NODELESS PAIRING STATE IN $YBa_2Cu_3O_7$

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Abstract Muon spin rotation (μ^+SR) results are reported on single-crystal $YBa_2Cu_3O_7$, having a transition temperature of T_c = 91.3 K with $\Delta T_c < 0.5$ K (in zero applied field). Flux motion and de-pinning can mask intrinsic properties such as the true underlying pairing state, and has led to misinterpretations of data. The present data exhibit a non-monotonic behavior for the second moment of the internal field distribution as a function of field as T→0, which rules out any single pairing state explanation of the data, without including other *extrinsic* effects. The data are, however, consistent with *s*-wave (or extended *s*-wave) pairing, provided that field-dependent and temperature-activated vortex de-pinning are first taken into account. Applying a self-consistent vortex de-pinning model, the data are found to be best described by an underlying two-fluid model, yielding a London penetration depth value of λ_{ab}(T=0,H=0) = 127.6 nm. Attempts to fit the data using BCS theory with varying coupling strengths and a *d*-wave model produced much poorer fits. In fact, the probability that the *d*-wave model gives a better fit than the two-fluid model is less that 4×10^{-6}. This work reveals that the *d*-wave interpretations are incorrect, confirms earlier work (Refs. 1-3) which first established *s*-wave pairing in $YBa_2Cu_3O_7$ powders and (heavily twinned) crystals, and re-establishes *s*-wave pairing for superconductivity in this material.

Keywords: High-T_c superconductivity, pairing state, muon spin rotation

J. Ashkenazi et al. (eds.), New Challenges in Superconductivity: Experimental Advances and Emerging Theories, 49-54.

1. Introduction

Already by 1990, the high-temperature superconductivity of $YBa_2Cu_3O_7$ had been observed (and confirmed) to reflect s-wave (or extended s-wave) pairing of holes, both in powders[1,2] and in single crystals,[3] using muon spin rotation (μ^+SR). Not only is μ^+SR a bulk probe, but it is one of the few measurements that probes *only the superconducting bands*, and is thus superior to many other techniques probing the high-T_c pairing state. The single-crystal measurements confirmed the earlier conclusion from powders that the pairing state was either s-wave or extended s-wave for both the 90 K ($\delta \sim$0.05) and the 60 K ($0.3 \leq \delta \leq 0.4$) bulk phases (with oxygen content $7 - \delta$). In all of the above-cited experiments, the vortex lattice was strongly pinned, suppressing fluxon motion and temperature-dependent de-pinning effects below T_c.

A comparable demonstration of agreement with s-wave pairing was also provided in 1991 for unannealed $Bi_2Sr_2CaCu_2O_8$ crystals.[4] In this case, the effects of vortex motion and temperature-activated de-pinning were clearly evident at 0.3 and 0.4 Tesla. However, the effects of vortex motion and de-pinning were suppressed in higher fields (1.5 Tesla), revealing the true underlying s-wave character, a result that has been recently corroborated.[5] Since these effects were much less evident in powder samples,[6] it was concluded that they were suppressed by the stronger pinning forces present in the powder samples.

Following this $Bi_2Sr_2CaCu_2O_8$ work, others,[7] citing primarily surface sensitive probes, have argued that the hole-pairing in high-T_c materials is primarily d-wave pairing. Indeed, other μ^+SR data on single-crystal $YBa_2Cu_3O_7$ were produced, from which the authors claimed evidence for d-wave pairing.[8]

In this paper, we concentrate on the μ^+SR measurements and determine if $YBa_2Cu_3O_7$ is a bulk s-wave (nodeless) superconductor, as determined in Refs. 1-3, or a d-wave superconductor, whose order parameter $\Delta(\mathbf{k})$, changes sign as a function of $\mathbf{k}$, as claimed in Ref. 8. In making this determination, we show that the features observed in the single-crystal data of Ref. 8 are actually due to temperature-activated fluxon de-pinning, an effect which is not readily observable in strongly pinned systems such as the early powder samples or the early heavily-twinned crystals.

To prove the s-wave character of the superconductivity, we first present μ^+SR data acquired in a high-quality $YBa_2Cu_3O_{6.95}$ crystal at applied magnetic fields of 0.05, 1.0, 3.0, and 6.0 Tesla. The measured temperature- and field-dependences of the second moment of the local field distribution, σ(T,H), are carefully compared using a self-consistent analysis in which deviations from s-wave symmetry are attributed to weak fluxon de-pinning phenomena, rather than to d-wave effects. We show that the purported intrinsic d-wave behavior previously claimed for muon experiments is actually not due to d-waves but is an extrinsic phenomenon caused by flux de-pinning.[9]