QUANTUM MATERIALS

One-way express ticket to quantum criticality

Dislocations engineered through plastic deformation are shown to enhance quantum fluctuations and superconductivity in $SrTiO_3$.

Mingda Li and Yao Wang

With a paper clip in hand, how to rapidly harden it? The answer is simple and can be done by hand: unbend it, bend it back, and after a few rounds of back and forth, you may find it's more and more difficult to deform — the paper clip is work-hardened. At a microscopic level, the planes of atoms in the deformed clip slip relative to each other, and there are numerous tiny, atomic-scale objects being multiplied in these atomic planes. These tiny, line- or ring-shaped objects, termed dislocations[1], are not anything resembling shoulder injury, but rather atomic-scale crystal lattice imperfections. There is no way to eliminate these dislocations after they are created, at least under regular conditions. Consequently, the multiplied dislocations will intertwine and prevent each other's motion, thus increasing the strength of the material.

For decades, it has been widely accepted that dislocations play a dominant role in mechanical properties, and can further tailor the electrical, optical and thermal properties[2]. However, unlike chemical doping, temperature or pressure, dislocations are generally considered as a tuning knob for classical structures and semi-classical properties, rather than quantum fluctuations, which arise primarily from electronic correlations. Now, writing in *Nature Materials*, Sanja Hameed and colleagues report that plastically deforming $SrTiO_3$ (STO) — a quantum paraelectric material displaying superconductivity[3] and promising energy applications[4] — is found to trigger unconventional superconducting phases[5] (Fig. 1a,b). The resulting superconducting transition temperature, T_c, shows a substantial enhancement by nearly threefold from 0.3 K in an undeformed sample to ~0.8 K in the plastically deformed sample. Signatures of superconducting correlation are observed up to 30–50 K, two orders of magnitude above T_c, as inferred from the anisotropy and temperature dependence of resistivity. This anomalous 'normal state' indicates a crucial role of quantum fluctuations.

On a quantitative level, such enhancement cannot be explained by the conventional dislocation scattering theory, but is found to be consistent with enhanced fluctuations in the proximity of a ferroelectric quantum critical point. This quantum critical point is usually unstable in single-crystal bulk STO. However, Hameed and colleagues show that it can be realized by utilizing dislocations. The effect of dislocations can be regarded as a combined effect of a substantial strain and dynamic fluctuations to the lattice structure[6], mimicking a negative pressure that cannot be realized by traditional control knobs. A consequence of the proximity to a quantum critical point is a dramatic softening of the transverse optical phonon mode. At the same time, both the Raman and magnetic susceptibility diverge at zero temperature and quantum fluctuations become extremely strong (Fig. 1c).

Engineering quantum fluctuations has a broader impact on the design and discovery of materials. New phases emerge from quantum materials because of the interplay of multiple degrees of freedom at comparable energy and timescales. Superconductivity is a well-known example. To overcome the repulsive Coulomb interactions between electrons and bind them as Cooper pairs, attractive interactions have to be mediated by bosonic excitations, in the same way virtual photons mediate the Coulomb force, to counteract the repulsion. Phonons seem to be the most common

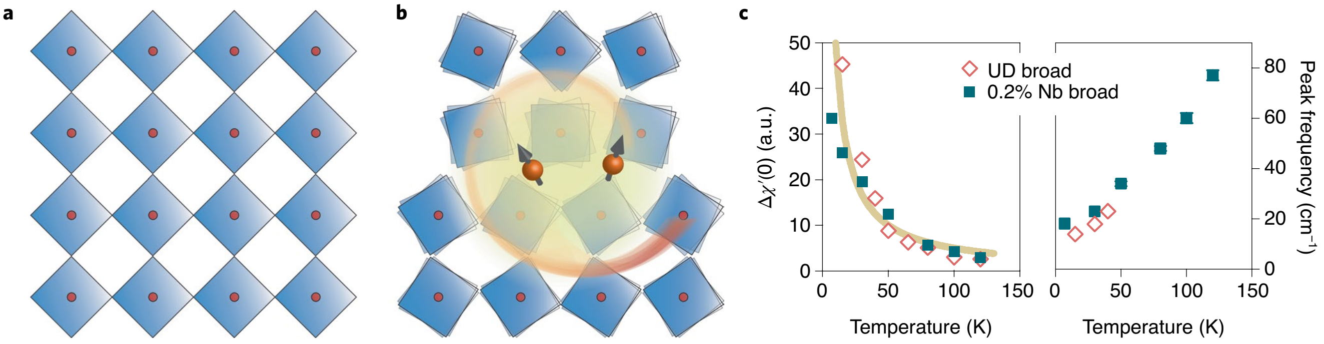

Fig. 1 | Schematic and experimental signatures of dislocation-enhanced fluctuations. a,**b**, Crystal structure of a perfect crystal (**a**) and a plastically deformed crystal (**b**), in which enhanced quantum fluctuations can be induced through dislocation formation. This mediates stronger coupling of Cooper pairs (red electron pairs) and thereby enhances superconductivity. **c**, The Raman susceptibility ($\Delta\chi'(0)$; left) and the Raman phonon frequency data (right) as a function of temperature in plastically deformed STO without carrier doping (UD; red diamonds) and with Nb doping (green squares). The divergence of the susceptibility with a $1/T$ dependence and phonon softening at low temperature indicate entering into a quantum critical regime. These behaviours are insensitive to the carrier doping levels, which further hints at a structural and phononic, rather than purely electronic, origin. a.u., arbitrary units. Panel **c** reproduced with permission from ref. [5], Springer Nature Ltd.

medium of such attractions. However, acting as a medium, such bosonic excitations have to be fluctuating instead of condensed. In the case of phonon-mediated Bardeen–Cooper–Schrieffer superconductors, a very strong electron–phonon coupling increases the binding energy of Cooper pairs and may favour an insulating charge-density wave over superconductivity[7]. A similar situation also exists for high-T_c cuprates, where spin excitations — the suspected pairing glue — condense into an antiferromagnet and prohibit superconductivity. Therefore, a design philosophy towards a better superconductor lies in both the strong coupling between electrons and the bosonic modes, and non-condensation of these modes. Dislocations provide a new tool to fluctuate phonons without evident suppression of the electron–phonon coupling. Such a fluctuation is maximized when the system is close to a quantum critical point.

The work of Hameed and colleagues adds quantum criticality to the properties that dislocations can tune, and presents dislocations as a new tuning knob to tailor electron correlation properties through fluctuations. Given the importance of quantum fluctuations to strongly correlated materials, and the link of dislocations to more exotic excitations such as fractons[8] and charge-density waves with electronic topological defects[9], we can anticipate a more prominent role for dislocations in tuning the interplay between the charge, spin, orbital and lattice degrees of freedom. ❐

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Competing interests

The authors declare no competing interests.

NEUROMORPHIC SPINTRONICS

Synchronization by memristors

Integration of memristors in a chain of nano-constriction spintronic oscillators allows for individual control of oscillation frequencies and emerging synchronization patterns. The control of such synchronization could enable learning through association like neurons in the brain.

Danijela Marković

Spintronic oscillators have been identified as compelling candidates for artificial hardware neurons[1]. Biological neurons produce action potential spikes at a frequency that depends nonlinearly on the current they receive from other neurons; similarly, spintronic oscillators emit a microwave voltage whose amplitude depends nonlinearly on the input current. Now, writing in *Nature Materials*, Mohammad Zahedinejad and colleagues report on a demonstration of systems of two and four spintronic oscillators whose oscillations can be controlled using two spintronic memristors[2]. This work combines two key advances: the realization of oscillators in the shape of nano-constrictions[3], which greatly simplifies fabrication compared with other approaches, and the non-volatile individual control of each oscillator. Such artificial neurons have promising applications in neuromorphic computing hardware that mimics the brain and its topology, where multiple processing units (neurons) are interconnected through memory units (synapses). This distributed architecture has been found to be much more energy efficient than conventional digital computers that separate central

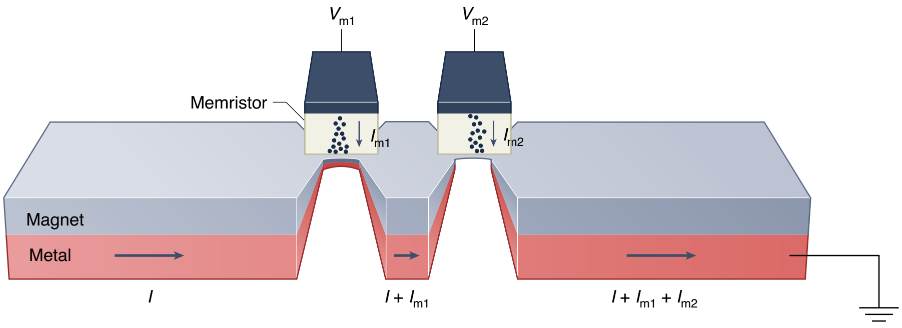

Fig. 1 | Chain of two nano-constriction spintronic oscillators with two integrated memristive gates above them. When voltages V_{m1} and V_{m2} are applied to each of the memristors, memristors' currents I_{m1} and I_{m2} are added to all the oscillators between the corresponding memristor and the ground. Figure adapted with permission from ref. [2], Springer Nature Ltd.