Physics

VIEWPOINT

Linking Two Quantum Dots with Single Photons

Researchers have transferred quantum information from one quantum dot to another dot 5 m away using photonic qubits as the relay.

by Oliver Benson*

In the future, encrypting messages and solving hard computational tasks may come to rely on a quantum internet, in which stationary quantum nodes share information via "flying" qubits [1]. The fixed components might be some sort of atomic or solid-state system that encodes information in electronic or spin states, while the flying elements will almost certainly be photons, as only light is capable of long-distance transport of quantum states without loss from decoherence. Transferring quantum information between these different media is a major challenge requiring a number of steps: encoding quantum states from an initial qubit onto photons, low-loss transmission of those photons, and then coherent absorption of those photons by a second qubit. A group led by Atac Imamoğlu at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland, succeeded in realizing all these steps with two semiconductor quantum dots separated by 5 m [2]. The experiment is unique in that the two dots are linked together by a single photon qubit, and the successful state transfer is indicated by a scattered photon from the second dot.

Researchers in the field of quantum information processing started at an early stage to realize efficient light-matter interfaces that convert information between stationary qubits and photonic qubits. One successful approach towards such quantum interfaces involves neutral atoms in cavities [3] or trapped ions [4]. However, a solid-state platform is in many ways a better option as it would provide compatibility with modern nanostructure technology and thus a more obvious route towards scalability. Moreover, semiconductor quantum systems offer optical transitions in the infrared, some of which even lie in the telecommunication band, which means researchers do not need to include an intermediate—and probably lossy—wavelength conversion to transmit over low-loss optical fibers.

One of the first instances of solid-state quantum interfaces concerned entanglement of photons and spin states of a single electron in a nitrogen-vacancy defect center in diamond

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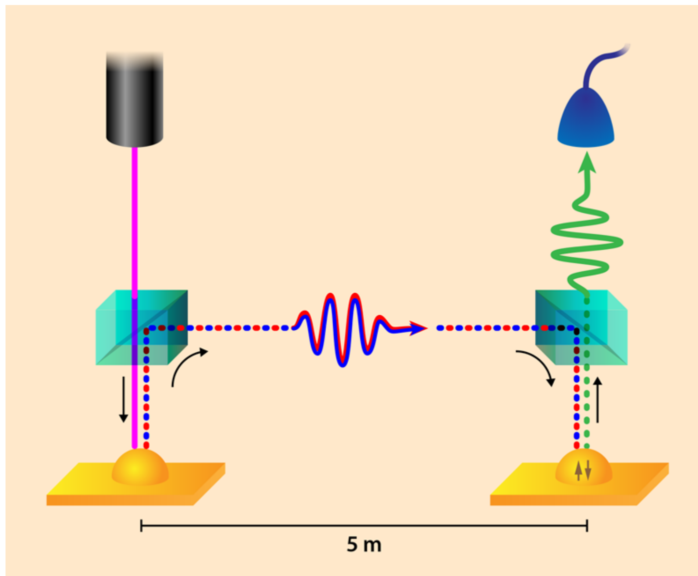

Figure 1: A clever optical system manages to transfer quantum information between two quantum dots (in yellow) separated by 5 m. The first dot on the left is resonantly driven by an incoming laser (pink), causing it to emit a single photon in a superposition of two colors (depicted as red and blue). The photon is subsequently absorbed by the second dot, where the photonic state is encoded in the (up-down) spin state of the dot's resident electron. The successful transfer is heralded by the emission of a photon (green) from the second dot. (APS/Alan Stonebraker)

[5]. A similar photon-electron entanglement was demonstrated in a semiconductor quantum dot [6, 7], a feat that was also achieved by the Zurich group. Other milestones with respect to solid-state quantum interfaces were the entanglement of two solid-state qubits 3 m apart [8], and the storage of photon states in a single nuclear spin [9]. Both these latter experiments used diamond defect centers.

To move forward with these quantum-interface designs, researchers must deal with the inevitable losses in photonic networks. If a single photon is sent over such a network, one can't be sure it will reach its target. That is why there must be some sort of signal that can verify or "herald" the successful transfer of a flying qubit to a stationary one. Previous work on solid-state quantum interfaces either did not have a heralding signal or utilized attenuated light pulses that only mimicked a photonic qubit. Imamoğlu and colleagues have now achieved the desired heralding with a "cascade" of two quantum systems: A single quantum dot generates a flying qubit that excites a secondary quantum dot. The second dot's subsequent relaxation to the ground state occurs via emission of another photon. This photon does not contain any information on the final state, but merely heralds successful state transfer.

In the experiment, two InGaAs/GaAs semiconductor quantum dots (QDs) were used. The first QD, which had two closely-separated excited states, was driven resonantly by a two-color laser in order to emit a single photon in a coherent superposition of two infrared wavelengths, labeled blue and red (Fig. 1). Subsequently, the single photon traveled over a 5-m optical fiber and impinged on the second QD, which was charged with a single resident electron. There, resonant absorption of the photon generated a superposition of two possible excited states. These excited states relax to different ground states, distinguished by the spin orientation of the resident electron. It is these spin states that retain the quantum information carried by the flying qubit. A red photon, for example, would leave the electron in a spin-up state, while a blue photon would produce a spin-down state.

The clever trick in the experiment was tailoring the energy level structure in the second QD in such a way that the transition energies from each excited state to its corresponding ground state were degenerate. In other words, the second QD emits the same color photon (call it green) no matter if the incoming photon is blue or red. In this way, detection of a scattered green photon heralds successful transfer of the photonic quantum state to the spin state of the resident electron in the second quantum dot. However, the green photon doesn't reveal any information about the electron's state, which is important for keeping its quantum nature undisturbed.

The Zurich group tuned the second QD's energy levels with external magnetic and electric fields, but applying strain is a possibility as well. Another crucial aspect of the experiment was background suppression, which the team achieved by employing crossed polarizers that filtered out the strong pump light from the single photon signal. In addition, the researchers enhanced the emission and absorption efficiency of their system by fabricating weak cavities around the dots and adding solid immersion lenses that facilitate the escape of photons from the semiconductor substrate.

The authors' key result was demonstrating a photon-to-spin-state transfer protocol. This involved measuring correlations between the two colors of the generated single photon from the first QD and the two final spin states of the second QD after the transfer was heralded as successful. The correlations were classical in the sense that an incoming red photon resulted in the spin-up state and an incoming blue photon in the spin-down state. A measurement of quantum correlations—in which a red-blue superposition produces an up-down superposition—was not yet feasible. Nevertheless, the group's impressive experiment demonstrated all steps required for a long-distance transfer of quantum information between stationary nodes.

The authors propose to extend their work to a full quantum transfer of arbitrary states—including superposition states—as needed in real quantum networks. For this purpose the transfer success rate has to be enhanced and the spin decoherence of the electrons has to be decreased. Established techniques, such as improving the absorption rate by better optical mode matching and utilizing dynamical decoupling techniques, respectively, could be utilized to achieve these goals. An exciting perspective of the work is to combine heralded quantum-state transfer with quantum error correction. According to the authors, if a total photon loss rate less than 2% is achieved, then qubit transfer with arbitrarily high efficiency will be possible. Finally, one could imagine schemes in which the photon that transfers information to the second QD originates from a different source than the first QD. Therefore, hybrid quantum networks connecting dissimilar physical systems via photons could be envisioned [10].

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