Experimental report

11/02/2021

Proposal: **4-02-586** **Council:** 4/2020

Title: pi,pi resonance mode in the superconducting state of Sr2RuO4

Research area: Physics

This proposal is a continuation of 4-02-537

Main proposer: **Kevin JENNI**

Experimental team: Paul STEFFENS

Local contacts: Paul STEFFENS

Samples: Sr2RuO4

Instrument	Requested days	Allocated days	From	To
THALES	7	7	16/09/2020	23/09/2020

Abstract:

The recent finding that the Knight shift drops in the superconducting phase of Sr2RuO4 renders the previously advocated p-wave superconducting symmetry very unlikely and stimulated new theoretical analyses. A dx2-y2 gap distribution has been proposed by several theoretical groups and is consistent with a tunneling study. For this symmetry one does not expect a resonance mode at the nesting position studied so far. Instead we propose to look for the resonance mode appearing at q=(pi,pi) and other q values consistent with the new theoretical analyses.

Experimental Report

Instrument	THALES
Proposal Number	4-02-586
Proposal	π,π resonance mode in the superconducting state of Sr_2RuO_4
Experimentalist	Kevin Jenni, Markus Braden
Local Contact	Paul Steffens

The superconducting (SC) state in Sr_2RuO_4 remains mysterious after over 25 years of efforts. The longtime advocated triplet p-wave pairing arises from coupling through quasi-ferromagnetic (FM) fluctuations. However, the dominant magnetic excitations in Sr_2RuO_4 are incommensurate (IC) fluctuations originating from strong nesting in the Q1D bands [1]. These fluctuations do not seem to play an active role in the SC pairing [2]. Polarized INS experiments have shown that there indeed exist quasi-FM fluctuations, which are significantly weaker than the IC ones but widely spread in Q-space [3], so that their q-averaged impact is at least comparable. In this experiment we wanted to further investigate the magnetic fluctuations in Sr_2RuO_4 in its superconducting state. Specifically the low energy response in and above the superconducting (SC) phase at proposed points in the Brillouin zone (e.g. (0.5,0.5)) could indicate the appearance of a spin resonance or a gap.

To reach the low background, the high energy resolution and the high flux needed for the described task we measured at ThALES in following configuration. The Si/PG monochromator-analyzer setup delivered the high energy resolution whereas the background could be minimized by installing the Be-filter as well as the radial collimator at the analyzer. Same setup was used in previous experiments at ThALES.

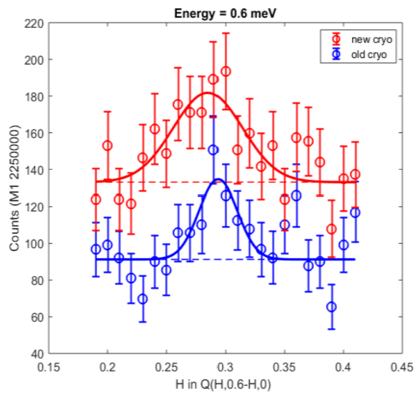

Fig. 1: Comparison of incommensurate signal at Q(0.3,0.3,0) for both cryostats

After a successful start of the experiment we could collect data for the incommensurate (IC) signal at Q_{IC1} = (0.3,0.3,0) at low temperature for comparison with previous experiments. Unfortunately the isolation vacuum of the cryostat broke during the first night. Therefore we had to change the cryostat and restart the experiment after 1.5 days after begin of the beam time. With the new cryostat we could measure the IC signal with the same strength but the background was increased significantly (Fig.1). With the new cryostat the experimental conditions became thus worse than with the setup we used in our previous experiment described in reference [2].

We started with the low energy response at the incommensurate positions Q_{IC1} = (0.3,0.3,0) and Q_{IC2} = (1.3,0.3,0) which are connected to the nesting between the one-dimensional sheets of the Fermi surface. Fig.2 shows the collected constant Q scans for both temperatures, in the SC and normal phase. The main focus lays on IC1 since the magnetic form factor should enhance the magnetic signal compared to IC2. The raw data clearly shows that the magnetic signal is only very weak since the background is almost identical with the data. To extract some tendency we subtracted the low temperature data from the high temperature data. If there is a spin resonance at a certain energy we should see a negative contribution in this difference, while the opening of a gap in the SC phase would be indicated by a positive enhancement of the difference. There seems to be no such features visible since the difference stays rather constant. With the few recorded background points we tried to clean up the raw data and analyzed also the difference between the temperatures. The overall shape is comparable between raw and subtracted data difference but no clear effect can be observed.

For the recently advocated $d_{x^2-y^2}$ gap distribution one expects no resonance modes or large gaps at the nesting vector, which is consistent with the previous observation [2] as well as with this new experiment. However this $d_{x^2-y^2}$ gap symmetry produces a sign change at (0.5,0.5) which can lead to the appearance of a resonance mode or sizeable gap. Therefore, we also studied the low energy response at Q_{ZB1} = (0.5,0.5,0) and Q_{ZB2} = (-0.5,0.5,0) similar to the IC positions (Fig.3). Also here the differences are subtle. The raw data does not indicate any clear difference between low and high temperature. Analyzing the difference of ZB1 one can assign a minimum around 0.42 meV which also is visible in ZB2, even though the data quality is poorer. Also when we subtract the measured background points for low temperature from both datasets of ZB1 of both temperatures, the feature in the difference stays. We note that the zero line in the difference is shifted because of a temperature dependent background. Evidence of a resonance feature can be deduced from the maximum negative difference pointing to an enhancement of the magnetic signal in the SC phase. The FWHM peak width of around 0.06 meV seems rather low but a broader feature is also consistent with the data.

Additionally, we also studied constant Q scans for both temperatures at Q_{ridge} = (0.5,0.3,0) (Fig.4). This Q vector is located between the incommensurate peaks at (0.3,0.3) and at (0.7,0.3) and calculations and INS experiments in the normal state have shown an enhanced susceptibility at this position [4,1,5]. But there is no difference visible when comparing data above and below T_c, see Fig. 4.

In conclusion we studied the low energy response of magnetic fluctuation at interesting points in the Brillouin zone below and above the SC transition. The data of IC positions confirms and extends the findings of previous experiments. In the data taken at Q=(0.5,0.5) a feature appears in the difference of the spectra taken above and below T_c . This feature appears at 0.42 meV, which is slightly below twice the maximum superconducting gap in Sr_2RuO_4, but one has to keep in mind the considerable uncertainty concerning the superconducting gap. In general the collection of data concerning the low energy response remains challenging. We have to operate the instrument at its performance limits to study very small signals at very low energies. Although the beam time was shortened and the instrument performance not ideal due to the cryostat failure we could obtain data on which new investigations can built. *– Part of the results are included in reference [5].*

References

[1] Y. Sidis et al., Phys. Rev. Lett. 83, 3320 (1999); M. Braden et al., Phys. Rev. B 66, 064522 (2002); F. Servant et al., Phys. Rev. B 65, 184511 (2002); M. Braden et al., Phys. Rev. Lett. 92, 097402 (2004); K. Iida et al., Phys. Rev. B 84, 060402(R) (2011); K. Iida et al., J. of Phys. Soc. Jpn. 81, 124710 (2012). **[2]** S. Kunkemöller et al., Phys. Rev. Lett., 147002 (2017). **[3]** P. Steffens et al., Phys. Rev. Lett. 120, 047004 (2019). **[4]** A. T. Rømer et al., Phys. Rev. Lett. 123, 247001 (2019). **[5]** K. Jenni, S. Kunkemoller, P. Steffens, Y. Sidis, R. Bewley, Z. Q. Mao, Y. Maeno, and M. Braden, *Neutron scattering studies on spin fluctuations in Sr_2RuO_4*, submitted to Phys. Rev. B

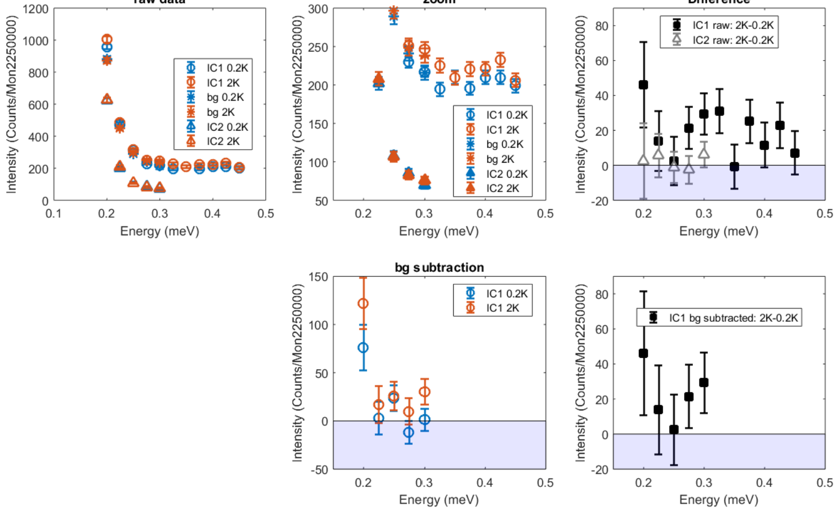

Fig. 2: Const Q scans at the positions Q_{IC1} = (0.3,0.3,0) and Q_{IC2} = (1.3,0.3,0) for two temperatures. The background has been collected for a Q vector with same length as IC1 (A3 rotation by 30°) at both temperatures. The top row shows the raw data where the last panel (top right) depicts the difference between the two temperatures. For the bottom row the collected background points were subtracted from the raw data of IC1.

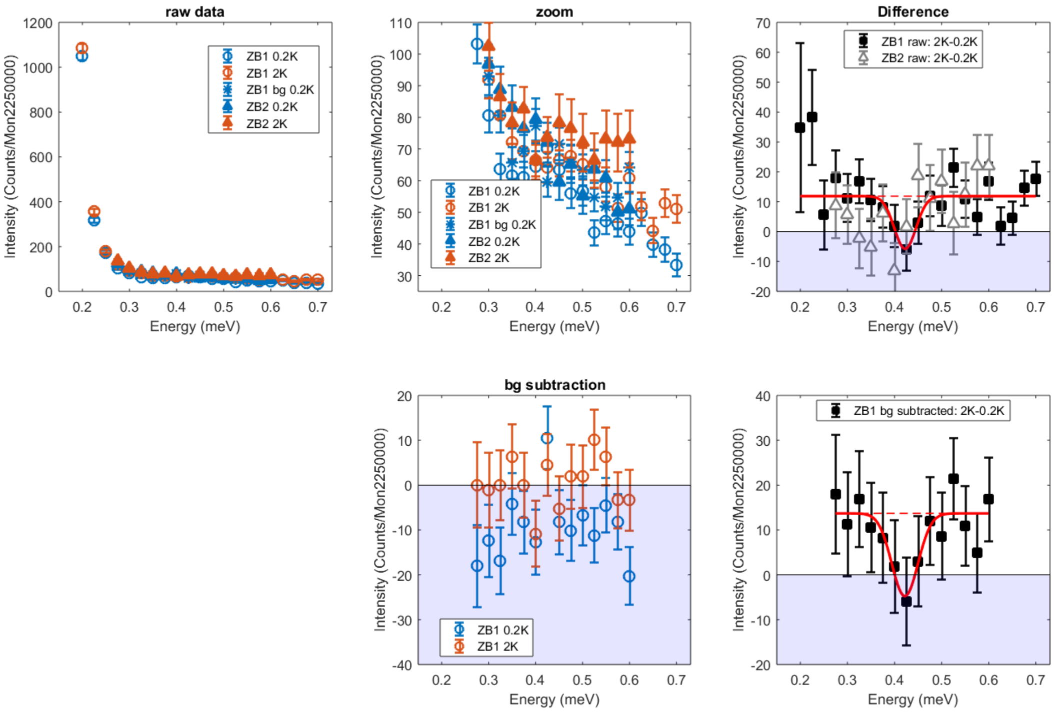

Fig. 3: Constant Q scans at the positions Q_{ZB1} = (0.5,0.5,0) and Q_{ZB2} = (-0.5,0.5,0) for two temperatures. The background has been collected for a Q vector with same length as ZB1 (A3 rotation by 30°) at the low temperature. The top row shows the raw data where the last panel (top right) depicts the difference between the two temperatures. For the bottom row the collected background points were subtracted from the raw data of ZB1 for both temperatures. The red lines denote Gaussian fits with constant backgrounds and underline evidence for a spin resonance mode.

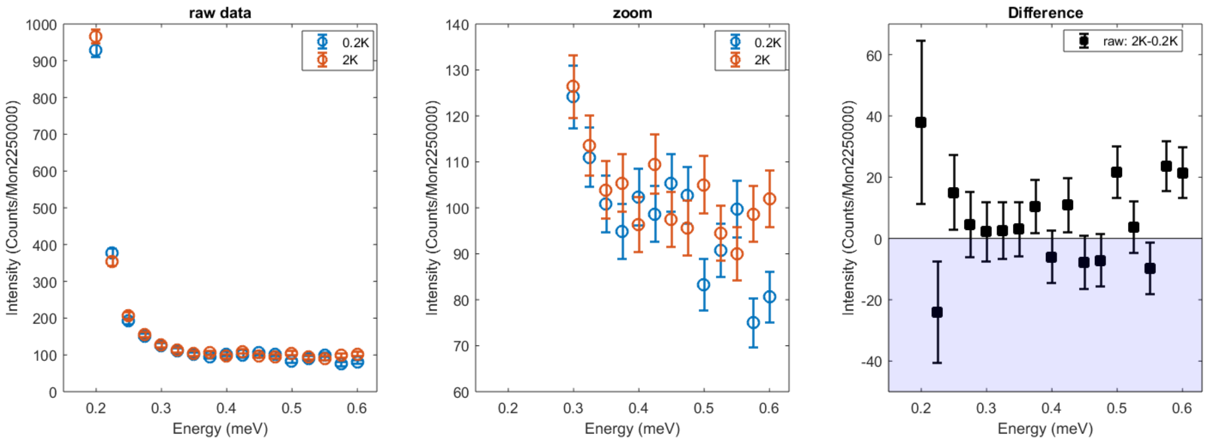

Fig. 4: Constant Q scans at the positions Q_{ridge} = (0.5,0.3,0) for two temperatures. The left and middle panels show the raw data and the right panel depicts the difference between the two temperatures. In contrast to Q=(0.5,0.5) there is no evidence for a resonance mode at this Q_{ridge} vector.