Muon-spin rotation studies of SmFeAs$_{0.85}$ and NdFeAs$_{0.85}$ superconductors

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Measurements of the in-plane magnetic field penetration depth $\lambda_{ab}$ in Fe-based superconductors with the nominal composition SmFeAs$_{0.85}$ (T$_c \approx 52$ K) and NdFeAs$_{0.85}$ (T$_c \approx 51$ K) were carried out by means of muon-spin rotation. The absolute values of $\lambda_{ab}$ at $T = 0$ were found to be 189(5) nm and 195(5) nm for Sm and Nd substituted samples, respectively. The analysis of the magnetic penetration depth data within the Uemura classification scheme, which considers the correlation between the superconducting transition temperature $T_c$ and the effective Fermi temperature $T_F$, reveal that both families of Fe-based superconductors (with and without fluorine) falls to the same class of unconventional superconductors.

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The recent discovery of the Fe-based layered superconductor LaO$_{1-x}$F$_x$FeAs [1] with the transition temperature $T_c = 26$ K has triggered an intense research in the oxypnictides. In its wake, a series of new superconductors with $T_c$ onset of up to 55 K have been synthesized successively by substituting La with other rare earth (Re) ions like Sm, Ce, Nd, Pr, and Gd [2,3]. Recently the new family of the oxypnictide superconductors ReFeAsO$_{1-x}$ with the doping induced by oxygen vacancies instead of fluorine substitution were synthesized [4,5]. The tunable oxygen content which leads to the occurrence of superconductivity strongly resembles the situation in high-temperature cuprate superconductors (HTS’s).

One of the interesting questions, which still awaits to be explored, is to which class of the superconducting materials the newly discovered Fe-based superconductors belong. The search for relations between the various physical variables such as transition temperature, magnetic field penetration depth, electrical conductivity, energy gap, Fermi temperature etc. may help to answer this question. Among others, there is a correlation between $T_c$ and the zero-temperature inverse squared magnetic field penetration depth [$\lambda^{-2}(0)$], that generally relates to the zero-temperature superfluid density ($\rho_s$) in terms of $\rho_s \propto \lambda^{-2}(0)$. In various families of underdoped HTS’s there is the empirical relation $T_c \propto \rho_s \propto \lambda^{-2}(0)$, first identified by Uemura et al. [6,7]. In this respect it is rather remarkable that the first magnetic field penetration measurements on LaO$_{1-x}$F$_x$FeAs ($x = 0.1, 0.075$) [8] and SmO$_{0.82}$F$_{0.18}$FeAs [9] result in values of the superfluid density which are close to the Uemura line for hole doped cuprates, indicating that the superfluid is also very dilute in the oxypnictides.

In this paper we focus on the different classification scheme proposed by Uemura [6,8] which considers the correlation between $T_c$ and the effective Fermi temperature $T_F$ determined from measurements of the in-plane magnetic penetration depth $\lambda_{ab}$. Within this scheme strongly correlated unconventional superconductors, as HTS’s, heavy fermions, Chevrel phases, or organic superconductors form a common but distinct group, characterized by a universal scaling of $T_c$ with $T_F$ such that $1/10 > T_c/T_F > 1/100$. We show that within the Uemura classification scheme both families of oxypnictide superconductors (with and without fluorine) falls to the same class of unconventional superconductors.

Details on the sample preparation for SmFeAsO$_{0.85}$ and NdFeAsO$_{0.85}$ can be found elsewhere [2]. The muon-spin rotation ($\mu$SR) experiments were performed at the $\pi$M3 beam line at the Paul Scherrer Institute (Villigen, Switzerland). During the experiments we were mostly concentrated on SmFeAsO$_{0.85}$ which shows the highest $T_c$ among other oxypnictide superconductors discovered till now. For NdFeAsO$_{0.85}$, we studied only the temperature dependence of the superfluid density in a field of 0.2 T.

We first start our discussion with zero-field (ZF) and longitudinal-field (LF) $\mu$SR experiments on SmFeAsO$_{0.85}$. The recent ZF $\mu$SR studies of the parent LaOFeAs compound reveal that there are two interstitial lattice sites where muons come into rest, namely, close to the Fe magnetic moments within the FeAs layers and near the LaO layers [11]. Bearing this in mind the ZF and the LF muon-time spectra for $T \lesssim 80$ K were analyzed by using the following depolarization function:

$$P_{ZF,LF}(t) = A_{slow} \exp(-\Lambda_{slow} t) + A_{fast} \exp(-\Lambda_{fast} t).$$

(1)

Here $A_{slow}$ ($A_{fast}$) and $\Lambda_{slow}$ ($\Lambda_{fast}$) are the asymmetry and the depolarization rate of the slow (fast) component, respectively. The whole set of ZF (LF) data was fitted simultaneously with the ratio $A_{slow}/A_{fast}$ as a common parameter and the relaxations ($\Lambda_{slow}$ and $\Lambda_{fast}$) as indi-
vidual parameters for each particular data point. The total asymmetry $A_{\text{slow}} + A_{\text{fast}}$ was kept constant within each set of the data (ZF or LF). Above 80 K the fit becomes statistically compatible with the single exponential component only. The results of the analysis and the representative ZF and LF muon-time spectra are shown in Fig. 1.

From the data presented in Fig. 1 the following important points emerge: (i) Both $A_{\text{fast}}(T)$ and $A_{\text{slow}}(T)$ measured in the zero and the longitudinal (up to 0.6 T) fields coincides within the whole temperature region. This, together with the exponential character of the muon polarization decay, reveal the existence of fast electronic fluctuations measurable within the $\mu$SR time-window. Assuming the fluctuation rate with a temperature dependence $\nu \sim \exp(E_0/k_B T)$ ($E_0$ is the activation energy) and accounting for the saturation of $\Lambda \simeq \Lambda_0$ at $10 \text{ K} \leq T \leq 35 \text{ K}$ the relaxation is expected to follow [12]:

$$\frac{1}{\Lambda} = \frac{1}{\Lambda_0} + \frac{1}{C \exp(E_0/k_B T)} \quad (2)$$

The fit of Eq. (2) to the experimental ZF $A_{\text{fast}}$ data yields $\Lambda_{0,\text{fast}} = 2.38(6) \, \mu\text{s}^{-1}$, $C = 0.012(2) \, \mu\text{s}$, and $E_0 = 23(2) \, \text{meV}$. This kind of activated process can be anticipated for a thermal population of Sm crystal field levels. (ii) The fact that both the slow and the fast relaxation rates exhibit similar temperature dependences [see Fig. 1(b)] strongly suggests that there is a common source for both relaxations which most probably relates to the fluctuation of Sm electronic moments. The magnitudes of $A_{\text{fast}}$ and $A_{\text{slow}}$ are thus related to the different couplings between muons and Sm moments at the distinct muon stopping sites. (iii) There are no features appearing in the vicinity of the superconducting transition. Fig. 1(b) implies that $A_{\text{fast}}$ increases continuously with decreasing temperature. This may suggest that the magnetic fluctuations responsible for the effects seen in Fig. 1 are not related to superconductivity. It is worth to mention that in systems exhibiting an interplay between the superconductivity and magnetism the slowing down of the spin fluctuations (increase of $\Lambda$) correlates with $T_c$ (see e.g. Ref. 13). Another argument comes from the comparison of $A_{\text{fast}}(T)$ for SmFeAsO$_{0.85}$ ($T_c \simeq 52 \text{ K}$), studied here, with that reported by Drew et al. [10] for SmO$_{0.82}$Fe$_{0.18}$As ($T_c \simeq 45 \text{ K}$), see Fig. 1(b). Apparently the Sm spin fluctuations are independent on $T_c$, which, therefore, suggests that their slowing down is not related to the superconductivity. (iv) The fast increase of both $A_{\text{fast}}$ and $A_{\text{slow}}$ below 5 K is most probably associated with additional local-field broadening due to the ordering of the Sm moments [10, 14].

The superconducting properties of SmFeAsO$_{0.85}$ and NdFeAsO$_{0.85}$ were studied in the transverse-field (TF) $\mu$SR experiments. The temperature scans were made after cooling the samples from above $T_c$ down to 1.7 K in $\mu_0 H = 0.2 \, \text{T}$. Following Hayano et al. [13] it can be shown that the effect of fast fluctuations on the longitudinal and transverse depolarization become similar. By taking this into account $\mu$SR data were analyzed by using the following functional form:

$$P_{\text{TF}}(t) = P_{\text{LF}}(t) \exp \left[ -\frac{(\sigma_{sc}^2 + \sigma_{nm}^2)^2}{2} \right] \cos(\gamma \mu B t + \phi). \quad (3)$$

Here $B$ is the average field inside the sample, $\gamma_\mu = 2\pi \times 135.5342 \, \text{MHz/T}$ is the muon gyromagnetic ratio, $\phi$ is the initial phase, and $P_{\text{LF}}(t)$ is described by Eq. 11. $\sigma_{nm}$ denotes the muon-spin relaxation rate caused by the nuclear moments and $\sigma_{sc}$ is the additional component appearing below $T_c$ due to nonuniform field distribution in the superconductor in the mixed state. During the fit $\sigma_{nm}$ was fixed to the values obtained above $T_c$.

Fig. 2 shows the $\sigma_{sc}(T)$ measured in $\mu_0 H = 0.2 \, \text{T}$. The inset shows the total Gaussian depolarization rate $\sigma = (\sigma_{sc}^2 + \sigma_{nm}^2)^{1/2}$. The fast increase of $\sigma_{sc}$ below $T \sim 50 \, \text{K}$ is due to the well-known fact that type-II superconductors exhibit a flux-line lattice leading to spatial inhomogeneity of the magnetic induction. As shown by Brandt [16], in a case of anisotropic powder supercon-


ductor the second moment of this inhomogeneous field distribution is related to the in-plane magnetic penetration depth \( \lambda_{ab} \) in terms of:

\[
(\Delta B^2) = \frac{\sigma_{sc}^2}{\sigma^2} = 0.0371 \frac{\Phi_0^2}{\lambda_{eff}^4} = 0.0126 \frac{\Phi_0^2}{\lambda_{ab}^4},
\]

where \( \Phi_0 = 2.068 \times 10^{-15} \text{ Wb} \) is the magnetic flux quantum. Here we also take into account that in anisotropic superconductor the effective magnetic penetration depth \( \lambda_{eff} \), measured in \( \mu \text{SR} \) experiments, is solely determined by the in-plane penetration depth as \( \lambda_{eff} = 1.31 \lambda_{ab} \). [17].

The data in Fig. 2 were fitted with the power law

\[
\sigma_{sc}(T)/\sigma_{sc}(0) = 1 - (T/T_c)^n
\]

with \( \sigma_{sc}(0) \), \( n \), and \( T_c \) as free parameters. Due to extra Sm and, most probably, Nd orderings (see the inset in Fig. 2) only the points above 5 K for Sm and above 10 K for Nd substituted samples were considered. The fit yields \( \sigma_{sc}(0) = 1.73(5) \mu \text{s}^{-1} \), \( T_c = 52.0(2) \text{ K} \), \( n = 3.74(16) \), and \( \sigma_{sc}(0) = 1.63(5) \mu \text{s}^{-1} \), \( T_c = 51.0(3) \text{ K} \), \( n = 1.98(14) \) for SmFeAsO\(_{0.85}\) and NdFeAsO\(_{0.85}\), respectively. From measured \( \sigma_{sc}(0) \) the absolute values of the in-plane magnetic penetration depth obtained by means of Eq. 4 are \( \lambda_{ab}(0) = 189(5) \text{ nm} \) and \( \lambda_{ab}(0) = 195(5) \text{ nm} \) for SmFeAsO\(_{0.85}\) and NdFeAsO\(_{0.85}\). At the present stage we are not going to discuss the temperature dependences of \( \sigma_{sc}(T) \) curves. We would only mention that the power law exponent \( n = 3.74(16) \) is very close to the universal two-fluid value \( n = 4 \), while \( n = 1.98(14) \) is close to \( n = 2 \), which is generally observed in a case of dirty \( d \)-wave superconductors.

The magnetic field dependence of \( \sigma_{sc} \) for SmFeAsO\(_{0.85}\) is shown in Fig. 3 (the corresponding \( \sigma_{nm} \) values were obtained from calibration runs made at \( T = 65 \text{ K} \)). At low fields a maximum in \( \sigma_{sc}(H) \) is observed followed by a decrease of the relaxation rate up to the highest fields. Consideration of the ideal triangular vortex lattice of an isotropic \( s \)-wave superconductor within the Ginsburg-Landau approach leads to the following expression for the magnetic field dependence of the second moment of the magnetic field distribution [18]:

\[
\sigma_{sc}[^{\text{[\mu s]}^{-1}}] = 4.83 \times 10^4 (1 - B/B_{c2}) \left[ 1 + 1.21 \left( 1 - \sqrt{B/B_{c2}} \right)^3 \right] \lambda^{-2}[\text{nm}].
\]

Here \( B \) is the magnetic induction, which for applied field in the region \( H_{c1} \ll H \ll H_{c2} \) is \( B \simeq \mu_0 H \) (\( H_{c1} \) is the first critical field, and \( B_{c2} = \mu_0 H_{c2} \) is the upper critical field). According to [18], Eq. 5 describes with less than 5 % error the field variation of \( \sigma_{sc} \) for an ideal triangular vortex lattice and holds for type-II superconductors with the value of the Ginsburg-Landau parameter \( \kappa \geq 5 \) in the range of fields \( 0.25/\kappa^3 \lesssim B/B_{c2} \lesssim 1 \). Since we are not aware of any reported values of the second critical field for SmFeAsO\(_{0.85}\), we used \( B_{c2}(15 \text{ K}) \approx 80 \text{ T} \) obtained from \( B_{c2}(0) \approx 100 \text{ T} \) reported by Senatore et al. [19] for SmO\(_{0.85}\)Fe\(_{0.15}\)FeAs. The black dotted line, derived by using Eq. 5, corresponds to \( \lambda = 232 \text{ nm} \). Fig. 3 implies that the experimental \( \sigma_{sc}(H) \) depends stronger on the magnetic field than it is expected in a case of fully gapped \( s \)-wave superconductor. As shown by Amin et al. [20] the field dependent correction to \( \rho_s \) may arise from the nonlocal and nonlinear response of a superconductor with nodes in the energy gap to the applied magnetic field. The solid line represent the result of the fit by means of the relation:

\[
\frac{\rho_s(H)}{\rho_s(H = 0)} = \frac{\sigma_{sc}(H)}{\sigma_{sc}(H = 0)} = 1 - K \cdot \sqrt{H},
\]

FIG. 3: (Color online) \( \sigma_{sc} \) as a function of applied field \( H \) for SmFeAsO\(_{0.85}\). Each point was obtained after field-cooling the sample from above \( T_c \) to \( T = 15 \text{ K} \) in the corresponding magnetic field. The solid and the dashed lines represents the results of analysis by means of Eqs. 5 and 6.
which takes into account the nonlinear correction to $\rho_s$ for a superconductor with a $d$-wave energy gap \[21\]. Here the parameter $K$ depends on the strength of nonlinear effect. Since Eq. \[6\] is valid for the intermediate fields ($H_{c1} \ll H \ll H_{c2}$) only the points above 0.02 T were considered in the analysis.

![Graph showing superconducting transition temperature ($T_c$) vs. effective Fermi temperature ($T_F$). The graph compares various types of superconductors, including HTS, heavy fermion, organic, and fullerene superconductors.](image)

FIG. 4: (Color online) The superconducting transition temperature $T_c$ vs. the effective Fermi temperature $T_F$. The unconventional superconductors fall within a common band for which $1/100 < T_c/T_F < 1/10$ as indicated by the grey region in the figure. The dashed line corresponds to the Bose-Einstein condensation temperature $T_B$ (see Ref. \[2\] for details). The points for SmFeAsO$_{0.85}$ and NdFeAsO$_{0.85}$ calculated from $\lambda_{ab}(0)$ values obtained in the present study and that for LaO$_{1-x}$Fe$_2$As ($x = 0.1$, 0.075) \[2\] and SmO$_{0.82}$F$_{0.18}$FeAs \[10\] are shown by solid red stars. As is seen the Fe-based superconductors follow the same linear trend as is established for various unconventional materials suggesting that they all probably share the common condensation mechanism.

As a next step we focus on the Uemura classification scheme which considers the correlation between the superconducting transition temperature $T_c$ and the effective Fermi temperature $T_F$ determined from measurements of the penetration depth. Using this parameterisation Uemura et al. \[2\] confirm a close correlation between $T_c$ and $T_F$. HTS’s, heavy fermion, organic, fullerene and Chevrel phase superconductors all follow a similar linear trend with $1/100 < T_c/T_F < 1/10$, in contrast to the conventional BCS superconductors (Nb, Sn, Al etc) for which $T_c/T_F < 1/1000$. The ”Uemura plot” of $\log(T_c)$ vs. $\log(T_F)$, shown in Fig. 4 thus appears to discriminate between the ”unconventional” and ”conventional” superconductors. The $T_B$ represents the Bose-Einstein condensation temperature for a non interacting 3D Bose gas having the boson density $n_B = n_s/2$ and mass $m_B = 2m^*$. Intriguingly, all the ”unconventional” superconductors are found to have values of $T_c/T_B$ in the range 1/3 to 1/30, thereby emphasizing the proximity of these systems to Bose-Einstein like condensation.

Following suggestions of Uemura et al. \[2\], the effective Fermi temperatures of the Fe-based superconductors were calculated as:

$$k_B T_F = \hbar \pi c_{int} \frac{n_s}{m^*} \propto c_{int} \sigma_{sc}.$$  \[7\]

Here $n_s/m^* = \rho_s$ is the superfluid density, which within the London approach is proportional to $\lambda^2$ and, thus, to $\sigma_{sc}$ ($n_s/m^* \propto \lambda^2 \propto \sigma_{sc}$), $n_s$ is the charge carrier concentration, $m^*$ is the charge carrier mass, and $c_{int}$ is the distance between the conducting planes. The points for SmFeAsO$_{0.85}$, NdFeAsO$_{0.85}$ and that obtained from $\lambda_{ab}(0)$ values of LaO$_{1-x}$Fe$_2$As ($x = 0.1$, 0.075) \[2\] and SmO$_{0.82}$F$_{0.18}$FeAs \[10\] are shown in Fig. 4 by solid red stars. As is seen the Fe-based superconductors follow the same linear trend as is established for various unconventional materials suggesting that they all probably share the common condensation mechanism.

To conclude, measurements of the in-plane magnetic field penetration depth $\lambda_{ab}$ in superconductors SmFeAsO$_{0.85}$ ($T_c \simeq 52$ K) and NdFeAsO$_{0.85}$ ($T_c \simeq 51$ K) were carried out by means of muon-spin-rotation. The absolute values of $\lambda_{ab}$ at $T = 0$ were estimated to be 189(5) nm and 195(5) nm for Sm and Nd substituted samples, respectively. The analysis within the Uemura classification scheme, considering the correlation between the superconducting transition temperature $T_c$ and the effective Fermi temperature $T_F$ reveal that both families of Fe-based superconductors (with and without fluorine) falls to the same class of unconventional superconductors.

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