Magnetic penetration depth of single crystal SmFeAsO$_{1-x}$F$_y$: a fully gapped superconducting state

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(Dated: June 24, 2008)

We report measurements of the in-plane magnetic penetration depth $\lambda$ in single crystals of SmFeAsO$_{1-x}$F$_y$ ($x \approx y \approx 0.2$) with $T_c \approx 45$ K. We find that at low temperature $\lambda$ has an exponential temperature dependence which suggests that the Fermi surface is fully gapped. The magnitude of the minimum energy gap, $\Delta_1 = 1.1 \pm 0.1 \hbar \omega_c T_c$ at $T = 0$ K, is significantly smaller than the BCS weak-coupling value suggesting that the gap is either strongly anisotropic or varies significantly between the different Fermi surface sheets. Our data fits well a two gap model with an additional larger gap of magnitude $\Delta_2 = 1.8 \pm 0.2 \hbar \omega_c T_c$ which is associated with $\approx 80\%$ of the total superfluid density.

Superconductivity in the Fe oxypnictide compounds, LnFeAsO$_{1-x}$F$_y$ (where Ln = La, Sm, Ce, Nd, or Pr) has generated an enormous amount of interest. The maximum value of $T_c \approx 55$ K [1] found so far in this series, is the highest for any non-cuprate superconductor. It is significantly higher than that found for the previous non-cuprate record holder MgB$_2$ ($T_c \approx 40$ K). The electronic structure of these materials has many similarities with the cuprates. Calculations have shown that the Fermi surface is expected to be quasi-two-dimensional and strong ferromagnetic and antiferromagnetic spin-fluctuations are predicted [2]. Importantly, the calculations suggest that the electron-phonon interactions are much too weak to produce a $T_c$ of $\approx 55$ K [3]. Hence, in many ways it might be expected that the superconductivity has more in common with the cuprates than the phonon mediated superconductor MgB$_2$.

The determination of the symmetry of the superconducting order parameter is an important first step toward uncovering the mechanism of superconductivity in any material. In this regard, measurements of the magnetic penetration depth in the Meissner state probe a few thousand Angstroms below the crystal surface and so should be reasonably representative of the bulk. However, experience with cuprates and MgB$_2$ has shown that the data are most reliable if measurements are performed on high quality single crystal samples — particularly for strongly anisotropic materials such as the pnictides [2,3].

There have been several reports of experiments to determine the superconducting gap structure in these pnictide materials. In particular, several groups have reported the results of point contact Andreev spectroscopy measurements (PCAS). Chien et al. [4] report data for polycrystalline SmFeAsO$_{0.85}$F$_{0.15}$ ($T_c=40$ K) which can be fitted by a single isotropic ($s$-wave) gap $\Delta_0/\hbar \omega_c = 1.9$ which follows well the BCS weak-coupling temperature dependence. However, Wang et al. [6] report PCAS data also on SmFeAsO$_{1-x}$F$_x$ with $T_c = 51.5$ K which is best described by a $d$-wave gap symmetry with two distinct gap magnitudes ($\Delta_0/\hbar \omega_c = 1.1$ and 2.9). The data show a pronounced zero bias anomaly which is interpreted as further evidence for nodes in the gap function. Zero bias anomalies have also been reported in PCAS data in the Nd compound [7]. It is likely these differences are reflective of the state of the surfaces of the samples, and further measurements are needed on high quality single crystals before the issue can be settled.

In this paper, we report measurement of the in-plane magnetic penetration depth of single crystal SmFeAsO$_{1-x}$F$_y$ ($x \approx y \approx 0.2$) with $T_c \approx 45$ K. The data below $T \sim 15$ K show that $\lambda$ follows an exponential temperature dependence, characteristic of an $s$ wave, fully gapped superconductor. The value of the minimum energy gap is found to be significantly lower than the BCS weak-coupling value.

Single crystals of nominal composition SmFeAsO$_{0.8}$F$_{0.2}$ were grown in Zürich using a high-pressure cubic anvil technique and a NaCl/KCl flux [8]. The small plate-like single crystals have typical dimensions $(80\times 80 \times 20) \mu m^3$, with the smallest dimension being along the c-axis. The penetration depth was measured using a radio frequency ($F \approx 12$ MHz) tunnel diode oscillator technique [9]. The sample was attached with vacuum grease to the end of a high purity sapphire rod and placed in a solenoid coil, which forms part of the inductor of the resonant circuit. The magnetic field was directed along the samples $c$ direction and hence all the screening currents flow in the $ab$ plane. We estimate that the RF field was $\sim 10^{-7}$ T and the Earth’s field was screened with a mu-metal can, hence, we do not expect any contributions from mobile vortices. The change in the resonant frequency of the circuit as the temperature is varied is directly proportional to the change in $\lambda_{ab}$. 

The constant of proportionality was determined from the measured ab-plane dimensions of the samples and the total frequency shift obtained when the sample was extracted from the coil at base temperature \([10]\). We estimate that this is accurate to \(\sim 20\%\).

Results for the low temperature behavior of two different samples are shown in Fig. 1. Here we denote the change in \(\lambda\) from the values at our lowest measurement temperature as \(\Delta\lambda(T)\). The results for both samples are very similar, showing that below \(T \approx 6\) K the penetration depth becomes independent of temperature within the noise of our measurements. The absolute change of \(\lambda\) between 2 K and 15 K was also quite consistent, being 105 Å for sample #1 and 95 Å for sample #2. This small difference is well within our expected error.

In the BCS theory for a fully gapped \(s\)-wave superconductor, the behavior of \(\lambda(T)\) asymptotically approaches

\[
\Delta\lambda(T) = \lambda(0) \frac{\Delta\lambda(0)}{2k_BT} \exp\left(-\frac{\Delta\lambda(0)}{k_BT}\right)
\]

at low temperature. Here \(\lambda(0)\) and \(\Delta\lambda(0)\) are the values of \(\lambda\) and the superconducting energy gap \(\Delta\) at \(T = 0\). In practice this provides a good approximation to the full theory for \(T \lesssim T_c/3\). If the energy gap is (weakly) anisotropic or there are distinct gaps on different Fermi surface sheets then the same behavior will still be found but with \(\Delta\lambda(0)\) now being approximately equal to the minimum energy gap in the system, and \(\lambda(0)\) is replaced by an effective value which depends on the details of the gap anisotropy.

The solid lines in Fig. 1 show fits of the data for samples #1 and #2 to Eq. (1) giving values of \(\Delta\lambda(0)/k_B = 49 \pm 2\) K and \(55 \pm 5\) K respectively (4.2 meV and 4.7 meV). The fitted values of \(\Delta\lambda(0)\) depend slightly on the upper temperature limit of the data included in the fit, and the quoted error bars encompassed the spread in values obtained for an upper temperature limit less than 15 K (\(\approx T_c/3\)). The behavior of the susceptibility close to the superconducting transition for these two samples is shown in the inset to Fig. 1. Although there are differences between the two samples in the structure near \(T_c\), the similarity of the low temperature results suggests that they are not affected by the slight inhomogeneity present. The onset of the transition is at around 50 K with the midpoint at around 45 K. From this we estimate that \(\Delta\lambda(0)/k_BT_c = 1.1 \pm 0.1\), which is significantly lower than the weak-coupling \(s\)-wave BCS value of 1.76, and suggests the possibility of significant gap anisotropy or multiple gaps such as is found, for example, in NbSe\(_2\) \([11]\) and MgB\(_2\) \([12]\). The value of \(\Delta\lambda(0)/k_BT_c\) found here is significantly higher than that found for the small gap in MgB\(_2\) (\(\Delta\lambda(0)/k_BT_c = 0.76\)), and is closer to the value found for the minimum gap in NbSe\(_2\) \([11]\). Evidence for multi-gap behavior in SmFeAsO\(_{1-x}\)F\(_x\) has also been inferred from strong observed temperature dependence of the anisotropy parameter \(\gamma\) \([3]\).

Given the many similarities with the cuprates, there has naturally been much speculation regarding the possibility that the superconductivity in these pnictide materials is unconventional. For a simple \(d\)-wave superconductor at low temperature, \(\Delta\lambda \approx 2\lambda(0)k_BT/\Delta\lambda(0)\). Assuming values appropriate for a \(d\)-wave state in these materials (\(\lambda(0) = 2000\) Å and \(\Delta\lambda = 2.14\) \(k_BT_c\)) we estimate that \(d\lambda/dT \approx 14\) Å/K which is at least two orders of magnitude larger than any linear term present in our data below \(\sim 6\) K. In a gapless superconductor, impurities produce a finite zero energy density of states and the temperature dependence of \(\lambda\) changes smoothly from \(T\) to \(T^2\), below an temperature scale determined by the impurity concentration \([13]\). This is also incompatible with our data, however, Cooper \([14]\) has shown that if the
normal state of a superconductor is strongly paramagnetic then there is an additional contribution to the measured $\lambda$ which is approximately equal to $\lambda(0)\chi_N(T)/2$, where $\chi_N$ is the normal state susceptibility. This additional term can produce a minimum in the measured $\lambda(T)$ which over a short range of temperature which can resemble an exponential BCS-like temperature dependence (see for example the measurements on the cuprate superconductor $\text{Nd}_{1.85}\text{Ce}_{0.15}\text{CuO}_4-y$ which are discussed and reanalysed in Ref. [14]). We have considered this possibility, assuming that $\chi_N = C/(T+T_M)$, but we were unable to obtain a reasonable fit to our data, even when we allowed all the parameters to vary freely. We conclude that a gapless superconducting state appears to be ruled out by our data.

Electronic structure calculations for the sister material $\text{LaFeAsO}_{1-x}\text{F}_x$ show that the bands crossing the Fermi level originate mostly from the two dimensional Fe layer and give rise to quasi-two-dimensional cylindrical sheets running along the c-axis and centered on the Γ point (hole) and the M point (electron). The general topology of this Fermi surface is consistent with recent angle resolved photoemission measurements [15]. As discussed by Mazin et al. [3], this Fermi surface topology places constraints on the type of pairing symmetries which are likely. In particular, these authors argue that the structure of the magnetic fluctuations favors an unusual type of multiple gap s-wave superconductivity where the order parameter on the electron and hole Fermi surface sheets have opposite phase. Our experiment does not tell us anything about the phase structure but our results are compatible with a fully gapped s-wave state with moderate anisotropy. Also, the presence of two different types of Fermi surface sheets suggests the possibility of two-gap superconductivity although there is expected to be significant intersheet scattering which would make the magnitudes of the two gaps similar [3].

As remarked above, fitting the low temperature $\lambda(T)$ data to Eq. (1) will deduce the size of the minimum superconducting gap. To deduce the presence of any other gaps or any other form of gap anisotropy it is necessary to analyze the full temperature dependence of the normalized superfluid density $\rho = \lambda^2(0)/\lambda^2(T)$ up to $T_c$. In our experiment we are not able to measure the absolute value of $\lambda$. So in order to calculate the superfluid density it is necessary to use an estimate of $\lambda(0)$ from other experiments. Weyeneth et al. [4] report measurement of $\lambda$ deduced from the reversible magnetic torque measured on samples produced using exactly the same method as those in the present work with a similar $T_c$. From their data they estimate $\lambda_{ab}(0)=2100 \pm 300$ Å. This is in reasonable agreement with the value of $\lambda \approx 1900$ Å measured by $\mu$SR for $\text{SmFeAsO}_{0.85}$ ($T_c = 52$ K) [16].

In Fig. 2 we plot the superfluid density calculated from our data using a range of values of $\lambda(0)$ that approximately encompass [17] both the expected uncertainty in both $\lambda(0)$ and our calibration factor relating the measured frequency shifts to $\Delta\lambda(T)$. We fit this superfluid density with a two-gap BCS model as used for MgB$_2$ [12, 13]. Here it is assumed that the gaps ($\Delta_1$ and $\Delta_2$) on each Fermi surface sheet (or group of sheets) follow the weak-coupling BCS temperature dependence but have a variable low temperature absolute value. There is an additional parameter $x$ which is the fraction of the superfluid density on the sheet with the smaller gap. In principle, there are four free parameters ($x$, $T_c$, $\Delta_1$ and $\Delta_2$) but we fix $\Delta_1 = 1.1 T_c$ as suggested by the low temperature exponential fits, and $T_c = 41.5$ K as suggested by a linear extrapolation of the superfluid density close to $T_c$. The fits suggest that in addition to the small gap found from the analysis of the low temperature data there is a larger gap of value $\Delta_2 = 1.8 \pm 0.2$ (6.4 ± 0.7 meV) which accounts for 80±5% of the superfluid density. This value of $\Delta_2$ is close to the gap value measured by Chien et al. [5] using PCAS on $\text{SmFeAsO}_{0.85}\text{F}_{0.15}$ ($T_c=40$ K) mentioned above. The small amount of superfluid density associated with the smaller gap may explain why this was not observed in these PCAS measurements. We note that we can also fit our data to a model where there is a smooth variation of the gap with in-plane angle [i.e., $\Delta(\phi) = \Delta(1+\sin 4\phi)$], so our data does not give definitive evidence for two gaps but rather just for a moderate variation of $\Delta(k)$.

In summary, our data for the in-plane penetration depth of the Sm Fe oxypnictide superconductor $\text{SmFeAsO}_{0.8}\text{F}_{0.2}$ show an exponential temperature de-
dependence at low temperature indicating a fully gapped pairing state. Our results also show evidence for a moderate variation of the gap on the different Fermi surface sheets. Fitting our data with a two-gap model suggest that the second gap is \(\sim 60\%\) larger than the first.

We thank J.R. Cooper and I.I. Mazin for useful discussions. This work was supported by the UK EPSRC, and the Swiss National Science Foundation through the NCCR pool MaNEP.

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