New classes of quantum material studied using ultra-high magnetic fields

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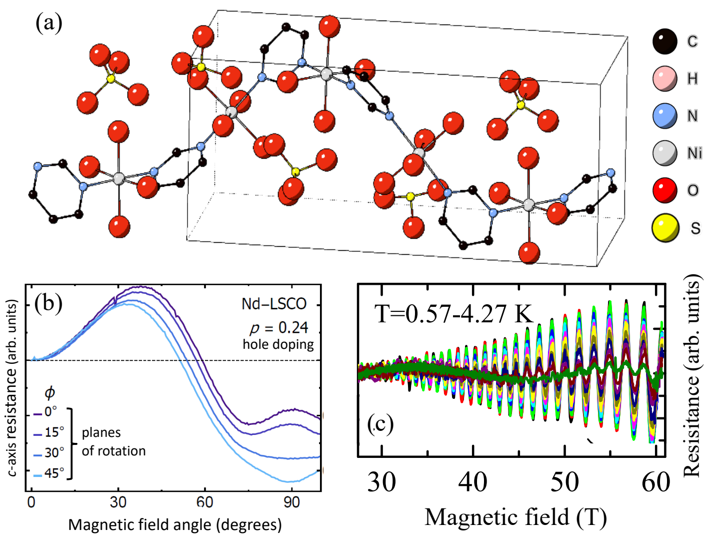
Many of today's most interesting, innovative and potentially useful materials display states of matter explicable only by applying quantum mechanical models that are on the edge of our current understanding. This is unsurprising as these *quantum materials* are typically host to a complex network of many-body interactions between spins, electrons and phonons, and are exquisitely sensitive to aspects such as dimensionality, quantum fluctuations and topology. The states that emerge from this microscopic soup frequently exhibit cooperative properties (superconductivity, charge or spin-order, multiferroicity) or exotic excitations (magnetic monopoles, skyrmions, Majorana fermions) of considerable fundamental interest. Understanding these properties and perhaps harnessing them for use in next-generation magnetic and electronic devices, sensors and actuators is one of the most pressing challenges facing modern physics.

As well as investigating new examples of inorganic materials showing novel conducting and magnetic states of matter, this PhD project will build on recent developments whereby non-ionic chemical bonding produces of new types of quantum material with properties not seen previously.

Hybrid organic-inorganic quantum magnets. Here, molecular bridges are used to link magnetic ions into low-dimensional, interacting networks that are difficult or impossible to realise using traditional oxide materials (see Fig. 3a). These structures combined with the low-spin magnetic moments ($S = 1/2$ or 1) produce ground states dominated by deeply quantum considerations.

2D quantum materials. These are materials whose layers are only weakly connected by van-der-Waals (vdW) bonding. Recently they have emerged as systems of considerable interest both from the point of view of their fundamental properties and their ability to be pulled apart layer-by-layer until only one or two sheets of atoms remain. They lie in the extreme 2D limit and provide for the first time the exciting possibility of studying quantum materials all the way from a bulk sample down to a single atomic layer.



(a) A hybrid organic-inorganic quantum spin chain. Pyrimidine molecules ($C_4H_4N_2$) are used to form bent bridges between $S = 1$ Ni^{2+} ions, resulting in strong magnetic interactions and a local spin-anisotropy axis that rotates by 90° from site to site along the chain. (b) Angle-dependent magnetoresistance measurements, in which a sample is rotated in a large fixed magnetic field, on a high-temperature superconductor performed at 45 T and 20 K [1]. These data shed light on the details of the Fermi surface in highly two-dimensional materials. (c) Magnetic quantum oscillations observed in material in which f-electrons undergo a field-induced change of character, from bonding to delocalised [2].

Applied magnetic field is an exceptionally useful tool for investigating quantum materials. The field is continuous, reversible and directional, and couples directly to charge carriers, superconducting pairs or spins, providing information on the nature, anisotropy and strength of the interactions present in the system. The stronger the interactions present, the higher the field required to understand them and in some cases successful experiments will require a visit to facilities that provide the highest available fields in the world (45 T for steady fields and 100 T for pulsed fields) such as the National High Magnetic Field Laboratory in the US.

By investigating these emerging classes of material, we hope to push our understanding of quantum systems beyond the current limits and open a route for exploiting the untapped potential of these materials to underpin future technology.

[1] G. Grissonnanche, *et al.*, Nature **595**, 667 (2021); [2] K. Gotze *et al.*, Phys. Rev. B **101**, 075102 (2020).

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