Anisotropic Hc2 of K0.8Fe(1.76)Se(2) determined up to 60 T

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Abstract
The anisotropic upper critical field, Hc2(T), curves for K0.8Fe1.76Se2 are determined over a wide range of temperatures down to 1.5 K and magnetic fields up to 60 T. Anisotropic initial slopes of Hc2 ~ −1.4 T/K and −4.6 T/K for magnetic field applied along c axis and ab plane, respectively, were observed. Whereas the c axis Hcc2 (T) increases quasilinearly with decreasing temperature, the ab plane Habc2(T) shows a flattening, starting near 25 K above 30 T. This leads to a nonmonotonic temperature dependence of the anisotropy parameter γH≡ Habc2/Hcc2. The anisotropy parameter is ~2 near Tc~32 K and rises to a maximum γH~ 3.6 around 27 K. For lower temperatures, γH decreases with T in a linear fashion, dropping to γH~2.5 by T~18 K. Despite the apparent differences between the K0.8Fe1.76Se2 and (Ba0.55K0.45)Fe2As2 or Ba(Fe0.926Co0.074)2As2, in terms of the magnetic state and proximity to an insulating state, the Hc2(T) curves are remarkably similar.

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Comments

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Anisotropic $H_{c2}$ of $\text{K}_0.8\text{Fe}_{1.76}\text{Se}_2$ determined up to 60 T

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The anisotropic upper critical field, $H_{c2}(T)$, curves for $\text{K}_0.8\text{Fe}_{1.76}\text{Se}_2$ are determined over a wide range of temperatures down to 1.5 K and magnetic fields up to 60 T. Anisotropic initial slopes of $H_{c2} \sim -1.4 \text{T/K}$ and $-4.6 \text{T/K}$ for magnetic field applied along $c$ axis and $ab$ plane, respectively, were observed. Whereas the $c$ axis $H_{c2}^c(T)$ increases quasilinearly with decreasing temperature, the $ab$ plane $H_{c2}^{ab}(T)$ shows a flattening, starting near 25 K above 30 T. This leads to a nonmonotonic temperature dependence of the anisotropy parameter $\gamma_H \equiv H_{c2}^{ab} / H_{c2}^c$. The anisotropy parameter is $\sim -2$ near $T_c \sim 32$ K and rises to a maximum $\gamma_H \sim 3.6$ around 27 K. For lower temperatures, $\gamma_H$ decreases with $T$ in a linear fashion, dropping to $\gamma_H \sim 2.5$ by $T \sim 18$ K. Despite the apparent differences between the $\text{K}_0.8\text{Fe}_{1.76}\text{Se}_2$ and (Ba0.5K0.5)Fe2As2 or (Ba(Fe0.95Co0.05)2As2, in terms of the magnetic state and proximity to an insulating state, the $H_{c2}(T)$ curves are remarkably similar.

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Since the discovery of superconductivity in the FeAs-based family, intensive research efforts have focused on finding Fe-based superconductors with a higher transition temperature, $T_c$, and clarifying the pairing mechanism of superconductivity.1–6 As additional families have been discovered, the Fe-based superconductors have been categorized into several types including 11 type (P4/nmm, FeSe), 122 type (I4/mmm, AFe2As2, $A = \text{K, Sr, Ba}$), and 1111 type (P4/nmm, RFeAsO, $R = \text{rare earth}$). Among these, FeSe is a simple binary system with $T_c \sim 8$ K that can be increased up to 37 K by external pressure.7 Very recently, higher critical fields, $H_{c2}$, values are comparable to $K$- and $Co$-doped members of the FeAs-based family.8–11

The single crystals of $\text{K}_0.8\text{Fe}_{1.76}\text{Se}_2$ were grown from $\text{K}_0.8\text{Fe}_{1.76}\text{Se}_2$ were determined over a wide range of temperatures down to 1.5 K and magnetic fields up to 60 T. Anisotropic initial slopes of $H_{c2} \sim -1.4 \text{T/K}$ and $-4.6 \text{T/K}$ for magnetic field applied along $c$ axis and $ab$ plane, respectively, were observed. Whereas the $c$ axis $H_{c2}^c(T)$ increases quasilinearly with decreasing temperature, the $ab$ plane $H_{c2}^{ab}(T)$ shows a flattening, starting near 25 K above 30 T. This leads to a nonmonotonic temperature dependence of the anisotropy parameter $\gamma_H \equiv H_{c2}^{ab} / H_{c2}^c$. The anisotropy parameter is $\sim -2$ near $T_c \sim 32$ K and rises to a maximum $\gamma_H \sim 3.6$ around 27 K. For lower temperatures, $\gamma_H$ decreases with $T$ in a linear fashion, dropping to $\gamma_H \sim 2.5$ by $T \sim 18$ K. Despite the apparent differences between the $\text{K}_0.8\text{Fe}_{1.76}\text{Se}_2$ and (Ba0.5K0.5)Fe2As2 or (Ba(Fe0.95Co0.05)2As2, in terms of the magnetic state and proximity to an insulating state, the $H_{c2}(T)$ curves are remarkably similar.

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The solid lines in Fig. 1(b) are warming curves of the rf shift $\Delta \nu / \Delta T$ for two different samples. As the temperature

Figure 1(a) shows the temperature dependence of the normalized resistivity for the $\text{K}_0.8\text{Fe}_{1.76}\text{Se}_2$ sample. A sharp drop, corresponding to the superconducting transition, was observed around 32 K. At high temperatures, the resistance increases with decreasing temperature and exhibits a broad maximum at around 220 K.12–15 The offset and zero-resistance ($R < 3 \times 10^{-5} \Omega$) temperatures were estimated to be $T_{\text{c,offset}} \simeq 32.2$ K and $T_{\text{c,zero}} \simeq 32$ K, respectively, as shown in Fig. 1(b). The solid lines in Fig. 1(b) are warming curves of the rf shift $\Delta \nu / \Delta T$ at $H = 0$ for two different samples. As the temperature decreases, the rf shift suddenly increases at $T_c$, where $T_c = 32$
and 32.4 K for two samples were determined from \(d\Delta F/dT\). A clear anisotropy in the response of the superconductivity under applied fields was observed between \(H = 0\) (closed symbols) and 14 T (open symbols) and the warming curves of rf shift (\(\Delta F\)) for two samples (solid lines). Vertical arrows indicate \(T_{\text{offset}}\) and lines on the top of the 14-T data are guide to the eye. (c) Comparison of the \(ab\) plane resistance \(R(H)\) and \(\Delta F\) for \(H \parallel ab\) at \(T = 31\) K. (d) Comparison of the \(ab\) plane resistance \(R(H)\) and \(\Delta F\) for \(H \parallel c\) at \(T = 28\) K. The dashed lines in (c) and (d) are the \(\Delta F\) taken at \(T = 35\) K as a normal-state background signal. The solid lines in (c) and (d) are guides to the eye for offset and onset criteria of \(H_c\) and vertical arrows indicate the deviation of \(\Delta F\) from the background signal (see text).

Using the deviation from normal-state criterion just discussed, the \(\Delta F\) versus \(H\) plots shown in Figs. 2 and 3 can be used to infer the temperature dependence of the upper critical field \(H_{c2}(T)\) by taking the slope of the rf signal intercepting the slope of the normal-state background or by simply taking the first point deviating from the normal-state background. Importantly, the difference between these two related criteria is small and does not affect the \(H_{c2}(T)\) curve. In the high-temperature region, the point at which the \(\Delta F\) signal deviates from the background is close to the \(T_{\text{offset}}\) of the resistance data as shown in Figs. 1(c) and 1(d). Therefore, \(H_{c2}\) was determined at the point at which \(\Delta F\) deviates from the background signal. Arrows in Figs. 2 and 3 indicate the determined \(H_{c2}\). The difference between the \(H_{c2}\) values determined by the first deviation and slope-

FIG. 1. (Color online) (a) Temperature dependence of the normalized \(ab\) plane resistivity \(\rho(T)\) of the \(K_{0.8}\)Fe\(_{1.76}\)Se\(_2\) single crystal at \(H = 0\), where \(\rho(300K) = 0.12\) cm\(^2\). (b) Low-temperature region of the resistance for two samples at \(H = 0\) (closed symbols) and 14 T (open symbols) and the warming curves of rf shift (\(\Delta F\)) for two samples (solid lines). Vertical arrows indicate \(T_{\text{offset}}\) and lines on the top of the 14-T data are guide to the eye. (c) Comparison of the \(ab\) plane resistance \(R(H)\) and \(\Delta F\) for \(H \parallel ab\) at \(T = 31\) K. (d) Comparison of the \(ab\) plane resistance \(R(H)\) and \(\Delta F\) for \(H \parallel c\) at \(T = 28\) K. The dashed lines in (c) and (d) are the \(\Delta F\) taken at \(T = 35\) K as a normal-state background signal. The solid lines in (c) and (d) are guides to the eye for offset and onset criteria of \(H_c\) and vertical arrows indicate the deviation of \(\Delta F\) from the background signal (see text).

FIG. 2. (Color online) Frequency shift (\(\Delta F\)) as a function of magnetic field for \(H \parallel ab\) at selected temperatures. Open symbols are \(\Delta F\) taken at \(T = 35\) K as a normal-state background signal. The arrows indicate \(H_{c2}\) determined from the point deviating from background signal. (Inset) The low-temperature data close to \(T_c\). The straight lines on the \(T = 25\) K curve are guides to the eye for determining the point at which the rf signal intercepts the slope of the normal-state background.
The zero temperature limit of \( H_c \) can be estimated by using the Wertherman-Helfand-Hohenberg (WHH) theory, which gives \( H_c(0) = 0.67T_c(dH_c/dT)_{T_c} \). The value of \( H_c(0) \) for \( H || ab \) and \( H || c \) is estimated to be \( \sim 102 \) and \( \sim 31 \) T, respectively, where \( T_c = 32 \) K, \( dH_c^{ab}/dT = -4.67 \) T/K, and \( dH_c^c/dT = -1.4 \) T/K were used. Clearly, these values do not capture the salient physics for this compound. On the other hand, in the simplest approximation, the Pauli limit \( (H_P) \) is given by \( 1.84T_c \), giving \( H_P \sim 59 \) T. This low-temperature value of \( H_c \) may indeed capture some of the basic physics associated with \( K_{0.8}Fe_{1.76}Se_2 \). To explain the observed \( H_c \) curves in detail, a more complete theoretical treatment is needed, one that does not exclude the strong electron-phonon coupling and multiband nature of Fe-based compounds. Anisotropic superconducting coherence length can be calculated using \( \xi_c = \sqrt{\hbar c/dH_c^c} \) and \( \xi_{ab} = \sqrt{\hbar c/dH_c^{ab}} \). If \( H_c^{ab} = 60 \) T and \( H_c^{ab}^{27} \) is assumed to be between 60 and 100 T, then \( \xi_{ab} \sim 2.3 \) nm and 1.4 nm \( \lesssim \xi_c \lesssim 2.3 \) nm.

On the basis of this study for \( K_{0.8}Fe_{1.76}Se_2 \), the behavior of \( H_c(T) \) is found to be very similar to that of several 122-type systems as well as doped FeSe. It should be noted that the \( H_c \) curves for two orientations in the K-doped \( BaFe_2As_2 \) system seem to cross at low temperatures due to the flattening of \( H_c^{ab}(T) \) curve. Additionally, the \( H_c \) curves for FeTe\(_{0.6}Se_{0.4}\) shows a crossing between \( H || ab \) and \( H || c \) curves below 4.5 K because of the subsequent flattening of the \( H_c^{ab}(T) \) curve. However, in the Co-doped system, the anisotropic \( H_c(T) \) curves do not show such crossing. A result similar to what was found in this study. Thus, an intriguing feature of \( H_c^{ab}(T) \) curves for Co- and K-doped \( BaFe_2As_2 \), FeTe\(_{0.6}Se_{0.4}\), and \( K_{0.8}Fe_{1.76}Se_2 \) systems is that the anisotropy near \( T_c \) is as large as 3 but drops toward \( \sim 1 \) as \( T \rightarrow 0 \) K. The \( H_c(T) \) anisotropy in \( K_{0.8}Fe_{1.76}Se_2 \) is particularly noteworthy given that it exists deep within an antiferromagnetically ordered state. In the Co-doped system, the \( H_c(T) \) value of \( \gamma_T(T) \sim 1 \) when \( T < T_N \) with clear anisotropy emerging only when the antiferromagnetic state is suppressed. These results raise the following question: To what extent is the antiferromagnetism in \( K_{0.8}Fe_{1.76}Se_2 \) interacting with lower-temperature superconductivity? Clearly more work will be needed to answer this key query.

In summary, the \( H_c(T) \) phase diagram for \( K_{0.8}Fe_{1.76}Se_2 \) has been constructed by means of measuring both the electrical resistance in a dc superconducting magnet \( (H < 14 \) T) and the rf contactless penetration depth in a pulsed magnetic field up to 60 T. The upper critical field of \( K_{0.8}Fe_{1.76}Se_2 \) is determined as \( H_c^{ab}(18 \) K) \( \sim 54 \) T and \( H_c^{ab}(1.6 \) K) \( \sim 56 \) T. The anisotropy parameter \( \gamma_T \) initially increases with decreasing temperature, passes through a maximum of \( \sim 3.6 \) near 27 K, and then decreases to \( \sim 2.5 \) at 18 K. The observed \( \gamma_T \) values show a weakening anisotropic effect at low temperatures. Although the Fe-based superconductors have a layered crystal structure, a weak anisotropy of \( H_c \) may be a common feature, suggesting that the interlayer coupling and the three-dimensional Fermi surface may play an important role in the superconductivity of this family.

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