



The use of superconducting magnets in inelastic neutron scattering experiments at ISIS



The ISIS team in the UK's Rutherford Appleton Laboratory.

When neutrons collide with a material, they are scattered by its atoms. Neutron detectors record the neutron's change in direction and collect a diffraction pattern. This works because the neutron wavelength is similar to the separation between atoms; this is elastic neutron scattering.

The positions and strengths of the peaks in the diffraction pattern are used to determine the atomic arrangement of the material.

The neutron may also lose or gain energy from atomic vibrations within the material during scattering. This is effective because the neutron and inter-atomic vibrational energies are similar in magnitude. This inelastic neutron scattering is used to probe many kinds of dynamic processes in materials, including changes in the magnetic response.

ISIS is the world's most intense Spallation Neutron source and is located at the UK's Rutherford Appleton Laboratory near

Oxford. ISIS supports an international community of around 1600 scientists who use neutrons and muons for research in physics, chemistry, materials science, geology, engineering and biology. Scientists study the dynamical properties of materials on an atomic scale, by inelastic neutron scattering (INS), of new materials using an Oxford Instruments 7.5 T superconducting magnet.

The availability of high field magnets at ISIS greatly enhances the research opportunities in the study of quantum magnets, novel superconductors and other correlated-electron systems. Magnetic fields can be used to directly manipulate quantum states in a clean way and induce new phenomena such as the condensation of excitations via a field, and in field-driven incommensurate ground states. Such field-induced phenomena require high fields comparable in energy with the exchange interactions.

In practice, working to a schedule outlined in the 4 – 6 week long ISIS running cycles, a 7-strong team of cryogenic technicians provide the fully operational suite of cryostats, cryomagnets and dilution refrigerator inserts, to the ISIS beamline instruments. The timescale for ISIS experiments varies considerably, from two up to twelve days; inelastic neutron scattering experiments typically being at the higher end of this scale.

The physicists in Oxford use the characteristic inelastic neutron scattering signals to determine magnetic fluctuations. There are many varied applications and in recent years condensed matter research has focussed mainly on strongly correlated electron systems. Amongst these are hightemperature superconductors (HTSC), quantum magnets, Colossal magnetoresistive manganites, Spinfrustrated systems and heavy fermion (HF) materials.

These systems are characterised by a complex phase diagram where small changes in a given parameter can drive the system into a rich variety of exotic phases.

Magnetic field is a particularly valuable parameter and is used in University laboratories to explore the competing phases through bulk measurements. However, understanding the microscopic interactions can only be done with neutrons.

Combining the reciprocal-space maps of the dynamics of a system via time-of-flight (TOF) neutron scattering with high magnetic fields provides the potential for high impact physics.

High-field neutron scattering studies are important for high-temperature superconductors (HTSC), heavy-fermion superconductors (HFSC) and organic superconductors.

The physical explanations for superconductivity can be constrained by

determining the nature of the closest competing ground state, and establishing if that state is universal among the HTSC materials.

Antiferromagnetism has been theoretically predicted to be the competing ground state¹. This has been revealed when superconductivity is destroyed by a magnetic field and antiferromagnetism has been observed in hole-doped $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ as well as in electron-doped $\text{Nd}_{1.85}\text{Cu}_{0.15}\text{CuO}_4$ ²⁻³. These measurements reveal the important interactions and the interplay between competing phases.

Clearly the greater the field the larger the number of superconductors that can be investigated at fields greater than their upper critical fields where complete suppression of superconductivity takes place. Even in the case of HTSCs with critical fields ~ 50 T, an applied field representing a significant proportion of the critical field have proved extremely useful in explorations of the vortex state where partial suppression of superconductivity occurs².

Measurements so far have been made on triple axis spectrometers at HMI and ILL. Studies with ISIS spectrometers allow investigations at higher energies and full coverage of the magnetic excitations across the Brillouin zone.

In comparison, the phases and phenomena displayed by quantum-dominated magnets are extremely rich. The exploitation of their potential for fundamental research on quantum many-body phenomena, and as a route to discovering new states of matter, is a current research priority. Since quantum magnetism is integral to the superconducting states in HTSC, and additionally is emerging as an important route for quantum information processing, tools to facilitate the study, and to manipulate such magnetic states, are necessary for future progress in these fields. Because neutrons can image the wave vector and frequency components of the magnetic correlations, INS is the most important technique for probing such quantum states, allowing theories to be tested in a detailed way.

Quantum magnetism has been undergoing a revolution due to the introduction of high magnetic fields, new classes of materials showing exotic physics, and the exploitation of TOF neutron methods.

Magnetic fields couple to the magnetic configurations and can cause transitions to new states. They may also promote quantum tunnelling and drive phase transitions.

To reveal the microscopic origin of these phenomena, and the nature of the excitations requires maps of the excitation spectrum over the entire Brillouin zone, for which the TOF spectrometers at ISIS are better suited than conventional triple-axis techniques at reactors.

Magnetic fields may also induce quantum driven textures via magnetoelastic couplings as studied in $\text{SrCu}_2\text{B}_3\text{O}_6$ and CuGeO_3 , and spin textures as in the flux vortices in $\text{La}_{1-x}\text{Sr}_x\text{CuO}_4$. Quantum tunnelling by applying transverse fields to LiHoF_4 provides a quantum computing analogue, and application to Cs_2CoCl_4 has generated a new state of matter, a gapped spin on phase⁴.

Finally, high fields provide a route to measuring the spin Hamiltonian itself in a direct link with theory. Such breakthroughs require high fields on neutron beamlines, and dilution refrigerator inserts are also frequently needed.

In recent years there has been considerable interest in the physics of heavy fermion (HF) systems due to the discovery of new unconventional superconductivity (HFSC), quantum critical point (QCP)/non-Fermi-liquid (NFL) phenomena, field-induced quadrupolar ordering, field-induced metamagnetic transitions as well as the observations of spin gaps in Kondo insulators.

New physical phenomena will be discovered in HFSC and QCP systems in INS studies on chopper spectrometers with high magnetic fields.

Studies of many HF-systems have demonstrated that they can be driven from non-Fermi-liquid to Fermi-liquid or vice versa with application of magnetic fields. Much experimental research has focused on finding the origin of unconventional HFSC and NFL behaviour. Hence high field INS measurements are crucial and may prove that a common theoretical model can be applied both to HTSC and HFSC.

Considering materials with possible device applications, high fields are essential in elucidating the mechanisms producing colossal magnetoresistance (CMR) in manganites. Examples have been provided by materials such as $\text{La}_{2-2x}\text{Sr}_{1+2x}\text{Mn}_2\text{O}_7$ and $\text{La}_{1-x}\text{Ca}_x\text{MnO}_3$ where the paramagnetic insulator to ferromagnetic conductor transition is increased in high magnetic fields and is accompanied by a large magnetostriction.

These materials have potential applications as transducers and field sensors. Here the spin waves as well as diffuse scattering measurements in high fields provide important information.

Neutron scattering is therefore a powerful tool for the investigation of microscopic properties of solids, liquids, soft materials, biological objects and condensed matter, in general as well as for non-destructive evaluation of bulk objects in materials testing and engineering studies. In the neutron beam experiments at ISIS, using inelastic scattering phenomena, microstructural properties as well as interaction behaviour of condensed matter can be probed with high precision.

Reference

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Contact: **Mr. Ian Bailey**, Sample Environment Section, ISIS Facility, Chilton, UK. i.f.bailey@rl.ac.uk