that Claassen and colleagues theoretically show how to induce transitions by means of sufficiently strong electromagnetic drive.

The qualitative idea is simple and elegant: application of an electromagnetic field can reduce the symmetry below that of the underlying crystal. For instance, application of a linearly polarized field can break the symmetry between p_x and p_y, and a circularly polarized field will do the same between $p_x + ip_y$ and $p_x - ip_y$ superconducting states.

Now, suppose we'd like to switch between the two chiral states, for example from $p_x + ip_y$ to $p_x - ip_y$. This can be done in two steps. First, apply linearly polarized light (red line in lower panel of Fig. 1) to make a particular polar state, for example p_x favoured. Since the evolution tends to follow the lowest energy branch, this leads to the evolution $p_x + ip_y \rightarrow p_x$ as shown by the dashed line in the upper panel of Fig. 1. Once the order parameter is near p_x, it is an equal superposition of the two chiral states, so a kick in the direction of $p_x - ip_y$, provided by a properly chosen circularly polarized light pulse (blue line in the lower panel of Fig. 1), will bias the system towards the target state.

As concrete examples, the authors model Sr_2RuO_4 and graphene, which are thought to be chiral *p*-wave and chiral *d*-wave superconductors, respectively. They start with realistic band structures of each material, and then apply a non-equilibrium mean field treatment. The calculations confirm their qualitative idea. Among the observables that can be used to test their scenario experimentally, they compute the time-resolved electronic spectral functions, which should be accessible in pump–probe experiments. While the calculations cannot be treated as physically exact given a number of simplifications that the authors had to make, they provide a physically transparent first approximation to this non-trivial problem.

One reason that chiral and other topological superconductors have attracted much attention recently is due to their potential application for topological quantum computing. Topological superconductors host Majorana fermion modes inside vortex cores. Being non-Abelian excitations, braiding of a pair of Majorana modes around each other induces transitions between many-body ground states of the superconductor, thus implementing a quantum operation. An appealing proposal has been made recently that circuits of propagating Majorana edge modes can also implement quantum operations, encoded in the topology of the edge mode network[2,3]. The approach proposed by Claassen and co-authors may help to program such circuit topologies with light by creating distinct domains of chiral superconductors.

However, it is important to mention that there are currently no unambiguously confirmed topological superconductors, although Sr_2RuO_4, UPt_3 and doped Bi_2Se_3 appear promising[4]. An exact identification of the type of superconductivity in these materials remains a challenging task. In fact, the pump–probe techniques of the type described by Claassen and colleagues may help in identification.

Ultrafast manipulation of correlated states of matter has emerged as an exciting new frontier in condensed matter and materials science[5]. Among experimental discoveries are signatures of light-induced superconductivity[6] and density wave orders[7]. New theoretical tools needed to understand correlated dynamics are currently being developed[8,9]. The confluence of experimental and theoretical advances is expected to lead to a clearer picture of these exciting physical phenomena, and will enhance our ability to control complex dynamics as it unfolds in space and time. ❒

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CHARGE DENSITY WAVES

Putting the gap on the map

The measurement of the charge density wave energy gap in high-temperature superconducting cuprates uncovers new links between competing states.

Jiarui Li and Riccardo Comin

Interactions between electrons in a low-dimensional metal will generically lead to an instability in its ground state at low temperature. This instability results in the emergence of collective electronic phases that break the symmetries of the high-temperature electronic fluid, and often open a gap in the band structure of the material at the Fermi energy (Fig. 1a,b). Charge density waves (CDWs) and superconductivity are two different forms of electronic order that open such a gap[1]. Now reporting in *Nature Physics*, Bastian Loret and co-workers have measured the CDW gap in various cuprates[2]. These observations not only unveil a key and elusive property of the CDW state, but also elucidate the relationship between these two intertwined phases in high-temperature superconductors.

The CDW and superconducting ground states arise from a coherent superposition of electron–hole and electron–electron (Cooper) pairs, respectively. These phases are, in a sense, quantum-mechanical twins, engaged in a sibling rivalry: while CDWs manifest as static ripples of the density of the electrons, the superconducting state is a dissipationless quantum fluid formed by a uniform, coherent superposition of Cooper pairs. They both appear in many strongly correlated electron systems, most notably in the high-temperature superconducting copper oxides. Here, they are in competition

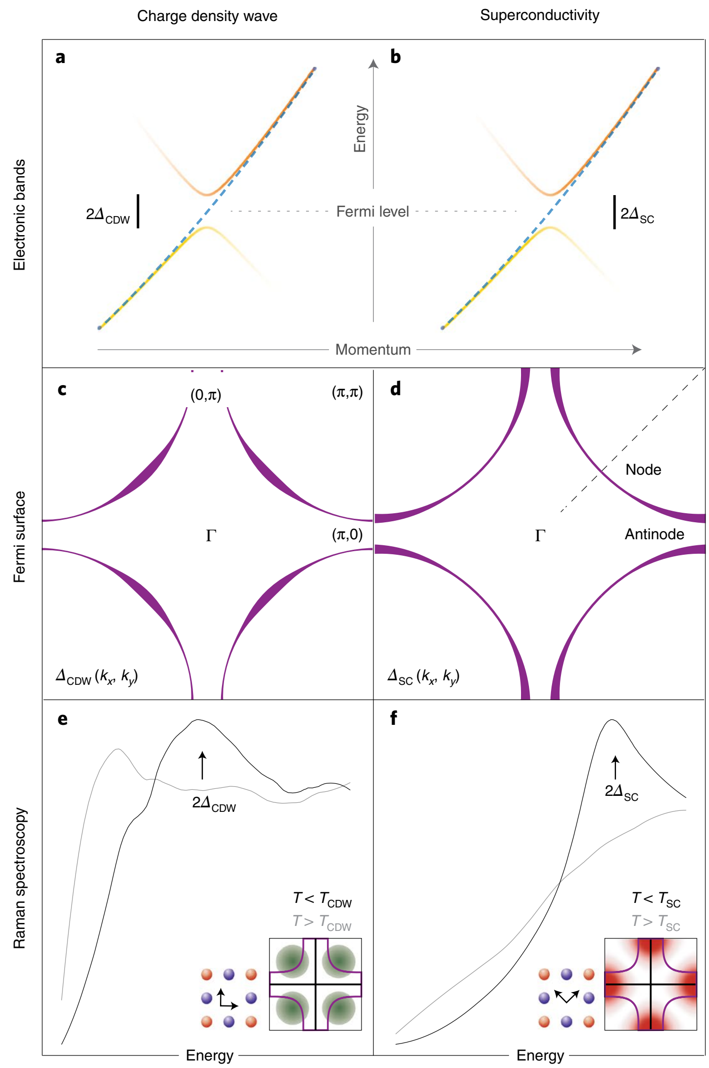

Fig. 1 | Comparison of charge density wave and superconducting systems. a,**b**, Momentum-energy representation of single-particle electronic bands of a correlated metal as it develops long-range CDW (**a**) and superconducting (**b**) order. The dashed blue line represents the bare bands in the absence of interactions. On formation of the ordered phase, an energy gap ($2\Delta_{CDW}$ or $2\Delta_{SC}$) opens at the Fermi level, modifying the quasiparticle dispersions (yellow and orange). **c**,**d**, Illustration of the CDW (**c**) and superconducting (**d**) gap functions overlaid on a representative cuprate Fermi surface. The gap amplitudes are represented by the linewidth. In **d**, the dashed line shows one direction in which the superconducting gap has a node (that is, where the gap is zero). **e**,**f**, Schematics of the Raman response in the CDW (**e**) and superconducting (**f**) states. A common feature is the depletion of spectral weight at subgap energies and resulting redistribution of Raman intensities at $2\Delta_{CDW}$ or $2\Delta_{SC}$. The insets show the regions of the Brillouin zone that are probed by Raman scattering using photons with polarization indicated by the double arrows. Raman spectra in **e** and **f** are adapted, respectively, from refs. [2,5], Springer Nature Limited.

in the underdoped region of the phase diagram[3]. Although the superconducting state has been broadly studied, the CDW instability has been extensively mapped out only in recent years. Yet, one of the defining traits of CDW order — the single-particle energy gap — has not been measured before.

To understand the energy gap, imagine a simple Fermi gas picture, where a non-interacting electron band crosses the Fermi energy at the Fermi momentum. When the electrons interact strongly, low-energy fermions pair up and condense into a quantum many-body ground state whose quasiparticle excitations are gapped at the Fermi energy (Fig. 1a,b). The size of the CDW or superconducting gap, Δ_{CDW} or Δ_{SC}, directly reflects the interaction strength.

The study of CDW phenomena has been a central theme of condensed-matter physics for over half a century and was reignited recently in the family of cuprate superconductors. The self-organization of electrons into periodic charge modulations breaks the native translational symmetry of the lattice. In the canonical Peierls picture in one dimension, the CDW order, with density-wave propagation vector $\mathbf{Q}_{CDW}$, manifests three key experimental signatures: (1) a periodic lattice distortion with wavelength $\lambda = 2\pi / |\mathbf{Q}_{CDW}|$; (2) a reduction in the energy of phonons with wave vector near $\mathbf{Q}_{CDW}$; and (3) the opening of a single-particle energy gap Δ_{CDW} at the Fermi level[1]. Considering the interplay between the CDW and superconductivity in the cuprates, and the ample body of evidence on the superconducting gap[4,5], the lack of information on the CDW energy scale has been a central issue that has hindered quantitative modelling of this phenomenology.

In this context, the measurement of the CDW energy scale and single-particle gap Δ_{CDW} by Loret and colleagues is a very important result. They have systematically evaluated Δ_{CDW} in three different cuprates using polarized electronic Raman spectroscopy. This technique is a probe of particle-hole excitations across the Fermi energy, and as such is sensitive to the opening of gaps in the quasiparticle energy spectrum. Unlike the superconducting gap, which is present for all states across the Fermi surface (Fig. 1d), the CDW gap opens up only around the regions connected by the CDW propagation vector $\mathbf{Q}_{CDW}$, as shown in Fig. 1c. In addition to Δ_{SC} and Δ_{CDW}, a pseudogap is also present near the anti-nodal points at $\mathbf{k} = (\pi, 0)$ and $(0, \pi)$, and, like the superconducting gap, is zero in the nodal direction. Using a specific combination of light polarizations, Loret and colleagues selectively measured the Raman response of the near-nodal regions of the Brillouin zone, where the CDW gap can be probed without interference from the superconducting gap or the pseudogap.

On cooling below the CDW transition temperature T_{CDW}, the Raman spectral weight is redistributed from low to high energies, signalling the opening of a CDW gap (Fig. 1e) in the form of a dip-and-hump structure akin to the one well known to occur in the superconducting state (Fig. 1f). The temperature dependence of the CDW Raman signatures closely tracks the onset of the ordered state and its interplay with superconductivity and the pseudogap in all samples. Furthermore, these experimental results reveal the distinct doping dependence of T_{CDW} and Δ_{CDW}, with the former tracing a dome-like shape while the latter decreases monotonically for increasing doping, as also observed for the pseudogap[5]. This correlation between Δ_{CDW} and Δ_{SC} and the strikingly similar gap size and pairing strength of the CDW and superconducting orders underscores a new important connection between these competing phenomena.

The measurement of the CDW energy scale in cuprate superconductors unveils essential details of the most recent entries of the club of electronic orders in unconventional superconductors. The experimental information uncovered by Loret and co-workers is a step towards a more complete understanding of intertwined electronic orders and moves closer to exposing the driving forces hiding behind the variegate phase diagram of high-temperature superconductors. ❒

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