Physica C: Superconductivity and its applications 000 (2016) 1–4

Contents lists available at ScienceDirect

Physica C: Superconductivity and its applications

journal homepage: www.elsevier.com/locate/physc

Direct measurement of the temperature dependence of the in-plane magnetic penetration depth in optimally doped $BaFe_2(As_{1-x}P_x)_2$ single crystals

A. Ramos-Álvarez [a,*], J. Mosqueira [a], F. Vidal [a], D. Hu [b], H.-Q. Luo [b], S.-L. Li [b]

[a] Laboratorio de Baixas Temperaturas e Superconductividade, Dept. Física de Partículas, Universidade de Santiago de Compostela, E15782 Spain
[b] Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Article history:
Received 10 January 2016
Revised 18 July 2016
Accepted 19 July 2016
Available online xxx

Keywords:
Fe-based superconductors
Penetration depth
Pairing symmetry
Doping level

ABSTRACT

Measurements of the temperature dependence of the in-plane magnetic penetration depth, $\Delta\lambda_{ab}(T) = \lambda_{ab}(T) - \lambda_{ab}(0)$, are presented in the isovalently substituted iron pnictide $BaFe_2(As_{1-x}P_x)_2$ near optimal doping ($T_c \sim 28$K). The data were obtained directly from the shielding magnetic susceptibility of thin single crystals (~ 20 μm thickness along the crystals *c*-axis) under magnetic fields parallel to the *ab* layers. Complications associated to flux penetration were avoided by using fields in the 10^{-4} T range, which ensured that the samples were well inside the Meissner region. At low temperatures ($T < 0.25T_c$) our data confirm the linear temperature dependence of $\lambda_{ab}(T)$ observed by using other procedures, and that is consistent with a nodal superconducting order parameter. By using values for $\lambda_{ab}(0)$ in the literature we obtained the temperature dependence up to T_c of the superfluid density, $n_s(T) \propto 1/\lambda_{ab}^2(T)$. It is found that samples with slightly different T_c values present a significantly different qualitative behavior of $n_s(T)$.

1. Introduction

Superconductivity may be induced in iron pnictides by suppressing the magnetic order by charge doping of the parent compound (e.g., by partially replacing Ba by K in $BaFe_2As_2$) [1], but also by introducing isovalent substitutions (like P by As, or Ru by Fe, also in $BaFe_2As_2$) [2–4]. While charge-dopants create very effective scattering potentials which affect many superconducting properties, isovalently-substituted compounds do not present appreciable impurity scattering [2,3,5,6], and have very different characteristics. In particular, contrary to charge-doped materials, they present clear evidences of nodes in the energy gap [7–11].

One of the most studied isovalently-substituted compounds is $BaFe_2(As_{1-x}P_x)_2$. In this material, it has been recently observed a sharp peak in the *x*-dependence of the in-plane penetration depth at $T \to 0$ K, $\lambda_{ab}(0)$, at the optimal doping level ($x = 0.30$) [12]. This effect has been confirmed by local measurements performed with magnetic-force microscopy [13], and has been related to the possible presence of a quantum critical point (QCP) [12,14–17]. Much less attention has been given to the temperature dependence of λ_{ab} in this compound. However, its study would allow to obtain the temperature dependence of the superfluid density, $n_s(T) \propto \lambda_{ab}^{-2}(T)$, and to obtain information about the gap symmetry, the couplings between electrons in the different bands, and their possible dependence on the doping level [18].

Here we present new measurements of the temperature-dependence of λ_{ab},

$$\Delta\lambda_{ab}(T) = \lambda_{ab}(T) - \lambda_{ab}(0), \quad (1)$$

in several high-quality $BaFe_2(As_{1-x}P_x)_2$ single crystals near the optimal doping level. The data were obtained from the shielding magnetic susceptibility (in the Meissner region) for fields parallel to the *ab* layers. This technique allows the use of DC magnetic fields in the Oe range, and is very direct ($\Delta\lambda_{ab}$ is proportional to the change with the temperature of the measured magnetic moment). Moreover, it avoids well known difficulties intrinsic to other techniques, like surface barriers (in the case of techniques based on the determination of the lower critical field) [19], or edge roughness [20–23]. Our data will allow to confirm the linear temperature dependence of λ_{ab} at low temperatures (a signature of nodes in the order parameter), and to obtain new information about the temperature dependence of n_s up to T_c. In particular, it will allow to probe possible changes with the doping level on approaching the QCP.

* Corresponding author.
E-mail address: albramalv@gmail.com (A. Ramos-Álvarez).

http://dx.doi.org/10.1016/j.physc.2016.07.014
0921-4534/

Table 1
Some parameters of the crystals studied. The thicknesses were obtained from the masses and from the theoretical density. $D_\perp$ is the demagnetizing factor used in Fig. 2(a). See main text for details.

Sample	Surface (mm^2)	Thickness (mm)	T_c (K)	$D_\perp$
1	0.312	0.0174	27.5	0.95
2	0.298	0.0144	27.4	0.96
3	1.575	0.0249	27.8	0.96

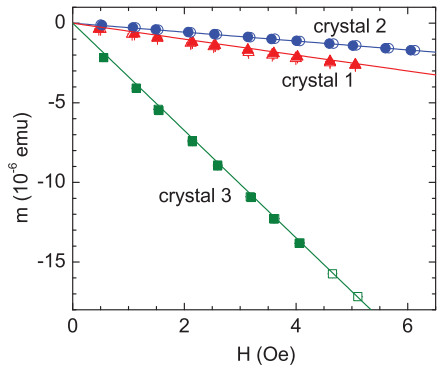

Fig. 1. Magnetic field dependence of the magnetic moment for all samples studied. These measurements were performed at 2 K after zero-field cooling. The linear and fully reversible behavior rules out possible spurious effects associated with magnetic flux trapped inside the crystals.

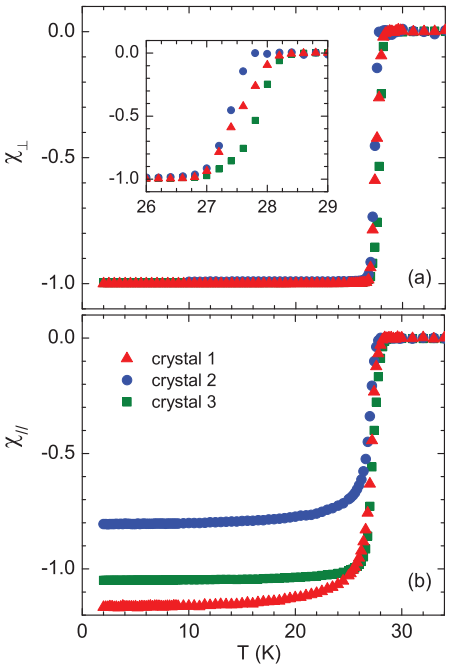

Fig. 2. (a) Temperature dependence of the magnetic susceptibility for $H\perp ab$ (a), and $H\|ab$ (b). These data were obtained with low applied magnetic fields (~ 5 Oe), so that the samples are well inside the Meissner region just below T_c. The rounding observed below T_c when $H\|ab$ is due to the competition between $\lambda_{ab}(T)$ and the crystals thickness. The inset in (a) is a detail around the diamagnetic transition.

2. Experimental details and results

The $BaFe_2(As_{1-x}P_x)_2$ crystals with used in this work (with $x \sim 0.35$, close to the value that maximizes T_c) were grown by using the Ba_2As_3/Ba_2P_3 self-flux method described in Ref. [24]. Details of their characterization may be seen in Refs. [14,25]. We used plate-like single crystals (see Table 1) with the FeAs (*ab*) layers parallel to their largest faces. They were cleaved from larger crystals by using adhesive tape.

The magnetic susceptibility was measured in three single crystals with the magnetic field, *H*, perpendicular and parallel to the *ab*-layers, $\chi_\perp$ and $\chi_\parallel$ respectively, with a commercial SQUID magnetometer (Quantum Design, model MPMS-XL). In the case that $H\|ab$ the samples were glued with a minute amount of GE varnish to a quartz sample holder (0.3 cm in diameter, 22 cm in length). Two plastic rods at the holder ends ensured an alignment better than 0.1°, although the GE varnish may introduce an additional uncertainty that will be commented below. The samples were zero-field cooled to 2 K by using the so-called *ultra-low-field* option, which reduces the magnetic field in the sample space to a value below 10^{-2} Oe.

The measurements were performed with magnetic fields between 4 and 6 Oe. As it is shown in Fig. 1, in this range the magnetic moment is linear with *H* and fully reversible, which rules out any spurious effect associated with magnetic flux trapping. Due to the small crystals and magnetic fields used, the magnetic moment resulted to be in the $\sim 10^{-6}$ emu range. By this reason, we used the *Reciprocating Sample Option* (RSO) and averaged eight measurements consisting of 10 cycles at 1 Hz, which resulted in an uncertainty in magnetic moment of the order of 10^{-8} emu.

The temperature dependence of $\chi_\perp$ is presented in Fig. 2(a). These data are already corrected for demagnetizing effects by using the demagnetizing factor, $D_\perp$, needed to attain the expected value of $\chi_\perp = -1$ when $T \to 0$ K (see Table 1), which resulted to be consistent with the values that may be obtained from the crystals' dimensions [26]. As it may be seen, the diamagnetic transitions are well defined (the full transition widths are around ~ 0.5 K in all the samples), and the T_c values (compiled in Table 1) were estimated from the transition midpoint. The temperature dependence of $\chi_\parallel$ is shown in Fig. 2(b). While $\chi_\perp$ is almost temperature independent, $\chi_\parallel$ presents an appreciable rounding (mainly close to T_c) due to the competition of $\lambda_{ab}(T)$ with the crystals' thicknesses, L_c. The low-temperature saturation values were determined by a linear fitting up to $0.3T_c \approx 9$ K. Samples 1 and 3 present values of $|\chi_\parallel(0)|$ larger than ~ 1, consistent with crystal misalignments about 5° (see next section). The reduced $|\chi_\parallel(0)|$ value for sample 2 may be attributed to the presence of some unscreened non-superconducting domains in the sample.

3. Data analysis and discussion

3.1. Low-temperature behavior of λ_{ab}(T)

Taking into account the plate-like geometry of the crystals, $\lambda_{ab}(T)$ may be obtained from $\chi_\parallel$ through[1]

$$\chi_\parallel = -1 + \frac{2\lambda_{ab}}{L_c}\tanh\left(\frac{L_c}{2\lambda_{ab}}\right). \quad (2)$$

The crystals' thicknesses are about 20 μm, and the reported $\lambda_{ab}(0)$ values for the studied compound are about 0.2 μm [12] and remain below ~ 1 μm up to very close to T_c (typically $0.9T_c$, see Fig. 3). Thus, in a wide temperature region below T_c it may be approximated

$$\chi_\parallel \approx -1 + \frac{2\lambda_{ab}}{L_c}. \quad (3)$$

[1] In Eq. (2) we have neglected an additive term, $\sim 2\lambda_c/L_{ab}$, associated to the competition between the out-of-plane magnetic penetration depth, λ_c, and the crystals width, L_{ab}, because of in the studied crystals this term is expected to be ~ 15 – 35 times smaller than $2\lambda_{ab}/L_c$ (note that in the samples used $L_{ab} \approx 0.5 - 1.2$ mm and $L_c \approx 0.02$ mm (see Table 1), and the anisotropy factor $\gamma = \lambda_c/\lambda_{ab} \approx 1.8$ [25]).

Please cite this article as: A. Ramos-Álvarez et al., Direct measurement of the temperature dependence of the in-plane magnetic penetration depth in optimally doped $BaFe_2(As_{1-x}P_x)_2$ single crystals, Physica C: Superconductivity and its applications (2016), http://dx.doi.org/10.1016/j.physc.2016.07.014