Temperature dependence of the magnetic penetration depth in $\mathbf{B}_{1-x}\mathbf{K}_{x}\mathbf{BiO}_{3}$ superconductor

Alexey Snezhko* and Ruslan Prozorov[†]

Department of Physics and Astronomy and NanoCenter,
University of South Carolina, 712 Main St, Columbia, SC 29208, USA
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Temperature dependence of the magnetic penetration depth, $\lambda(T)$, was measured in the Meissner state in single crystals $B_{1-x}K_xBiO_3$ (x=0.37) using tunnel diode resonator technique. At low temperatures, $0.013 \le T/T_c \le 0.4$, $\lambda(T)$ is exponentially flat, which provides a strong evidence for conventional s-wave BCS behavior. Numerical analysis of the data rules out the possibility of a gap with nodes.

Magnetic penetration depth is an effective tool to study electromagnetic properties of superconductors. At low temperatures, its temperature dependence is directly related to the density of low energy quasiparticles, which in turn can be related to the anisotropy of the superconducting energy gap on the Fermi surface. For investigation of the low lying excitations and thus the anisotropy of the energy gap, the analysis is considerably less ambiguous if measurements are performed on high quality single crystal and temperatures well below $T_c/3$. In this paper we report magnetic penetration depth measurements on single crystals $B_{0.63}K_{0.37}BiO_3$ ($T_c \approx 31 \text{ K}$) down to 0.4 K. The investigation of mechanisms of superconductivity in $B_{1-x}K_xBiO_3$ (BKBO) system has been one of the important subjects in studies of high T_c superconductivity in oxide materials. The significance of BKBO lies in observations that some of its superconducting properties are consistent with the conventional s-wave isotropic superconductivity, but others are resembling high- T_c cuprates. In particular, substantial isotope effect [1, 2], strong phonon contribution from the neutron scattering measurements [3], and a superconducting gap with $2\Delta_0/T_c=3.5\pm0.3$ from the tunnelling and optical experiments [4, 5, 6, 7] indicate significant role of electron-phonon interactions in mechanism of superconductivity of BKBO. However the low density of states at the Fermi level with T_c as high as 30K [2] and insulator-superconductor transition by doping [8] are similar to high- T_c cuprates. However, in contrast to high T_c cuprates which have two dimensional CuO_2 planes, BKBO has simple three dimensional cubic perovskite structure.

Single crystal of $B_{1-x}K_xBiO_3$ (x=0.37) was grown by the electro-chemical method reported elsewhere [9]. DC magnetization was measured by using *Quantum Design* MPMS SQUID magnetometer. Zero-field cooled and field cooled temperature scans taken in external field of 10 Oe are shown in Fig. 1. Superconducting transition temperature of the sample is $T_c \approx 31 \mathrm{K}$ and the curves show regular superconducting screening with the Meissner expulsion of about 20%, which provides an indication of relatively low pinning. Magnetization loops confirm

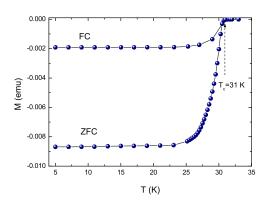


FIG. 1: Temperature dependence of magnetic moment in B-K-Bi-O single crystal in zero-field cooled and field cooled experiment in an external applied field of 10 Oe.

low pinning behavior.

Penetration depth measurements were carried out using a 13 MHz tunnel diode LC resonator [10, 11] mounted on a He³ cryostat. The sample was placed on the sapphire stage with temperature control from 0.35 to 40K. During the measurements the sample is exposed to the small ac field $H_{ac} \simeq 20$ mOe much less than the first critical field, $H_{c1} \approx 750$ Oe at 5 K [12]. The relative resonance frequency shift, $\Delta f = f(T) - f(T_{min})$, is related to the change of the magnetic penetration depth via $\Delta f = -G\Delta\lambda$, where G is geometrical factor that depends upon the sample shape and volume as well as the coil geometry [11]. Low temperature behavior of magnetic penetration depth is shown in the Fig.2. The frequency shift in Fig. 2 was normalized by the value $\Delta f_0 \approx 3500$ Hz, which represents the total frequency shift cooling from normal to superconducting state. The solid line in Fig. 2 shows the fit to a low temperature BCS expression for an s-wave material,

$$\Delta \lambda \approx \lambda(0) \sqrt{\frac{\pi \Delta_0}{2T}} \exp\left(-\frac{\Delta_0}{T}\right)$$
 (1)

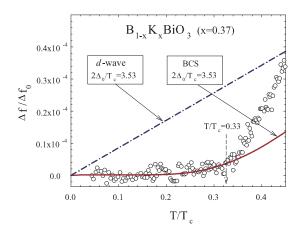


FIG. 2: Low temperature penetration depth variation in $B_{1-x}K_xBiO_3$ (x=0.37) single crystal. The solid line shows the low temperature exponential fit to the weak-coupling BCS expression. Dash-dotted line represents low temperature d-wave behavior. See text for details.

Here Δ_0 is the value of the energy gap at zero temperature [13]. The fitting range was chosen up to $0.33T_c$ to ensure the validity of the low temperature expansion. $2\Delta_0/T_c=3.53$ corresponds to standard weak coupling BCS value. The dash-dotted line shows the low temperature behavior of the magnetic penetration depth predicted for a clean d-wave superconductor [14]. The value of $2\Delta_0/T_c$ for d-wave case was again chosen to be 3.53 in accordance with results of tunnelling and optical experiments.

$$\Delta \lambda \approx \lambda(0) \left(1 - \frac{\ln 2}{\Delta_0} T \right)$$
 (2)

Clearly the isotropic s-wave BCS curve provides best description of the low temperature penetration depth variation indicating the isotropic nature of superconducting gap for BKBO. Some apparent noise in the data is because in the temperature interval of interest, the penetration depth is exponentially flat with no systematic temperature dependence.

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- * Electronic address: snezhko@physics.sc.edu
- † Electronic address: prozorov@sc.edu
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