New Concepts of Metals and Insulators Explored Using Anomalous Quantum Oscillations.

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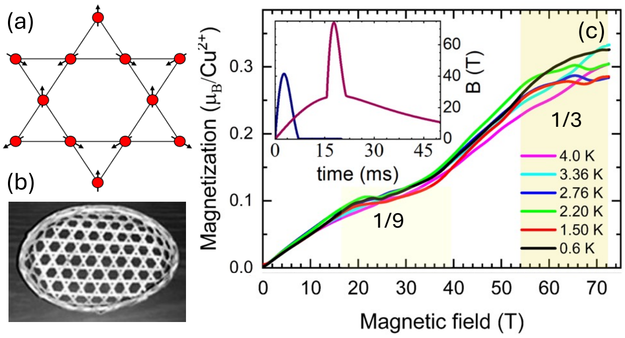

Quantum Heisenberg antiferromagnets are one class of material in which anomalous quantum oscillations have been reported [3]. (a) The kagome lattice is made up of spins located on triangles and hexagons and are so called after (b) a type of Japanese basket weaving. (c) A 1/9 magnetzation plateau has recently been observed in high-field, low temperature measurements of Y-kappelasite [4]. The inset shows the magnetic field pulses used to take the experimental data. The 1/9 plateau is theoretically predicted but has only been observed in one other material in which it is proposed to be the result of a Fermi surface of chargeless Dirac spinons [3].

What is a metal? Surprisingly, the answer to this fundamental question is no longer clear. Physical phenomena that were long thought to define the metallic state have recently been observed in materials that are evidently electric insulators. This emerging situation challenges long-held concepts and could well reshape how we teach basic physics principles. Moreover, the materials in question are believed to host hitherto unidentified quasiparticles that are expected to be important for new technologies that address societal challenges, including novel spintronic devices and fault-tolerant quantum computation.

State of the field. In school we learn that metals are lustrous, malleable, and ductile. At university, undergraduates learn a deeper truth, that the defining feature of a metal is its Fermi surface, the boundary between filled and empty electron states. This concept underpins a striking phenomenon — quantum oscillations — where properties such as magnetization and resistance oscillate with applied magnetic field at low temperatures. For decades, quantum oscillations have been considered the smoking gun of metallic behaviour. However, recent discoveries contradict this view. A handful of materials, though insulating at low temperatures, exhibit quantum oscillations in very high magnetic fields, implying the presence of a Fermi surface without electrical conduction [1,2]. These results have sparked intense debate and a wave of theoretical explanations. Some theories adapt existing models, while others propose radical new ideas, including exotic quasiparticles like Majorana fermions or chargeless spinons. These entities are not only of profound scientific interest but are also seen as key to future quantum technologies. However, consensus on which of the theories are correct remains elusive, partly because so few materials have so far been discovered that display the anomalous quantum oscillations, leaving insufficient data to discriminate between competing models.

This fully funded PhD project aims to resolve this problem. Working within the Warwick Superconductivity and Magnetism research group, the student will identify and characterize new materials exhibiting anomalous quantum oscillations using in-house equipment. Prior results highlight which research directions to pursue, but success will require training in several interdisciplinary capabilities, including single-crystal growth, structural characterization and expertise in a range of high-magnetic-field measurement techniques. Two key collaborating partners will provide support to this project: (1) HFML-FELIX, Nijmegen is the premier dc-magnetic-field facility in Europe providing access to equipment, know-how and magnets delivering steady fields up to 38 tesla. (2). NHMFL-LANL, Los Alamos is the world's leading laboratory for pulsed-magnetic-field measurements, housing unique facilities for measuring materials in fields up to 100 tesla.

It is an extremely exciting time to be working in this field. Established ideas are being challenged, bold theories proposed, and fresh experimental evidence is urgently needed. The potential for uncovering new properties of fundamental and functional significance is high.

Paul Goddard joined Warwick University in 2013 and is expert in the use of high magnetic fields to elucidate the properties of new materials. In 2023, he was awarded the Pippard Prize by the Institute of Physics for his developmental work on the technique of angle-dependent magnetoresistance. For further information about the project do not hesitate to contact Paul Goddard directly at p.goddard@warwick.ac.uk

For information on how to apply please see https://warwick.ac.uk/go/physicspgadmissions

[1] Tan *et al.*, Science **349**, 287 (2015); [2] Z. Xiang *et al.*, Science **362**, 65 (2018); [3] Zheng *et al.*, PNAS **122**, e2421390122 (2025); PRX 15, 021076 (2025); [4] Chatterjee, Goddard *et al.*, arXiv:2605.08067 (2026).