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.

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 ($T_{\text{Curie}} = 20–40$ K) under $P \geq 1–1.6$ 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 $T_{\text{sc}}$ was found to be well fitted by the line-node gap model with the residual density of states (RDOS) $N_{\text{res}}$ at the Fermi level. The marked $P$ dependence of $N_{\text{res}}$ 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...
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 \( N_{\text{res}} \) at the Fermi level, the magnitude of the superconducting energy gap \( \Delta \) and \( N_{\text{res}}/N_0 \) are estimated to be \( 2\Delta/k_BT_{\text{sc}} \approx 3.8, 3.6 \) and \( 3.6 \) with \( N_{\text{res}}/N_0 = 0.65, 0.37 \) 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 \( T_{\text{sc}} = 0.45 \) and \( 0.25 \) K at \( P = 1.17 \) and \( 1.41 \) GPa, \( \Delta \) and \( N_{\text{res}}/N_0 \) are estimated to be \( 2\Delta/k_BT_{\text{sc}} \approx 3.6 \) and \( 3.5 \) with \( N_{\text{res}} = 0.50 \) and \( 0.31 \) at \( P = 1.17 \) and \( 1.41 \) GPa, respectively. In this model, the origin of \( N_{\text{res}}/N_0 \) is expected from some impurity effect. Remarkably, however, as \( T_{\text{sc}} \) decreases from \( 0.41 \) to \( 0.25 \) K, \( N_{\text{res}}/N_0 \) 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 \( T_{\text{sc}} \) 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 \( N_{\text{res}}/N_0 \) 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.

**References**