Muon spin rotation measurement of the magnetic field penetration depth in $Ba(Fe_{0.926}Co_{0.074})_2As_2$: Evidence for multiple superconducting gaps

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We have performed transverse field muon spin rotation measurements of single crystals of $Ba(Fe_{0.926}Co_{0.074})_2As_2$ with the applied magnetic field along the $\hat{c}$ direction. Fourier transforms of the measured spectra reveal an anisotropic line-shape characteristic of an Abrikosov vortex lattice. We have fit the μSR spectra to a microscopic model in terms of the penetration depth λ and the Ginzburg-Landau parameter κ. We find that as a function of temperature, the penetration depth varies more rapidly than in standard weak-coupled BCS theory. For this reason we first fit the temperature dependence to a power law where the power varies from 1.6 to 2.2 as the field changes from 0.02 to 0.1 T. Due to the surprisingly strong field dependence of the power and the superfluid density we proceeded to fit the temperature dependence to a two-gap model, where the size of the two gaps is field independent. From this model, we obtained gaps of $2\Delta_1 = 3.77 k_B T_C$ and $2\Delta_2 = 1.57 k_B T_C$, corresponding to roughly 6 and 3 meV, respectively.

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Recently, a new family of high-temperature superconductors were discovered[1] based on layers of FeAs. Several groups of these structures have been found, including the so-called 1111 compounds, such as LaFeAsO and the 122 compounds, such as $BaFe_2As_2$. Superconductivity was discovered in these systems by doping, such as partially replacing oxygen by fluorine in LaFeAsO (electron doping) or partially substituting potassium for barium in $BaFe_2As_2$ (hole doping). The resulting superconductors have remarkably high T_C's, for example, up to 56 K for $LaFeAs(O_{1-x}F_x)$ (Refs. 2–4) and up to 38 K for $(Ba_{1-x}K_x)Fe_2As_2$.[5–7]

At room temperature the parent compounds have a tetragonal structure, which then undergoes an orthorhombic distortion somewhat below 200 K. Either at or just below the structural phase transition, there is a magnetic phase transition to an antiferromagnetic (AF) ground state. With doping, the AF transition is suppressed, and superconductivity emerges. The proximity to AF magnetic order has led to a belief that Fe spin fluctuations are important for developing the superconducting ground state.[8] More recently, it was found that superconductivity can be induced in these systems through electron doping through substitution of iron in the FeAs layers; both $La(Fe_{1-x}Co_x)AsO$ (Ref. 9) and $Ba(Fe_{1-x}Co_x)_2As_2$ (Refs. 10 and 11) become superconducting with T_c's as high as 14 and 23 K, respectively. In contrast to the cuprates, the iron pnictides are apparently surprisingly robust against in-plane disorder.

At this point there is no consensus on the pairing symmetry in pnictides. In the 1111 system most experiments indicate a fully gapped Fermi surface, although the presence of magnetic rare-earth atoms and the lack of large single crystals complicates the interpretation.[12] In the 122 systems the situation is also unclear. Tunnel-diode resonator measurements[13,14] of $Ba(Fe_{1-x}Co_x)_2As_2$ exhibit power-law temperature dependences for the penetration depth $\Delta\lambda(T) \sim T^n$ with n between 2 and 2.5 which have been interpreted in terms of gap nodes. Similar measurements of $Ba_{1-x}K_xFe_2As_2$ (Ref. 15) exhibited a power law n of about 2 for low $(T/T_C \leq 0.25)$ and were fit with a two gap s-wave model with somewhat unphysical parameters. Muon spin rotation measurements of single crystal $Ba_{1-x}K_xFe_2As_2$ exhibited phase separation into magnetic and superconducting regions,[16,17] with different temperature dependences for the superfluid density $(n_s \propto 1/\lambda^2)$ depending on the value of x. NMR $1/T_1$ measurements[18] show no Hebel-Slichter peak below T_C which generally indicates non-s-wave pairing, whereas the ^{59}Co and ^{75}As Knight shifts decrease below T_C for fields both along the c axis and in the a-b plane; behavior which is consistent with s-wave pairing.

Muon spin rotation (μSR) is a powerful local microscopic tool for characterizing the magnetic properties of materials in superconducting or other states. A thorough description of the application of μSR to studies of superconductivity can be found elsewhere.[19] In a transverse field (TF) μSR experiment, spin-polarized positive muons are implanted one at a time into a sample. The muon spins precess around the local magnetic field, and decay into a positron, which is preferentially ejected along the direction of the muon spin at the time of decay (as well as two neutrinos which are not detected). In the presence of a vortex lattice, the spatial variation in the magnetic field distribution results in a dephasing of the muon spin polarization and a relaxation of the precession signal. A Fourier transform of the spin-polarization function essentially reveals the field distribution which exhibits a charac-

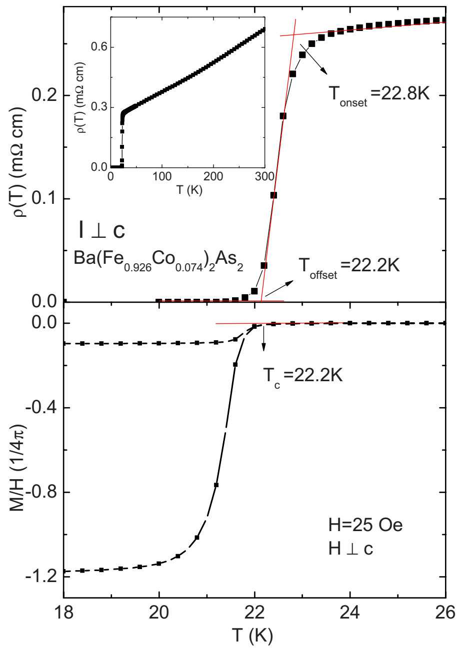

FIG. 1. (Color online) (Top) Resistivity of $Ba(Fe_{0.926}Co_{0.074})_2As_2$ in the vicinity of T_C and (inset) from 2 to 300 K. (Bottom) Field-cooled and zero-field-cooled magnetization measured in the vicinity of T_C.

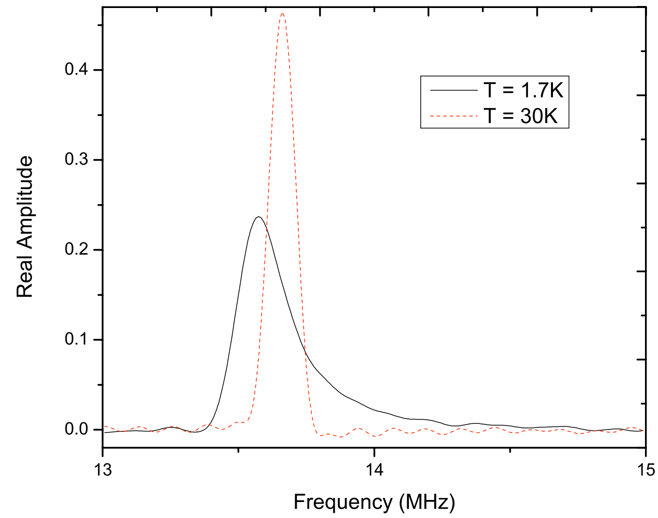

FIG. 2. (Color online) FFT of the TF μSR signal in B_{ext} $=0.1$ T at $T=1.7$ K (black solid line) and at $T=30$ K (red dashed line). The anisotropic line shape at low temperature is characteristic of a well-ordered vortex lattice.

teristic Abrikosov line shape. The line shape (or equivalently the relaxation function in the time domain) depends on the lattice geometry, magnetic field penetration depth λ, coherence length, ξ, and the amount of lattice disorder. As a result, careful analysis of the relaxation function allows these microscopic parameters to be determined in the vortex state. Such measurements demonstrated the presence of gap nodes characteristic of d-wave pairing in high-quality single crystals of $YBa_2Cu_3O_{6.97}$.[19] In ceramic samples this anisotropic line shape is generally not observed, rather the broadened line is generally well described by a Gaussian distribution; however, the width of this distribution (the Gaussian relaxation rate) σ has been shown to be proportional to the superfluid density $\sigma \propto n_s \propto 1/\lambda^2$.[20,21] Previous studies of cuprates found that extrinsic effects in ceramics can result in the correct temperature dependence of the superfluid density being masked; for this reason, reliable measurements of the superfluid density require the use of single crystals and the observation of an anisotropic line-shape characteristic of a vortex lattice.

A high-quality single crystal of $Ba(Fe_{0.926}Co_{0.074})_2As_2$ was grown from self flux as described in detail elsewhere.[11] Resistivity measurements, shown in Fig. 1 of our sample gave a sharp transition with a midpoint of 22.5 K while dc-susceptibility measurements gave $T_C=22.2$ K. This crystal of roughly 1 cm^2 area was mounted in a helium gas flow cryostat on the M20 surface muon beamline at TRIUMF, using a low background arrangement such that only positrons originating from muons landing in the specimens were collected in the experimental spectra.

Previous μSR work on $(Ba,K)Fe_2As_2$ found regions of phase-separated magnetic order with spontaneous muon precession in ZF-μSR spectra.[17] In a recent ZF-μSR study of $Ba(Fe_{0.9}Co_{0.1})_2As_2$,[22] weak, temperature-dependent relaxation was also observed. The presence of relaxation due to magnetism largely precludes detailed analysis of the properties of the vortex lattice and therefore it is important to check that such relaxation is absent. We performed ZF-μSR measurements at temperatures both above T_C and at $T=2$ K, finding that the spectra were identical, showing only weak temperature-independent relaxation, such as would be expected for nuclear dipole moments. Fits to a Gaussian Kubo-Toyabe relaxation function gave a characteristic value of the relaxation rate $\Delta=0.15$ μs^{-1}.

Figure 2 shows a fast Fourier transform (FFT) of the TF μSR signal measured in an applied field of 0.1 T at $T=1.7$ K and above T_C at $T=30$ K. The anisotropic line shape is characteristic of an Abrikosov vortex lattice and indicates the presence of at least locally well-ordered vortices within the superconducting state. The lower cutoff in the line shape corresponds to muons landing at the center of the lattice (furthest from vortex cores), the maximum in the line shape comes from muons at the saddle-point midway between vortices while the cutoff at high field comes from muons at the vortex cores. The overall width of the line shape is dominated by the magnetic penetration depth λ while the high-field cutoff mainly reflects the coherence length ξ. The high-field cutoff is most evident in the highest applied fields which is furthest from the London limit where the field would actually diverge at the vortex cores, giving a high-field tail with no cutoff.

The data was analyzed by simultaneously fitting several runs in an applied field of 0.1 T to an analytical Ginzburg-Landau model.[19] This Ginzburg-Landau model allows us to calculate internal magnetic field distributions as a function of the magnetic field penetration depth and superconducting coherence length. These field distributions were then Fourier transformed to give theoretical time spectra which were then compared to our data, allowing us to fit values of the microscopic parameters by minimizing χ^2. From this fit we were

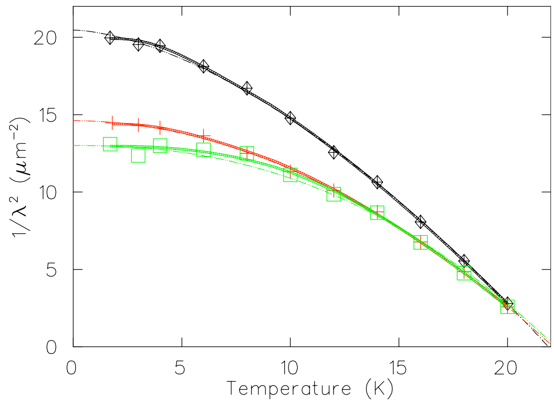

FIG. 3. (Color online) Combined two-gap fit (solid line) and power-law fit (dashed line) to the superfluid density measured from the TF μSR measurements at 0.02 T (black diamonds), 0.05 T (red crosses) and 0.1 T (green squares). Error bars are smaller than the plotting symbol sizes.

able to determine the Ginzburg-Landau parameter, $\kappa=\lambda/\xi$, obtaining $\kappa=44$; this value was held fixed for the remainder of the analysis, noting that measurements at lower fields are not sensitive to κ as long as it remains large. Temperature-independent relaxation due to nuclear dipolar fields was measured above T_C and included in all fits. Small-angle neutron-scattering (SANS) measurements[23] of vortices in applied fields above 0.2 T found a highly disordered vortex arrangement. We included the effects of vortex lattice disorder in our analysis via an additional Gaussian broadening of our μSR spectrum,[20,24] where we assumed that this broadening was proportional to $1/\lambda^2$ as observed in previous studies of cuprates and other high-κ superconductors.[19] Our fitted result shows that the rms deviation of the vortex positions ($\langle s^2\rangle^{1/2}$) relative to the vortex separation (L_0) was $\langle s^2\rangle^{1/2}/L_0 \approx 2.4\%$ at 1.7 K in $H_{\text{ext}}=0.1$ T and decreased with increasing temperature. The fractional disorder is larger in lower fields, (7% in $H_{\text{ext}}=0.05$ T and 30% in $H_{\text{ext}}=0.02$ T). This relatively small amount of disorder (at least in 0.1 T) as seen in the field distribution is somewhat in contrast with the SANS results. This may reflect the fact that μSR, as a real-space probe is less affected by a loss of true long-range order than is a reciprocal space probe such as SANS. We note that Bitter decoration measurements[23] (in low fields) provide evidence for at least regions of well-ordered vortices, although there is substantial disorder in the lattice seen both with muons and with Bitter decoration in low fields. In any case, we stress that we have included the effects of disorder in our analysis and that the penetration depth values we report should not be affected by this disorder.

At this point, we were able to fit the rest of the parameters in the μSR signal, including the penetration depth, $\lambda(H,T)$ to the analytical Ginzburg-Landau model.[19] Results of this analysis for $1/\lambda^2 \propto n_s$ (where n_s is the superfluid density) are shown in Fig. 3 for applied fields of 0.1, 0.05, and 0.02 T where it can be clearly seen that both the temperature dependence and zero-temperature value $n_s(T\to 0)$ depend on the applied field.

The temperature dependence of the superfluid density reflects how easily thermal fluctuations are able to create quasiparticles. In conventional weak-coupling BCS theory one finds that the low-temperature behavior of n_s becomes exponentially flat, whereas the presence of gap nodes is reflected in a low-temperature power-law behavior (such as T linear in the case of the d-wave cuprates). We first fit to a power law, $n_s(T)=n_s(0)[1-(T/T_C)^p]$. The results of this fit are indicated by the dashed lines in Fig. 3. We found that the fitted power increases with increasing field, from 1.62 ± 0.03 at 0.02 T to 2.27 ± 0.03 at 0.1 T while the superfluid density at $T=0$ decreased with field, from 20.47 ± 0.15 to 13.01 ± 0.05 μm^{-3}. We note that this model provides a fairly good fit to the data but the strong field dependence of both the superfluid density and the power are somewhat surprising for a range of fields much less than H_{C2} (Ref. 11) which encourages us to try different possible models to characterize the superfluid density.

Angle resolved photoemission spectroscopy (ARPES) measurements of the iron pnictides have demonstrated that the Fermi surface has multiple sheets and that there are at least two different superconducting gaps on these bands and as a result, a multiband model of the superconducting state has been proposed for these systems.[4,25–29] Multigap superconductivity has been seen in a number of systems including MgB_2,[30,31] which is an s-wave superconductor with a T_C of 39 K and where theoretical calculations predict that the smaller gap is an induced gap associated with the three-dimensional bands, and the larger gap is associated with the superconducting two-dimensional bands.[32] The possibility of other materials exhibiting multiband superconductivity was realized with the discovery of the two-band superconductor $NbSe_2$ by ARPES measurements.[33] This situation has been clearly observed in μSR measurements.[19,34] Like MgB_2, this material had two gaps of very different sizes, which reside on two sets of Fermi-surface sheets.[33] Multiband superconductivity has been proposed in many other materials, including $CeCoIn_5$,[35,36] $BaNi_2P_2$,[37] and $PrOs_4Sb_{12}$.[38]

We next fit the superfluid density to a phenomenological two-gap model[39,40] which has been employed in a previous μSR study of LaFeAs(O,F), Ca(Fe,Co)AsO, and $(Ba,K)Fe_2As_2$ [41]

$$n_s(T) = n_s(0) - w \cdot \delta n_s(\Delta_1,T) - (1-w)\cdot \delta n_s(\Delta_2,T), \quad (1)$$

where w is the relative weight for the first gap, Δ_1. Here, the gap functions are given by

$$\delta n(\Delta,T) = \frac{2n_s(0)}{k_BT}\int_0^\infty f(\epsilon,T)\cdot[1-f(\epsilon,T)]d\epsilon, \quad (2)$$

where $f(\epsilon,T)$ is the Fermi distribution given by

$$f(\epsilon,T) = (1+e^{\sqrt{\epsilon^2+\Delta(T)^2}/k_BT})^{-1}. \quad (3)$$

Here, Δ_i ($i=1$ and 2) are the energy gaps at $T=0$ and $\Delta_i(T)$ were taken to follow the standard BCS temperature dependence. The size of the gaps, Δ_1 and Δ_2, and T_C were fit globally while $n_s(0)$ and the weighting factor, w, were allowed to be field dependent.

The results of this analysis are shown by the solid lines in Fig. 3. It can be seen that this gives a very good fit with a χ^2 that are approximately half of that for the power-law fit.

Based on other experimental support for a two-gap model, this gives support to our choice of fit.

From the fit, we obtained the values of the gaps $2\Delta_1/k_BT_C=3.768\pm0.009$ and $2\Delta_2/k_BT_C=1.57\pm0.05$, and $T_C=22.1\pm0.2$ K. The larger of the two-gap values is quite close to the BCS value while the smaller gap is roughly half the BCS gap. These gaps are lower than has been reported for other iron pnictide compounds, which presumably indicates that the strength of the superconducting pairing varies from system to system.

The relative weighting factor for the larger gap increases with B_{ext}, from $w=0.655(7)$ at 0.02 T, $w=0.766(6)$ at 0.05 T to $w=0.909(4)$ at 0.1 T. This indicates that the applied field acts to weaken superconductivity on the bands with the smaller gap. The superfluid density at $T=0$, $n_s(0)$, decreases with B_{ext}, giving $n_s(0)=19.1(1), 14.411(4), 13.0(1)$ for these fields, respectively.

In addition to measuring the full temperature dependence of the penetration depth for three applied fields, we also studied the magnetic field dependence of n_s at $T=1.7$ K (following field cooling through T_C for each applied field). We simultaneously fit pairs of μSR spectra at $T=1.7$ K and in the normal state using the same procedure as before to obtain the penetration depth at $T=1.7$ K. The results of this analysis are shown in Fig. 4. We can see that the superfluid density shows a small peak near 0.02 T, then decreases with increasing field, which is in agreement with the trend found in our full temperature scans. The peak at low fields may reflect the proximity of the applied field to the lower critical field, which is about 0.007 T at $T=5$ K,[13] although we expect that demagnetization effects should dramatically reduce the effective H_{C1} from its thermodynamic value (the sample was a flat plate with the field applied normal to its surface). The penetration depth tends to a constant value of around 300 nm for higher fields. Recalling the field dependence of the relative gap weighting factor w, this high-field saturation behavior presumably reflects the loss of superconductivity on the bands with the smaller gap.

In conclusion, we have performed transverse field μSR measurements in the mixed state of single crystal $Ba(Fe_{0.926}Co_{0.074})_2As_2$. Employing an analytic Ginzburg-Landau theory to obtain the penetration depth λ and Ginzburg-Landau parameter κ we find that the superfluid density $n_s\propto 1/\lambda^2$ can be well described by a s-wave two-gap model where the corresponding field-independent gaps are $2\Delta_1=3.77k_BT_C$ and $2\Delta_2=1.57k_BT_C$, respectively.

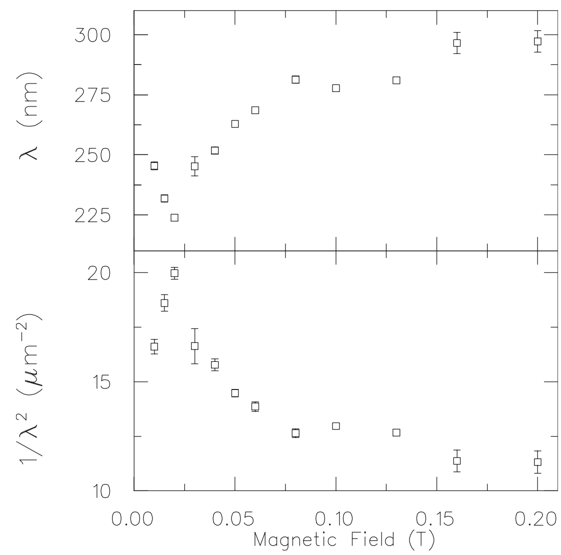

FIG. 4. (Top) Magnetic field dependence of the magnetic field penetration depth in $Ba(Fe_{0.926}Co_{0.074})_2As_2$ measured at $T=1.7$ K. (Bottom) $1/\lambda^2\propto$ superfluid density, n_s, measured at $T=1.7$ K.

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