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Unconventional superconductivity in the itinerant ferromagnet UGe_2:^{73}Ge-NQR study under pressure

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Abstract

The superconducting characteristics on the itinerant ferromagnetic superconductor UGe_2 have been investigated via the ^{73}Ge-NQR measurements under pressure (P) near the critical pressure P_x where the first-order transition takes place from the low-temperature (T) and low-P ferromagnetic phase (FM2) to high-T and high-P one (FM1). The measurements of nuclear spin-lattice relaxation rate $1/T_1$ have revealed a power-law like behavior as T^n without the coherence peak, whereas at low temperatures, it deviates from the T^n dependence to a T-linear like behavior. These results that depend on the pressure are well understood in terms of non-unitary spin-triplet pairing state where the ferromagnetic up-spin band is gapped, but the down-spin band remains gapless at the Fermi level. We will argue an intimate relationship of the onset of SC with FM1 and FM2.

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The emergence of superconductivity (SC) under the background of ferromagnetic state is a great surprise among the phenomena in strongly correlated electron systems. The pressure (P)-induced SC was discovered in 5f-electron based itinerant ferromagnet UGe_2 well below its Curie temperature ($T_{curie} = 20$–40 K) under $P = 1$–1.6 GPa [1,2]. The phase diagram determined in the previous work is shown in Fig. 1(a) [2–5]. The occurrence of SC under the background of ferromagnetism (FM) is thus relevant with the first-order transition at P_x. The temperature (T) dependence of $1/T_1$ below T_{sc} was found to be well fitted by the line-node gap model with the residual density of states (RDOS) N_{res} at the Fermi level. The marked P dependence of N_{res} cannot be ascribed to some impurity effect. Further experiments are required for understanding novel superconducting characteristics and for addressing a possible order parameter symmetry in UGe_2, either a unitary or a non-unitary spin-triplet pairing state [5].

Here we address an possible origin for the RDOS presenting for the SC under the background of FM1 and FM2. A new polycrystalline sample used here was carefully crushed into powder, which was annealed to restore microscopic crystal order. Fig. 1(b) indicates the ^{73}Ge-NQR spectra for the previous and present samples. The spectra for the present sample are significantly narrower than for the previous one, demonstrating the quite better quality for the present sample than the previous one. In fact, the spectra for FM2 at $P = 1.17$ GPa very close to $P_x \sim 1.2$ GPa do not evidence any phase separation which

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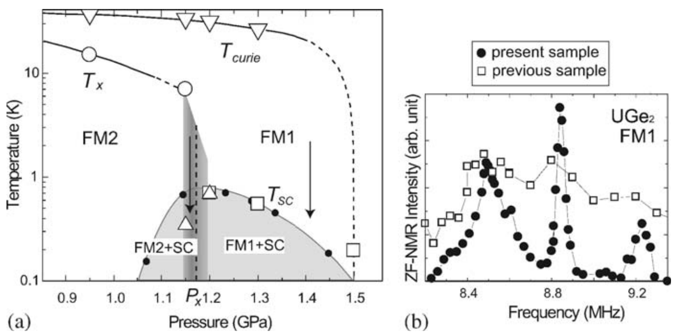

Fig. 1. (a) The pressure versus temperature phase diagram of UGe_2 [5]. Arrows show values of P where the present NQR measurements have been done. (b) NQR spectra at FM1 for the previous ($P = 1.3$ GPa, $T = 4.2$ K) and the present samples ($P = 1.41$ GPa, $T = 1.4$ K).

was observed for the previous sample [5]. In this context, the present sample allows us to deduce the superconducting characteristics inherent to FM1 and FM2 without concern for sample quality.

Next, in Fig. 2, we present the temperature (T) dependence of $1/T_1$ for FM2 and FM1 at $P = 1.17$ and 1.41 GPa, respectively. Note that a unique $1/T_1$ value is determined at each temperature. In the previous sample, the line-node gap model was applied assuming N_{res} at the Fermi level, the magnitude of the superconducting energy gap Δ and N_{res}/N_0 are estimated to be $2\Delta/k_{\mathrm{B}}T_{\mathrm{sc}}{\sim}3.8$, 3.6 and 3.6 with $N_{\mathrm{res}}/N_0 = 0.65$, 0.37 and 0.30 at $P = 1.15$, 1.2 and 1.3 GPa, respectively. Here N_0 is the DOS at the Fermi level in the normal ferromagnetic phase. In the present sample with $T_{\mathrm{sc}} = 0.45$ and 0.25 K at $P = 1.17$ and 1.41 GPa, Δ and N_{res}/N_0 are estimated to be $2\Delta/k_{\mathrm{B}}T_{\mathrm{sc}}\sim$ 3.6 and 3.5 with $N_{\mathrm{res}} = 0.50$ and 0.31 at $P = 1.17$ and 1.41 GPa, respectively. In this model, the origin of N_{res}/N_0 is expected from some impurity effect. Remarkably, however, as T_{sc} decreases from 0.41 to 0.25 K, N_{res}/N_0 *does decrease* from 0.50 to 0.31. This result cannot be ascribed to the impurity effect. Rather, the systematic P dependence of $1/T_1$ below T_{sc} is associated with the sudden increase of N_0 as passing over P_x, which was also reported in the previous sample [5]. Thus, it has been shown that N_{res}/N_0 decreases when the first-order transition takes place from FM2 to FM1 at $P_x{\sim}1.2$ GPa.

In a non-unitary odd-parity pairing model [6,7], a unique relaxation behavior has been predicted to depend on the angle between the quantization axis of nuclear-spin system and that of electron-spin one in the non-unitary odd-parity (spin-triplet) SC [8]. When the former axis is not parallel to the latter one, $1/T_1{\sim}T$ is expected at low T because the down-spin band remains gapless. Further analysis on the basis of this model is required using the more systematic and detailed experiments under pressure. This is now in progress.

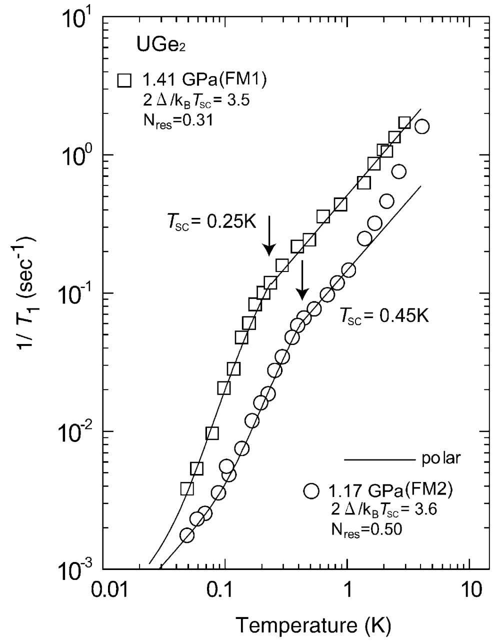

Fig. 2. The temperature dependence of $1/T_1$ at $P = 1.17$ and 1.41 GPa. The solid curve is a calculation based on an unconventional line-node gap model by incorporating the fractional residual DOS N_{res}/N_0 (see the text).

In summary, the ^{73}Ge-NQR spectra for the new sample do not reveal the phase separation into FM1 and FM2 even at $P = 1.17$ GPa just below P_x, reinforcing that the transition from FM2 to FM1 is of quantum first-order type as the function of pressure. The presence of N_{res} that is independent of T_{sc} does not arise from the impurity and/or imperfection effect in the sample, but due to the novel feature relevant with the non-unitary spin-triplet pairing state where the up-spin band parallel to the ferromagnetic moments is gapped, but the down-spin band remains gapless, giving rise to N_{res}.

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