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Supporting Online Material

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Entangling Macroscopic Diamonds at Room Temperature

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Quantum entanglement in the motion of macroscopic solid bodies has implications both for quantum technologies and foundational studies of the boundary between the quantum and classical worlds. Entanglement is usually fragile in room-temperature solids, owing to strong interactions both internally and with the noisy environment. We generated motional entanglement between vibrational states of two spatially separated, millimeter-sized diamonds at room temperature. By measuring strong nonclassical correlations between Raman-scattered photons, we showed that the quantum state of the diamonds has positive concurrence with 98% probability. Our results show that entanglement can persist in the classical context of moving macroscopic solids in ambient conditions.

Our intuition about the nature of the physical world is strongly conditioned by the experience that macroscopic solids move according to the rules of classical mechanics. Quantum theory, however, asserts that superpositions and entanglement are possible even for large objects. Therefore, exploration of the persistence of quantum correlations in the traditionally classical realm is important for both fundamental science and technology, because of the implications for physics beyond conventional quantum mechanics (*1*) and for quantum information processing, which requires sustained coherence across many particles (*2*).

The two main barriers for creating superpositions and entanglement in the mechanical motion of macroscopic systems are strong internal interactions, which complicate the dynamics, and strong coupling with the environment, which leads to short decoherence times. The standard approach is to design systems with well-defined and long-lived normal modes that can be selectively excited, and then to cool them to remove thermal noise and isolate them from the environment. Substantial progress has been made toward demonstrating strong quantum signatures in larger systems—for example, in optomechanical (*3*–*5*), molecular (*6*), and superconducting (*7*) systems. Mechanical oscillators can now be cooled to the thermal ground state (*7*–*9*).

A different approach is required, however, to reveal quantum features in the motion of "ordinary" solids in the high-entropy environment present at ambient conditions. Without a specially engineered system, measurements must be made on time scales shorter than the characteristically fast coherence decay times of a real-world system. This can be achieved with ultrashort optical pulses. Recent studies of quantum coherence in biology have used ultrafast probes and interference measurements to establish the persistence of quantum behavior in naturally occurring bulk systems (*10*, *11*). To probe entanglement, however, it is also necessary to access the correlations of the excited modes.

We study excitations of the optical phonon mode in diamond, a bulk vibration consisting of two counter-oscillating sublattices within the diamond structure. The optical phonons are macroscopic, persistent excitations distributed over ~10^{16} atoms within the crystals. The phonons have a very high carrier frequency of 40 THz owing to the extremely strong interactions between neighboring atoms, giving rise to a mechanically stiff lattice. This large energy, compatible with the ultrashort pulses in our experiment (bandwidth ~7 THz), also eliminates the need for cooling or optical pumping, because thermal excitations are negligible at room temperature. The specific experimental protocol that we use is based on the well-known DLCZ scheme (*12*) and previous pioneering experiments in cold atomic ensembles (*13*–*16*). We first create a phonon via spontaneous Raman scattering from a strong optical pump pulse, an event that is simultaneously accompanied by the emission of a Stokes photon (red-shifted from the pump). After this interaction, the joint state of the diamond and the Stokes mode can be written as

$$|\psi_s\rangle \approx \left[1 + \varepsilon_s s^\dagger(t_s) b^\dagger(t_s)\right] |\mathrm{vac}\rangle \qquad (1)$$

where $|\varepsilon_s|^2 << 1$ is the scattering probability and $|\mathrm{vac}\rangle = |\mathrm{vac}_{opt}\rangle \otimes |\mathrm{vac}_{vib}\rangle$ is the joint optical and vibrational vacuum state containing no photons and no phonons; s and b are the bosonic annihilation operators for the Stokes and phonon modes, respectively, evaluated at the time t_s when the pump pulse exits the diamond. Equation 1 describes an entangled state of optical and material modes, which is already nonclassical. To entangle two diamonds, we simultaneously pump two separate crystals—producing the state $|\Psi_s\rangle = |\psi_{sL}\rangle|\psi_{sR}\rangle$, where L and R denote the left and right diamonds, respectively—and we combine their Stokes modes on a polarizing beamsplitter (Fig. 1). The Stokes modes are caused to interfere with relative phase φ_s by means of a half-wave plate and polarizer. Detection of a Stokes photon at a detector D_s placed behind the polarizer corresponds to application of the measurement (*17*) $E = \langle \mathrm{vac}_{opt}|s(t'_s)$, where t'_s is

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