QUANTUM PHYSICS

Photons paired with phonons

The force exerted by light on an object has been used to pair photons with quantum units of mechanical vibration. This paves the way for mechanical oscillators to act as interfaces between photons and other quantum systems. SEE LETTER P.313

MILES BLENCOWE

Quantum entanglement[1] is a bizarre state in which it is meaningless to describe the properties of individual objects in a collection; only the properties of the collection as a whole may be described. On page 313 of this issue, Riedinger *et al.*[2] report the quantum pairing of light and vibrations of microscopic mechanical oscillators comprising more than 10^{12} atoms — large for a quantum object. This is a big step towards the goal of using light to achieve the quantum entanglement of the vibrational motion of two widely separated mechanical oscillators, aiding the development of quantum-information processing systems that have practical applications.

Riedinger and colleagues exploit the fact that light shining on an object exerts a force[3]. If the object is a freely suspended wire that is clamped at both ends, such as a silicon nanobeam, then an incident light pulse will set it vibrating, like tapping a bell with a hammer. The silicon nanobeam used in the authors' experiments was about 15 micrometres long, 500 nm wide and 250 nm thick, and was engineered so that a fraction of the incident light from a near-infrared laser source could be trapped in a segment of the nanobeam.

This segment functions like an optical cavity (a system used to trap light at certain frequencies known as resonances), in which the cavity length is comparable to the wavelengths of both the light and of a particular vibrational mode of the nanobeam. The force exerted by the light is considerably enhanced[4] by co-locating the optical cavity and the vibrating regions, rather than letting the light 'tap' the nanobeam from the outside. The mechanical-vibration mode is driven from within by the trapped light, and manifests as a 'breathing' mode: rapidly alternating expansions and contractions of the beam's width at about 5.3 gigahertz.

At the very low light intensities used in Riedinger and co-workers' experiments, a quantum description of the system is necessary in which the light consists of photons and the vibrational energy of the nanobeam comes only in discrete lumps called phonons. Describing the action of the light force at the quantum level, an incident photon can emit and hence create a phonon only if the energy lost by the resulting scattered photon corresponds to the resonance frequency of the cavity[3] (Fig. 1a). Similarly, an incident photon can absorb and hence annihilate a single phonon only if the energy of the resulting scattered photon corresponds to the resonance frequency of the cavity (Fig. 1b). Higher-energy incident photons that can emit phonons are said to be blue-detuned with respect to the cavity's resonance frequency, whereas lower-energy incident photons that can absorb phonons are red-detuned.

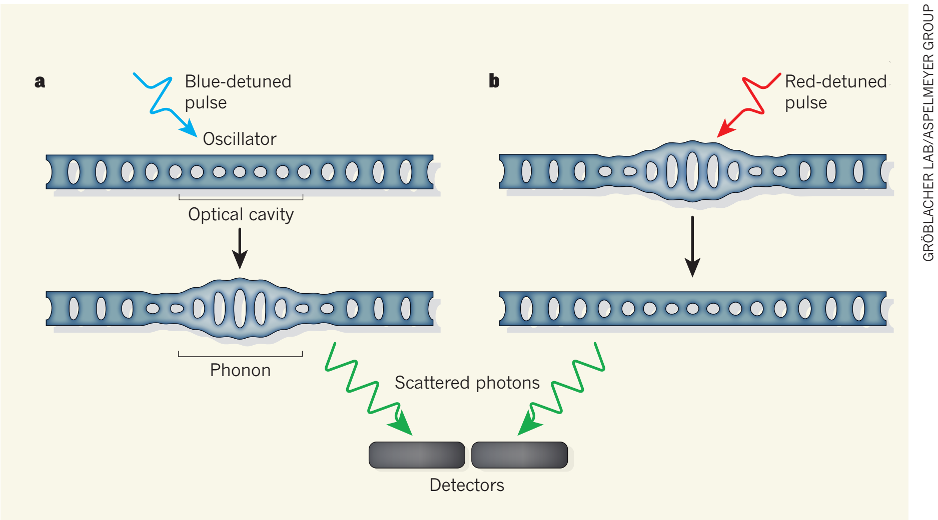

Figure 1 | A photon–phonon interface. **a**, Riedinger *et al.*[2] shone pairs of light pulses on a microscopic mechanical oscillator (a silicon nanobeam) that also incorporated an optical cavity — a section with different-sized holes that traps standing waves of light at a resonant frequency. The first light pulses in each pair were blue-detuned (their energy is slightly higher than the resonance frequency of the optical cavity) and could induce the formation of a single phonon (a quantum unit of vibration) in the oscillator and produce a scattered photon at the resonance frequency. **b**, The second pulses were red-detuned (with slightly lower energy than the resonance frequency) and could absorb the single phonon from the nanobeam, again generating a scattered photon at the resonance frequency. By measuring the joint probabilities of scattered photons produced from the two types of light pulse, the authors established that the number of photons in the cavity correlates with the number of phonons.

Riedinger *et al.* cooled the silicon nanobeam to a few hundredths of a kelvin, and verified that the vibrational breathing mode was in its quantum ground state, to a good approximation — the breathing mode did not contain even one phonon for about 97% of the time. They then fired a long train of pairs of laser light pulses (a few tens of millions) at the nanobeam, for which the intensity of the individual pulses was sufficiently low, and the intervals between the pulse pairs were sufficiently long, to allow the nanobeam breathing mode to relax to its quantum ground state before the arrival of the next pulse pair.

The first pulse in a given pair was blue-detuned, enabling the pulse to 'write' a phonon into the nanobeam breathing mode, whereas the second pulse was red-detuned, potentially allowing it to 'read' a phonon out of the mode. The authors tuned the time interval between a given pulse pair, from a delay of one-tenth of a microsecond to a few microseconds, to determine how long the breathing mode could store a single phonon for. The scattered light produced from the nanobeam was split into two, and each half was directed to a different single-photon detector; each detector registered a voltage pulse only for a scattered photon that had written or read a phonon. Having two single-photon detectors enabled the detection of two scattered 'write' or 'read' photons resulting from the same light pulse. The probability of such detection events is extremely low because of the inherent weakness of the photon force and the low photon-detection efficiencies, which is why so many pulse pairs were needed.

Riedinger and colleagues observed that the joint probability of detecting a scattered 'write' photon and a subsequent scattered 'read' photon significantly exceeds the joint probabilities of detecting two scattered 'write' photons or two scattered 'read' photons for the same pulse pair. This inequality, together with measurements of the latter two joint probabilities, provides strong evidence that the blue-detuned 'write' pulse puts the experimental system into a correlated quantum state, in which the number of photons in the cavity is always paired with the same number of phonons in the mechanical breathing mode. In particular, when the cavity is in the vacuum state (no scattered 'write' photons detected), then the mechanical mode must also be in the quantum ground state (no phonons). And for the rarer situation in which the cavity contains a single photon (one scattered 'write' photon detected), then the mechanical mode must also contain a single phonon. This photon–phonon pairing is the key result of the experiment.

The authors find that the correlated quantum states persisted for up to about 1 μs, well short of the time taken for the vibrations of the breathing mode to dissipate (a few tens of microseconds). This might be because the nanobeam heats up during each 'write'-pulse stage. The storage lifetime of phonons might be lengthened by reducing the pulse intensities.

Having convincingly demonstrated a photon–phonon interface, a striking next step would be to generate an entangled quantum state that involves a single, breathing-mode phonon at the micrometre-wavelength scale on two silicon nanobeams separated from each other by up to 1 m or more. This could be achieved by bringing together 'write' photons scattered from both nanobeams and allowing them to interfere before being detected[5]. While the entangled state survives (possibly for up to a few microseconds), it would be meaningless to ascribe the phonon to one of the nanobeams and the vibrational ground state to the other. All that could be said is that the two nanobeams collectively possess the single phonon of vibrational energy — a bizarre state of affairs indeed. Such an entangled state has previously been demonstrated, but with much shorter-lived, higher-frequency (tens of terahertz) phonons[6].

The ability to couple gigahertz and lower-frequency mechanical quantum-vibrational motion to other quantum systems (consisting of, for example, a few atoms, electrons or microwave photons) would allow nanomechanical resonators to serve as versatile interfaces that facilitate the transfer of quantum states between light and these other systems[7]. Together with the ability of light to transmit quantum states over large distances, this would enable entanglement to be distributed between widely separated quantum systems — which would be useful for quantum information-processing applications. ■

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ANTHROPOLOGY

Hand of the gods in human civilization

Cross-cultural experiments find that belief in moralistic, knowledgeable and punishing gods promotes cooperation with strangers, supporting a role for religion in the expansion of human societies. SEE LETTER P.327

DOMINIC D. P. JOHNSON

In the modern world, we rely on governments, courts and the police to deter and punish those who would otherwise undermine social cooperation. But how did human societies achieve and sustain cooperation before these institutions existed? One possibility is religion: under the watchful gaze of supernatural agents, people modify their behaviour in an effort to avoid the wrath of the gods. In this issue, Purzycki *et al.*[1] (page 327) report a cross-cultural field-study finding that people are consistently more willing to give money to strangers of the same religion if the donor believes in a god that is moralizing (concerned about good and bad behaviour), knowledgeable (aware of one's thoughts and actions) and punishing (able to exact harm).

Pioneering anthropologists, such as Émile Durkheim and Bronisław Malinowski in the early twentieth century, have long argued that supernatural beliefs offer a powerful way to build materially cooperative societies. But in

Figure 1 | Weighing of the heart. This papyrus manuscript, a detail from the ancient Egyptian 'Book of the Dead' called *Papyrus of Ani*, depicts a scene in which the dead Ani's heart is weighed against a feather, representing Maat, goddess of truth and justice. At the top of the scene are the great Egyptian gods, ready to pronounce judgment on whether Ani should be granted entrance to the afterlife or banished to the underworld.