Probing the Energy Gaps of a Multi-Gap Superconductor: $Ba_{(1-x)}K_xFe_2As_2$

Keeran Ramanathan, Luke Conover, Oberon Wackwitz, and Roberto Ramos

University of the Sciences,Philadelphia, PA, 19104, USA

[a)]Corresponding author: r.ramos@usciences.edu

Abstract. In order to spectroscopically probe the superconducting energy gap of potassium-doped Ba122 iron pnictides, in particular $Ba_{(1-x)}K_xFe_2As_2$ where x = 0.33 (under-doped regime), we have performed four-wire conductance measurements from T = 2K to 52K. We report evidence for multi-gap features with gaps corresponding to directional tunneling through the *ab*- axes of this iron pnictide. The multi-gap features a predominant result of tunneling across the *ab*- plane with gaps of Δ_1 = 2-4 meV and Δ_2 = 9-11 meV. These gap values are temperature dependent.

Introduction

Multi-band superconductors, such as the iron pnictides, can exhibit multiple energy gaps depending on the crystal growth conditions and on which tunneling directions are made accessible by the sample fabrication process.[1] The energy gaps are often anisotropic with respect to the crystal lattice, corresponding to superconductivity along directions parallel or perpendicular to the c-axis of the lattice.[1,2] We present and discuss results of measurements of the energy gaps of single crystals of iron pnictides (K-doped Ba-based 122 family) using point contact spectroscopy.

Transport through a point contact is classified into three separate regimes: diffusive, quantum, and ballistic.[3] Each regime correlates to the contact diameter *a* and the electronic mean free path of *l* of the contact material; the mean free path stems from the successive elastic and inelastic scattering of electrons. In the diffusive regime, the sample size is much larger than the mean free path so that transport is independent of the form of the system. In the quantum regime, the sample is similar to the mean free path so that edge and boundary effects dominate. In the ballistic regime, the charge carriers make ballistic motion while boundaries play the role of scatterer. Spectra such as the superconducting energy gap has been shown to be readable from point contact data if the interface between normal metal leads and the superconductor is in the ballistic regime, when heating effects are minimized.[4] It has been recently demonstrated that if the junction size is reduced to the ballistic regime, where the electron mean path is longer than the junction size, that conductance measurements using PCS (Point Contact Spectroscopy) can be reduced to a simpler tunneling model. This allows the PCS technique to sample the effective density of states obtained from integrating over the whole Fermi surface, and has been appropriately applied to iron pnictides that behave like a non-Fermi liquid.[4]

Our measurements that use nanometer-size gold wires pressed against crystals are ideally within the ballistic regime. Features such as Andreev reflections occur within the point-contact between a normal metal N and a superconductor S, and is a charge-transfer process by which normal current in N is converted to supercurrent in S.[1] When the electronic energy of the applied voltage is within the value of the superconducting gap (Fermi level of the superconductor), the electron is physically not allowed to tunnel across the two-state junction and as a result, a cooper pair is formed within the superconductor while a hole is reflected back inside the normal metal. Thus, identifying Andreev reflections can reveal spectroscopic properties of the superconductor.[4] More generally, measuring the differential conductance *dI/dV* as a function of applied voltage *V,* which is a direct measure of the superconducting energy gap, can show the important spectroscopic properties of the superconductor and give insight into the mechanisms driving superconductivity in these materials. This allows for the probing of single- and multi-gap structures of superconductors and serves as the basis for point-contact spectroscopy.

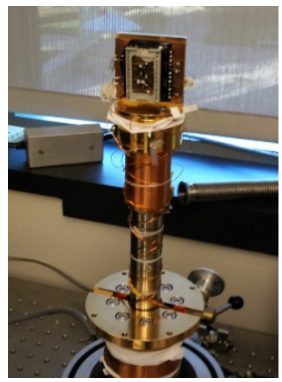
EXPERIMENTAL PROCEDURE

Single crystals of $Ba_{0.67}K_{0.33}Fe_2As_2$ of high crystalline quality were obtained from collaborators who had grown samples by using the self-flux method with FeAs as flux, as described in the literature.[5] The crystals were then cleaved by means of mechanical exfoliation using Scotch tape, to produce a fresh, shiny surface. To prepare the samples for current-voltage measurements, four soft point contacts were made by controlled application of silver paint on nanometer-diameter gold wires set upon the crystals mounted on a copper platform.

Four contacts were made in order to implement four-wire measurement technique designed to eliminate contributions from lead resistances.[6] To access the *ab*- and *c*-axes simultaneously through the crystal, V-shaped gold wires connecting the point contact are oriented between 30-45° relative to the copper platform.

The sample was then mounted onto a custom-built sample holder thermally anchored using black Stycast Epoxy on the second stage cold finger of a Janis Cryocooler with a base temperature of 2 Kelvin. The second stage is covered by a metal shroud that acts doubles as a 2 Kelvin radiation shield, which is then covered with a vacuum can pumped down with an Edwards TS-75 turbomolecular pump.

(a)



(b)

FIGURE 1: (a) The Iron Pnictide Crystal sample (~2mm across) was mounted on a copper platform. Soft point contacts were made using nm-sized gold wire and silver paint (white dots centered on iron pnictide crystal). (b) The sample holder was thermally anchored to the second stage of a Janis Cryocooler.

At base temperature, a current bias was provided by a ramped waveform generator and the voltage response and conductance were measured through two Stanford SR830 low-noise lock-in amplifiers to reduce external noise and produce high resolution measurements. A temperature series of conductance as a function of voltage was collected through a data acquisition device (DAQ) and controlled through Labview and analyzed using Python.

RESULTS AND DISCUSSION

Using the four-wire approach, the resistance of the under-doped iron pnictide $Ba_{(1-x)}K_{(x)}Fe_2As_2$ where x = 0.33, was measured and found to have a superconducting critical temperature of 38 Kelvin. This can be observed in Figure 2, where there is a dramatic change in the magnitude and sharpness of the conductance curve dI/dV vs V. For temperatures at and below T_c = 38 Kelvin, there is marked enhancement of conductance in the form of a peak while below Tc, the signal becomes rounded and progressively reduced. Furthermore, a temperature series of the conductance measurements from 2.0 – 52.0 Kelvin show features in the form of a broad shoulder and a peak. These features – enhancements in conductance are typically interpreted to correspond to superconducting energy gaps, in this case, a small gap Δ_1 symmetric about 2-4 meV and a large gap Δ_2 symmetric about 9-11 meV (See Figure 2). These two predominant features for $Ba_{0.67}K_{0.33}Fe_2As_2$ are consistent with two flavors of tunneling along the ab plane. The insets of Figure 2 show that the peaks move with temperature, which is characteristic of the temperature dependence of conventional superconducting energy gaps.[1] Looking at the literature, these results are very similar to data from *P. Samuely et al.*[7] that report two energy gaps with similar values for a nominally similar composition of $Ba_{0.55}K_{0.45}Fe_2As_2$ at temperatures below its T_c of 30K. In 2008, *Gonnelli et al.*[9] also obtained two-gap spectra on the $LaFeAsO_{1-x}F_x$ polycrystals that compare remarkably well with these values. In addition, two-gap spectra were also observed in under-doped $Ba_{(1-x)}K_{(x)}Fe_2As_2$ using Raman scattering.[9] On the other hand, there have been observations of only single energy gap features, using STM, in iron pnictides that are doped with cobalt[10] and potassium.[11]

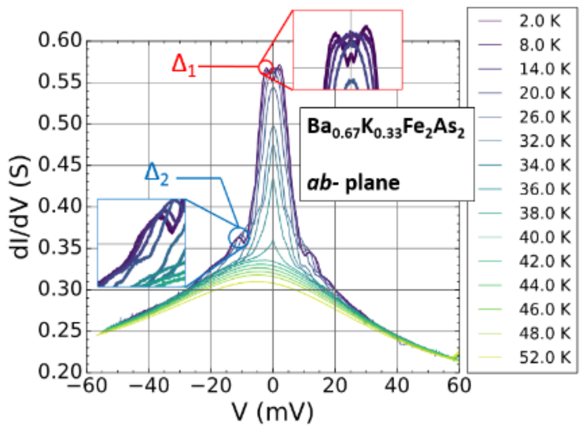


FIGURE 2: Data for Differential Conductance dI/dV vs Voltage V of iron pnictide $Ba_{(1-x)}K_{(x)}Fe_2As_2$ where x = 0.33 (under-doped regime) and T = 2.0 K to 52.0 K. Two gap values Δ_1 at 2-4 meV and Δ_2 at 9-11 meV are suggested by the shoulders and bumps on the conductance curves. Similar features have been observed in the literature for other superconductors. The two insets show that within each gap, peaks move with temperature, which is characteristic of conventional superconducting energy gaps.

Conclusion and Future Work

We have performed PCS measurements on under-doped iron pnictide $Ba_{0.67}K_{0.33}Fe_2As_2$ and observed two temperature-dependent features that correspond to gap values: a small Δ_1 = 2-4 meV, and a large gap, Δ_2 = 9-11 meV. For future work, we will plot the normalized superconducting energy gap values $\Delta(T)/\Delta(0)$, where $\Delta(0)$ is the gap at zero temperature, that should decrease with T/T_c, and compare with results of other research. We plan to determine the common underlying factor shared by various superconductors studied by different groups that exhibit these similar two-gap structures. Towards this, we plan to measure more doping regimes of potassium-based iron pnictide and other doping types of iron pnictides such as phosphorus and cobalt.

Acknowledgements

We acknowledge Joseph Lambert (National Radio Astronomy Observatory) for help with setting our experimental apparatus. We gratefully acknowledge our collaborators from Rice University, Pencheng Dai, Chengling Zhang, Yu Song, and Guotai Tai, for providing us with high-quality iron pnictide single-crystals. Finally, we acknowledge support from the National Science Foundation Grant DMR-1555775 and the Charles Kaufman Foundation.

References

1. X.Zhang, Y.-S. Oh, Y. Liu, L. Yan, S.R. Saha, N.P. Butch, K. Kirshenbaum, K.H. Kim, J. Paglione, R.L. Greene, and I.Takeuchi, Physical Review B **82**, 020515 (2010)
2. P. Szabó, Z. Pribulová, G. Pristáš, S. L. Bud'ko, P. C. Canfield, and P. Samuely, Physical Review B **79**, 012503 (2009).
3. W.R. Clarke, M.Y. Simmons, and C.-T. Liang, Comprehensive Semiconductor Science and Technology **1**, 279, (2011).
4. W-C. Lee, W.K. Park, H.Z. Arham, L. H. Greene, and P. Phillips, Proceedings of the National Academy of Sciences of the United States of America **112**(3), 651-656 (2015).

5. B. Shen, H. Yang, Z-S. Wang, F. Han, B. Zeng, L. Shan, C. Ren, and H.-H. Wen, Physical Review B **84**, 184512 (2011).
6. R. Richardson, *Experimental Techniques In Condensed Matter Physics At Low Temperatures* (CRC Press, 2019).
7. P. Samuely, Z. Pribulová, P. Szabó, G. Pristáš, S. L. Bud'ko, P. C. Canfield, Physica C, **469**(9-12), 507 (2009).
8. S.-F. Wu, P. Richard, H. Ding, H.-H. Wen, G. Tan, M. Wang, C. Zhang, P. Dai, and G. Blumberg, Physical Review B **95**, 085125 (2017).
9. R. S. Gonnelli, D. Daghero, M. Tortello, G. A. Ummarino, V. A. Stepanov, J. S. Kim, and R. K. Kremer, "Coexistence of two order parameters and a pseudogaplike feature in the iron-based superconductor LaFeAsO_(1-x)F_x," arXiv:0807.3149 (unpublished).
10. Yi Yin, M. Zech, T. L. Williams, X. F. Wang, G. Wu, X. H. Chen, and J. E. Hoffman, Physical Review Letters **102**, 097002 (2009).
11. M. C. Boyer, Kamalesh Chatterjee, W. D. Wise, G. F. Chen, J. L. Luo, N. L. Wang, E. W. Hudson, " Scanning tunneling microscopy of the 32 K superconductor (Sr1-xKx)Fe2As2," arXiv:0806.4400 (unpublished).