced transparency (EIT) or far-off resonance. Siverns et al. used two D$_2$ absorption resonances established via hyperfine ground state splitting of $^{87}$Rb with a less complex experimental setup compared to EIT methods, which only required single photons at the correct frequency. The researchers then derived the group velocity of the photons emitted from Ba$^+$ ions after QFC (quantum frequency conversion). They tuned the photon's optical frequency to achieve a maximum in transmission and greatly reduced group velocity. Siverns et al. tuned the photon delay by changing the atomic number density (N).
As the source of the 493-nm single photons, the research team used $^{138}$Ba$^+$ ions, which they trapped by applying voltages to segmented blades housed in an ultrahigh vacuum chamber. They collected the photons using a 0.4 numerical aperture (NA) lens; fiber coupled them and sent them to the QFC setup. The research team coupled the photons of a specific frequency with a pump laser to form a different frequency near 1343 nm, which they coupled into a periodically poled lithium niobate (PPLN) waveguide for difference frequency generation (DFG). After frequency tuning the pump laser, the team produced 780-nm photons with a frequency between two optical absorption resonances to implement slow light. The scientists showed the conversion efficiency of the PPLN device as a function of the pump power coupled into the waveguide.

Siverns et al. maximized the signal-to-noise ratio (SNR) of the converted light instead of using the total amount of converted light. They converted the 493-nm photons using DFG (difference frequency generation) to tune the pump optical frequency. The scientists coupled the output of the PPLN to an 800-nm single-mode fiber to capture 780-nm photons and spatially filtered the other modes away. Upon filtering the photons, the research team sent them through a 75-mm long heated glass cell filled with enriched $^{87}$Rb, which they detected using an avalanche photodiode (APD). When the photons passed through the rubidium cell at room temperature, their absorption and scattering
decreased the signal-to-noise ratio to ~6. To measure the temporal shape, they recorded the arrival time of the photons at the APD, relative to the 650-nm excitation acoustic-optic modulator (AOM) and transistor-transistor logic (TTL) pulse with a time-correlated, single-photon counter at a resolution of 512 picoseconds (ps). With increased atomic density of the vapor cell, the SNR monotonically decreased to approach ~1 at 395 K. Despite lower SNR, the photon delays remained clearly visible.

The research team determined the photon delay by temporally shifting each delayed photon to overlap with a photon shape at room temperature. The scientists noted the photons emitted by the Ba⁺ ion and the drift of the pump laser to impact the stability of the optical frequency of the converted photons. They aim to increase photon delays and improve transmission by increasing the nonlinear refractive index in the vapor using **advanced methods such as EIT** (electromagnetically induced transparency) in the future.

The new approach will offer a path toward photonic quantum gates between remote ions and neutral atoms, where each system can independently emit photons of a comparable profile. The work will also pave the way for future quantum-state transfer between ions and neutral atoms to facilitate experimental, ion-neutral atom photonic entanglement distribution, and photonic storage of **flying qubits** emitted from trapped ions combined with existing, advanced atom technologies.


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