Summary of thesis: Superconducting Spin Susceptibility in UTe_2

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There are two types of spin states in the superconducting (SC) state: spin-singlet (S = 0) and spin-triplet (S = 1). Since the SC order parameter of the spin-triplet pairing state has the spin degrees of freedom, unusual behaviors such as multiple SC phases, and magnetic field (H) boosted superconductivity are expected. However, there are few examples of the spin-triplet superconductors, and thus the physical properties of the spin-triplet superconductivity have not been well understood.

Uranium (U) -based ferromagnetic (FM) superconductors UGe_2, URhGe and UCoGe are promising candidates for a spin-triplet superconductor, as their SC phases are inside or overlapped with the FM phase, and their upper critical field H_{c2} is far beyond the Pauli-limiting field (H_P)[1]. Unfortunately, the investigation of the spin-triplet SC properties without the FM ordering is difficult in these systems.

In 2018, S. Ran *et al*. discovered superconductivity in UTe_2 with T_c = 1.6 K[2]. UTe_2 also exhibits very large and anisotropic H_{c2} exceeding H_P along the three crystalline principal axes[2, 3] as observed in the U-based FM superconductors[1]. Particularly, in $H \parallel b$, T_c shows an upturn around 15 T and the superconductivity remains up to 35 T until it is terminated by a metamagnetic transition[4]. Thus, UTe_2 has also been considered to be a promising candidate for a spin-triplet superconductor as the spin-singlet SC state could not survive in such a high-H region. An important feature of UTe_2 is the absence of any magnetic order at ambient pressure, in contrast to U-based FM superconductors, which enables us to investigate intrinsic spin-triplet SC properties.

I. Superconducting properties of UTe_2 [5]

To investigate the SC properties of the SC state, we performed the ^{125}Te-nuclear magnetic resonance (NMR) measurement on a single-crystal UTe_2. In the first study, we measured the nuclear spin-lattice relaxation rate and found that it decreases below T_c without showing a coherence peak. This excludes the possibility of a conventional s-wave pairing in UTe_2. In addition, the Knight shift (K) along b axis (K_b) slightly decreases in the SC state. The amount of the decrease is much smaller than the spin part of K, which was estimated from the Sommerfeld coefficient term γ in the specific-heat measurement. This strongly support the spin-triplet scenario.

II. Anisotropic response of the superconducting spin susceptibility in UTe_2 [6]

In the first study, the signal intensity was not sufficient to measure K along the c axis (K_c) as the spectrum in $H \parallel c$ is broader than that in $H \parallel b$. Thus, in the following studies we prepared a ^{125}Te-enriched single-crystal samples that contain 99.9% of ^{125}Te, since the NMR active isotope is only 7% in natural Te. The intense intensity by the ^{125}Te-enrich UTe_2 enables us to obtain more reliable NMR results. We confirmed that K_b and K_c slightly decreases at 1 T in the SC state. The decrease in K (ΔK_{spin}) in $H \parallel b$ is consistent with the previous results. The H response of SC spin susceptibility in the SC state is anisotropic; although $|\Delta K_{spin}|$ in $H \parallel b$ is almost independent of H up to 6.5 T, the $|\Delta K_{spin}|$ in $H \parallel c$ decreased with increasing H. In particular, at 5.5 T, K_c was unchanged through T_c.

This indicates that the spin degrees of freedom remain even in the SC state and excludes the possibility of spin-singlet pairing. The observed decrease in K at low H indicates the SC vector order parameter $\boldsymbol{d}$ has the b and c components and limits the SC symmetry to the A_u or B_{3u} state. In addition, the constant ΔK_{spin} in $H \parallel b$ suggests that the $\boldsymbol{d}$ vector is pinned along the b axis. We estimate the pinning field H_{pin} to be 12.6 T and predict that the b-axis component of the $\boldsymbol{d}$ vector cannot remain above H_{pin} and that the SC properties are different between the low H and high-H SC phases.

III. Inhomogeneous Superconducting State in UTe_2 [7]

In the second study, we found that an additional shoulder signal appears in the SC-state NMR spectrum in $H \parallel b$ as well as the shift of the main peak. Although the presence of the additional signals suggests the appearance of another ordered state inside the SC phase, we cannot clarify the origin and characteristics from the previous experiments. In addition, it is also unclear whether the $\boldsymbol{d}$ vector rotation occurs in a high $H \parallel b$ is unclear. The reduction in K_b in the SC state implies that such a SC state is unstable above H_{pin}. This is due to the competition between the SC-condensation and Zeeman energies.

To solve these issues, in the third study, we performed precise NMR linewidth measurements up to 6.5 T in $H \parallel b$ and $H \parallel c$, and a high-H NMR measurement up to 14.5 T in $H \parallel b$. The intensity of the shoulder signal observed in $H \parallel b$ decreases with an increasing H above 7 T and it seems to vanish at 10 T. In contrast, an unexpected broadening without the shoulder signal was observed in $H \parallel c$. Although the shape of the NMR spectrum is different between in $H \parallel b$ and $H \parallel c$, both NMR spectra suggest that an inhomogeneous SC state coexist with the main SC state in a spatial modulation. In addition, we measured $|\Delta K_{spin}|$ in $H \parallel b$ and found that it starts to decrease around 7 T and almost zero at 12.5 T. This indicates that the $\boldsymbol{d}$ vector gradually rotates away from the b axis with the application of H.

On the basis of the NMR measurements, we construct the H-T phase diagram for $H \parallel b$ and $H \parallel c$. The SC phase can be distinguished into four regions based on the character of the SC spin states. In particular, the inhomogeneous SC state, which spatially coexists with the main uniform SC state, is expected to be realized in the low-H and low-T region. The inhomogeneous SC state probably originates from the presence of the spin degrees of freedom. These findings place strong constraints on the SC symmetry of UTe_2, and it also opens up new possibilities for the spin-triplet SC states.

References

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