Experimental report

13/02/2019

Proposal: **4-02-534** **Council:** 4/2018

Title: Study of spin resonance by polarized inelastic neutron scattering in heavy fermion superconductor CeCu2Si2

Research area: Physics

This proposal is a new proposal

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Samples: CeCu2Si2

Instrument	Requested days	Allocated days	From	To
THALES	8	7	25/09/2018	02/10/2018

Abstract:

Superconductivity in materials with strong magnetic fluctuations captures the attention of the condensed matter community. The question is how superconductivity can emerge with the help of magnetism, and how the latter is affected by the emergence of superconductivity. We propose to study the magnetic excitations of heavy-fermion superconductor CeCu2Si2 (S-type) using polarized inelastic neutron scattering. The goal is to determine which component of the dynamic magnetic susceptibility is most strongly related to superconductivity.

Experiment

Our polarized neutron scattering experiment are carried out on the THALES triple-axis spectrometers at Institut Laue-Langevin, Grenoble, France. Polarized neutrons were produced using a focusing Heusler monochromator and analyzed with a focusing Heusler analyzer by a final wave vector of K_f = *1.15* Å^{-1}. About 10 grams co-aligned single crystals with an in-plane mosaic < *2°* are used in our polarized neutron scattering experiment. The scattering plane is *[H,H,L]* plane. The superconducting transition temperature T_c is about 0.5 *K* [Fig.1(d)] and the tetragonal lattice parameters of the unit cell are $a = b = 4.094$ *Å* and $c = 9.930$ *Å*. The wave vector transfer Q in three-dimensional reciprocal space in Å^{-1} is defined as $Q = Ha^* + Kb^* + Lc^*$, with $a^* = \frac{2\pi}{\vec{a}}$, $b^* = \frac{2\pi}{\vec{b}}$ and $c^* = \frac{2\pi}{\vec{c}}$, where *H,K* and *L* are Miller indices. We define neutron polarization directions as x, y and z, with x parallel to Q, y perpendicular to Q within the scattering plane, and z perpendicular the scattering plane, respectively [Fig.1(c)]. The measured neutron cross sections are then accordingly written as σ_α^{NSF} and σ_α^{SF}, where α is x, y and z. A flipping ratio (R = $\sigma_{Bragg}^{NSF}/\sigma_{Bragg}^{SF}$) of about 17 which was measured at Bragg point (0,0,1) is maintained throughout our experiment. All scans were measured at two equivalent antiferromagnetic vectors Q_1 = (0.215,0.215,1.456) and Q_2 = (0.215,0.215,0.55).

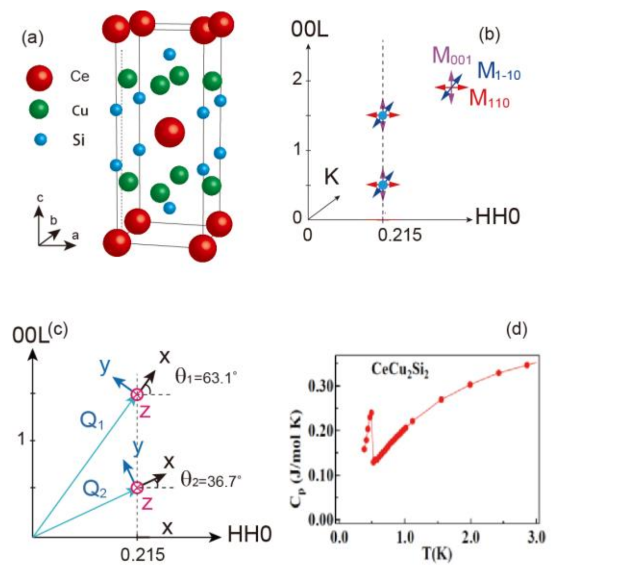

Figure 1. (a) A schematic diagram of the tetragonal unit cell of $CeCu_2Si_2$. (b) The positions of reciprocal space probed in our polarized neutron experiment. Magnetic fluctuations polarized along the (110), (1-10), and (001) directions are marked as M_{110}, $M_{1\bar{1}0}$, and M_{001}, respectively. (c) Schematic of the [H,H,L] scattering plane, where the equivalent antiferromagnetic wave vectors Q1=(0.215,0.215,1.456) and Q2=(0.215,0.215,0.55) are probed. The neutron polarization directions are along the x, y, and z. The angle between the direction along Q and (HH0) axis is denoted as θ. (d) The temperature dependence of specific heat measured by transport method. The T_c is at 0.5 K.

Result

Our polarized INS result is shown in Figure.2. To determine the resonance energy position in superconducting $CeCu_2Si_2$, we did the energy scan at T = 50 mk with Q_1 at first. Figure 2(a) and 2(b) shows the raw data of energy transfer dependence of neutron spin-flip (SF) scattering cross section σ_α^{SF} and the sum of σ_α^{SF} of all polarized channels, respectively. The resonance energy is E_r = 0.23 meV which has a 0.3 meV shift compares previous unpolarized INS experiment [1]. Since the low signal-to-background ratio, spin gap which is indicate by the missing weight below E_r is obscure in our experiment. Figure 2(d) and 2(e) shows the raw data of wave vector dependence of σ_α^{SF} in the superconducting sate (T=50 mK) at E_r with Q_1 and Q_2, respectively. Only three points were measured at Q_2 due to the time limiting, that lead the different analysis process between Q1 and Q2. If the scattering is isotropic in spin space, the signal distribution of σ_y^{SF} and σ_z^{SF} should be same, the σ_y^{SF} and σ_z^{SF} at Q1 is clearly not the case. They are the same at Q2 may due to the contribution of the three component of magnetic moment is the same at Q2. From the observed σ_x^{SF}, $\sigma_y^{SF}$and σ_z^{SF} at Q1 and Q2 in Figure 2(d) and 2(e), we can get the three magnetic moment components via fitting the model [17-18], as following

$$\sigma_x^{SF}(Q_1) = F^2(Q_1)sin^2\theta_{Q_1}\frac{R}{R+1}M_{110} + F^2(Q_1)\frac{R}{R+1}M_{1-10} + F^2(Q_1)cos^2\theta_{Q_1}\frac{R}{R+1}M_{001} + B(Q_1) \quad (1)$$
$$\sigma_y^{SF}(Q_1) = F^2(Q_1)sin^2\theta_{Q_1}\frac{1}{R+1}M_{110} + F^2(Q_1)\frac{R}{R+1}M_{1-10} + F^2(Q_1)cos^2\theta_{Q_1}\frac{1}{R+1}M_{001} + B(Q_1) \quad (2)$$
$$\sigma_z^{SF}(Q_1) = F^2(Q_1)sin^2\theta_{Q_1}\frac{R}{R+1}M_{110} + F^2(Q_1)\frac{1}{R+1}M_{1-10} + F^2(Q_1)cos^2\theta_{Q_1}\frac{R}{R+1}M_{001} + B(Q_1) \quad (3)$$
$$\sigma_x^{SF}(Q_2) = rF^2(Q_2)sin^2\theta_{Q_2}\frac{R}{R+1}M_{110} + rF^2(Q_2)\frac{R}{R+1}M_{1-10} + rF^2(Q_2)cos^2\theta_{Q_2}\frac{R}{R+1}M_{001} + B(Q_2) \quad (4)$$
$$\sigma_y^{SF}(Q_2) = rF^2(Q_2)sin^2\theta_{Q_2}\frac{1}{R+1}M_{110} + rF^2(Q_2)\frac{R}{R+1}M_{1-10} + rF^2(Q_2)cos^2\theta_{Q_2}\frac{1}{R+1}M_{001} + B(Q_2) \quad (5)$$
$$\sigma_z^{SF}(Q_2) = rF^2(Q_2)sin^2\theta_{Q_2}\frac{R}{R+1}M_{110} + rF^2(Q_2)\frac{1}{R+1}M_{1-10} + rF^2(Q_2)cos^2\theta_{Q_2}\frac{R}{R+1}M_{001} + B(Q_2) \quad (6)$$

In our case, the R=17 is the flipping ratio, F(Q) is the magnetic form factor of Ce^{2+} , θ(Q) is the angle between Q and [1,1,0] [Fig.1(c)], B is the wave vector dependence but polarization independent background scattering and r is the normalized factor between Q1 and Q2. The magnetic responses along (110), (1-10) and (001) are marked as M_{110}, $M_{1\bar{1}0}$and M_{001},respectively, as shown in Fig1(b). The fitting result is shown in Figure 2(f), the indices of horizontal axis represent corresponding indices of $\sigma_\alpha^{SF}$of equations (1)-(6). We found $M_{110} > M_{1\bar{1}0} > M_{001}$ that is consistent with the 3D SDW in CeCu2Si2, and the main contribution of magnetic moment is comes from ab plane.

To gain insight into the spin fluctuation anisotropy below and above T_c at E_r with Q_{AF}, the temperature dependence of σ_α^{SF} at Q1 is shown in Figure 2(c). below T_c, a clear difference between σ_y^{SF} and σ_z^{SF}

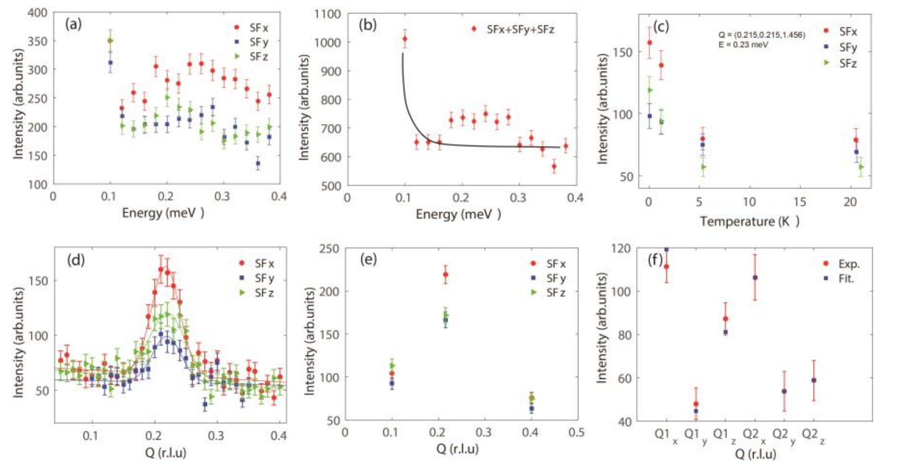

Fig.1. The main result of polarized INS. (a) the energy scan of σ_x^{SF}, $\sigma_y^{SF}$and σ_z^{SF} at Q_{AF} = (0.215,0.215,1.456) below T_c, and together all intensity of the three channels (b), the solid line in (b) is a quasielastic Lorentzian line. (c) The temperature dependence of σ_x^{SF}, $\sigma_y^{SF}$and σ_z^{SF}at E_r with Q_{AF}. (d) Wave vector dependence of σ_x^{SF}, $\sigma_y^{SF}$and σ_z^{SF} at E_r with Q1= (H, H,1.456) and with Q2= (H, H,0.55) (e), the solid lines in (d) are the fitting curves by Gaussian function. (f) the fitting result of our model based on (d) and (e), the solid red dots and solid blue dots are experiment data and fitting results, respectively. The integral intensity of Q1 was used with a normalized factor r when during fitting. All scans except (c) are measured at T = 50 mk.

indicate the spin fluctuation is anisotropic. For paramagnetic isotropic scattering we should expect $(\sigma_x^{SF} - B) = 2(\sigma_y^{SF} - B) = 2(\sigma_z^{SF})$ and the scattering becomes featureless. We indeed found the spin fluctuation isotropy when T = 1.2 K where in paramagnetic state. The σ_x^{SF}, $\sigma_y^{SF}$and σ_z^{SF} almost the same and do not change any more above 5K, that indicates the magnetic response is no longer as the primary contribution to σ_α^{SF}.

Discussion and Conclusion

The spin fluctuation anisotropy can be explained by many models, the single-ion anisotropy which is associated with local moment, the SOC in an itinerant electron description, spin-orbit interaction coupling with nematic order and so on. In other heavy fermion superconductor, $CeCoIn_5$, the fluctuation polarized along c direction without any in-plane contribution, the strong anisotropy is consistent with ordered magnetic moments in magnetic field induced Q phase. The spin resonance anisotropy is identified as the result of crystal field anisotropy. In $CeCu_2Si_2$, to date we do not have any information of the degree of anisotropy of the spin excitation or single-ion anisotropy energy, it is hard to separate the anisotropy induced by SOC or by single-ion anisotropy. Hence, the resonance anisotropy may come from the coaction of spin-orbital coupling and the crystal field effect. The unpolarized INS experiment [13] at E_r with Q_{AF}, the spin correlation length almost the same along [110] and [001] direction and that result is agreement with 3D SDW in $CeCu_2Si_2$.

The calculation shows [2], under the situation that crystal of $CeCu_2Si_2$ has the inversion symmetry property, SOC competes with the condensation energy that will hamper the formation of Cooper pairing. To prove that should need further experiment. That will help to elucidate the relationship between SOC and superconductivity is whether like in iron-based superconductor.

Suggestion for further measurement

In this experiment, the signal of resonance and spin gap is ambiguous as previous experiment [3] due to a low signal-to-background ratio. Like Stocker who chooses the IN12 (ILL) for the INS of $CeCu_2Si_2$ and gets high signal-to-background ratio signal [13]. Furthermore, IN12 has the setup of polarized neutron scattering. Therefore, polarized INS at IN12 for future experiment is an ideal choice. We just do constant-energy scans which cross the two equivalent antiferromagnetic vectors Q_1 = (0.215,0.215,1.456) and Q_2 = (0.215,0.215,0.55). Energy scan both at Q_1 and Q_2 below and above T_c need to do to capture the energy and temperature dependence of σ_x^{SF}, $\sigma_y^{SF}$and σ_z^{SF}. Therefore, we can get the full physical picture of the relation between superconductivity and the SOC in $CeCu_2Si_2$.

Reference

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[3] Stockert, O et al., Phys. B. Cond. Matt 403, 973-976 (2008)