Study of muon spin rotation of the superconducting state of organic superconductor λ-(BETS)$_2$GaCl$_4$

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The Cooper pairing symmetry of the third-generation organic superconductor λ-(BETS)$_2$GaCl$_4$ has attracted interest owing to the strongly correlated nature of this system lying near the Mott insulating phase.1) A recent high-resolution thermodynamic measurement reported *d*-wave pairing symmetry 2) whereas other experiments such as microwave conductivity measurement reported *s*-wave.3) We report our experimental result of zero field (ZF) and transverse field (TF) μSR in the fields of 30 G down to 0.3 K at the RIKEN-RAL Muon Facility in the UK. From ZF-μSR, a slight increase in the muon-spin relaxation rate was observed below T_C = 5 K indicating a signature of the appearance of an unconventional SC state. The TF-μSR time spectrum at the base temperature of 0.3 K shows a damping behavior in comparison with that of the one at the normal state at 10 K owing to the appearance of the flux state, which produces a distribution of penetrated magnetic fields in the sample, as shown in Fig. 1.

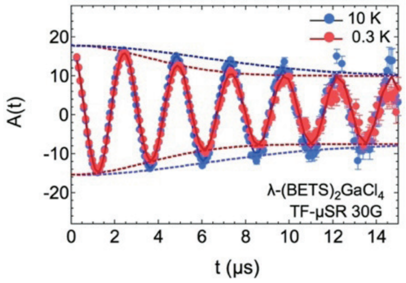

Fig. 1. TF-μSR time spectra of λ-(BETS)$_2$GaCl$_4$ in TF = 30 G at 0.3 K and 10 K. The red and blue dashed line are the results of fitting the data with Eq. (1).

We analyse the time spectra by using the following function

$$P^{TF}(t) \;\; = A_1 e^{-(\sigma^2 t^2)} \cos(\gamma_\mu H_1 t + \phi) + A_2 \cos(\gamma_\mu H_2 t + \phi) \quad (1)$$

Here, σ is the Gaussian damping rate representing the symmetric field distribution in the vortices felt by muons. The H_1 is the averaged field at the muon site in the sample and H_2 is the one in the Ag foil. A_1 and A_2 are initial asymmetry parameters of the Gaussian-type damping and the background components, respectively. A_2 was fixed to be that achieved at 0.3 K, and ϕ is the phase of the muon-spin precession. In the normal state, σ was estimated to be 0.1172 ± 0.0023 μs^{-1}.

The Gaussian damping rate in the SC state at 0.3 K, σ_{SC}, is estimated to be 0.1708 ± 0.0022 μs^{-1} by the relation $\sigma^2 = \sigma_{SC}^2 + \sigma_{NM}^2$ where σ_{NM} is the Gaussian damping rate by the nuclear moment in the normal state. For a pollycrystalline sample and large Ginzburg-Landau parameter κ ≫70, σ_{SC} is related to the superconducting penetration depth by the relation $\sigma_{SC} = \sqrt{0.00371}\,\Phi_0/\lambda^2$, where Φ_0= 2.07 x 10^{-15} is the flux quantum.

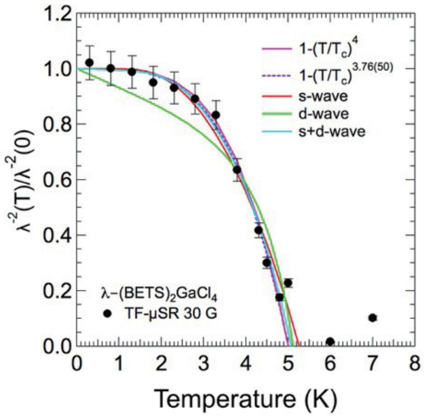

Fig. 2. Extracted temperature dependence of the normalized inverse magnetic penetration depth squared. The red, blue, and green solid lines show the result of fit using Eq. (2).

We could find a *d*–wave pairing contribution in the power-law fitting of λ(T) as a deviation from that expected for a typically full-gap *s*–wave pairing, power-value of which is 4. Furthermore, λ(T) curves can be fit in the clean limit using the following expression 4):

$$\frac{\lambda^{-2}(T)}{\lambda^{-2}(0)} = 1 + \frac{1}{\pi}\int_0^{2\pi}\int_{\Delta(T)}^{\infty}\left(\frac{\partial f}{\partial E}\right)\frac{E dE d\phi}{\sqrt{E^2-\Delta^2(\phi,T)}} \quad (2)$$

where $f = [1+\exp(E/k_B T)]^{-1}$ is the Fermi function and the temperature dependence of the gap is approximated by $\Delta(T) = \Delta(0)\tanh\{1.82[1.018(T_C/T-1)]^{0.51}\}$. The angular function $\Delta(\phi) = \Delta_0$ in the *s*-wave model and $\Delta(\phi) = \Delta_0\cos(2\phi)$ in the *d*-wave model, where Δ_0 is constant. The curve can be well fit by the *s*-wave model. Interestingly, the data just below the T_c down to about 3 K well follow the fitting of the *d*-wave model and show a close agreement with the extracted critical temperature T_C = 5.1(1) K. Furthermore, we attempted to fit the data by using a simple superposition of a single-gap s-wave and single-gap *d*-wave, as shown in Fig. 2, in order to study if there is any hint of coexistence of *s*- and *d*-wave. Further experiments on TF-μSR under different fields and with higher statistics may be needed to make the current experimental results convincing.

References

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