Quantum materials under extreme conditions

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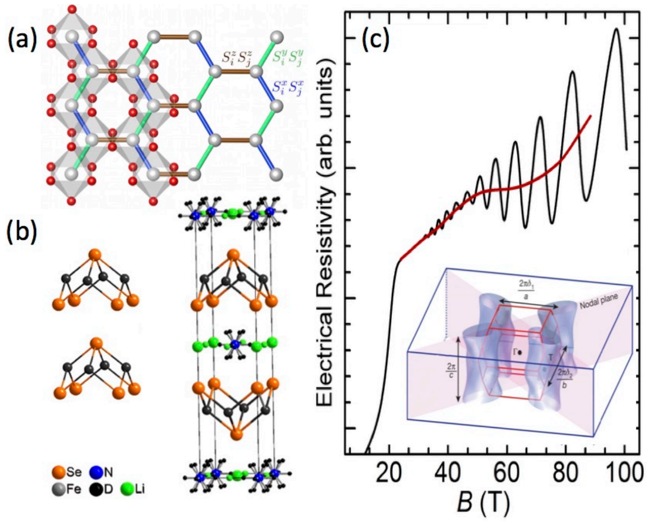
The exploration of new and exotic states of matter is as fundamental to our grasp of the inner workings of the universe as is the detection of elementary particles or the discovery of celestial objects.

Nonetheless, many of today's most interesting, innovative and potentially useful materials display states of matter that seem to be explicable only by applying quantum mechanical models that are on the edge of our current understanding. This is perhaps unsurprising as these materials can be host to a complex medley of ingredients that include many-body interactions between spins, electrons and phonons. The ground states that emerge from this complexity frequently exhibit cooperative properties (superconductivity, Bose-Einstein condensation, charge or spin-order, multiferroicity) or exotic excitations (fractional excitations and composite fermions, anyons, magnetic monopoles, skyrmions, Majorana fermions). Besides the fundamental interest in understanding such materials, there is also the prospect of controlling their properties and putting them to use. Potential applications include efficient electrical power generation, transmission and storage; fast and secure communications; medical imaging and treatment; architectures for processing and caching quantum information; and compact solid-state devices, sensors and actuators. For these reasons, deciphering what causes quantum states of matter to form remains one of the most pressing challenges facing modern physics.



Examples of low-dimensional quantum materials: (a) Na_2IrO_3 is a layered magnet with a honeycomb structure that is a potential realization of the much sought-after *Kitaev model* of magnetism [1]; (b) the critical temperature of certain iron-based superconductors for some reason increase by a factor of of up to five after intercalation of molecules between the conducting layers [2,3]. (c) Quantum oscillations measured at low temperatures and in ultra high magnetic fields can be used to elucidate Fermi surface properties. The data shown here is for a high-temperature superconductor [4].

This fully funded PhD project is part of a larger program of work supported by the European Research Council, which aims to advance our knowledge of these states by using extreme conditions of magnetic field and pressure to enable a continuous, clean and reversible tuning of quantum interactions, thereby shedding light on the building blocks of exotic magnetism and unconventional superconductivity.

The project takes as its starting point recent theoretical and experimental discoveries in the area of quantum materials. In particular, we will focus on a selected series of materials, both low-dimensional magnetic systems and unconventional superconductors, that are on the verge of a phase instability. Ultra-high fields and applied pressure will push these systems through the critical region where the state of matter changes and inherently quantum effects dominate. Electronic, magnetic and structural properties will be measured as the tipping point is breached and the resulting data compared with predictions of theoretical models. We hope that the results will provide answers to questions of deep concern to modern physics, such how quantum fluctuations, topology and disorder can be used to create states of matter with fascinating and functional properties.

[1] P. Gegenwart and S. Trebst, Nature Physics **11**, 444 (2015).
[2] M. Burrard-Lucas *et al.*, Nature Materials **12**, 15 (2013).
[3] F. Foronda *et al.*, Physical Review B **92**, 134517 (2015).
[4] S. Sebastian *et al.*, Nature **511**, 61 (2014).

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