Evidence for multi-band strongly coupled superconductivity in SmFeAsO$_{0.8}$F$_{0.2}$ single crystals by high-field vortex torque magnetometry

L. Balicas,¹ A. Gurevich,¹ Y. J. Jo,¹ J. Jaroszynski,¹ D. C. Larbalestier,¹ R. H. Liu,² H. Chen,² X. H. Chen,² N. D. Zhigadlo,³ S. Katrych,³ Z. Bukowski,³ and J. Karpinski,³
¹National High Magnetic Field Laboratory, Florida State University, Tallahassee-FL 32310, USA
²Hefei National Laboratory for Physical Science a Microscale and Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, People’s Republic of China and
³Laboratory for Solid State Physics, ETH Zürich, CH-8093 Zürich, Switzerland
(Dated: January 14, 2009)

To probe manifestations of multiband superconductivity in oxypnictides, we measured the angular dependence of magnetic torque $\tau(\theta)$ in the mixed state of SmO$_{0.8}$F$_{0.2}$FeAs single crystals as functions of temperature $T$ and high magnetic field $H$ up to 30 T. We show that the effective mass anisotropy parameter $\gamma$ extracted from $\tau(\theta)$, can be greatly overestimated if the strong paramagnetism of Sm or Fe ions is not properly taken into account. The correctly extracted $\gamma$ depends on both $T$ and $H$, saturating at $\gamma \approx 9$ at lower temperatures. Neither the London penetration depth nor the superfluid density is affected by high fields fields up to the upper critical field. Our results indicate two strongly-coupled superconducting gaps of nearly equal magnitudes.

PACS numbers: 74.25.-q, 74.25.Ha, 74.25.Op, 74.70.Dd

The recently discovered superconducting oxypnictides have similarities with the high $T_c$ cuprates, such as the emergence of superconductivity upon doping a parent antiferromagnetic compound. Several theoretical models suggest unconventional superconducting pairing, while the Andreev spectroscopy, penetration depth, and photoemission measurements indicate nodeless s-wave pairing symmetry. Experiments have found evidence for multi-gap superconductivity, in agreement with theoretical predictions.

The comparatively high $T_c$ values and extremely high upper critical fields $H_{c2}$ of the oxypnictides indicate promising prospects for technological applications if, unlike the layered cuprates, a sizeable vortex liquid region responsible for dissipative flux flow does not dominate their temperature-magnetic field ($T - H$) phase diagram. It is therefore important to reveal the true behavior of the anisotropic magnetization in the vortex state of the oxypnictides, particularly the extent to which vortex properties are affected by strong magnetic correlations, multiband effects and possible interband phase shift between the order parameters on different pieces of the Fermi surface. For instance, multiband effects in MgB$_2$ can manifest themselves in strong temperature and field dependencies for the mass anisotropy parameter $\gamma(T, H)$ and the London penetration depth $\lambda(T, H)$ even at $H \ll H_{c2}$. Yet, there are significant differences between two-band superconductivity in MgB$_2$ and in oxypnictides: in MgB$_2$ the interband coupling is weak, while in the oxypnictides it is the strong interband coupling which is expected to result in the high $T_c$. Thus, probing multiband superconductivity in oxypnictides by magnetization measurements requires high magnetic fields, which can suppress the superfluid density in the band with the largest coherence length above the "virtual upper critical field" ($H_v$) at which the vortex cores in this band overlap. In this Letter we address these issues, presenting the first high-field torque measurements of anisotropic reversible magnetization of the vortex lattice in SmO$_{0.8}$F$_{0.2}$FeAs single crystals. Our measurements of $\gamma(T, H)$ up to 30 T and extended temperature range, $20 < T < 40$ K have revealed a different behavior of $\gamma(T, H)$ as compared to recent low-field torque measurements.

Measurements of anisotropic equilibrium magnetization $m(T, H)$ in SmO$_{0.8}$F$_{0.2}$FeAs are complicated by the smallness of $m(H, T)$ caused by the large Ginzburg-Landau parameter, $\kappa = \lambda/\xi > 100$ and by the strong paramagnetism of Sm$^{3+}$ ions, which can mask the true behavior of $m(T, H)$. In this situation torque magnetometry is the most sensitive technique to measure the fundamental anisotropy parameters of $m(T, H)$ in small single crystals. The torque $\tau = m \times H$ acting upon a uniaxial superconductor is given by

$$\tau(\theta) = \frac{HV\phi_0(\gamma^2 - 1)\sin 2\theta}{16\pi\mu_0\lambda_{ab}^2\gamma c(\theta)} \ln \left[ \frac{\eta H^{ab}\theta}{\gamma(\theta)H} \right] + \tau_m \sin 2\theta, \quad (1)$$

where $V$ is the sample volume, $\phi_0$ is the flux quantum, $H_{c2}^{ab}$ is the upper critical field along the ab planes, $\eta \sim 1$ accounts for the structure of the vortex core, $\theta$ is the angle between $H$ and the c-axis, $c(\theta) = (\sin^2 \theta + \gamma^2 \cos^2 \theta)^{-1/2}$ and $\gamma = \lambda_c/\lambda_{ab}$ is the ratio of the London penetration depths along the c-axis and the ab-plane. The first term in Eq. (1) was derived by Kogan in the London approximation valid at $H_c1 \ll H \ll H_{c2}$. The last term in Eq. (1) describes the torque due to paramagnetism of the SmO layers and possible intrinsic magnetism of the FeAs layers. Here $\tau_m = (\chi_c - \chi_a)VH^2/2$ and $\chi_c$ and $\chi_a$ are the normal state magnetic susceptibilities of a uniaxial crystal along the c-axis and ab plane.
respectively. As will be shown below, the paramagnetic term in Eq. (1) in SmO$_{0.8}$F$_{0.2}$FeAs can be larger than the superconducting torque, which makes extraction of the equilibrium vortex magnetization rather nontrivial. In this Letter we develop a method, which enables us to resolve this problem and measure the true angular dependence of the superconducting torque as a function of both field and temperature, probing the concomitant behavior of $\gamma(T, H)$ and $\lambda_{ab}(T, H)$ and manifestations of multiband effects in SmO$_{0.8}$F$_{0.2}$FeAs single crystals.

![FIG. 1: (color online) (a) Magnetic torque $\tau(\theta)$ for a SmO$_{0.8}$F$_{0.2}$FeAs single crystal for increasing and decreasing angle sweeps (black lines) at 3 T and 27 K. The equilibrium $\tau_{av}(\theta)$ (blue markers) is obtained by averaging both traces. (b) $\tau_{av}(\theta)$ for 40 K and 30 T exhibits a nearly sinusoidal angular dependence. Red line corresponds to a fit to the first term in Eq. (1) with $\gamma = 11.5$.](image1.png)

![FIG. 2: (color online) (a) Angular dependence of $\tau_{av}(\theta)$ at 3 T and several temperatures. (b) Same as in (a) for 30 T.](image2.png)

Fig. 1 (a) shows typical angular dependence of $\tau(\theta)$ at 27 K and 3 T. Since we are only interested in temperature and field dependencies of $\gamma$ and $\lambda$, the torque data are provided in arbitrary units. A hysteresis, resulting from the irreversible magnetization is observed between increasing and decreasing angle sweeps. Black markers depict the average value of both traces. The red line is a fit to the first term in Eq. (1) with $\gamma \approx 11.5$. However, this multiparameter fit is not very suitable for extraction of the true values of $\gamma$ due to pronounced error bars for $H_{c2}^{ab}$ and a significant paramagnetic component particularly at 30 T. The complete set of the raw $\tau_{av}(\theta)$ data is shown in Figs. 2 (a) and (b).

The superconducting component of the torque can be unambiguously extracted from the data by fitting the sum of two measured curves $\tau_{av}(\theta) + \tau_{av}(\theta + 90^\circ)$, in which the paramagnetic component cancels out:

$$\tau(\theta) + \tau(\theta + 90^\circ) = \frac{V_{ao}(\gamma^2 - 1)H \sin 2\theta}{16\pi\mu_0\lambda_{ab}^2 \gamma} \left[ \frac{1}{\varepsilon(\theta)} \ln \left( \frac{\eta H_{c2}^{ab}}{\varepsilon(\theta) H} \right) - \frac{1}{\varepsilon^*(\theta)} \ln \left( \frac{\eta H_{c2}^{ab}}{\varepsilon^*(\theta) H} \right) \right],$$

where $\varepsilon(\theta)$ and $\varepsilon^*(\theta)$ are the real and imaginary parts of the complex dielectric function, $H_{c2}^{ab}$ is the upper critical field along the $ab$-plane, and $\gamma$ is the ratio of the superfluid density at $T_c$ to that at zero temperature.
where \( \varepsilon^*(\theta) = (\cos^2 \theta + \gamma^2 \sin^2 \theta)^{1/2} \). This procedure is illustrated by Fig. 3 (a) where \( \tau_{av}(\theta) \) for 3 T and 30 K is plotted together with \( \tau_{av}(\theta + 90^\circ) \). Black markers depict the sum of both traces which is entirely determined by the superconducting response. Red line corresponds to a fit of \( \tau_{av}(\theta) + \tau_{av}(\theta + 90^\circ) \) to Eq. (2). An example of the fit of \( \tau_{av}(\theta) \) to Eq. (1) with the parameters taken from Fig. 3 (a).

The obtained temperature dependence of \( \gamma(T, H) \) is reminiscent of the behavior of \( \gamma(T, H) \) previously reported for MgB\(_2\) which was explained in terms of multiband effects. Yet the extracted London penetration depth shown in Fig. 5 (a) does not exhibit a significant field dependence which would indicate an abrupt depression of the superfluid density in one of the bands above \( H_c \) (produced by the suppression of the respective superconducting gap). This is quite remarkable given that we measured \( \lambda(T, H) \) up to the applicability limit of the London theory, i.e. \( \eta H'_c / H \approx 1 \) at \( H = 30 \) T. Overall, the behaviors of \( \gamma(T, H) \) and \( \lambda(T, H) \) shown in Fig. 5 (a) would suggest two strongly coupled gaps of similar magnitude but not too different mass anisotropies. The decrease of \( \gamma(H) \) as \( H \) increases may indicate that the band with the shorter coherence length \( \xi \sim h v_F / \Delta \) is the least anisotropic.

The relative contributions of the superconducting and magnetic components in \( \tau_{av}(\theta, T, H) \) are shown in Fig. 5 (b). At higher \( T \) the behavior of \( \tau_{av}(T) \propto C_1|T|K| + C_2, C_2 \approx -C_1/43 \) at 3T is consistent with the Curie-Weiss paramagnetism of Sm\(^{3+}\) ions. However, this temperature dependence of \( \tau_{av}(T) \) changes at \( H = 30 \) T, for
where $n$ is the density of paramagnetic ions, $g_\theta = (g^2 \cos^2 \theta + g^2 \sin^2 \theta)^{1/2}$. For weak fields or $\mu_B g_\theta H \ll T$, Eq. (3) gives $\tau_p = (\chi_c - \chi_\alpha) H^3 \sin 2\theta/2$ and $\chi_\alpha = \mu_B^2 g^2 / 4T$ as used in our analysis. However, for higher fields $\mu_B g_\theta H > T$, the paramagnetic torque $\tau_p \approx n\mu_B (g^2 - g^2_\alpha) H \sin 2\theta/2 g_\theta$ acquires higher order harmonics. This case may pertain to our data at 30T and $T < 30K$, for which the pure $\sin 2\theta$ component in $\tau(\theta)$ decreases as $T$ decreases, but $\tau_p(\theta)$ may not be completely eliminated by the procedure described above. Deviations from Eq. (4) also come from corrections to the London theory at high fields resulting in additional terms $\propto \alpha H_{c2}/H - (\ln 2 + \alpha) H / H_{c2}$. $\alpha \sim 1$ in $m(T, H, \theta)$ due to pairbreaking and nonlocal effects [20].

In summary, our torque measurements at high-fields reveal the temperature and field dependencies of the anisotropic reversible magnetization which is strongly coupled with the magnetism of rare earth ions in SmO$_{0.8}$F$_{0.2}$FeAs single crystals. Our results indicate a temperature and field dependent mass anisotropy $\gamma(T, H)$ which saturates at $\gamma \approx 9$ at low temperatures under a modest field. This value is higher than $\gamma = H_{c2}' / H_{c2} \approx 5$ at low temperatures in NdO$_{1.7}$F$_{0.3}$FeAs single crystals [21] and $\gamma \approx 5 - 7$ for YBa$_2$Cu$_3$O$_{7-\delta}$, but is much smaller than $\gamma \geq 30$ suggested by Ref. [22]. The observed insensitivity of the London penetration depth at fields up to 30T is indicative of strong coupling superconductivity, which in addition to a not very high $\gamma$ is very important for applications. Our results are consistent with strongly coupled gaps of nearly equal magnitudes in distinct bands.

The NHMFL is supported by NSF through NSF-DMR-0084173 and the State of Florida. This work was also supported by NHMFL/IHRP (LB, AG, DCL), NHMFL-Schuller program (YJJ) and by AFOSR (DCL and AG). Work in Zurich was supported by the Swiss National Science Foundation through the NCCR pool MaNEP.

[1] Y. Kamihara et al., Nature 130, 3296 (2008); H. Takahashi et al., Nature 453, 376 (2008); X. H. Chen et al., Nature 453, 761 (2008).
[2] G. F. Chen et al., Phys. Rev. Lett. 100, 247002 (2008).
[3] Y. Takabayashi et al., J. Am. Chem. Soc. 130, 9242 (2008).
[4] C. de la Cruz et al., Nature 453, 899 (2008).
[5] I. I. Mazin, D. J. Singh, M. D. Johannes, and M. H. Du, Phys. Rev. Lett. 101, 057003 (2008).
[6] K. Haule, J. H. Shim, and G. Kotliar, Phys. Rev. Lett. 100, 226402 (2008); Q. Si and E. Abrahams, Phys. Rev. Lett. 101, 076401 (2008); P. A. Lee, X. G. Wen, arXiv:0804.1739 (2008).
[7] T. Y. Chen, Z. Tesanovic, R. H. Liu, X. H. Chen, and C. L. Chien, Nature 453, 1224 (2008).
[8] L. Malone et al., arXiv:0806.3908 (2008).
[9] H. Ding et al., Europhys. Lett. 83, 47001 (2008).
[10] F. Hunte et al., Nature 453, 903 (2008).
[11] S. Weyeneth et al., arXiv:0806.1024v1 (2008)
[12] Y. J. Jo, et al. (unpublished); J. Jaroszynski et al., Phys. Rev. B 78, 064511 (2008).
[13] M. Angst et al., Phys. Rev. Lett. 88, 167004 (2002); A. V. Sologubenko et al. Phys. Rev. B 65, 180505(R) (2002); S. L. Bud’ko and P. C. Canfield, ibid. 65, 212501 (2002)
[14] R. Cubitt et al., Phys. Rev. Lett. 91, 047002, (2003); M. Angst et al., Phys. Rev. B 70, 224513 (2004).
[15] V. G. Kogan, Phys. Rev. B 24, 1572 (1981); Phys. Rev. Lett. 89, 237005 (2002).
[16] N. D. Zhigadlo, S. Katrych, Z. Bukowski, and J. Karpinski, J. Phys.: Condens. Matter 20, 342202 (2008).
[17] See, for example, T. Goko et al., arXiv:0808.1425 (2008).
[18] V. F. Mitrovic et al., Nature 413, 501 (2001); B. Lake et al., Nature 415, 299 (2002); H. J. Kang et al., Nature 423, 522 (2003).
[19] R. M. White Quantum Theory of Magnetism, Springer-Verlag, Berlin, Heidelberg, New York, 1983.
[20] V. G. Kogan et al, Phys. Rev. B 74, 184521 (2006).
[21] J. Jaroszynski et al., Phys. Rev. B 78, 174523 (2008).
[22] A. Dubroka et al., Phys. Rev. Lett. 101, 097011 (2008).