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## Effects of Vortex Pinning on the Temperature Dependence of the Magnetic Field Distributions in Superconductors

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### Abstract

The temperature and applied-magnetic-field dependence of the second moments of the magnetic-field distributions as measured by  $\mu$ SR for YBCO and BSCCO have been fit for four different intrinsic-field-distribution models (d-wave, 2-fluid, empirical, and BCS). It is found that if a pinning potential becomes important at about 20 K, all of the models can fit the data reasonably well. The fits and the associated fitting parameters are presented.

**Keywords:** superconductivity, vortices, pinning, muon spin rotation

**PACS:** 74.25.Ha, 74.72.Gh

### 1. Introduction

The pinning of vortices in superconductors can lead to either broadening or narrowing of the apparent field distribution as was pointed out by Brandt[1]. The extra degrees of freedom associated with this pinning allow one to obtain good fits for a variety of underlying field distributions. We present here the results of data analysis which includes the effect of pinning.

### 2. Data Analysis Techniques

Data were taken at TRIUMF on single crystals of  $YBa_2Cu_3O_{7-\delta}$  (YBCO) and  $Ba_2Sr_2CaCu_2O_8$  (BSCCO). We fit in the time domain using a heterodyning technique and then obtain field distribution second moments,  $\sigma^2$ . For YBCO, we used a London field distribution convoluted with a gaussian distribution and for BSCCO, an asymmetric back-to-back gaussian field distribution. For YBCO we added the London  $\sigma_L^2$  and the convolution  $\sigma_M^2$ , and then subtracted the background  $\sigma_B^2$ . For BSCCO the background  $\sigma_B^2$  was subtracted from back-to-back  $\sigma_{bb}^2$ . For the two-fluid model:

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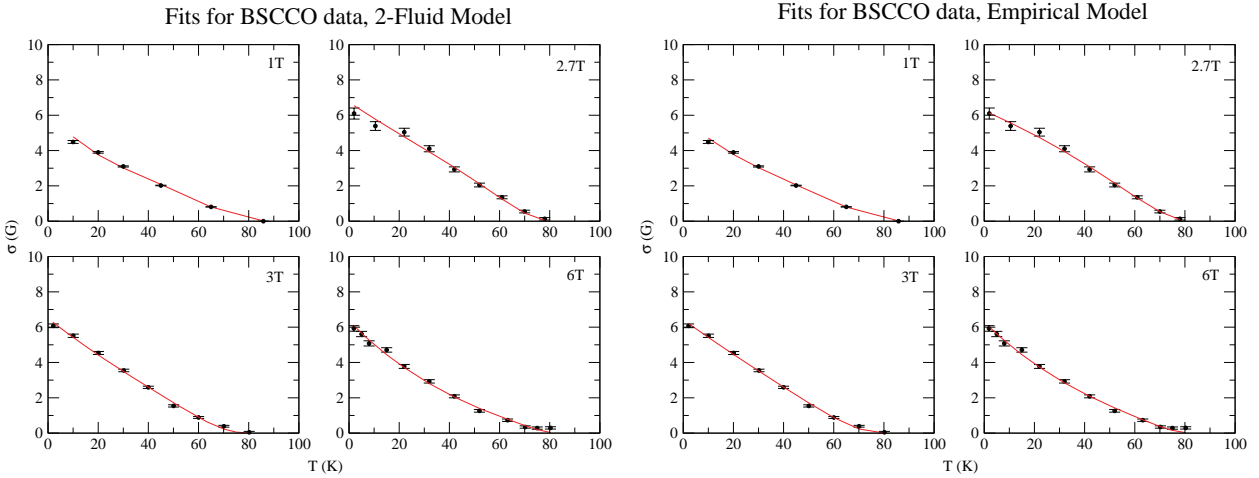


Figure 1: Fits for the 2-Fluid and Empirical Models for BSCCO

$\lambda(0)^2/\lambda(T)^2 = 1 - (T/T_c)^4$ , and for the empirical model:  $\lambda(0)^2/\lambda(T)^2 = 1 - (T/T_c)^2$ . We followed the description in Tinkham's book[2] for the BCS model. For the d-wave we used results of Amin et al.[3] interpolating for our fields. We then fit the temperature dependent  $\sigma$ s with disorder following the general procedure of Fiory et al.[4] So:

$$\sigma^2 \approx \sigma_0^2 [\exp(-26.3u^2/a^2) + 24.8 \langle u_\ell^2 \rangle / a^2 \ln(\tilde{\kappa})] \quad (1)$$

The local displacement of a vortex is modeled by  $u^2 = \langle u_\ell^2 \rangle + \langle u_p^2 \rangle$  and  $\tilde{\kappa}^2 = (\langle u_\ell^2 \rangle + 2\lambda_{ab}^2)/(u^2 + 4\xi_{ab}^2)$ , where  $\epsilon_0$  is an activation energy for vortex depinning from a trap, so that  $u_\ell^2 = u_{\ell 0}^2 [1 - \exp(-\epsilon_0/T)]$  and is the displacement squared of the vortex line away from its regular lattice position.  $\langle u_p^2 \rangle = u_{p1}^2(H) + (T/T_c)u_{p2}^2(H)$  is the displacement squared of an individual vortex pancake (fluxon) from the mean position of the vortex line, see Brandt[1].

### 3. Results

In the figures the solid lines are the fitting function. In Table 1 are typical parameters for BSCCO. These should be compared to those for YBCO in Tables 2 and 3. For YBCO the data for all the values of the field were fit at once with the global parameters the same for all fields and the field dependent parameters allowed to change for each field.

Table 1: Parameters for 6T fit for BSCCO. Length measurements are in  $k\text{\AA}$ ,  $\epsilon_0$  is in degrees Kelvin

Model	$\lambda_0$	$T_c$ (K)	B (T)	$\epsilon_0$	$u_{l0}$	$u_{p1}$	$u_{p2}$	$\xi_0$	$\chi^2$	$\chi_N^2$
Empirical	2.424	92.0	6	129.183	0.0184	1.465	3.455	0.02	33.112	2.729
2-Fluid	2.992	92.0	6	65.141	0.0333	2.292	3.832	0.02	32.424	2.702
BCS	3.203	92.0	6	121.134	0.0326	1.953	4.879	0.02	33.087	2.757
d-Wave	3.381	92.0	6	108.204	0.0366	2.634	5.208	0.02	29.767	2.481

Table 2: Global parameters for YBCO

$\lambda_0(k\text{\AA})$	$\delta\lambda_0$	$T_c(K)$	$\delta T_c$	$\epsilon_0(K)$	$\xi_0(k\text{\AA})$
1.276	.015	90.8	0.5	19.6	0.02913

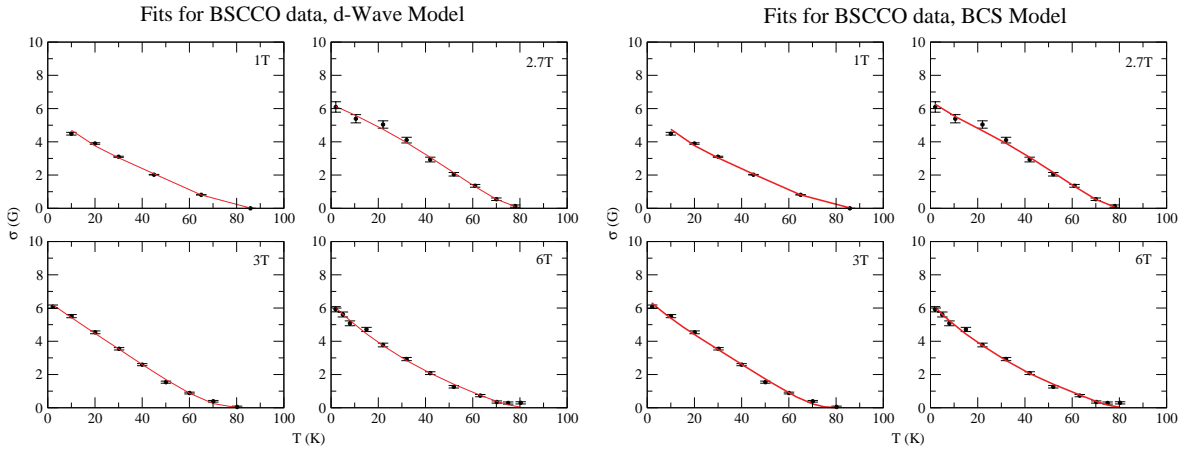


Figure 2: Fits for the d-wave and BCS Models for BSCCO

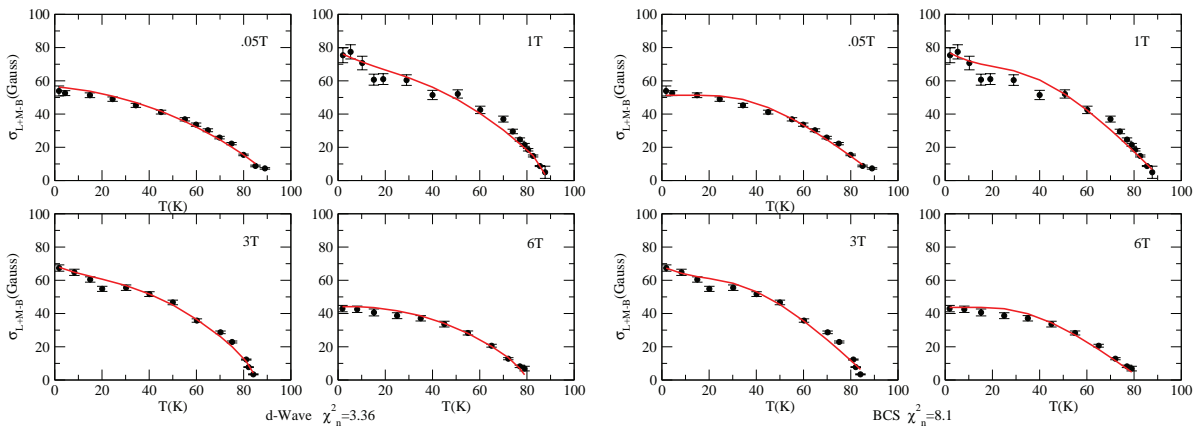


Figure 3: Fits for the d-wave and BCS models for YBCO

#### 4. Conclusions

From the figures one sees the data are reasonably well fit. The BSCCO data require a very large degree of pancake disorder to fit. One could argue that the  $u_p$  values here imply that there is hardly any order at all. Further, there is no quality of fit distinction among the models. The YBCO data have indications of a kink around 20 K. This can be reproduced with a trapping-induced increase in the second moment which sets in at about that temperature. For YBCO the best fit is with the 2-fluid model (see the  $\chi^2$ s on the figures). This is due to the flatness of this  $\sigma$  temperature-dependence near  $T=0$  allowing a better fit to the observed kink. This is consistent with the results previously published for YBCO by Harshman et al. [5] and Fiory et al.[4]. However, more complex pinning behavior has not been considered.

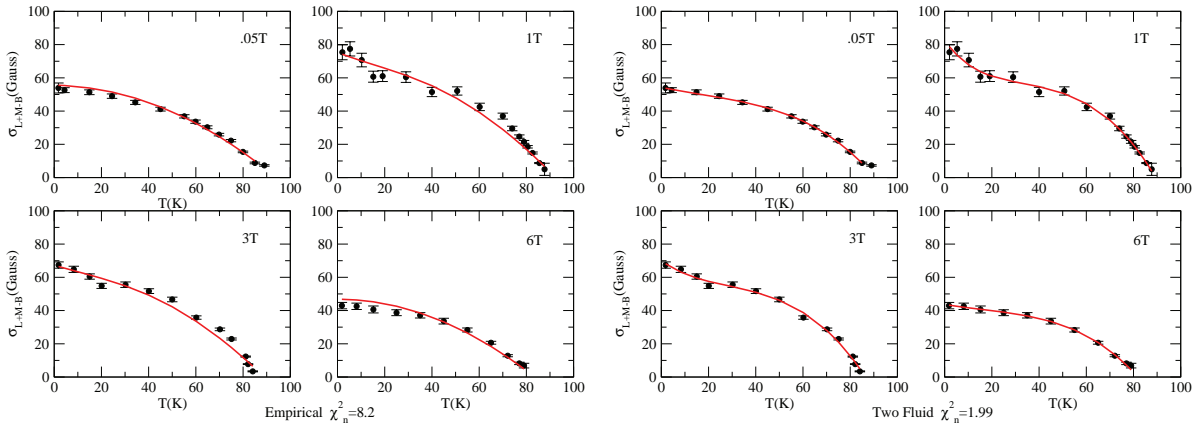


Figure 4: Fits to YBCO with the empirical model and with the two-fluid model.

Table 3: Field-dependent parameters for YBCO using the two-fluid model as an example.

H(T)	$u_\ell(k\text{\AA})$	$\langle u_p^2 \rangle^{1/2} (k\text{\AA})$	$\delta \langle u_p^2 \rangle^{1/2} (k\text{\AA})$
0.05	0.0677	0.4559	0.03
1	0.0523	0.06258	0.012
3	0.02484	0.02456	0.0084
6	0.01966	0.02375	0.0064

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