Flux-line lattice state in FeAs-based superconductor KFe$_2$As$_2$

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Abstract. We report on transverse field muon spin rotation measurements of the magnetic penetration depth $\lambda$ in the iron-based superconductor KFe$_2$As$_2$ in order to investigate the superconducting gap mechanism. We have found that temperature dependence of $\lambda$ shows multiple gap like behavior and $\lambda$ depends on the field. These results suggests the existence of quasiparticle excitations outside the vortices.

1. Introduction

The discovery of superconductivity at $T_c = 26$ K in LaFeAsO$_{1-x}$F$_x$ [1] has stimulated a tremendous research effort to elucidate the superconducting pairing mechanism and symmetry in iron pnictide superconductors. In a hole-doped system of Ba$_{1-x}$K$_x$Fe$_2$As$_2$, one of the important features is that the superconductivity occurs even for $x = 1.0$, although $T_c$ itself is much lower ($T_c \approx 3.5$ K) than the optimum $T_c = 38$ K. According to the phase diagram of Ba$_{1-x}$K$_x$Fe$_2$As$_2$ in ref. [2], $T_c$ decreases to zero from a maximum $T_c$ side toward $x \sim 0.7$ with increasing $x$, but it remains finite value above $x = 0.7$.

In the optimally doped Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$, the Fermi surface consists of well-separated hole and electron sheets, which seem to exhibit good interband nesting, as found in many iron pnictide superconductors. For example, the angle resolved photoemission spectroscopy (ARPES) [3], muon spin rotation ($\mu$SR) [4], and NMR [5] have suggested the multiple full gap with sign change between these two different bands, namely $s_{\pm}$-wave. Meanwhile, de Haas-van Alphen experiment and the accompanying band structure calculations in KFe$_2$As$_2$ have shown that the electron sheets centered at the X point of a Brillouin zone are replaced with small hole tubes [6], therefore, the interband nesting observed in optimally doped sample is not there anymore. This unusual electronic properties was also confirmed by ARPES [7]. Recent studies, i.e., NQR.
and specific heat \([8]\), thermal conductivity \([9]\) and penetration depth \([10]\), have suggested that the superconducting gap in \(\text{KFe}_2\text{As}_2\) has line nodes in contrast to the nodeless gap suggested in \(\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2\). On the other hand, the small angle neutron scattering (SANS) observed isotropic triangular flux-line lattice (FLL) without FLL transitions up to \(H_{c2}\) with the condition of \(H\parallel c\)-axis \([11]\). This result suggests that an interaction between vortices is isotropic. In order to elucidate the superconducting gap structure, we have observed the temperature and the magnetic field dependence of penetration depth for both \(H\parallel c\) and \(H\perp c\)-axis. In this paper, we show our preliminary results for the condition of \(H\parallel c\).

![TF-\(\mu\)SR time spectra observed in \(\text{KFe}_2\text{As}_2\) at 4 and 2 K with \(\mu_0H = 24\, \text{mT}\), displayed in a rotating reference frame frequency of 2 MHz.](image)

**Figure 1.** TF-\(\mu\)SR time spectra observed in \(\text{KFe}_2\text{As}_2\) at 4 and 2 K with \(\mu_0H = 24\, \text{mT}\), displayed in a rotating reference frame frequency of 2 MHz.

2. Experimental Details

High quality single crystalline samples of \(\text{KFe}_2\text{As}_2\) were grown by a self-flux method which will be described in detail elsewhere \([12]\). The \(T_c\) was estimated to be 3.5 K from the temperature dependence of susceptibility. The \(\mu\)SR measurements were conducted both at M15 beamline at TRIUMF, Vancouver, Canada and at RIKEN-RAL Muon Facility in the Ruthreford Appleton Laboratory, Didcot, UK. The transverse field (TF) \(\mu\)SR measurements were performed at temperatures between 20 mK to 5 K. The sample was field cooled at the measured magnetic fields to minimize disorder of the FLL due to flux pinning. Since the muons stop randomly on the length scale of the FLL, the muon spin precession signal provides a random sampling of the internal field distribution in the FLL state.

The time evolution of the muon spin polarization signals measured with \(\mu_0H = 24\, \text{mT}\) parallel to \(c\)-axis above and below \(T_c\) are presented in Fig. 1. Under a TF below \(T_c\), implanted muons experience an inhomogeneity of the field due to FLL formation that leads to relaxation. As shown in Fig. 1, complete depolarization is observed at 2 K, indicating that the entire volume falls into the superconducting state. We have observed that the FLL forms triangular symmetry down to 20 mK with \(H\parallel c\) (data not shown here), consistent with SANS result \([11]\).

The spacial magnetic field distribution in a FLL state is

\[
B(\mathbf{r}) = B_0 \sum_K \frac{e^{-i\mathbf{K} \cdot \mathbf{r}} e^{-K^2 \xi_v^2}}{1 + K^2 \lambda^2},
\]

\[
P(B) = \langle \delta (B - B(\mathbf{r})) \rangle_r
\]

where \(\mathbf{K}\) is the reciprocal lattice vector, \(B_0\) is the average internal field, \(\mathbf{r}\) is the vector coordinate, and \(\xi_v\) is the cutoff parameter. The TF-\(\mu\)SR time spectra were fitted to a theoretical function by assuming the internal field distribution \(P(B)\) and accounting for the FLL disorder and the
nuclear moment contributions,

\[ A(t) = A_0 e^{-\frac{(\sigma_p^2 + \sigma_n^2) t^2}{2}} \int P(B) e^{i(\gamma \mu B t - \phi)} dB, \]

where \( A \) is the asymmetry, \( \sigma_p \) and \( \sigma_n \) denote the relaxation due to the FLL disorder and the nuclear moment, respectively, \( \gamma \mu / 2 \pi = 135.5 \) MHz/T is the muon gyromagnetic ratio and \( \phi \) is the initial phase.

3. Results and Discussion

Figure 2 shows the preliminary result of temperature dependence of the inverse squared magnetic penetration depth \( 1/\lambda_{ab}^2 \) obtained with \( \mu_0 H = 24 \) mT parallel to the c-axis. A kink was observed around 0.75 K, similar to the results in (Ba,K)Fe\(_2\)As\(_2\) [4, 13, 14], which are well described by the multiple full-gap behavior. As shown in Fig. 2, both single s- and d-wave curves show significant departure from the experimental data.

The field dependence of \( \lambda_{ab} \) observed at \( T = 0.03T_c \) is shown in Fig. 3. It exhibits two kinds of field dependence, where the gradient may change at around \( H/H_{c2} = 0.1 \). The increase of \( \lambda \) against field is attributed to the anisotropic order parameters and the associated nonlinear effect due to the Doppler shift of the quasiparticles in the nodal region \( (\Delta(k) \simeq 0) \) [16]. It is predicted that \( \lambda \) is independent of \( H \) for the isotropic s-wave pairing because the finite gap prevents the shifted levels of quasiparticle excitations from being occupied at low temperatures. Therefore, the finite value of the gradient, \( d\lambda/d(H/H_{c2}) \), means the existence of quasiparticle excitations. The field dependence of \( \lambda \) is expected to be stronger when the phase space satisfying \( \Delta(k) \simeq 0 \) has larger volume [17], so that the quasiparticle excitation below \( H/H_{c2} = 0.1 \) is larger than that above \( H/H_{c2} = 0.1 \). However, we need more data points around \( H/H_{c2} = 0.1 \) to confirm this. According to our preliminary measurements with \( H \perp c \), \( T \)-linear like behavior of \( \lambda_c \) has been observed [18], supposing the existence of quasiparticle excitations. Further analysis and experiments are needed to clarify the superconducting gap mechanism in detail.

4. Conclusions

In conclusion, we have performed TF-\( \mu \)SR experiments as a function of temperature and magnetic field on a single crystalline sample of KFe\(_2\)As\(_2\) with \( H \parallel c \). We have observed an excess
quasiparticle excitations. This result is inconsistent with a simple $s$- or $d$-wave superconducting gap model.

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