Experimental report

03/11/2015

Proposal: **5-42-389** **Council:** 10/2014

Title: Resolving the spin and orbital part of the Sr2RuO4 superconducting order parameter

Research area: Physics

This proposal is a continuation of 5-42-341

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Samples: Sr2RuO4

Instrument	Requested days	Allocated days	From	To
D33	6	5	18/07/2015	23/07/2015
D22	6	0		
D11	6	0		

Abstract:

Stronthium ruthenate (SRO) has long been considered a paradigm for p-wave superconductivity, but recent results have raised important questions in this regard. These include recent SANS experiments by our group [C. Rastovski et al., Phys. Rev. Lett. 111, 087003 (2013)] that found an intrinsic superconducting anisotropy 3 times greater than the Hc2 anisotropy, and the observation of a first order transition at the upper critical fields for T < 0.8 Tc. Both of these results suggest Pauli limiting in SRO, and are difficult to reconcile with equal spin pairing. However, there is still other compelling evidence for p-wave pairing, and it is therefore important to resolve the nature of the superconducting state in SRO.

We propose a continuation of our SANS measurements of the SRO vortex lattice (VL) to provide further information about the order parameter. Two distinct measurements are foreseen:

1. High fields studies to investigate possible Pauli paramagnetic effects that would support Pauli limiting.
2. T-dependence for different directions of in-plane directions to directly resolve gap nodes.

Experiment Summary for Proposal 5-42-389: Resolving the spin and orbital part of the Sr_2RuO_4 superconducting order parameter

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Parameter	Value
Wavelength (λ)	12, 17 Å
Temperature	50, 750 mK
Magnetic Field	0.5, 0.75
Collimation	12.8 m
Detector 1 Distance	1.2 m
Detector 2 Distance	13 m
Source Aperture	30 mm
Sample Aperture	-custom-

TABLE I: D33 Instrument Settings

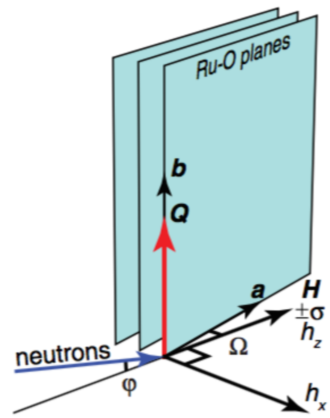

FIG. 1: Experimental geometry. Neutrons are incident at an angle ϕ and either parallel or anitparallel spins ($\pm\sigma$) relative to the applied magnetic field **H**. The field is offset from the Ru-O basal planes by an angle Ω, resulting in a longitudinal (h_z) and transverse (h_x) field modulation in the sample. It is h_x that causes the spin flip scattering [1].

INTRODUCTION

The purpose of this experiment was to search for non-spin flip scattering (NSF) as well as to extend measurements of the vortex lattice anisotropy (Γ_{VL}) in the unconventional superconductor Sr_2RuO_4. The general experiment is the same as in earlier experiments and can be seen in Fig. 1. Spin flip (SF) scattering results from the transverse field modulation, which flips the neutron spin ($\sigma \perp h_x$) and creates a Zeeman splitting of the VL rocking curves [1]. A NSF signal from the vortex lattice (VL) in Sr_2RuO_4 has never been observed in prior measurements.

Previous experiments performed involved characterizing the spin flip form factor's dependence on different parameters, and in this experiment, additional sets of measurements were taken to augment the previous data. To characterize the angular dependence in the form factor of the magnetic field with respect to the crystalline a-axis, rocking curves were taken at multiple Ω. High temperature rocking curves were also taken to evaluate how the form factor changes with temperature.

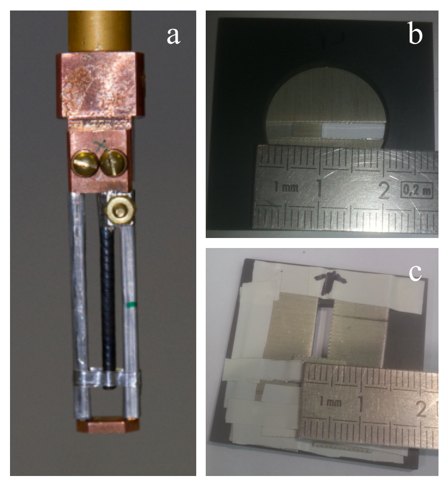

FIG. 2: The SRO crystal is a cylindrical rod; it was cleaved and attached with silver epoxy to a copper holder (a). The legs provide protection and are wrapped in cadmium to both make the sample easier to find and prevent the copper from becoming activated. The head is tilted at a 10.5 °angle from the vertical. A custom aperture was created to match the crystal shape, (b) and (c). Masking off the bottom third of the sample reduced the background noise significantly.

EXPERIMENT DETAILS

The experiment was performed on the D33 beam line at the ILL using the standard SANS configuration. The specific instrument settings used for the experiment are listed in Table I.

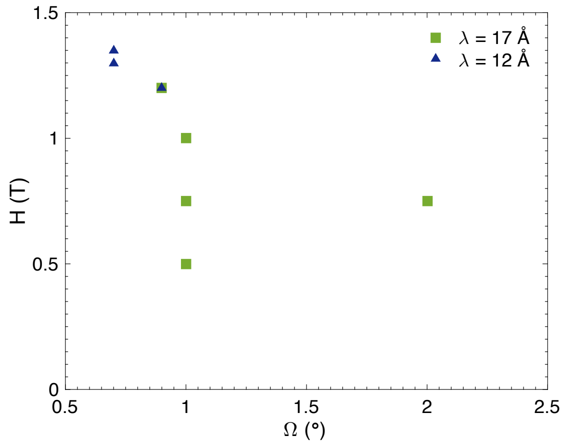

FIG. 3: Experimental parameter space explored while searching for NSF scattering peaks.

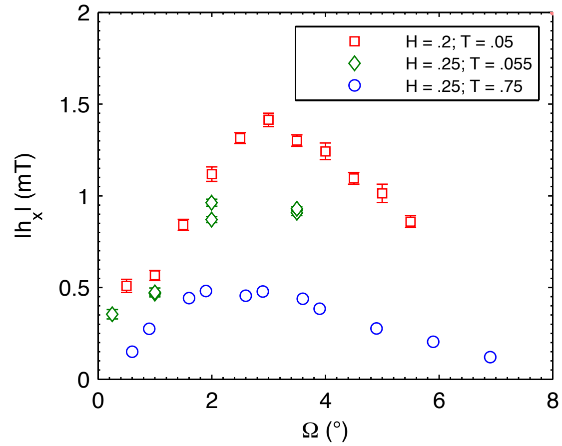

FIG. 4: Sr_2RuO_4 form factor. The blue data set was collected on this experiment, and is plotted with data from 2013 (red) and 2012 (green) for comparison.

Sample Mount and Alignment

A cylindrical, single-crystal rod of Sr_2RuO_4 was cleaved and attached with silver epoxy to a copper mount, see Fig. 2a. A custom rectangular aperture designed to match the elongated shape of the Sr_2RuO_4 crystal was created by masking off a 20 mm circular aperture with cadmium. The exact dimensions of the aperture were determined by optimizing the signal to noise ratio, and the final aperture can be seen in Fig. 2 b and c.

In addition to the usual phi and san alignment, an Ω alignment was also necessary. The form factor, and thus integrated intensity of the scattering, is highly sensitive to the value of Ω, dropping quickly to 0 at Ω=0. A scan in Ω was performed in a field of 0.5 T to determine the alignment. After every change in Ω , a DC field oscillation around the final field value of 0.5 T was performed to ensure the VL was well ordered.

Measurements

The intensity of the direct beam was weak enough to perform all of the measurements without a beam stop. For each new magnetic field or Ωvalue, the VL was reordered using a damped DC field oscillation around the final field value. This method has been used in the past as it produces a well-ordered VL and eliminates the need for a field-cooling procedure before each measurement.

Rocking curves for NSF scattering peaks were attempted at base temperature ($T = 50$ mK) and various Ωs, magnetic fields, and wavelengths. The parameter space explored can be seen in Fig. 3. None of the data sets yielded a convincing rocking curve, and even long count times with the sample "rocked on" did not produce identifiable Bragg peaks.

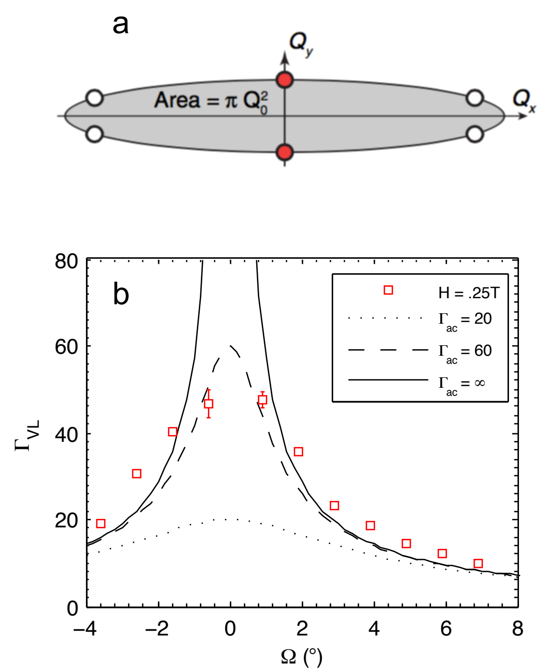

FIG. 5: Vortex lattice anisotropy. The VL Bragg reflections lie on an ellipse in an anisotropic superconductor (a), with the ratio of the major-to-minor axes given by Γ_{VL}. Only the red peaks are observed at a scattering vector of Q. The measured VL anisotropy as a function of Ω (b) and compared with various intrinsic anisotropies: Γ_{ac} = 20 (dotted), 60 (dashed), and ∞ (solid).

When it became clear that the NSF peak search was not going to be successful, a high temperature Ω scan was performed to augment previous experimental data. Rocking curves were measured at $T = 750$ mK, $\lambda = 17\AA$, and $H = 0.25$T, for $|\Omega|$ ranging from 0.5° to 7°.

RESULTS

The form factor (h_x) can be calculated from the integrated VL reflectivity (R):

$$|h_x|^2 = \frac{16\Phi_0 Q}{2\pi t(\gamma\lambda_n)^2} R \tag{1}$$

where γ is the neutron magnetic moment, λ_n is the neutron wavelength, t is the sample thickness, Φ_0 is the flux quantum, and Q is the scattering vector. The form factor is plotted as a function of Ω in Fig. 4.

In an anisotropic superconductor, the VL Bragg reflections lie on an ellipse, see Fig. 5a, where the ratio of the major-to-minor axes gives the VL anisotropy (Γ_{VL}). Because each vortex carries exactly one quantum of flux (Φ_0), the area of an undistorted hexagonal lattice and the anisotropic ellipse are equivalent and determined solely by the magnetic field. Therefore the anisotropy is given by:

$$\Gamma_{VL} = \left(\frac{Q_0}{Q}\right)^2 = \left(\frac{2\pi}{Q}\right)^2 \frac{2\mu_0 H}{\sqrt{3}\Phi_0} \tag{2}$$

and can be related to the intrinsic anisotropy (Γ_{ac}) by:

$$\Gamma_{VL} = \frac{\Gamma_{ac}}{\sqrt{cos^2\Omega + (\Gamma_{ac} sin\Omega)^2}} \tag{3}$$

which enables the comparison of the experimentally determined Γ_{VL} with that expected for various intrinsic anisotropies, as in Fig. 5b.

TECHNICAL DIFFICULTIES

There is currently no standard monitor on D33, and data is typically normalized to counts per standard monitor. Fortunately, the reactor power was consistent for the duration of this SRO experiment, so data could be normalized to exposure time.

[1] C. Rastovski, *et.al.*, PRL **111**, 087003 (2013).