Anisotropic Magnetic Fluctuations and Superconductivity in Ferromagnetic Superconductor UCoGe

T Hattori, Y Ihara, K Karube, Y Nakai, K Ishida, K Deguchi, N K Sato and I Satoh

1 Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan.
2 Transformative Research Project on Iron Pnictides (TRIP), Japan Science and Technology Agency (JST), Tokyo 102-0075, Japan.
3 Department of Physics, Graduate School of Science, Nagoya University, Nagoya 464-8602, Japan.
4 Institute for Materials Research, Tohoku University, Sendai 980-8577 Japan.

E-mail: y.hattori@scphys.kyoto-u.ac.jp

Abstract. We have performed $^{59}$Co NQR / NMR measurements on the single-crystalline UCoGe, in order to investigate the relationship between ferromagnetism and superconductivity. The measurements of Knight-shift and nuclear spin-lattice relaxation rate provide clear evidence that both static and dynamic susceptibilities are ferromagnetic with Ising anisotropy. In addition, $H_{c2}$ also shows extremely large anisotropy which can not be explained by the GL model with anisotropy of effective mass. These data suggest intimate relationship between Ising magnetization and anisotropic superconductivity in UCoGe.

1. Introduction
After the discovery of superconductivity in the ferromagnetic UGe$_2$ under pressure, the relationship between ferromagnetism and superconductivity has attracted much interest. In 2007, Huy et al. reported superconductivity with $T_{SC} \approx 0.6$ K in the U-based compound UCoGe at ambient pressure, where ferromagnetic(FM) ordering occurs at $T_{Curie} \approx 3.0$ K, and ferromagnetism and superconductivity are considered to coexist[1]. From our NQR / NMR measurements, we have shown that superconductivity coexists with ferromagnetism microscopically[2]. For further study on the relationship between ferromagnetism and superconductivity, we investigated the anisotropic properties of the superconductivity via the angle resolved Meissner-signal measurements, as well as of magnetic fluctuations via the direction dependence of nuclear spin-lattice relaxation rate $1/T_1$ measurements[3].

2. Experiment
We used a 55 mg single crystal sample with $1.65 \times 1.65 \times 1.89$ mm$^3$, grown by the Czochralski method in a tetra-arc furnace. $T_{Curie}$ of the single-crystal sample was evaluated to be $2.55 \pm 0.1$ K from the Arrot plots[2]. Figure 1 represents the resistivity measured along each direction, and the temperature dependence below 2 K is approximately expressed $\rho = \rho_0 + AT^2$ as shown in the inset. From the anisotropy of $A$ coefficient, the anisotropy of effective mass is estimated as $m^*_c/m^*_b \approx 1.65$ using a relation of $A \propto \sqrt{m^*}$. In contrast to the small anisotropy of $m^*$,
magnetization has large Ising-type anisotropy with the easy axis along the c axis. The FM and superconducting(SC) properties of our single crystal are in good agreement with previous reports by Huy et al.[4] and Aoki et al.[5]. Large Residual-Resistivity-Ratio ($RRR \parallel b$ axis $\approx 30$) and the clear specific-heat jump at $T_{\text{Curie}}$ and $T_{\text{SC}}$ ensure high quality of the sample[6].

We measured the direction dependences of the Knight-shift ($K$) and $1/T_1$ with field orientations controlled carefully in situ using a single-axis rotator. The nuclear quadrupole splitting of the $^{59}$Co NMR spectra allowed us to determine the field directions precisely[7].

3. Result and Discussion

Figure 2 shows the temperature dependence of $K$. Large enhancement of $K_c$ and small $K_{a,b}$ ensures the Ising anisotropy from microscopic view. $K_\alpha$ is related to the static susceptibility $\chi(q = 0)$ as $K_\alpha = A_{\text{hf}}^\alpha \chi^\alpha(0) + K_{\text{orb}}^\alpha$, where $A_{\text{hf}}^\alpha$ is a hyperfine coupling constant along the $\alpha$ direction, and $K_{\text{orb}}$ is an orbital contribution, and temperature independent. $K$ versus $\chi$ plot, presented in Fig. 2 inset, indicates that a hyperfine coupling constant $A_{\text{hf}}^\alpha$ is nearly isotropic. This indicates that the U-5f spins themselves possess the anisotropy due to the spin-orbit interaction, since $A_{\text{hf}}^\alpha$ is positive and isotropic when the U-5f electrons are transferred to the Co-4s orbital and interact with the Co nuclei directly.

Dynamic susceptibility which is detected with the measurement of $1/T_1$ has also Ising anisotropy. Figure 3 presents the temperature dependence of $1/T_1/T$, which is proportional to the magnetic fluctuations perpendicular to the magnetic field.
even if field dependence of $m$ this steep angular dependence of $H$ the values are different with a factor 3 with each other, as shown in Fig. 7. It should be noted that along $c$ $H$ of the Meissner signal is plotted in Fig. 6. Determined from the angular dependence of $H$ for suppression of the superconductivity when the magnetic field is applied to $c$ axis. This angular dependence of $H$ in the SC pairing mechanism in UCoGe, and it is considered that another mechanism might work to be stable when field is applied along the spin easy axis ($c$ anisotropy of onset of the Meissner signal, the temperature dependence of $H$ dependence of ac susceptibility by the transverse spin fluctuations.

Pointed out that the Ising FM fluctuations are favorable for spin-triplet superconductivity since noteworthily that magnetic fluctuations are along the magnetic easy axis (longitudinal mode). In addition, it is noteworthy that $S_c$ scales linearly to $K^{c}_{\text{spin}}$ above 8 K, indicative of the predominance of the FM fluctuations, since this scaling is anticipated for three-dimensional FM fluctuations on the basis of the self-consistent renormalization (SCR) theory[8]. As for the relationship between magnetic fluctuations and superconductivity, P. Monthoux and G. G. Lonzarich[9] and Fujimoto[10] have pointed out that the Ising FM fluctuations are favorable for spin-triplet superconductivity since the Ising FM fluctuations with only the longitudinal mode can minimize the pair breaking caused by the transverse spin fluctuations.

In order to investigate the anisotropic properties of superconductivity, the temperature dependence of ac susceptibility $\chi_{ac}$ along each direction was measured (Fig. 4). From the onset of the Meissner signal, the temperature dependence of $H_{c2}$ was plotted in Fig. 5. The anisotropy of $H_{c2}$ is in good agreement with the previous reports[4, 5]. The smallest $H_{c2}$ along $c$ axis is one of the mysterious behaviors of UCoGe, since spin-triplet superconductivity seems to be stable when field is applied along the spin easy axis ($c$ axis).

To further examine, we measured the angular dependence of $H_{c2}$ in the $ac$ plane. $H_{c2}$ is determined from the angular dependence of $\chi_{ac}$ in various applied fields at 85 mK, and the onset of the Meissner signal is plotted in Fig. 6. $H_{c2}$ is drastically suppressed by the magnetic field along $c$ axis. This angular dependence of $H_{c2}$ is qualitatively the same as previous report[5], but the values are different with a factor 3 with each other, as shown in Fig. 7. It should be noted that this steep angular dependence of $H_{c2}$ cannot be explained at all with the anisotropic GL formula even if field dependence of $m^*$ is taken into account, since $m^*(H^c = 1T)/ m^*(H = 0) \simeq 0.75$ was reported around $H_{c2}$ along $c$ axis[5].

Therefore interpretation of the extraordinary anisotropy of $H_{c2}$ is crucial for understanding the SC pairing mechanism in UCoGe, and it is considered that another mechanism might work for suppression of the superconductivity when the magnetic field is applied to $c$ axis.
Figure 6. Angular dependence of the Meissner signals detected by the ac susceptibility in various magnetic fields in ac plane at $T = 85$ mK.

Figure 7. Angle dependence of $H_{c2}$ in ac plane at $T = 85$ mK, which is determined by the onset of Meissner signal. $H_{c2}$ data reported by D. Aoki et al. are also plotted, which are determined by resistive measurements[5].

4. Summary

Direction-dependent $^{59}$Co NMR was performed, and the $K$ and $1/T_1$ measurements provide microscopic evidence that both static and dynamic susceptibilities are ferromagnetic with strong Ising anisotropy along $c$ axis. In addition, we measured the angular dependence of $H_{c2}$ from observation of the Meissner signal probed by ac susceptibility. $H_{c2}$ also shows extremely large anisotropy, which cannot be explained by anisotropic GL model. Interpretation of these behaviors is crucial for understanding the SC pairing mechanism in UCoGe.

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