The Absolute Value of The Magnetic Penetration Depth in the Meissner State of YBCO

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Introduction

One fundamental quantity in the characterization of superconductors is the London penetration depth λ[1], which is closely related to superfluid density ($\rho_s \approx \lambda^2(0)/\lambda^2 \propto n_s/m^*$). The absolute value of λ and its variation as a function of temperature, magnetic field, crystal orientation, doping are important parameters in testing theories of novel superconductivity. For example, the linear variation of $1/\lambda^2$ with respect to temperature was instrumental in confirming the *d*-wave nature of the pairing in $Yba_2Cu_3O_x$[2,3] Also, early μSR studies of the vortex phase in polycrystalline samples found a linear correlation between $1/\lambda^2$ and T_c in the underdoped region[4-6]. The resulting Uemura plot has helped bring an enhanced understanding of high-T_c superconductivity[6]. However, measurements of λ on single crystals of $Yba_2Cu_3O_x$ both in the Meissner state[7, broun-2005}] and vortex phases[7] have found a $1/\lambda^2$ being sublinear in T_c. Departure from Uemura scaling and the decline of the slope as the T_c=0 quantum critical point is approached can be understood in terms of a three-dimensional (3D) quantum critical point (QCP) model[9]. Scaling of T_c with $n_s(0)$ in the underdoped region may also be due to quantum fluctuations near a 2D quantum critical point[10].

Measurements of the absolute value of λ are challenging and all methods have systematic uncertainties. As an example, in a bulk measurement, the assumption of an exponential decay of the field in the Meissner state is only valid in the local London limit of a perfect surface [1]. Also, Non-exponential decay of field may result from depth dependent change in order parameter symmetry. All conventional bulk measurements suffers from this added uncertainty where field profile is assumed and not directly measured. The most unambiguous measurement is to measure the magnetic field profile and thereby extracting λ in the Meissner state using a low energy beam of muons. A novel background suppression method has been developed at PSI to study high purity small crystals via low energy μSR method. The procedure to measure of λ in $Yba_2Cu_3O_x$ can easily be extended to other exotic superconductors.

Theory and Discussions

• Muons in sample experience a magnetic field in Meissner state according to London equation

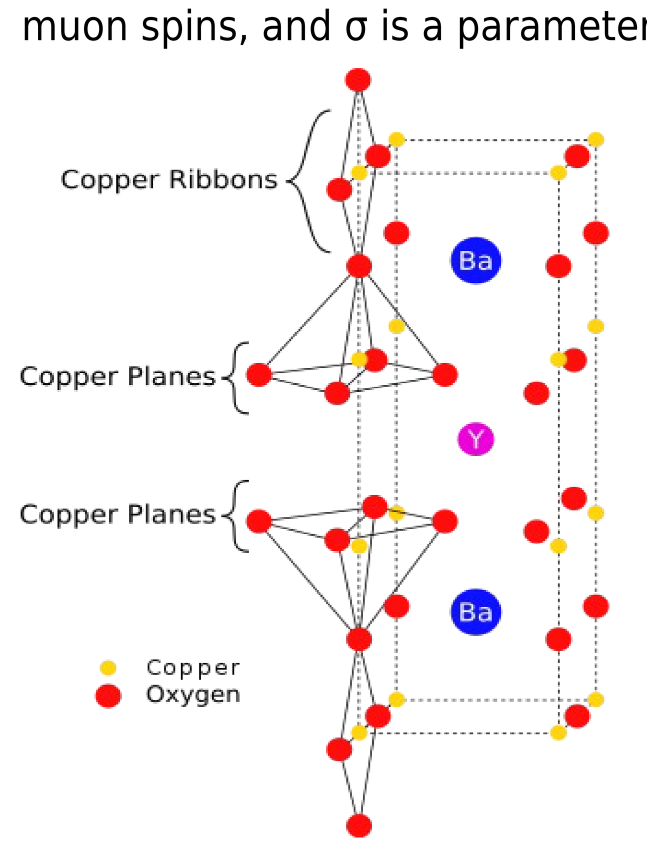
$$B(z) = \begin{cases} B_0 \exp[-(z-d)/\lambda_{a,b}] & z \geq d \\ B_0 & z < d \end{cases}$$

Where B_0 is the applied field, $\lambda_{a,b}$ is the magnetic penetration depth in the a/b direction

• Theoretical muon precession signal at each energy is generated by taking signal at a particular depth *z* and then averaging over the calculated stopping distribution ρ(z), according to equation

$$\mathcal{A}(t) = A\ \exp\left[-\sigma^2 t^2/2\right] \times \int \rho(z) \cos\left[\gamma_\mu B(z) t + \phi\right]\ dz$$

where γ_μ is the muon gyromagnetic ratio, A is the initial amplitude of precession, φ is the initial phase of the incoming muon spins, and σ is a parameter which reflects any inhomogeneous broadening



YBCO has a layered perovskite structure. Primarily the CuO_2 planes are thought to be responsible for superconductivity. Parallel to these planes are CuO chains/ribbons. Fully oxygenated $YBa_2Cu_3O_7$ is stoichiometric whereas $YBa_2Cu_3O_{7-x}$ is non-stoichiometric and all properties strongly depend on the oxygen content *x*. Penetration depth anisotropy measurements indicate that chains become superconducting at the same temperature as CuO_2 planes[11]. Due to differences in band structures between chains and planes[12], one naturalexplanation for the same transition temperature is proximity effect[13] where electron hoppingbetween chains and planes contribute to superfluidity along chain direction.

$Yba_2Cu_3O_{6.92}$ Results

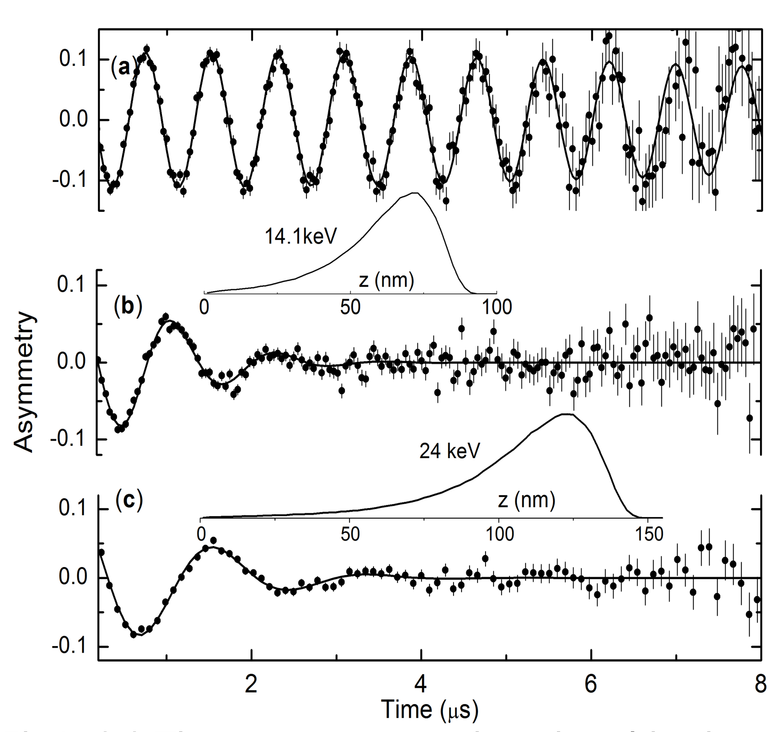
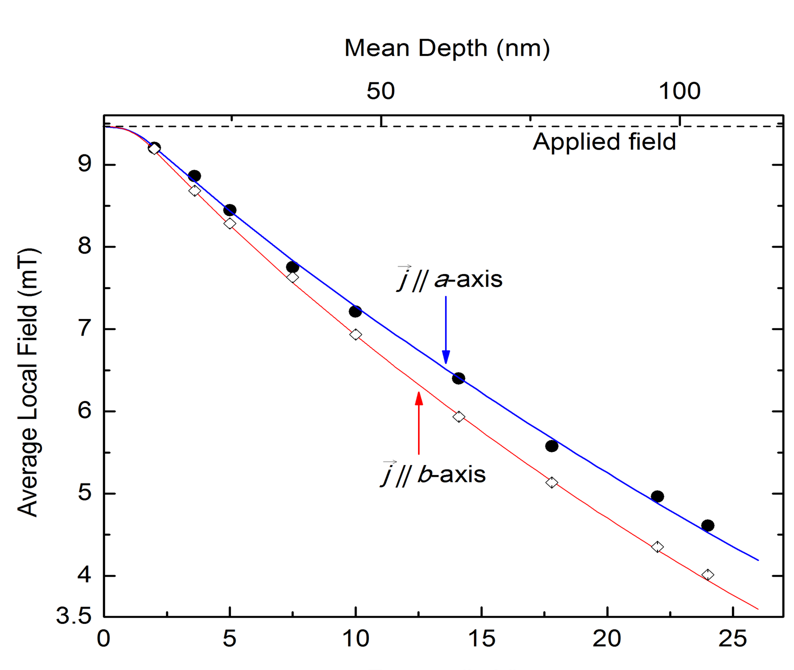
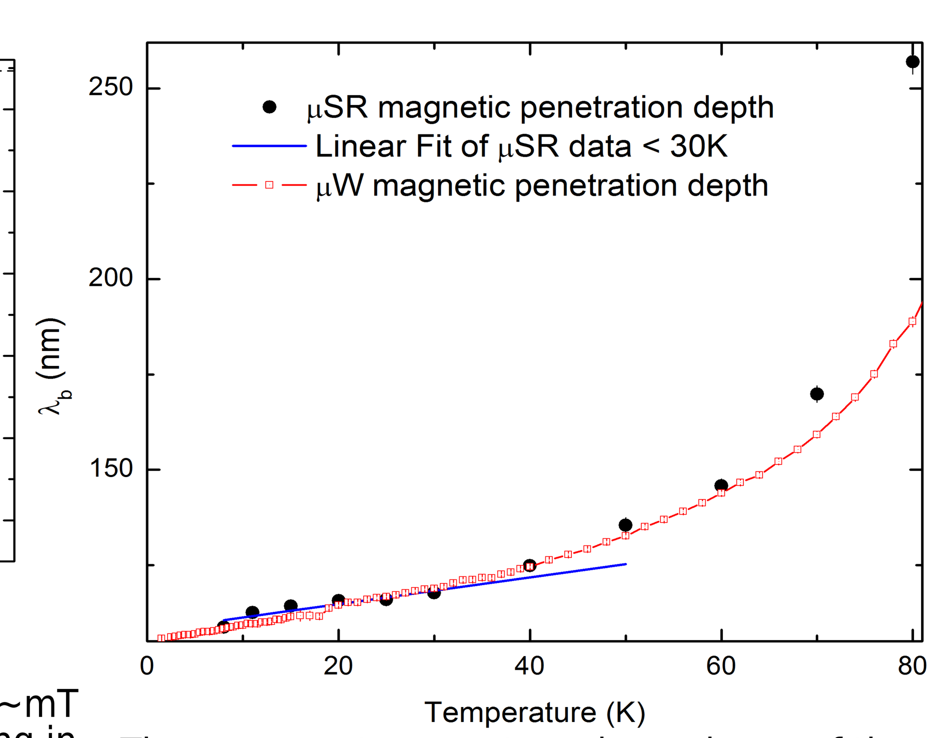


Fig1 (a) The muon precession signal in the normal state of $Yba_2Cu_3O_{6.92}$ at 110 K in an external field of 9.46 mT applied parallel to the a direction. The mean implantation energy E = 14.1 keV which corresponds to a mean implantation depth of 62.8 nm. (b) The same conditions as (a) except in the superconducting state at T=89 K. The inset shows the calculated stopping distribution. (c) The same conditions as (b) except the energy of implantation is increased to 24 keV.

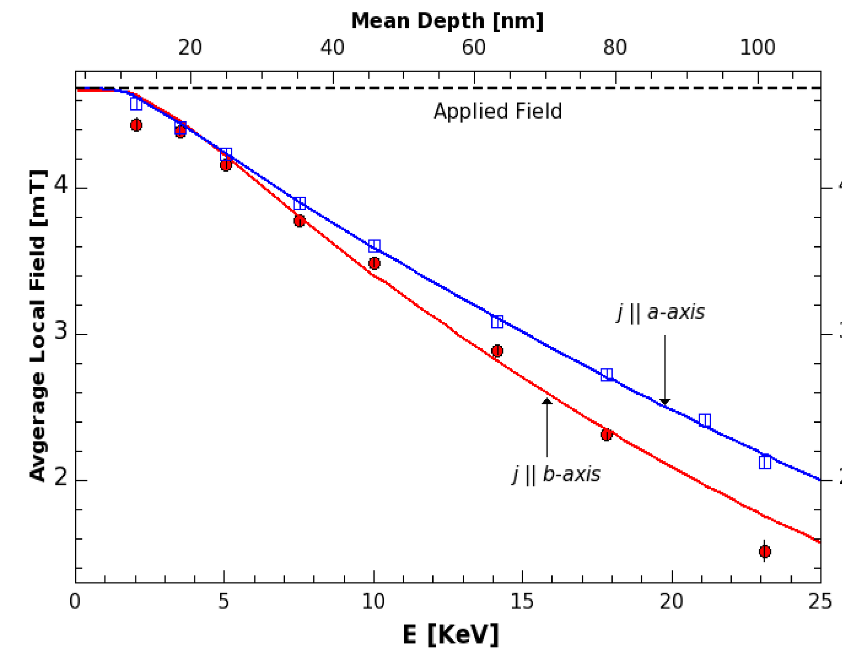


The average magnetic field versus mean stopping depth in an applied field of 9.46~mT such that the shielding currents are flowing in the *a* direction, **j**||*a* (open squares) and *b* direction **j**||b (filled circles). The curves are the average fields generated from a global fit of all the spectra at {8~K} taken at all energies and for both orientations. The common parameters are λ_a, λ_b and *d*. The individual points are from a fit to the same model but at a single depth. The differences between the data points and curves reflect how closely the data at a single energy agrees with the global fit.

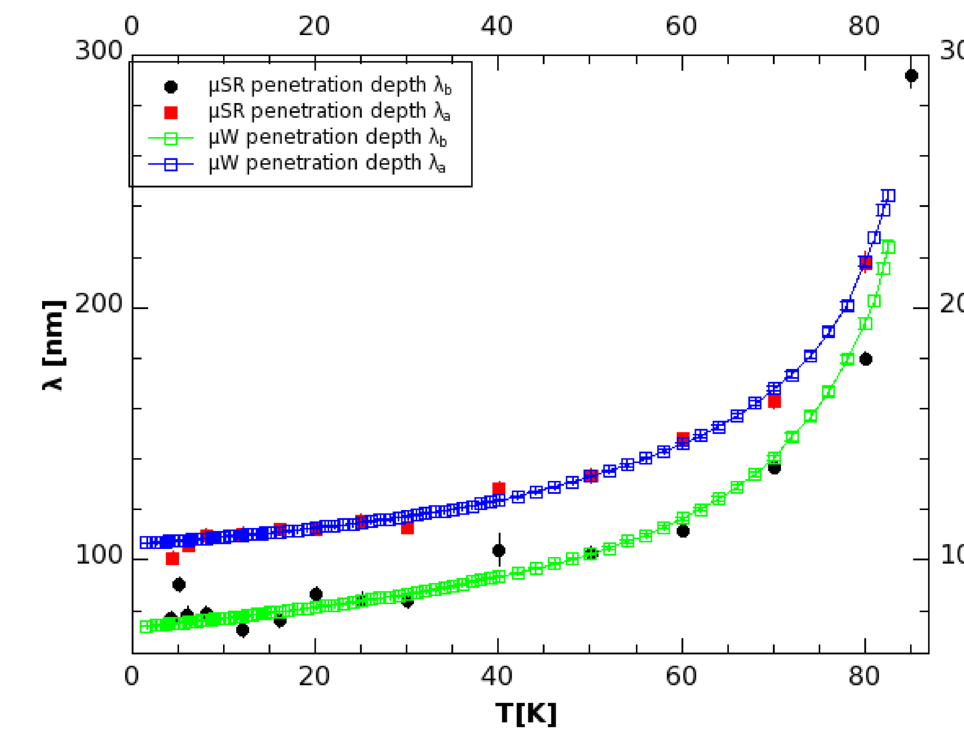


The common temperature dependence of the London penetration depth in an external field of 9.46 mT applied parallel to the *a* axis so that the shielding currents are in the *b* direction and parallel to the CuO chains. Penetration depths are calculated via μSR and μW. Both methods are in excellent agreement in low temperatures, however, they diverge in high temperature possibly because of vortex penetration in μSR method at high field & temperature.

$Yba_2Cu_3O_{6.998}$ Results



The average magnetic field versus mean stopping depth in an applied field of 4.68~mT such that the shielding currents are flowing in the *a* direction, **j**|| *a* (open squares) and *b* direction **j**||b (filled circles). The curves are the average fields generated from a global fit of all the spectra at {5~K} taken at all energies and for both orientations. The common parameters are λ_a, λ_b and *d*. The individual points are from a fit to the same model but at a single depth. The differences between the data points and curves reflect how closely the data at a single energy agrees with the global fit.



The common temperature dependence of the London penetration depth in an external field of ~4.68 mT applied parallel to the *a* axis so that the shielding currents are in the *b* direction and parallel to the CuO chains. Penetration depths are calculated via μSR and μW. Both methods' results are in excellent agreement in contrast to the ~10mT measurement in $Yba_2Cu_3O_{6.92}$

Summary Of Results

λ_a (nm)	λ_b (nm)	λ_{ab} (nm)	λ_a/λ_b	Comment
$126\pm0.8\pm3$	$105.5\pm0.7\pm3$	$115.3\pm0.5\pm3$	1.19 ± 0.01	$YBa_2Cu_3O_{6.92}$
$107.9\pm2.1\pm3$	$85.6\pm0.5\pm3$	$96.1\pm1.1\pm3$	1.26 ± 0.02	$YBa_2Cu_3O_{6.998}$
		118 ± 0.4		conventional μSR in vortex state
		146 ± 3		low energy μSR in thin film at 20 K
160	100	126.5	1.6	IR reflectivity at 10 K
103 ± 8	80 ± 5	91 ± 7	1.29 ± 0.07	ESR on Ortho-I $YBa_2Cu_3O_{6.995}$
		150 ± 10	1.16 ± 0.02	μSR at 10 K
		138 ± 5	1.18 ± 0.02	SANS at 10 K

Conclusions

The in-plane anisotropy in $Yba_2Cu_3O_{6.92}$, λ_a/λ_b= 1.19 ± 0.01 is considerably less than reported from early IR studies and is close to that found in electron spin resonance studies studies on Gd doped $Yba_2Cu_3O_{6.995}$ and {in early μSR and SANS experiments} on a large detwinned crystal. The in-plane anisotropy in $Yba_2Cu_3O_{6.998}$, λ_a/λ_b= 1.26 ± 0.02, which shows that superfluidity is strongly dependent on oxygen concentration (~44% increase in average superfluid density) of CuO chains.

The field profiles are exponential on the scale of λ but there are deviations close to the surface which are not yet understood. Most importantly we have demonstrated that low-energy μSR can be used to study fundamental properties of small crystals. This will greatly increase the scientific impact of low-energy μSR in the study of exotic superconductors.

Acknowledgements

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References

- [1]C.P. Poole et al, Superconductivity, 2nd ed. (Academic Press)
- [2]W.N. Hardy et al. Phys. Rev. Lett. **70** 1993 3999-4002
- [3] J. E. Sonier et al. Phys. Rev. Lett. **72** 744-747, (1994)
- [4]Y. J. Uemura et al, Phys. Rev. Lett. **62** 2317 (1989)
- [5]Y. J. Uemura et al, Phys. Rev. Lett. **66** 2665 (1991)
- [6]A. J. Drew et al, Phys. Rev. Lett. **101**(9) 087010 (2008)
- [7] J. E. Sonier et al, Phys. Rev. B. **76** 13, (2007)
- [8] D. M. Broun et al, Phys. Rev. Lett. **99** 23, (2007)
- [9] M. Franz et al, Phys. Rev. Lett. **96,** 4, (2006)
- [10] Iulian Hetel et al, Nature Physics, 3, 700-702, (2007)
- [11] Kuan Zhang et al, Phys. Rev. Lett. 73(18):2484-2487, 1994
- [12] S. Grabowski et al, Physica C: Superconductivity, 282-287, 1997