Ferromagnetic fluctuation and possible relationship between superconductivity in Sr_2RuO_4

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1. Introduction

Despite many theoretical and experimental studies done since the discovery of superconductivity below T_c = 1.5 K, the nature of the superconductivity in a strontium ruthenate Sr_2RuO_4 is still under debate. The t_{2g} electrons of Ru^{4+} ions form three bands near the Fermi surface. The d_{xz} and d_{yz} orbitals form quasi-one-dimensional α and β sheets while the d_{xy} orbital forms a two-dimensional γ sheet. The former sheets generate incommensurate (IC) magnetic fluctuations while the latter appears as ferromagnetic fluctuations. The most promising superconducting (SC) order parameter is a *p*-wave state with a chiral $p_x \pm ip_y$ symmetry; the origin of the *p*-wave superconductivity was thought to be ferromagnetic fluctuations due to the γ sheets. To examine this scenario, several neutron and NMR measurements were done, but they are not fully consistent. The dynamical spin susceptibility obtained by inelastic neutron scattering measurements mainly shows the IC magnetic fluctuations around **Q** = (0.3, 0.3). On the other hand, in ^{17}O-NMR measurements, $^{17}1/T_1$ shows ferromagnetic correlations. To investigate the details of magnetic fluctuations in Sr_2RuO_4, we performed inelastic neutron scattering (INS) measurements on superconducting Sr_2RuO_4.

2. Experiment

Three crystals were co-aligned (Fig. 1), and the (*HHL*) plane is perpendicular to the rotation axis. The crystals were attached to the ^{3}He cryostat, and the most measurements were done at 0.3 K. Oscillating radial collimator was installed to reduce the background. We rotate the crystals in the range of 15° < ψ < 110° with 0.5° step. We define ψ = 0 when $\mathbf{k}_i \parallel$ (110).

INS measurements were conducted using the disk chopper spectrometer AMATERAS. The disk chopper 02 was rotating the frequency of 300 Hz, and the combination of E_i with 2.6, 5.9, and 23.7 meV was used for our INS measurements.

3. Results

Constant energy map in (*HK*0) plane with the energy window of [0.8, 1.4] meV is shown in Fig. 2(a). Magnetic signals are observed at the IC position (0.3, 0.3). To see the energy dependence, INS intensity map as a function of energy transfer ($\hbar\omega$) and *HH*0 is plotted in Figs. 2(b) and 2(c). The IC fluctuation persists up to at least 10 meV. On the other hand, the low-energy IC fluctuation clearly show the gap below 0.25 meV. The gap behavior is also clearly seen in the energy cuts as plotted in Fig. 2(d). To see the *L* dependence of the IC fluctuation, (*HHL*) maps of two different energy windows are shown in Figs. 2(e) and 2(f), by integrating [2.0, 3.5] meV and [0.8, 1.4] meV, respectively. In higher energy, the INS intensity decreases

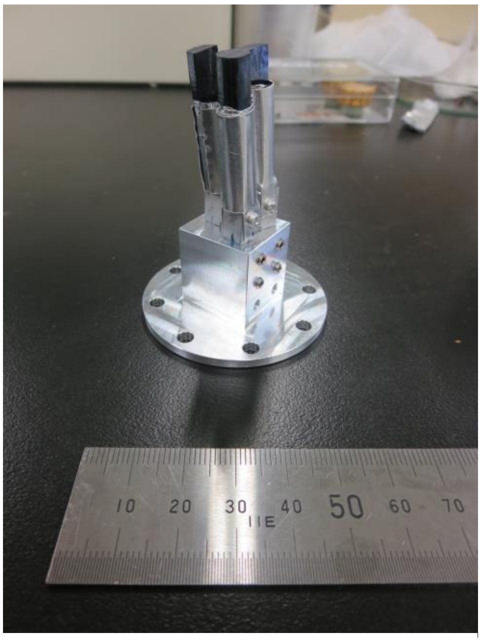

Figure 1. Picture of co-aligned crystals.

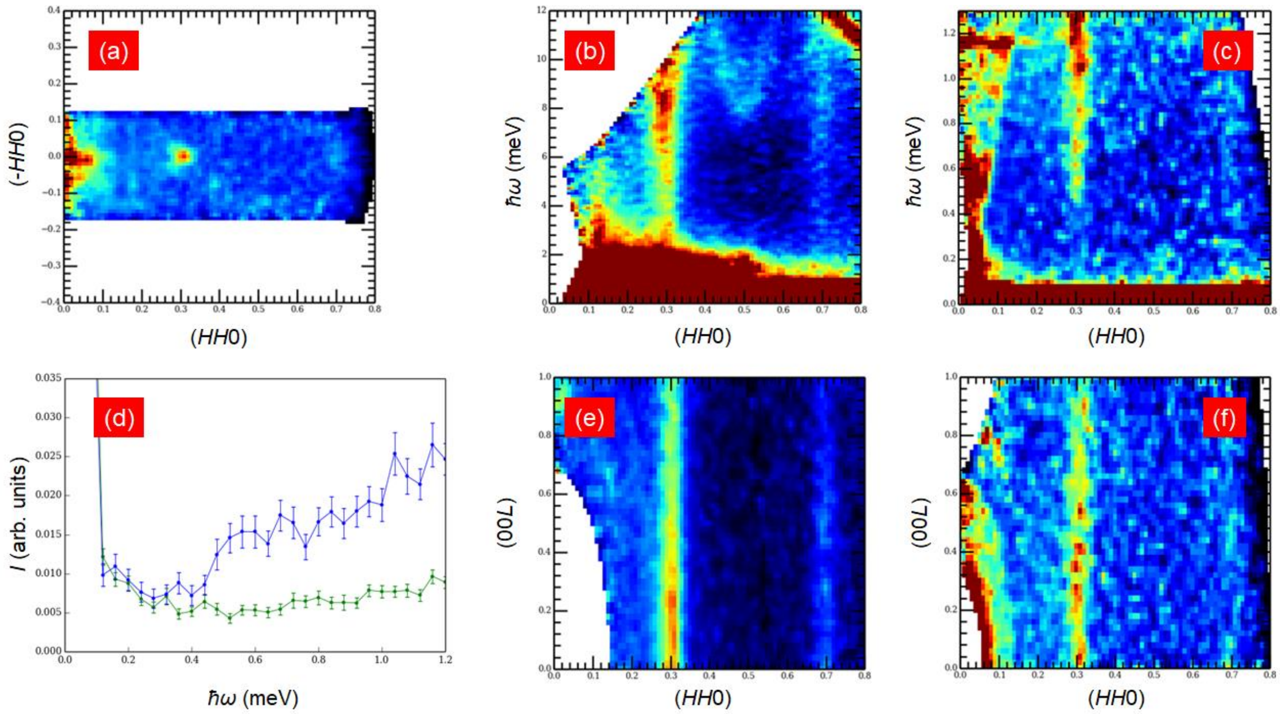

Figure 2. (a) Constant energy map in (*HK*0) plane with the energy window of [0.8, 1.4] meV. L was integrated in [-0.7, 0.7] r.l.u. (b) – (c) INS intensity map as a function of $\hbar\omega$ and *HH*0 with (b) E_i = 23.7 and (c) 2.6 meV. L was integrated in [-1, 1] r.l.u. and [-0.7, 0.7] r.l.u., respectively. (d) Energy cut at the IC position $\mathbf{Q}$ = (0.3, 0.3). Background at $\mathbf{Q}$ = (0.46, 0.45) is also plotted. L was integrated in [-0.7, 0.7] r.l.u. (e) – (f) L dependences of the IC fluctuation with the energy window of (e) [2.0, 3.5] meV and (f) [0.8, 1.4] meV.

monotonically with increasing L [Fig. 2(e)]. This behavior can be well explained by the magnetic form factor. In contrast, in lower energy, the INS intensity shows the maximum at L = 0.25 [Fig. 2(f)]. This signature is most likely representing the superconducting gap symmetry in Sr_2RuO_4 and thus may be the crucial information of the SC order parameter in Sr_2RuO_4. It should be mentioned that the magnetic signal also appears at (0.5, 0.5) above 7.5 meV [Fig. 2(b)].

On the other hand, as seen in Fig. 2(a), we see some intensity around $\mathbf{Q}$ = (0.1, 0.1), which is supposed to be the ferromagnetic fluctuation originating in the γ sheet. This ferromagnetic fluctuation persists up to at least 6 meV as shown in Fig. 2(b). But the ferromagnetic signature is not conclusive.

4. Conclusion

We successfully investigated in detail the magnetic fluctuations in Sr_2RuO_4 below T_c using AMATERAS. Our most important results are (1) the IC magnetic fluctuation exhibit the superconducting gap of 0.25 meV, (2) L dependence of the scattering intensity of the low-energy IC fluctuation shows the maximum intensity at $L \sim 0.25$, and (3) possible FM fluctuation around $\mathbf{Q}$ = (0.1, 0.1) is observed.

Since the magnetic signal is very weak, we focus on the measurements below T_c in the current experiment. We want to perform further experiment above T_c. If the L dependence of the low-energy IC fluctuation represents the superconducting gap, the observed L dependence will disappear above T_c, which will provide us the crucial information on the superconducting gap in Sr_2RuO_4.