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Quantum criticality and the formation of a putative electronic liquid crystal in $Sr_3Ru_2O_7$

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ABSTRACT

We present a brief review of the physical properties of $Sr_3Ru_2O_7$, in which the approach to a magnetic-field-tuned quantum critical point is cut off by the formation of a novel phase with transport characteristics consistent with those of a nematic electronic liquid crystal. Our goal is to summarise the physics that led to that conclusion being drawn, describing the key experiments and discussing the theoretical approaches that have been adopted. Throughout the review we also attempt to highlight observations that are not yet understood, and to discuss the future challenges that will need to be addressed by both experiment and theory.

1. Introduction

The focus of this paper is the layered perovskite metal $Sr_3Ru_2O_7$, in which quasi-two-dimensional conduction takes place in Ru–O bilayers [1]. Below approximately 1 K, $Sr_3Ru_2O_7$ is thought to support an electronic fluid with broken orientational symmetry, the electronic analogue of a nematic liquid crystal. The purpose of the article is to review what is known about that nematic phase, and how it relates to the broader phase diagram in which it appears. The bulk of the paper (Sections 2–8) will be devoted to a review of experimental results, with the theoretical work discussed more briefly in Section 9, and some open questions highlighted in Section 10.

The experimental evidence for electronic nematicity in $Sr_3Ru_2O_7$ is summarised in Fig. 1, which shows its magnetoresistance at $T = 100$ mK in magnetic fields up to 8.5 T, applied at angles θ ranging from 0°, corresponding to field along the crystallographic c axis, to 90°, when the field is applied in the ab plane. In each of panels 1a and 1b the resistivity is studied along orthogonal Ru–Ru bond directions (the a and b directions of a fully unfolded Brillouin zone assuming tetragonal symmetry), and the tilt is performed such that the in-plane field component aligns along one of those directions. The magnetoresistance is the same along both directions over most of this field-angle phase space, corresponding to the fourfold behaviour expected of transport in Ru-4d bands in a two-dimensional square planar Ru lattice. However, the magnetoresistance along the two directions differs significantly in two separate, well-defined regions (indicated by green arrows), corresponding to twofold symmetric electrical transport [2]. The 'easy axis' is found to be perpendicular to the in-plane component of the applied field; if the in-plane field is switched from one crystal axis to the other, the easy and hard axes are exchanged, similar to behaviour seen in high purity 2D electron gases [3–6].

Although the resistivity changes are striking for a metal at low temperatures, the essential physics in $Sr_3Ru_2O_7$ seems to be that of a series of electron fluids. De Haas–van Alphen oscillations can be observed in the anisotropic region for low θ [7], and searches for structures such as stripes that break translational symmetry and open a gap have not revealed anything. In any correlated electron material such as $Sr_3Ru_2O_7$, there will be a significant electron-lattice coupling. A physical property such as magnetoresistance changing from being fourfold to twofold therefore has to be accompanied by a change in the crystal lattice. An obvious question, therefore, is whether a large structural transition might be the driver of the observed anisotropy. In the original paper reporting the magnetoresistance [2], elastic neutron scattering put an upper limit of $\sim 10^{-5}$ on the lattice anisotropy change associated with entering the state supporting the strongly twofold transport, indicating that the effect is intrinsic to the correlated electron fluid rather than being lattice-driven. Recently, an important measurement has been performed of the anisotropic thermal expansion in the phase, showing a relative lattice parameter change of two parts in 10^7 for small θ, increasing to approximately 1 part in 10^6 for $10° < \theta < 15°$ [8].

Given the facts summarised above, the best current classification for the anisotropic in-plane behaviour of $Sr_3Ru_2O_7$ is as a

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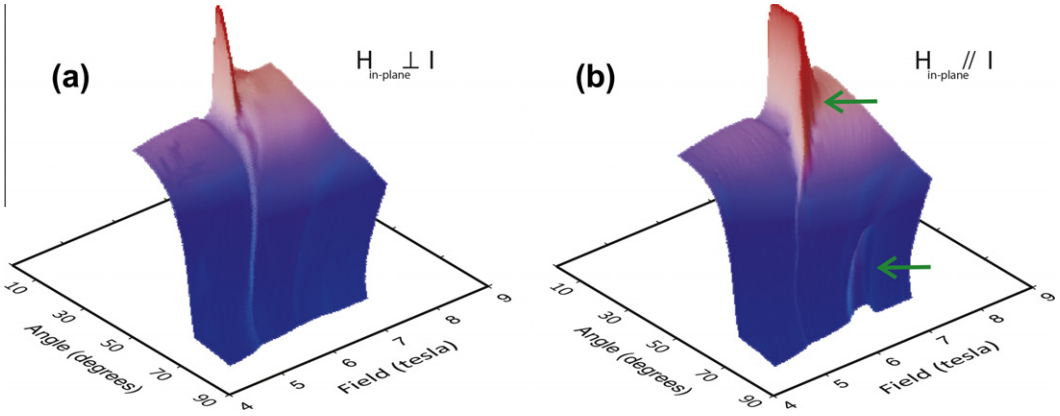

Fig. 1. Resistivity of $Sr_3Ru_2O_7$ as a function of magnetic field and tilt angle from the *ab* plane, at 100 mK. If the in-plane field component is parallel to a Ru–Ru bond direction and parallel to the applied current, the resistivity is much larger than for the orthogonal current direction in two distinct regions of the phase diagram, marked by green arrows. The tilt shown is parallel to the tetragonal *a* axis. If the field is rotated by 90° in the plane, the direction of the anisotropy also switches. Figure adapted from [2]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

nematic electronic fluid [9]. The actual anisotropy probably reflects scattering from domain walls [2], but evidence to date suggests that, whatever the details of domain formation, the underlying microscopics involve a state with orientational but not translational order. Future experiments may of course uncover translational order; if that were to happen, it would be more appropriate to describe the state as a smectic fluid, but the fact that we are dealing with a fluid with a very weak back-coupling to the lattice seems to have been established.

In the remainder of this brief review we will attempt to summarise the properties of the overall phase diagram in which this unusual behaviour appears. A key point of emphasis will be the extremely high purity that is required for the behaviour shown in Fig. 1 to be observable. For that reason, coupled with space restrictions, we will not be able to review other interesting aspects of the physics of $Sr_3Ru_2O_7$ such as the results of chemical doping experiments, the properties of the $Sr_{3-x}Ca_xRu_2O_7$ solid solution or those of eutectic mixtures of $Sr_3Ru_2O_7$ with other ruthenates. Coverage of those topics will have to await a long and comprehensive review of the field.

2. Crystal structure, material growth and characterisation

Building on early reports of the synthesis of $Sr_3Ru_2O_7$ [10–14], structural powder neutron scattering studies reported the crystal structure to be Bbcb [15–17], with no difference in the orthogonal in-plane lattice parameters. The reason for the symmetry being lowered from tetragonal is the presence of oxygen octahedra rotated by approximately 7°, centred on Ru atoms whose positional shift due to this rotation was expected to be tiny. Subsequent neutron and convergent beam electron diffraction studies on single crystals reported the room temperature difference in the *a* and *b* lattice parameters to be five parts in 10^4, meaning that the in-plane Ru atoms can be thought of as square planar to a good approximation [18].

From the first studies of the material, $Sr_3Ru_2O_7$ was known to be close to ferromagnetism. In fact, the first reported single crystals, which were flux grown in Pt crucibles [19] were reported to be itinerant ferromagnets. Once higher purity crystals were grown in an image furnace the ground state was established to be a strongly enhanced paramagnet with a Wilson ratio of approximately 10 [1] but ferromagnetism appeared to result from the application of hydrostatic pressure. Subsequent work [20–22] then revealed that uniaxial rather than purely hydrostatic pressure led to long-range magnetic order.

Although the ground state of $Sr_3Ru_2O_7$ did not prove to be ferromagnetic, a key manifestation of its proximity to ferromagnetism was the appearance of metamagnetism, namely the development of enhanced magnetism in an externally applied magnetic field [23,24]. The first generation of image furnace grown crystals had residual resistivities of several μΩ cm, corresponding to mean free paths of a few hundred Ångstrom. In a breakthrough that proved vital to the observation of the nematic physics, Perry and Maeno deduced that in-plane Ru vacancies were the most likely source of the remaining defect scattering, and improved the low temperature mean free path by approximately an order of magnitude [25].

3. Electronic structure

$Sr_3Ru_2O_7$ is the $n = 2$ member of the Ruddlesden–Popper series $Sr_{n+1}Ru_nO_{3n+1}$, in all of whose members Ru exists in the formal valence of 4+. The electronic structure of the materials is based on partially filled bands formed from the hybridisation of Ru 4*d* levels with oxygen 2*p* states. The crudest approximation to the electronic structure comes from assuming a tetragonal crystal structure and a simple bilayer split [26]. However, the true Bbcb structure leads to a $\sqrt{2} \times \sqrt{2}$ reconstruction of the in-plane Brillouin zone, and a complicated Fermi surface involving hybridising bands with Ru $4d_{xy}$, $4d_{xz}$, $4d_{yz}$ and even $4d_{x^2-y^2}$ character [27]. Including spin–orbit coupling is also important; this has been done both in LDA calculations [28] and in tight-binding approaches that have been constructed to form the foundations for extended many-body calculations [29–32]. Experimentally, several studies have been performed on $Sr_3Ru_2O_7$ using Angle Resolved Photoemission (ARPES) [28,33,34], resulting in the Fermi surface shown in Fig. 2 and described in its caption. Strong many-body mass enhancements are evident both from the ARPES band dispersions and from measurements of the masses in dHvA experiments [7,35,36]. These are particularly pronounced in γ_3, which is believed to be in the vicinity of a van Hove singularity [37], a point which is stressed in a number of the theoretical models reviewed in Section 9 of this article.

4. Magnetic field-angle phase diagram determination from magnetic susceptibility

Although the magnetoresistance study summarised in Fig. 1 above is a sensitive indicator of electronic nematicity, it is important that it be combined with measurements sensitive to crossing