Probing the Gap Structure of KFe_2As_2

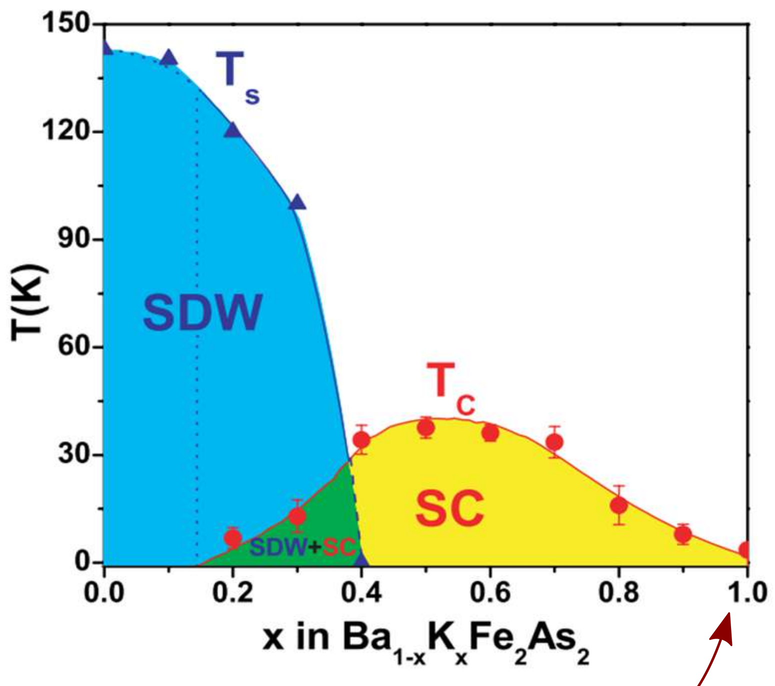
Centre for Doctoral Training in Condensed Matter Physics

University of BRISTOL

J. A. Wilcox[1], L. Malone[1], F. Hardy[2], C. Puztke[1], T. Wolf[2], P. Adelmann[2], C. Meingast[2] and A. Carrington[1]

[1]H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom
[2]Institute for Solid State Physics, Karlsruhe Institute of Technology, P.O. Box 3640, 76021 Karlsruhe, Germany

The Gap Structure of $(Ba_{1-x},K_x)Fe_2As_2$



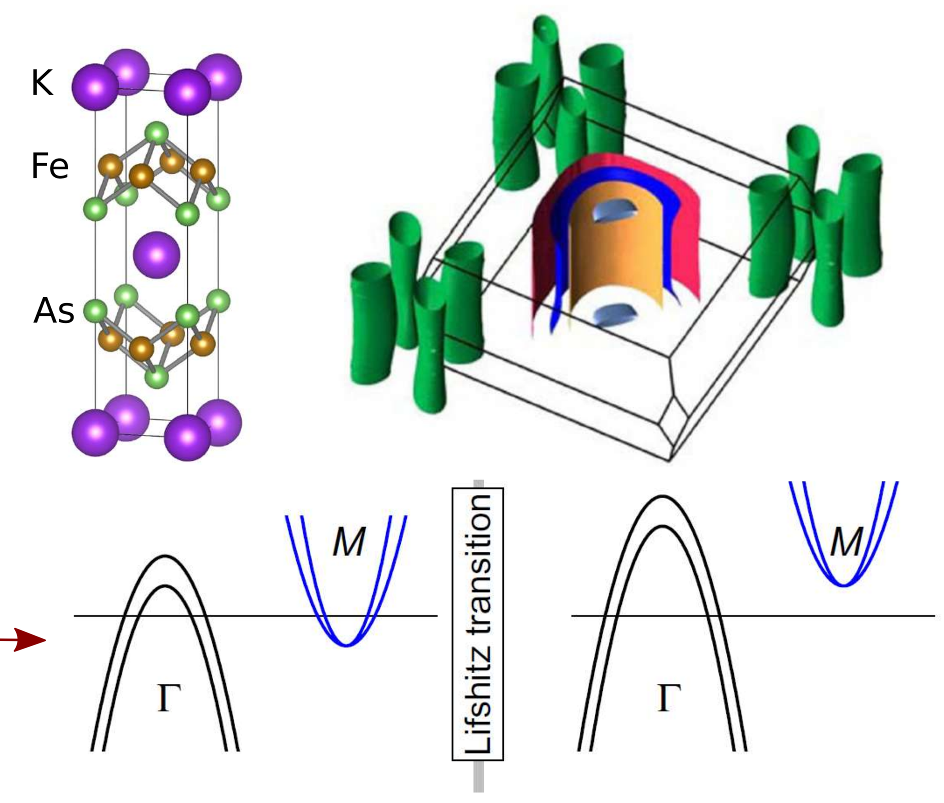
From Chen et al. [1]

KFe_2As_2 is the end-member (**x=1**) of the $(Ba_{1-x},K_x)Fe_2As_2$ series of Fe-based superconductors. It has $T_C \approx 3.5$ K, and a **tetragonal crystal structure**.

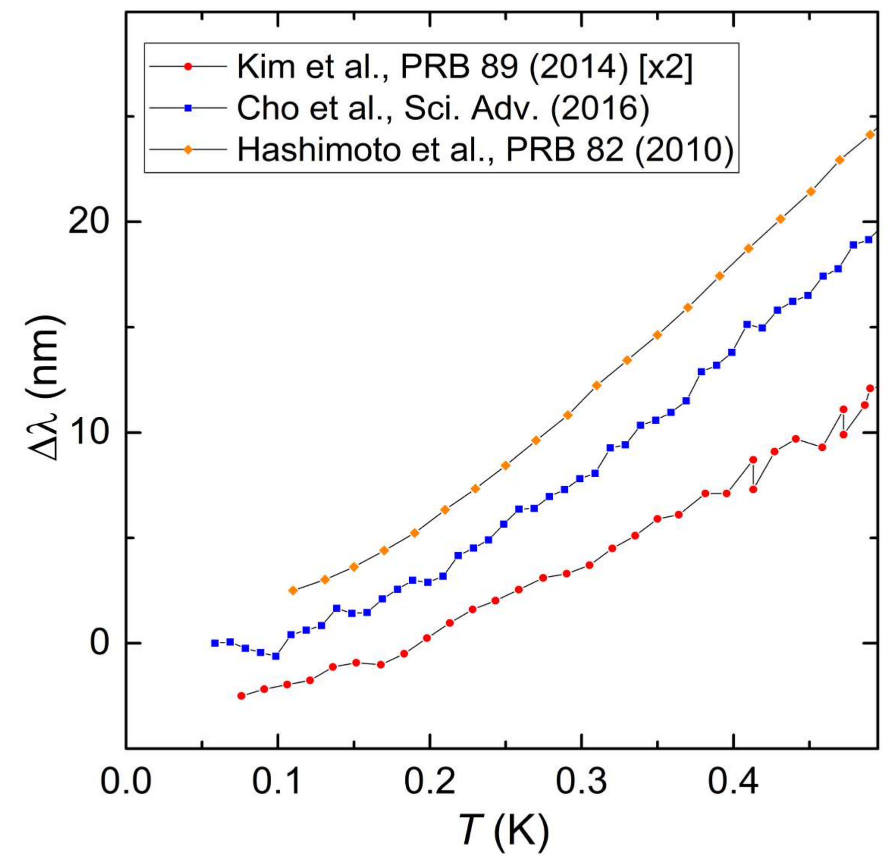
The series is a multi-band system and generally considered to be fully gapped at optimal doping, with s± pairing [2], as indicated by a number of measurements including magnetic (London) penetration depth [3] and thermal conductivity. [4]

A number of **Lifshitz transitions** occur at x ≈ 0.7 - 0.9, such that the electron pockets at the corner of the Brillouin zone are completely lifted and replaced by hole pockets.

There is less consensus on the pairing symmetry in the overdoped region and, specifically, in KFe_2As_2. A number of measurements have been performed that indicate the presence of nodes (or at least, a high degree of anisotropy) in the gap structure - such as heat capacity [5], **penetration depth** [2,6,7] and thermal conductivity. [8,9]



From Cho et al. [2]



It has been debated whether these nodes are *accidental*, due to anisotropy in the pairing interaction, or if they are symmetry imposed, such as in the case of $d_{x^2-y^2}$ pairing in $YBa_2Cu_3O_{7-x}$.

Determining the symmetry of the order parameter in KFe_2As_2 is an important factor in determining a theory to describe the pairing interaction in the series.

The Magnetic Penetration Depth in KFe_2As_2

Some Fe-based compounds known to degrade when exposed to air. In previous measurements, it is unclear what precautions were taken to avoid this.

We investigated how **deliberately exposing samples to air** affects the superconductivity through measurement of the temperature dependence of the magnetic penetration depth, Δλ(T) - a **probe of low energy excitations**.

Samples of **single crystal** KFe_2As_2 were prepared from a parent sample, kept under argon atmosphere. The samples were encapsulated in grease and all six sides were cleaved to expose fresh surfaces.

Measurements of Δλ(T) were made using the tunnel diode oscillator (TDO) technique on a $^3He/^4He$ dilution refrigerator with a base temperature of < 50 mK.

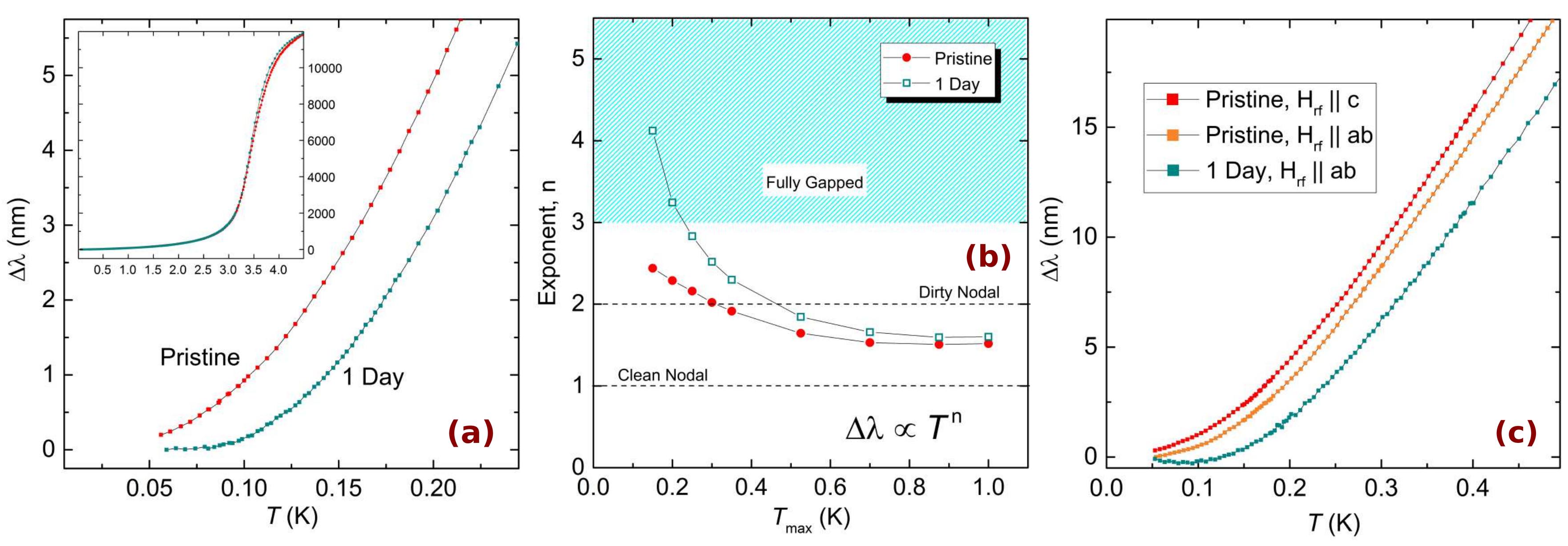
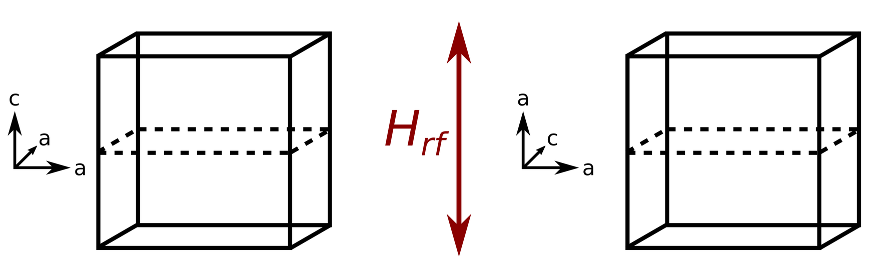


Fig. (a) shows Δλ(T) for a freshly cut sample ('pristine') and the same sample after exposing to air for one day. T_C is largely unaffected (inset), but at low T the pristine sample shows a **strong T dependence down to 50 mK**, whereas the aged sample appears to **saturate at ~ 100 mK**, suggesting the formation of a small gap.

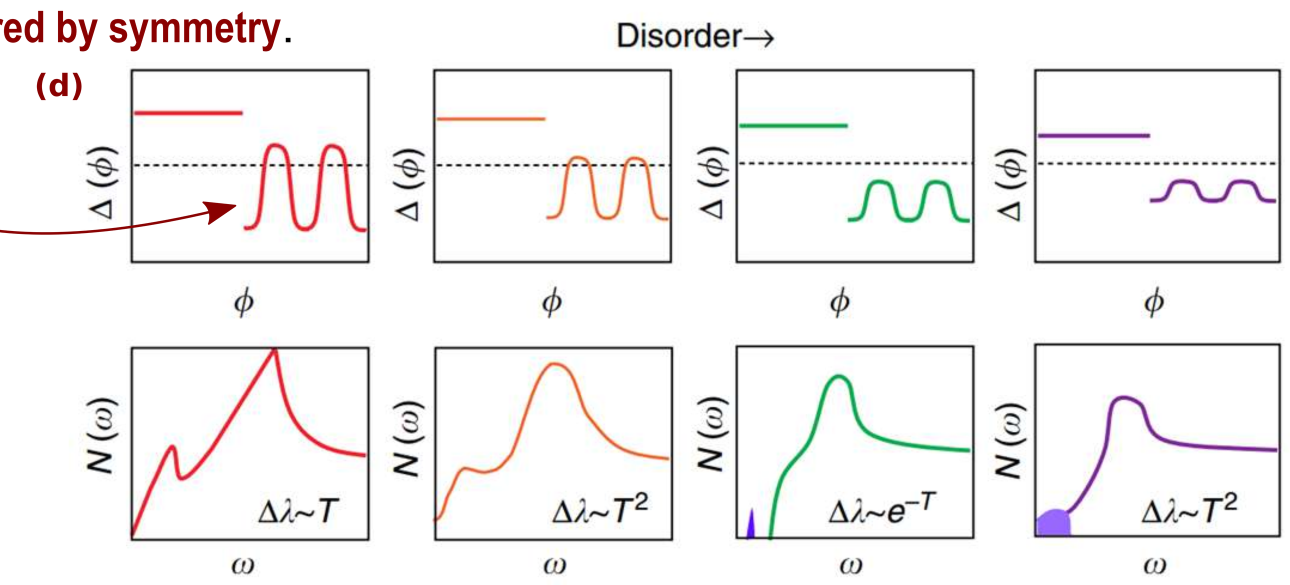
Fitting the data with a power law of the form $\Delta\lambda(T) \propto T^n$ and varying the upper limit (T_{max}) of the fit can provide useful insight, as shown in **Fig. (b)**. The pristine sample yields an exponent of ~ 1.5 to a bit more than 2, suggesting possibly a very small gap or that the pristine sample is not completely clean.

The aged sample shows significant change with a diverging exponent, a sign of **exponential temperature dependence** and a full, though possibly anisotropic, gap.

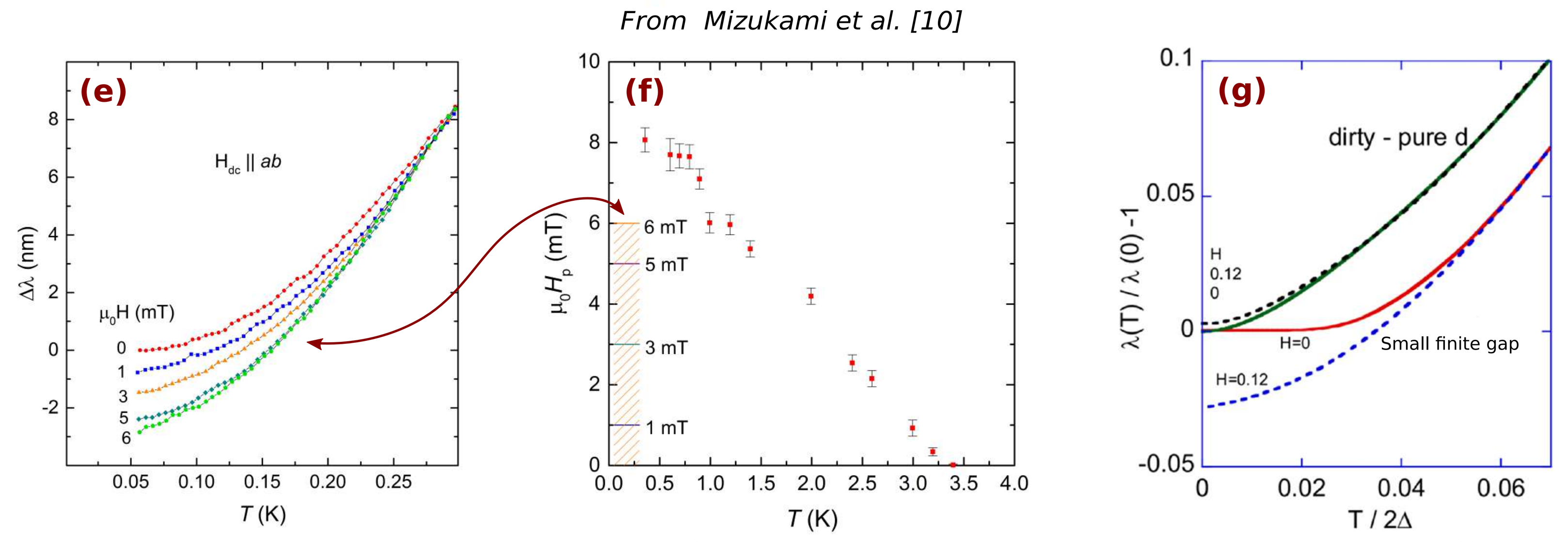
Fig. (c) shows Δλ(T) for a second sample, oriented with the RF field parallel and perpendicular to the *ab* plane. The results show nominally the same behaviour as the first sample.



A disorder-induced change in the gap structure has been shown to occur in another Fe-based compound, $BaFe_2(As_{1-x},P_x)_2$, also believed to have **s± pairing**. [10] This is shown schematically in **Fig. d** for two gaps of opposite sign, one of which has **accidental nodes**, which are ultimately lifted by the disorder This scenario is fundamentally different to a **d-wave** order parameter, where the nodes cannot be lifted by disorder but are **required by symmetry**.



From Mizukami et al. [10]



It is possible to probe the symmetry of the gap via the non-linear Meissner effect, by applying a **small dc field** to the sample while measuring Δλ(T), as shown in **Fig (e)**. This was done with the field **parallel to the ab-plane** to reduce the demagnetising factor. The field of first flux penetration was measured in this orientation to ensure the sample was in the Meissner state, shown in **Fig (f)**.

Comparing to calculation (**Fig. (g)**), it can be seen that the field has the effect of making the penetration more temperature dependent, as is the case for a small but finite gap, by shifting the energies of some pairs closer to zero. In the case of a pure clean or dirty d-wave, the penetration depth would become less temperature dependent as it excites pairs at the nodes.

In conclusion, the temperature and field dependent data of the magnetic penetration depth strongly suggests that the pairing symmetry of KFe_2As_2 is **not pure d-wave**, but could be interpreted as an extended s-wave scenario, such as s± as in the rest of the series, or as a complex admixture of s- and d-wave.

[1] Chen, H., et al., Europhys. Lett. 85, 17006 (2009)
[2] Cho, K., et al., Sci. Adv., 2:e1600807 (2016)
[3] Kim, H., et al., Phys. Rev. B 90, 014517 (2014)
[4] Luo, X. G., et al., Phys. Rev. B 80, 140503 (2009)
[5] Hardy, F., et al., J. Phys. Soc. Jpn. 83, 014711 (2014)
[6] Hashimoto, K., et al., Phys. Rev. B 82, 014526 (2010)
[7] Kim, H., et al., Phys. Rev. B 89, 174519 (2014)
[8] Dong, J. K., et al., PRL 104, 087005 (2010)
[9] Reid, J.-P., et al., PRL 109, 087001 (2012)
[10] Mizukami, Y., et al., Nat. Comms., 5:5657 (2014)

EPSRC Engineering and Physical Sciences Research Council