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# Field-Induced Ferromagnetic Correlation in the Heavy-Fermion Compound $CeRu_2Si_2$

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In order to study the origin of the metamagnetic behavior in heavy fermion systems, we have performed inelastic neutron scattering experiments on the compound $CeRu_2Si_2$ under magnetic field ($H \| c$) around the crossover field $H_m$=7.7 T. The result is that around $H_m$ the quasi-elastic magnetic excitation with an energy of about 0.4 meV is significantly enhanced in the vicinity of the reciprocal lattice point (110). This result indicates that a metamagnetic behavior must be associated with field-induced ferromagnetic correlation, and this is consistent with the recent theoretical prediction by Satoh and Ohkawa based on the quasi-particle band spectrum considerations.

KEYWORDS: $CeRu_2Si_2$, spin fluctuation, metamagnetism, heavy fermion, inelastic neutron scattering

## §1. Introduction

$CeRu_2Si_2$ is a moderately heavy fermion compound (the $\gamma$-coefficient of the electronic specific heat as large as 360 mJ/(K$^2$ mol)[1]), which is well known as a Pauli paramagnet exhibiting a metamagnetic behavior. It crystallizes in the $ThCr_2Si_2$-type body centered tetragonal structure. Applying a magnetic field parallel to the $c$-axis at the low temperature, the magnetization jumps abruptly around $H_m$=7.7 T.[5,6] In the vicinity of $H_m$ the other macroscopic properties such as the specific heat,[7] magnetostriction,[8,9] and etc. are anomalous. Because the susceptibility at $H_m$ tend to saturate as temperature approaches 0 K, this metamagnetic behavior has been concluded to be not a phase transition but a cross-over behavior.[6]

In the absence of magnetic field, it has been observed by inelastic neutron scattering experiments that three antiferromagnetic correlations develop into dynamical spin fluctuations below 60 K. The magnetic wave vectors are $\boldsymbol{k}$=(0.3,0,0) (hereafter denoted as $\boldsymbol{k}_1$), (0.3,0.3,0) ($\boldsymbol{k}_2$)[3] and (0,0,0.35) ($\boldsymbol{k}_3$)[4] in r.l.u., respectively. Rossat-Mignod *et al.* have investigated the field dependence of these antiferromagnetic fluctuations and found that they disappear abruptly around $H_m$.[10]

Recently, the metamagnetic behavior has been theoretically studied on the basis of the quasi-particle band spectrum considerations by Satoh and Ohkawa.[11,12] They have explained the anomalous properties assuming a pseudo-gap structure of the density of state around the Fermi level. This model has predicted that a ferromagnetic fluctuation is induced by magnetic field around the metamagnetic point. However, the evidence of the ferromagnetic fluctuation around $H_m$ has not been observed in the previous studies.

In order to establish whether the ferromagnetic fluctuation is induced around $H_m$ or not, we carried out inelastic neutron scattering experiments under high magnetic field. In conclusion we succeeded to discover the field induced ferromagnetic fluctuation around $H_m$.

## §2. Experimental

We prepared four single crystalline samples with cylindrical shape grown along the $c$-axis. The mosaic spreads of the crystals were less than 0.5 degree. In order to get large volume of samples, we assembled four crystals with the total volume of about 3 cc. The experiments were carried out at LTAS, a cold triple axis spectrometer installed at the C2 cold neutron guide tube of the JRR-3M reactor of JAERI, Tokai. We performed scans with the energy of the scattered neutrons fixed at 3.8 meV using a horizontally-focusing-analyzer (HFA) in order to improve the efficiency of collecting the scattered neutrons. With the HFA, the momentum resolution of measurement had a full width of about 0.09 Å$^{-1}$ in the direction perpendicular to the scattering beam, which we found sharp enough because the spectrum of the magnetic scattering in this compound is broad in the reciprocal lattice space. In this configuration, the instrumental energy resolution was about 0.3 meV. For controlling the configuration of the sample, we used the liquid-He-free type 10T Magnet with a liquid-He-free type dilution refrigerator, which are developed by JAERI.[13]

## §3. Results and Discussion

In Fig. 1 are shown the field-dependence of the uniform magnetization at $T$=0.4, 5.5, 10K, estimating from the intensity of the Bragg peak at (110). We observed

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that the intensity of (110) increases with applying field. This increase is due to the ferromagnetic scattering superimposed on the nuclear scattering. It can be seen in this figure that the metamagnetic behavior is exhibited around $H_m$ at $T$=0.4 K. As the temperature increases, the jump becomes broader and disappears at $T$=10 K. These features are in good agreement with the results of the previous magnetization measurements.

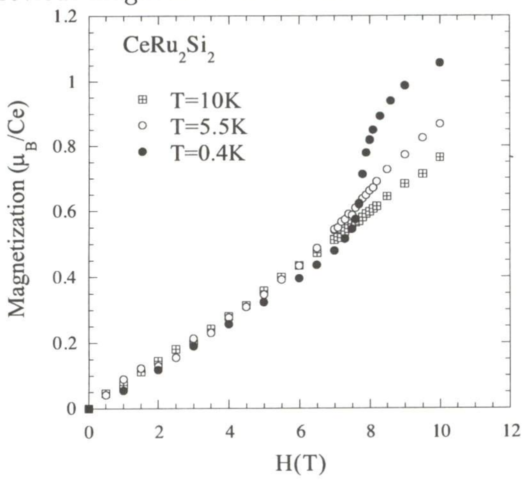


Fig. 1. Field-dependence of the uniform magnetization with the field $H \| c$-axis at $T$=0.4, 5.5, 10 K estimated from the intensity of the Bragg peak for (110).

In Fig. 2 is shown the field dependence of the low-energy magnetic excitation. These data indicate the results of constant-$E$ scans with the energy transfer $\hbar\omega$=0.4 meV at $T$=0.4 K carried out along the line between the Γ-point (110) and (0.5,1,0) which is located near the zone boundary. These data are corrected by the calculated magnetic form factor of Ce free ion[14,15] after subtracting the instrumental background. In the absence of the field, it can be seen that the peak due to the antiferromagnetic fluctuation exists at (0.7,1,0) shown by the broken line in Fig. 2. Applying field of $H_m$, this peak disappears abruptly, which is consistent with the report by Rossat-Mignod *et al.* Instead of the antiferromagnetic correlation, we observed a broad peak around the Γ-point, (110), as shown by the solid line in Fig. 2. The existence of this broad peak indicates that a ferromagnetic correlation is induced by the field. At 10 T, this ferromagnetic fluctuation is strongly suppressed. It means that the field-induced ferromagnetic correlation is enhanced around $H_m$. It should be noted that the strong intensity very close to (110) is due to the Bragg contamination. The detailed field dependence of the intensity with $\hbar\omega$=0.4 meV at (0.9,1,0) is shown in Fig. 3. As shown in this figure, the intensity forms a peak around $H_m$. These results suggest that a ferromagnetic correlation is induced around $H_m$. It is consistent with the prediction by Satoh and Ohkawa. In their theoretical works, the field dependence of the energy spectrum of the ferromagentic fluctuation has been calculated. For the verification of such the detail, we need more information. This study is proceeding now and the results will be reported soon elsewhere.

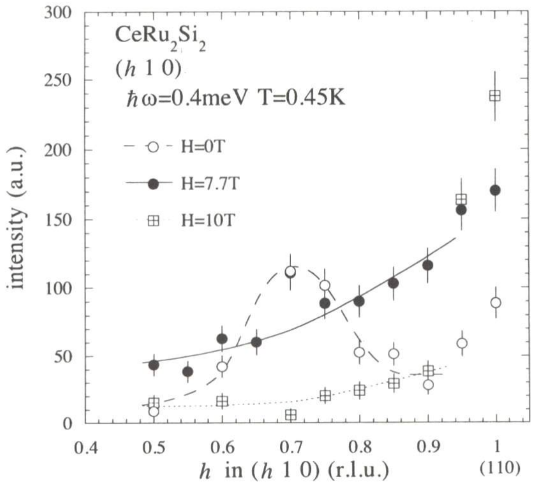


Fig. 2. Field-dependence of constant-$E$ scan with $\hbar\omega$=0.4 meV at $T$=0.4 K carried out along the line between (110) and (0.5,1,0). The intensities of signals are corrected by the magnetic form factor after subtracting the instrumental background.

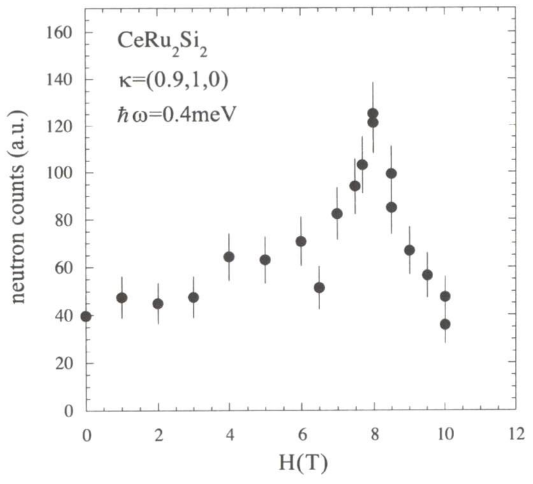


Fig. 3. Field-dependence of the scattering intensity for (0.9,1,0) with $\hbar\omega$=0.4 meV at $T$=0.4, 5.5, 10K.

## §4. Conclusion

We have investigated the field dependence of the spin fluctuation in $CeRu_2Si_2$ at the low temperature by inelastic neutron scattering experiments under magnetic field up to 10 T. As the result, we found that a ferromagnetic correlation is induced around the metamagnetic point.


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