NEWS AND VIEWS

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Single photon-chiral phonon entanglement in monolayer WSe_2

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Entanglement is a defining feature of quantum physics with no classical analog. On the one hand, it is a powerful concept used in the fundamental study of quantum systems, many-body physics and even black hole physics. On the other hand, it is a key resource in quantum communication and information processing. Entanglement has been realized between photons[1], ions[2], spins[3], quantum dots[4] and even larger objects such as macroscopic diamonds[5]. Entanglement involving macroscopic objects is particularly intriguing and holds promise for novel quantum technologies. In a recent paper[6] published in *Nature Physics*, Srivastava and coworkers have unveiled an intriguing entanglement between collective and macroscopic vibration involving billions of atoms of the crystal (phonon) and a single optical excitation of a quantum dot (QD) in monolayer WSe_2 (Fig. 1(a)). This is the first report on single photon entangled with phonon.

According to Lu and Chen, who were directly involved in the study, the use of WSe_2 monolayer with its underlying honeycomb lattice was crucial due to the presence of degenerate chiral phonons which carry pseudo-angular momenta. Moreover, neutral quantum dot in WSe_2 exhibit two linearly polarized emission peaks which can be considered as superposition of circularly polarized valley excitons, mixed due to electron-hole exchange interaction. Owing to conservation of angular momentum, in a photon scattering process, the chiral phonon with pseudo-angular momentum $l = -1$ (+1) phonon can only couple with the σ+ (σ–) state of the single photon emitted by a neutral quantum dot. Due to strong electron-phonon coupling in WSe_2, the authors observed strong phonon replica of the parent neutral quantum dot emission peak which is red-shifted by exactly the energy of a single chiral phonon. As shown in Fig. 1(b), there are two indistinguishable paths by which this replica photon can be emitted, leading to scattering into σ–/σ+ states. As a result, after the scattering process, the state of photon and phonon system is described by an entangled state. Unlike the linearly polarized emission of the parent peak, the polarization of the phonon replica is completely unpolarized as confirmed by both linear and circular basis measurements (Fig. 1(d)). This randomization of polarization is completely unexpected for a coherent Raman-like phonon emission and occurs due to the fact that in their measurement the information about the phonon part of the entangled state is not recovered and as a result, the polarization information of the photon is also lost.

To further confirm this behaviour, the two paths are made distinguishable by lifting the degeneracy of the circularly polarized photon states by applying a small magnetic field in what can be considered as a valley analogue of the Zeeman effect. Indeed the authors observed a recovery of polarization in agreement with the entanglement scheme and also rule out other mechanisms such as the phonon polarization being oriented in arbitrary directions during the emission events.

This novel finding could open up novel possibilities for entangling two distant quantum emitters via a single chiral phonon. The chiral coupling can also be utilized to manipulate the quantum state of the collective excitation (phonon) by an all-op-

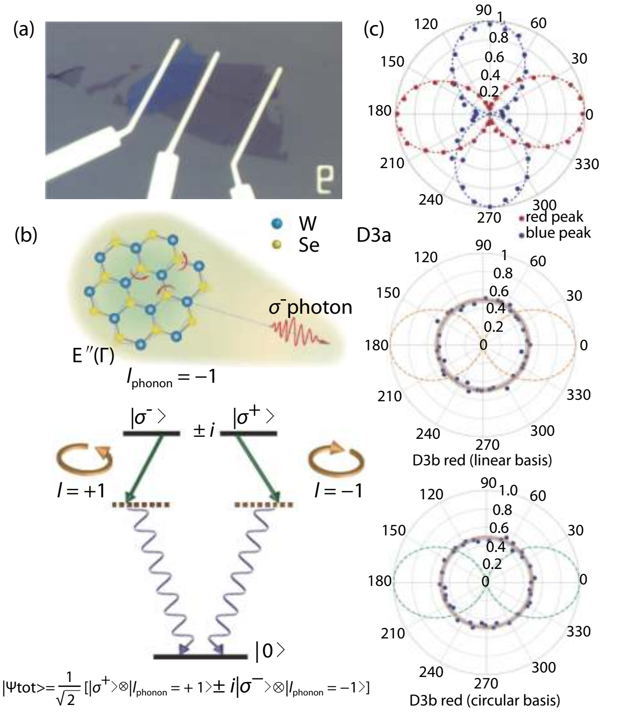

Fig. 1. Phonon-photon interaction in monolayer WSe_2. (a) Optical image of the monolayer WSe_2 FET device. (b) Schematic of phonon-photon entanglement. The circularly polarized states (σ–/σ+) with angular momentum of $l = -1/+1$ are degenerate in WSe_2. The σ–(σ+) photon state can only couple with $l = +1$ (–1) phonon and scatter to σ+(σ–) state due to conservation of angular momentum. The indistinguishability of the two paths leads to phonon-photon entanglement. (c, d) Polarization of QDs and their phonon replicas. D3a doublets are linearly polarized and orthogonal to each other, as expected from a localized neutral exciton. D3b doublets, the phonon replica of D3a, do not show any dependence on collection polarization, indicating that D3b are unpolarized. The lost of polarization information from parent peaks to phonon replicas is a result of phonon–photon entanglement.

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tical control of the QD, possibly leading to non-classical states of phonons. The chiral nature of phonons can also be exploited for non-reciprocal propagation of energy and information at single quantum level. This result also provides a new source of single phonons which benefits from the strong single exciton–phonon coupling in the QDs of two-dimensional materials.

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