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Viewpoint

Single Dot Meets Single Ion

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Researchers show that a single photon can transfer an excitation from a quantum dot to an ion.

Subject Areas: **Atomic and Molecular Physics, Quantum Information, Nanophysics**

A Viewpoint on:
Direct Photonic Coupling of a Semiconductor Quantum Dot and a Trapped Ion
H. M. Meyer, R. Stockill, M. Steiner, C. Le Gall, C. Matthiesen, E. Clarke, A. Ludwig, J. Reichel, M. Atatüre, and M. Köhl
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Researchers have made many advances in controlling atomic, solid-state, and other types of quantum systems. Hybrid quantum systems bring together two or more such systems and allow them to interact. Hybrid systems combine the advantages of each component and as such, are of interest for a number of proposed technologies, including a hybrid quantum network. One hybrid system of particular interest is a single artificial atom (e.g., a quantum dot) coupled to a natural atom (e.g., a trapped ion). Combining these two components is, however, a challenge: specialized techniques are needed to control single artificial atoms and single natural atoms, while experimentalists have so far mastered only one system or the other. Research groups at the University of Cambridge, UK, led by Mete Atatüre, an expert on quantum dots, and Michael Köhl, an expert on trapped ions, now overcome this challenge to demonstrate a photonic link between a single ion and a single quantum dot—a nanoscale semiconductor that behaves like an atom [1].

Artificial and natural atoms are conceptually the same physical systems. Both have confined electrons that can only occupy well-defined discrete energy levels. And in both systems, an external field (such as the optical field from a laser) can be used to “move” the electrons between the levels to generate single and entangled photons, prepare an electron spin in a quantum superposition, and implement quantum memories.

For particular applications, however, each system has its own unique advantages and limitations. A key difference is that a natural atom is an isolated system while an artificial atom is not. A single trapped atom typically sits in a vacuum, while a single artificial atom is usually embedded in a host material. As a result, natural atoms are “cleaner” systems, and their electrons can be prepared in quantum states that have long coherence times. Artificial atoms are, in contrast, easier to manipulate. For instance, contacts can be fabricated around the host material and used to control the electrons in the artificial atom electrically. But electron quantum states in artificial atoms tend to have shorter coherence times than those associated with ions because of their interaction with the host material.

The first hybrid semiconductor-atomic system [2, 3] was an interface between a single GaAs quantum dot and a vapor of rubidium atoms. In one experiment, the atomic system was used as a slow light medium [2] for single photons generated by an artificial atom. In another experiment, the frequency of single photons emitted by the artificial atoms was locked to the frequency of an atomic optical transition [3]. Ultimately, the nodes in a hybrid quantum network have to be able to exchange quantum information. Research so far suggests single artificial and natural atoms could, if placed in the nodes of a network, perform this function. The next significant milestone is therefore a “single-to-single” interface that couples a single artificial atom to a single natural atom.

This is exactly what the researchers from the University of Cambridge have demonstrated. The natural atom in their experiment is a single Yb^+ ion trapped between two needle-shaped electrodes. The artificial atom is a single InAs quantum dot. The quantum dot is surrounded by a host material (GaAs), which is electrically contacted. An electric field applied through the contacts serves two purposes: it controls the number of electrons present in the dot, and it can be used to tune an optical transition of the quantum dot so it is in resonance with a transition of the Yb^+ ion. When the frequencies of the optical transitions are matched, the quantum dot and the ion can exchange single photons.

With a laser, Atatüre, Köhl, and their colleagues excite an electron in the quantum dot, which emits a single photon when the electron relaxes (Fig. 1). A periodic excitation of the quantum dot generates a stream of single photons that are channeled into an optical fiber and sent 25 meters away to the trapped ion. An electron in the ion is prepared in a state such that it can absorb a

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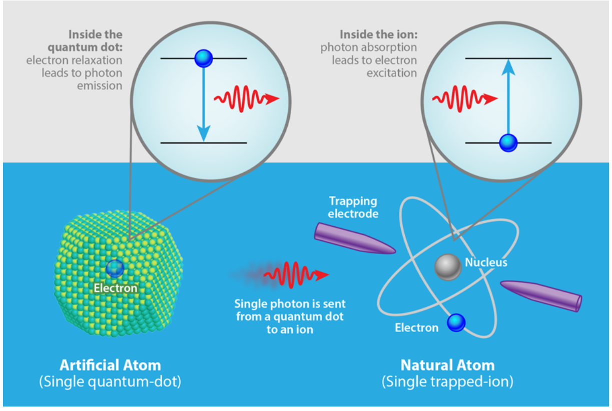

FIG. 1: Researchers have shown that a single photon emitted by a quantum dot can excite an ion 25 meters away. (Left) A laser excites an electron in the quantum dot. When the electron relaxes, it emits a photon, which travels through a fiber (not shown) to the ion (right). The ion is prepared in a state that allows it to absorb the photon. The efficiency of this process is only 0.0005%, but various strategies exist to improve it. (APS/Alan Stonebraker)

single photon from the quantum dot. This absorption leads to an electron excitation that the researchers are able to detect.

The experiment demonstrates that an excitation in a single quantum dot can be transferred to an excitation in a single ion by means of a single photon. A great advantage of this type of "single-to-single" interface is that it provides the starting infrastructure for exchanging quantum information between a single quantum dot and a single ion. This, however, is yet to be demonstrated. Atatüre, Köhl, and their colleagues have made a preliminary step forward towards this goal by showing that the spin of an electron in the quantum dot is correlated with the excitation transfer. In this experiment, the quantum dot is first prepared to have one excess electron, and the spin of this electron is controlled to be either up or down. When an excitation laser is turned on, it can only excite the dot if the electron has its spin up. This excitation is then transferred to an ion and detected, exactly as in the first experiment. If the electron's spin is down, however, the laser can't excite the dot, so no photon is transferred to the ion. In other words, if the researchers detect the ion in an excited state, they know the spin state of the electron in the quantum dot.

The photonic link between a quantum dot and an ion, developed in this work, can, in principle, be extended to hybrid quantum networks [4], where the strength of each system can be combined to gain new functionalities. For instance, solid-state systems can be used as scalable and fast processing units, while atomic systems can serve as long-lived quantum memories. But physicists are still in the early stages of developing a hybrid network technology. The first challenge to overcome is the low transfer efficiency between the dot and the ion. In the experiments of Atatüre, Köhl, and their colleagues, only 5 out of 1 million photons from the quantum dot excite the ion. Photon loss occurs at every step in the transfer, but various techniques exist to reduce it. Another challenge is demonstrating that a quantum state can be transferred between the quantum dot and the ion, and that the two objects can be entangled [5]. We should also be able to send information in the reverse direction, from an ion to a quantum dot.

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About the Author

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Nika Akopian received his Ph.D. in physics in 2008 from the Technion – Israel Institute of Technology. He then worked as a postdoc at Delft and Eindhoven Universities of Technology in the Netherlands. He is now an Associate Professor at the Department of Photonics Engineering, Technical University of Denmark. Nika's research interests include quantum information, quantum optics, and nanoscience.

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