Editorial

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A deeper understanding

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The scientific community has become more aware of issues surrounding reproducibility. We should remain cognizant that as we develop better understanding we can revise our knowledge of a problem and scientific findings that are considered valid today might not be in the future.

Mapping out the electronic phase diagram of superconducting materials is a common approach toward developing a more complete understanding of the key ingredients that allow certain materials to superconduct at high temperatures. Phases characterized by spin, charge, orbital and lattice degrees of freedom may compete or coexist with each other (Fig. 1). It is often the case that these phase diagrams become more detailed and complex as more powerful experimental methods are applied to probe these materials.

An exemplary case is the establishment of charge order across several families of copper oxide high-temperature superconductors, or cuprates. While charge order had been already identified in the phase diagram of some cuprates, its near universal detection came about from the continued development of resonant X-ray scattering at synchrotron X-ray sources[1]. A charge density wave (CDW) is a modulation of the electronic structure of a material that can be commensurate with the underlying crystal structure, or in some cases independent of it, known as an incommensurate modulation. While such a modulation might be apparent with standard X-ray diffraction, the signal can be tiny, rendering the use of tunable synchrotron X-ray beams resonant with the elements under consideration necessary to enhance the signal. In addition, energy discrimination provided by advanced spectrometers allows experimentalists to further isolate the signals.

Following the long-anticipated discovery of superconducting nickelates[2], scientists swiftly applied their commanding suite of probes to map out the phase diagram of this new material playground. Parallels were immediately drawn to the cuprates and indeed several independent studies utilized resonant inelastic X-ray scattering to show that the parent compound $NdNiO_2$ apparently hosted CDW order[3–5]. However, differences were also apparent with a commensurate CDW in the parent nickelates versus an incommensurate CDW in the doped cuprates and an unusual lack of temperature dependence of the nickelate CDW. The community was driven to investigate further.

Nickelates had long been sought after as an ideal candidate to replicate cuprate superconductivity, but most studies failed to evidence superconductivity until breakthrough work reported in 2019 (ref. 2). That it took some time to realize this can be understood from the difficult and meticulous sample preparation that must be undertaken to synthesize these materials that, so far, only superconduct when prepared as thin films. As reported in an Article in this issue of *Nature Materials*, Kyle Shen and collaborators used molecular beam epitaxy to grow $NdNiO_{2+x}$ samples with fine control over the oxygen content and came back with intriguing results from their X-ray measurements — the CDW was not present in single-phase samples. To understand this, they studied a series of samples with varying degrees of reduction using a combination of resonant X-ray scattering, electrical transport measurements, X-ray absorption spectroscopy, micro X-ray diffraction and scanning transmission electron microscopy to conclude that the purported CDW in the superconducting nickelate phase diagram is in fact not intrinsic but rather arises from the ordering of excess oxygen in small amounts of included impurity phases.

In an accompanying News & Views article, Giacomo Ghiringhelli outlines the importance and implications of these results. He discusses how these results may bring the cuprates and nickelates closer together, as the parent compound of the cuprates does not display intrinsic charge order either. Whether the doped nickelates host charge order remains an open question.

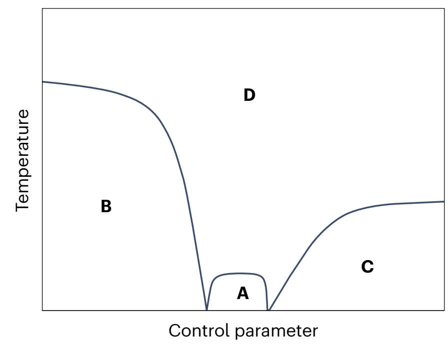

Fig. 1 | Electronic phase diagram of a superconducting material. Phases A, B, C and D are characterized by various degrees of freedom such as spin, charge, orbital or lattice. The control parameter might be chemical doping, external pressure or light excitation.

The story of CDWs in the phase diagram of superconducting nickelates is an exemplary case of scientists advancing our understanding of a complex issue in materials science in a rather short space of time, with other examples being the photophysics of halide perovskites, or the engineering of mRNA vaccines to treat infectious diseases. We look forward to seeing further discoveries in the phase diagrams of superconducting materials, with the ultimate hope of understanding the key ingredients for high-temperature superconductivity and making this field truly hot.

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