with temperature that corroborates their mobility and, in principle, polability.

There may still be other, entirely unexplored types of ferroic order. Thanks to Jin and colleagues we now have candidates for all the vector-like forms of ferroic order. Yet there is only one type of ferroic order so far parameterized by a higher-rank tensor, namely ferroelasticity. Furthermore, apart from the non-local distribution of magnetization, polarization or displacement across the crystallographic unit cell, the spontaneous order may occur locally, as uniform multipolar distribution of magnetic and electric charges on the ions themselves[8].

At present, the ferro-rotational, ferrotoroidic and ferro-multipolar types of order face the problem that the exact nature of the conjugate field is ill-defined. This discussion is crucial for deciding to what extent the new materials can actually be regarded as ferroic. We have conjugate magnetic, electric and stress fields for the established ferroics, but there is no device that would, for example, generate a conjugate 'rotational field'. In the case of $RbFe(MoO_4)_2$, it is a combination of four electric fields and it is yet unclear how this relates to the existence of a solitary conjugate field that the definition of a ferroic requires[5].

On the other hand, there is still much to discover in the known ferroics. For example, the definition of a ferroic state is strictly macroscopic[3] so it is not quite correct to rigidly associate ferromagnetism with the quantum-mechanical exchange interaction. Irrespective of the microscopy, a spontaneous magnetization adhering to the criteria of a ferroic would be called ferromagnetic, and in fact, ferromagnetics driven by the classical magnetic dipole interaction are now being considered[9]. Similarly, research on multiferroics — materials that exhibit more than one form of ferroic order — leads to the realization that there are many sources for ferroelectricity beyond the atomic displacements that generate electric dipoles as in $BaTiO_3$ (ref. [10]). ❐

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NANOELECTROMECHANICS

Currents cool and drive

Electrons driven through a suspended carbon nanotube by a constant bias excite mechanical vibrations — including self-sustaining oscillations — and, in some cases, even suppress them down to only a few quanta.

Martino Poggio and Nicola Rossi

By virtue of their tiny mass and high mechanical quality, suspended carbon nanotubes react to minute forces, making them record-setting force sensors[1]. At the same time, they host a range of electronic transport phenomena[2]. Now, writing in *Nature Physics*, two groups of researchers — led by Adrian Bachtold[3] and Edward Laird[4] — have reported that simply flowing a constant current through a nanotube can excite self-sustaining oscillations or even suppress its motion to such an extent that its fundamental mode is left with only a few quanta of vibrational energy.

Electromechanical effects have been exploited for hundreds of years, notably in the design of mechanical electrometers, such as Coulomb's torsion balance (Fig. 1a), to measure electric charge. Today, nanomechanical devices are ever more susceptible to small forces and thus to the effects of individual charges. In particular, carbon nanotubes are sensitive enough that the force exerted by an electron can be larger than both quantum and thermal force fluctuations. This strong electromechanical coupling also means that the slightest motion of the nanotube can affect the flow of electrons through the device, making a suspended nanotube an excellent electromechanical transducer that converts mechanical motion into electrical current and vice versa (Fig. 1b).

The ultimate sensitivity of this transducer is set by quantum uncertainty, which relates the minimum measurable mechanical displacement to a minimum force exerted by this measurement. In real devices, such as the ones studied in both experiments, these so-called back-action forces are much larger than this lower limit. Nevertheless, the natural feedback created by the relationship between sensitivity and back-action sets the stage for the experimentalists' latest observations.

Bachtold and colleagues have shown that vibrations of a suspended nanotube can be both amplified and damped by driving a constant electrical current through it. The amplification can lead to self-sustaining oscillations, while the damping — by drastically reducing the vibration amplitude — can 'cool' a mechanical mode to just five quanta of vibrational energy. This result is striking not only because it represents a 40-fold improvement of the best previous electron-mediated mechanical cooling[5], but mostly because it has been obtained by simply passing a current through the device.

The researchers attributed the observed amplification and damping to an electrothermal effect. Joule heating due

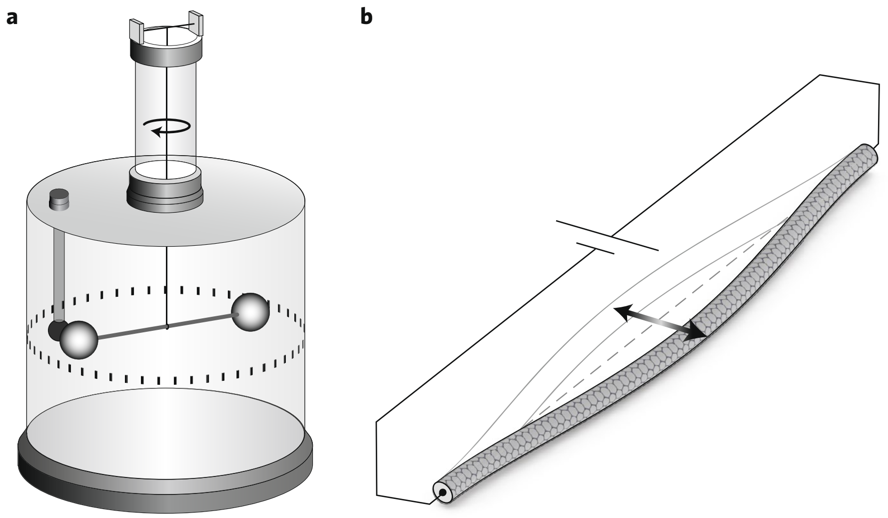

Fig. 1 | Electromechanical forces. a, A Coulomb torsion balance used to measure electrostatic forces since the eighteenth century. The electrostatic force between two charges acts on the suspended rod resulting in a measurable rotation. **b**, A current flowing through a suspended carbon nanotube excites self-sustaining oscillations.

to current flow modified the tension of the nanotube through thermal expansion, resulting in a back-action force delayed by both the circuit capacitance and the thermalization of the device. This retarded force then accounted for the observed amplification and damping. It is especially surprising that resistive heating, which increases the nanotube's overall temperature, can be used to extract energy from one of its mechanical modes, ultimately bringing it close to its ground state. An analogous photothermal effect has been shown to cool optomechanical systems, but it has never successfully put a resonator close to the quantum regime because of the heating associated with optical absorption.

Laird and colleagues also observed strong effects on the motion of their nanotube device due to a constant current. In particular, their study focused on the amplification regime, in which the nanotube executed self-sustained oscillations. In many ways, this behaviour was analogous to a laser only with the optical field replaced by the mechanical displacement. Exploiting this similarity, the researchers used techniques from laser physics to stabilize the nanotube oscillator's frequency, thereby extracting its intrinsic mechanical linewidth, rather than a linewidth limited by charge noise, surface contamination and other external factors, all of which could, in principle, be eliminated by better fabrication or filtering. The researchers attributed the retarded back-action force that drives the nanotube oscillations to a combination of device capacitance and delayed electron tunnelling, although an electrothermal mechanism, like the one observed by Bachtold and colleagues, may also be present.

In the past 10 years, experimentalists have succeeded in reducing the effective temperature of mechanical modes to the ground state in a variety of nanometre to millimetre-scale systems. At cryogenic temperatures, it is not particularly surprising to find gigahertz-frequency mechanical modes in the ground state, since the thermal energy at 100 mK is equivalent to that of a 2.1 GHz phonon. In fact, in a suspended nanotube device similar to those of Bachtold and colleagues and of Laird and colleagues, a 31-GHz mechanical mode in its ground state was exploited to measure the torque produced by the magnetic reversal of an individual molecular magnet[6].

Such cooled modes only become significant when they can be measured, initialized and manipulated, in order to study their quantum nature or exploit them for sensing applications. This can be achieved by coupling the modes to other degrees of freedom, such as optical modes, electrical transport or magnetic moments. In a restricted set of systems, researchers have already demonstrated quantum-limited measurements of displacement; they have created single phonons, and they have taken the first steps to full quantum control of mechanical modes. These feats were first realized by cryogenically cooling a gigahertz-frequency mode and coupling it to a superconducting qubit[7] and later by using a variety of optomechanical systems that exploit cavity effects[8,9] or electronic feedback[10] to reduce the occupation of modes with frequencies as low as 1 MHz. Quantum states of low-frequency modes are particularly interesting, because they involve extended objects with large and easily observable displacements.

The possibility of bringing electromechanical systems into the quantum regime by simply applying a d.c. current is therefore very enticing. If the technique in these two experiments[3,4] can be applied to other suspended devices — such as nanowires and graphene — quantum control over motional states may soon become possible not only in optomechanical, but also in electromechanical systems. ❐

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