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## MEASUREMENTS OF THE LONDON PENETRATION DEPTH IN YBa<sub>2</sub>Cu<sub>3</sub>O<sub>x</sub> BY MEANS OF MUON SPIN ROTATION ( $\mu$ SR)

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**Abstract:** Muon spin rotation ( $\mu$ SR) measurements on a high-quality sintered YBa<sub>2</sub>Cu<sub>3</sub>O<sub>x</sub> sample [ $x = 6.970(1)$ ] were performed in order to get an accurate value of the London penetration depth  $\lambda$ . The results are consistent with the two-fluid model and yield the effective penetration depth  $\lambda(0) = 1550(100)\text{\AA}$ .

### 1. INTRODUCTION

An accurate measurement of the London penetration depth  $\lambda$  is of great importance to understand more about the mechanisms of high- $T_c$  superconductivity. For s-wave superconductors, the temperature dependence of  $\lambda$  is generally given by the two-fluid model:  $\lambda(T) = \lambda(0)[1 - (T/T_c)^4]^{-1/2}$ . The  $\mu$ SR technique provides a sensitive probe (the muon) of the local magnetic field distribution  $p(B)$  in a superconductor. Assuming that a perfect triangular vortex lattice is formed in the sample, it is possible to calculate the magnetic penetration depth  $\lambda$  by means of

$$\lambda^4 = 0.00371 \Phi_0^2 / \langle \Delta B^2 \rangle, \quad (1)$$

where  $\langle \Delta B^2 \rangle$  is the second moment of  $p(B)$  [1]. Note that this equation is only valid in high magnetic fields, where  $\langle \Delta B^2 \rangle$  is independent of the applied field.

### 2. EXPERIMENTS AND RESULTS

$\mu$ SR experiments were performed on a high-quality sintered sample of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>x</sub> [ $x = 6.970(1)$ ] at the Paul Scherrer Institut (PSI) using low momentum muons (29 MeV/c). Magnetization measurements of the sample exhibit a very sharp transition at  $T_c = 89.5(5)$  K with a width of 8 K (10 - 90%) and a Meissner fraction of approximately 60% in a field of 1.42 mT. To keep the background as low as possible, the sample with a diameter of 14.5 mm and a thickness of 3.5 mm was mounted on an Fe<sub>2</sub>O<sub>3</sub> target holder, using a beam spot of only 4 mm in diameter. With this experimental setup, about 95% of all the muons stopped in the superconductor. To make sure that the applied field was high enough to use Eq. (1), a field scan between 5 mT and 350 mT was performed (Fig. 1). Every single data point of this scan was obtained after field-cooling (FC) the sample to 10 K. The  $\mu$ SR time spectra

were analysed by assuming a Gaussian relaxation function  $\exp(-\sigma^2 t^2)$ , which corresponds to a Gaussian distribution  $p(B)$ . The second moment of  $p(B)$  can be determined by means of the equation  $\langle \Delta B^2 \rangle = 2\sigma^2/\gamma_\mu^2$ , where  $\gamma_\mu$  is the gyromagnetic ratio of the muon. As shown in Fig. 1, the depolarization rate  $\sigma$  is constant above 150 mT, indicating that flux pinning effects are negligible at large fields. As a consequence, a field-cooled temperature scan was performed in a magnetic field of 350 mT.

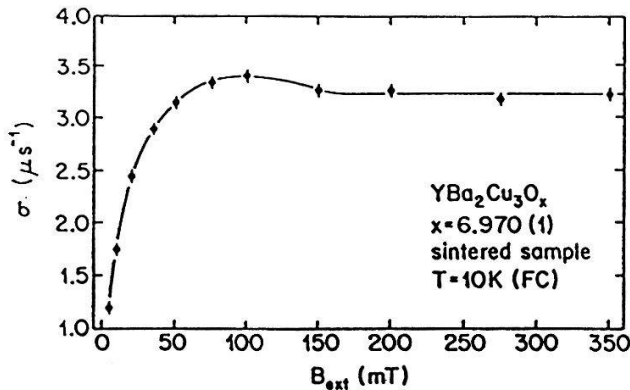


Figure 1: Depolarization rate  $\sigma$  as a function of the external field  $B_{ext}$  at 10 K (FC). The line is a guide to the eye.

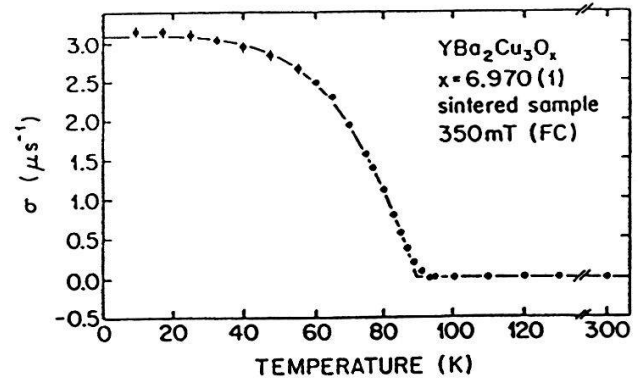


Figure 2: Depolarization rate  $\sigma$  as a function of temperature in a field of 350 mT (FC). The line is a fit to the data using the temperature dependence given by the two-fluid model.

The temperature dependence of  $\lambda$  for sintered YBa<sub>2</sub>Cu<sub>3</sub>O<sub>x</sub> is well described by the conventional two-fluid model, as shown by the solid line in Fig. 2. A complete analysis of this data (with a model-independent determination of  $\langle \Delta B^2 \rangle$  [1]) yields an effective penetration depth  $\lambda(0) = 1550(100)$  Å, where the estimated error is mainly due to systematic effects. The value of  $\lambda$  for a sintered sample is an average over all orientations. However, Barford et al. [2] have shown, that  $\lambda_{ab}$  can be extracted from this average, if the fraction  $\lambda_c/\lambda_{ab}$  is of the order of 5 or larger. In this case, the average value  $\lambda$  is 1.23 times bigger than  $\lambda_{ab}$ .  $\mu$ SR-investigations on a *c*-axis-oriented polycrystal [3], torque [4] and dc-magnetization [5] measurements indicate that the anisotropy is of the right order of magnitude for YBa<sub>2</sub>Cu<sub>3</sub>O<sub>x</sub>. Thus, the calculated value of  $\lambda_{ab}$  is 1300(100) Å.

In conclusion, measurements of the local field distribution in a high-quality ceramic sample have been performed. The temperature dependence of the depolarization rate  $\sigma \propto \lambda^{-2}$  was found to be in excellent agreement with the behavior observed for an ordinary s-wave superconductor, yielding an effective penetration depth  $\lambda = 1550(100)$  Å.

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