Graduate Projects in Quantum Matter

Projects are always changing, so if you don't see something on the list that catches your interest please send us an email to discuss other possibilities.

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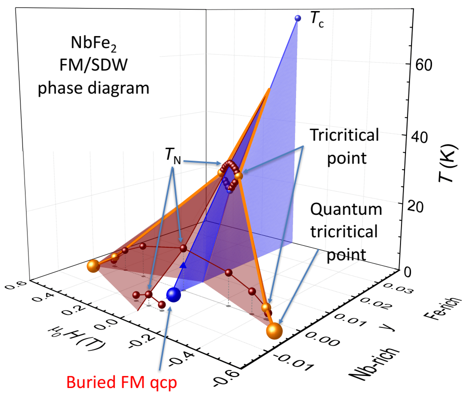
New Materials for Electrodes for Li-ion batteries

Small portable electronic devices are powered by Li-ion batteries, but improvements are required for larger applications. One limiting components, when looking to extend the use of Li-ion batteries to electric vehicles, are the electrodes. This project involves the synthesis of new materials to explore their potential as electrodes in Li-ion batteries. Materials will be synthesised using a variety of techniques, including ceramic, sol-gel and hydrothermal routes. Students will use high-quality X-ray diffraction to explore the structure. Neutron diffraction will be used to provide further information about the structural properties. The electrochemical properties will be probed by cycling vs. Li in electrochemical cells. Ex-situ and in-situ diffraction studies of the charge/discharged material will also be carried out to probe changes to the structure. By using a combination of chemical manipulation and theoretical calculations the properties of the materials under investigation will be optimized.

Prof. Malte Grosche `fmg12@cam.ac.uk`

Transition metal compounds offer a fertile ground for electronic self-organisation. Known forms of order include various types of magnetism, conventional and unconventional superconductivity and charge or orbital order. More subtle and exotic low temperature states include electron nematic order, spin liquids and various types of excitonic condensates. Beyond these waits a multitude of yet unknown, novel states of quantum matter, which only experiment can bring to light. These may be accessed by using pressure or magnetic field to tune high purity materials at low temperature. These states are investigated by low temperature studies which probe transport and thermodynamic properties or directly access the geometry of the Fermi surface.

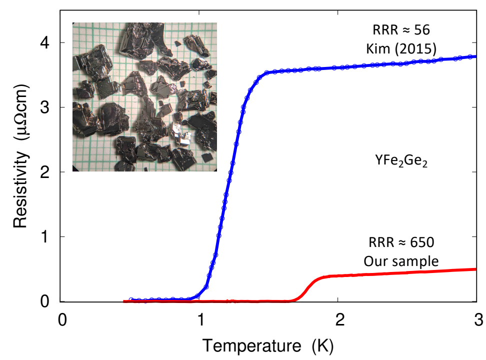
[1] *Quantum tricritical points in $NbFe_2$*, Nature Physics **14,** 62 (2018)

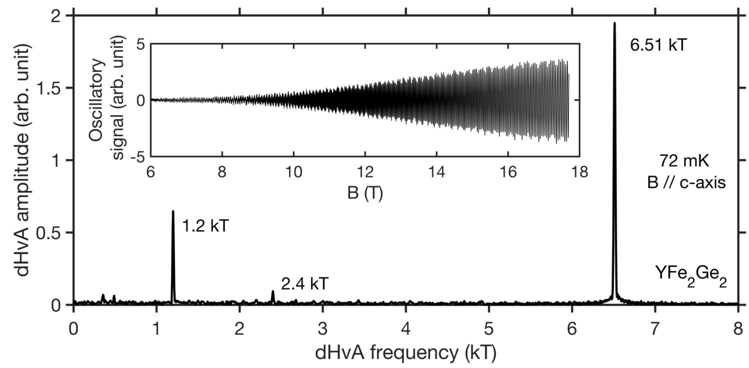


Specific projects:

Unconventional superconductivity in transition metal compounds

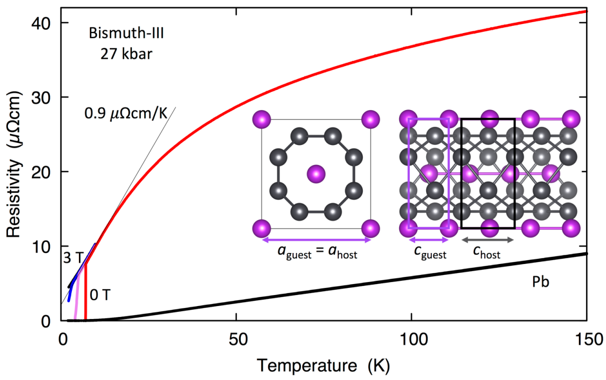
In many strongly correlated electron materials, notably cuprates, iron pnictides and Ce- and U-based heavy fermion compounds, superconductivity cannot be explained by conventional phonon-mediated pairing. We investigate the nature and origin of such unconventional superconductivity in the new Fe-based superconductor YFe_2Ge_2 and in related materials. Ultra-high quality single crystals of YFe_2Ge_2 can now be produced (Fig. below), which enable detailed spectroscopic measurements of superconducting and normal state properties such as the de Haas-van Alphen effect (Fig. below). This presents us with a jigsaw of data and theoretical models which needs to be solved in order to determine the origin of superconductivity in this material and gain new insights about Fe-based superconductors more generally.





[2] *Unconventional superconductivity in the layered iron germanide YFe_2Ge_2,* Phys. Rev. Lett. **116**, 127001 (2016).

Electronic and lattice excitations in aperiodic crystals

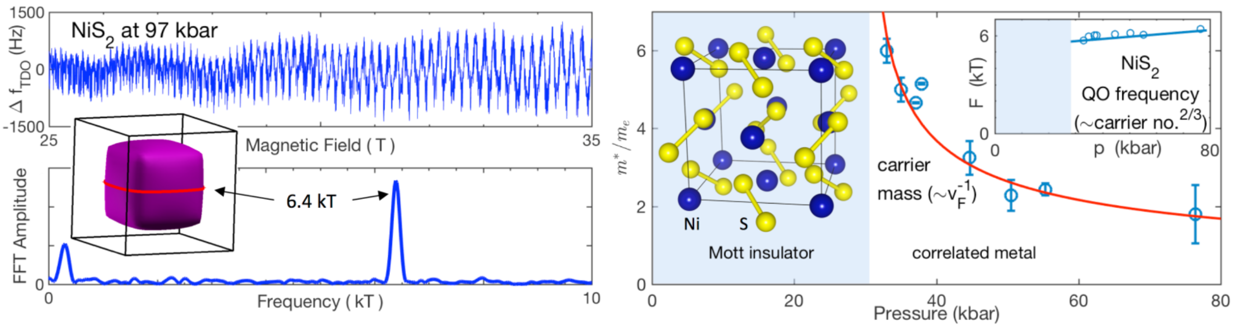


Arguably one of the most surprising discoveries in recent condensed matter physics research was the realisation that some elements under high pressure adopt structures that have two sublattices with incommensurate lattice constants. Such structures have no discrete translational symmetry, no unit cell, and no Brillouin zones. Little is known about their vibrational and electronic excitations. We will examine the consequences for superconductivity of the unusual phonon spectrum expected in these systems and investigate their electronic structure.

[3] *Strong coupling superconductivity in a quasiperiodic host-guest structure,* Science Advances **4**, eaao4793 (2018)

Fermi-surface instabilities near pressure-induced quantum phase transitions

Using high pressure quantum oscillation measurements, we map out the electronic structure of strongly correlated electron materials in regions of the phase diagram which are of particular scientific interest, e.g. in metallised Mott insulators.



These projects involve a wide range of experimental techniques:

- *Single crystal growth:* new materials and cleaner samples hold the key to scientific breakthroughs in the strongly correlated electron systems. We use a combination of material synthesis methods, including flux growth, heating by radio frequency induction or in an infrared mirror furnace and arc melting.
- *Advanced high pressure, low temperature and high magnetic field instrumentation:* identifying electronic order requires multiple experimental probes at low temperature and in high magnetic field. We develop these probes in a new generation of pressure cells, using contactless tank circuit signal detection techniques and focused-ion-beam approaches to sample handling on the microscale.

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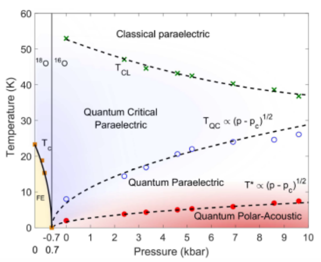
Quantum phase transitions and novel quantum order



The research programme focuses on novel forms of quantum order in metallic and insulating magnets, 2D and van der Waals compounds, ferroelectric systems and multi-ferroic materials. Pressure-induced superconductivity and critical phenomena in the vicinity of quantum phase transitions is of particular interest. In our case, we focus on the study of model materials in which the magnetic and charge ordered states give way to emergence of exotic superconductivity and other forms of novel quantum order. All projects offer flexibility of working on different aspects of measurements at extreme conditions of high pressures, low temperatures and high electric and magnetic fields, sample growth and also to work with international partners and theoretical collaborators. Up to three MPhil places are available. All projects can be scaled down to MPhil level. Two PhD places will be available in the area of quantum critical phenomena in metallic and insulating materials with spin and/or charge order. One PhD place is available in the area of novel graphite and chalcogenide intercalates to explore low dimensional magnetic and charge order and superconductivity.

References: *Ferroelectric quantum criticality, NATURE PHYSICS, Volume:10, Issue: 5, MAY (2014), Emergence of a quantum coherent state at the border of ferroelectricity (arXiv:1808.02428) August 2019, Pressure-Induced Electronic and Structural Phase Evolution in the van der Waals Compound FePS3, PHYSICAL REVIEW LETTERS Volume: 121, Issue:26, 266801, DEC 28 2018*

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Quantum oscillations in Kondo Insulators

The project will involve quantum oscillation measurements on an unusual Kondo insulator. This material exhibits puzzling dual characteristics of electrical insulating behaviour, while simultaneously displaying a conduction electron Fermi surface characteristic of a metal [1,2]. Measurements of the Fermi surface involve high precision measurements of thermodynamic and transport properties under conditions of low temperatures and high magnetic fields. The project will involve quantum oscillation measurements in the magnetisation to probe the Fermi surface of the Kondo insulator under these conditions.

[1] *Unconventional Fermi Surface in an Insulating State*, Science 349 pp. 287-290 (2015).
[2] https://www.quantamagazine.org/20150702-paradoxical-crystal-baffles-physicists/

Transport and thermodynamic measurements in high temperature copper-oxide superconductors

The project will involve a comprehensive sequence of high-purity copper oxide single crystal growth, electrical transport and magnetisation measurements. These materials, in addition to exhibiting remarkably high superconducting temperatures, display a variety of baffling quantum behaviours that cannot be explained by conventional Fermi liquid theories. An array of experiments including quantum oscillations will be used to measure and explain mysterious quantum effects in these materials under conditions of low temperatures and high magnetic fields. Experiments will be performed both using in-house superconducting magnets and international high magnetic field facilities.

[1] *Normal-state nodal electronic structure in underdoped high-T_c copper oxides*, Nature 511, 61–64 (2014)

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Probing correlated electron systems with low temperature heat transport

The project involves studying how systems with strongly interacting electrons transport entropy at millikelvin temperatures. Such measurements of thermal conductivity may be used as a probe of fundamental excitations in condensed matter systems, providing valuable information on the quantum ground state, as well as low energy scattering processes. Students would be involved in developing cryogenic infrastructure and ultra-low temperature probes that would operate in very high magnetic fields and under extreme pressures. These tools would be used to explore a number of possible materials including exotic superconductors and non-Fermi liquid states near the border of magnetism. One especially interesting possibility is exploring Kondo insulators, which are expected to be electrically insulating, but may play host to exotic excitations that give rise to a Fermi surface [1].

[1] *Fermi surface in the absence of a Fermi liquid in the Kondo insulator SmB_6* Nature Physics (2017)

If you are interested in pursuing a PhD or MPhil with members in the Quantum Matter group, please don't hesitate to get in touch. Prospective PhD students are encouraged to contact us, and we are always available for informal inquiries or discussions.

The official channel for applications is through the Board of Graduate Studies (BoGS): https://www.graduate.study.cam.ac.uk. They will forward your application to the Department of Physics - however, it is advisable to get in touch with your prospective PhD supervisor separately – or contact all of us together at mott.hub@phy.cam.ac.uk.

www.qm.phy.cam.ac.uk/applying.php

20.4 Tesla dilution refrigerator cryomagnet