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Reply to "Comment on 'Nodeless pairing state in single-crystal $YBa_2Cu_3O_7$' "

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For $YBa_2Cu_3O_{6.95}$, both fluxon depinning and a nodeless symmetry of the pairing holes are required to describe the μ^+SR data. Our work properly identifies and corrects for the effects of fluxon depinning (with an activation temperature of about 20 K), and shows that the underlying ground-state symmetry is undoubtedly nodeless in character, consistent with *s*-wave or extended *s*-wave pairing. Fluxon depinning has also been independently confirmed by microwave studies indicating activated microscopic vortex pinning at low temperatures. While ignoring the fully established importance of fluxon depinning, Sonier *et al.* continue to proffer the notion that the μ^+SR data instead provide evidence of *d*-wave pairing (without fluxon pinning). Even a cursory examination of the published *d*-wave theories reveals that the predicted low-field linear-in-temperature signature of the *d*-wave penetration depth (claimed to have been observed in fields $H \geqslant 0.2$ T by Sonier *et al.*) should have been quenched by the magnetic fields applied. The fact that it was not quenched proves that the *d*-wave conjecture is incorrect: those authors continue to confuse the fluxon depinning evident at ~20 K with a nonexistent *d*-wave linear term.

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I. INTRODUCTION

In their Comment,[1] Sonier *et al.* continue to argue that their previous analyses of $YBa_2Cu_3O_{6.95}$ transverse-field muon spin rotation (μ^+SR) data are correct. They assert, in the absence of adequate proof, that the superconductivity of $YBa_2Cu_3O_{6.95}$ is well described by a *d*-wave cuprate-plane model, without disproving our recent work[2] showing that $YBa_2Cu_3O_{6.95}$ is in fact a strong-coupled nodeless superconductor, consistent with *s*-wave or extended *s*-wave pairing.

In this Reply, we first show that both fluxon depinning (which Sonier *et al.* omit) and a nodeless gap symmetry are required to describe the muon data. Secondly, we examine the Comment's authors' assertion that evidence for *d*-wave superconductivity can be obtained by comparison of transverse-field μ^+SR and zero-field microwave data, and call into question their claims by showing that the μ^+SR data do not agree with the predictions of Sonier *et al.*'s *d*-wave cuprate-plane superconductivity. Finally, we address some criticisms of our pinning model in the Comment, and show that both our analyses of the μ^+SR data and our finding of bulk nodeless behavior in $YBa_2Cu_3O_{6.95}$ still stand,[2] confirming earlier work.[3–5]

II. THE NECESSITY OF FLUXON DEPINNING

One cannot explain the transverse-field μ^+SR data by simply varying the pairing-state symmetry alone (i.e., *s* wave or *d* wave). This was clearly demonstrated in Sec. III of Ref. 2, and is consistent with the theoretical work of Amin *et al.*,[6] wherein their *d*-wave theory (alone) was found to compare poorly with the data of Sonier *et al.* One must account for both fluxon depinning and the pairing-state symmetry.

The data exhibit two distinct features that must be addressed by any successful theoretical model: (i) the inflection due to fluxon depinning in the data at ~20 K; see also Ref. 7; and (ii) the nonmonotonic behavior of the root second moment of the internal magnetic field distribution at low temperatures $\sigma(T \rightarrow 0,H)$ (see Fig. 2 of Ref. 2). Accounting for these two features assuming strong-coupled (nodeless) pairing (approximated by the two-fluid model) gives the following result: the zero-field extrapolations, $\lambda_{ab}(T,H=0)$, for data taken at four fields (0.05, 9.0, 3.0, and 6.0 T), collapse onto a single curve.[8,9] [See Fig. 4(b) of Ref. 2.] Attempts to describe the same data with the $d_{x^2-y^2}$-wave pairing function of Ref. 6, even with modifications (as described in Ref. 2) to help the *d*-wave model fit better, produced far worse results. In fact, the probability that a noded gap function (e.g., *d* wave) gives a better fit than the two-fluid model, even with fluxon depinning, is estimated to be less than 4×10^{-6}.

III. COMPARISON OF μ^+SR AND MICROWAVE DATA

The central assertion of Sonier *et al.*[1] is displayed in their Fig. 1, which shows the temperature dependence of λ_{ab}^{-2}, the inverse square of the magnetic penetration depth in $YBa_2Cu_3O_{6.95}$ obtained by μ^+SR for *strong* magnetic fields, $H \geqslant 0.2$ T. The difficulties with this figure and with the assertions of Sonier *et al.* are clear: First, the effects of fluxon depinning are assumed nonexistent. Second, the microwave data (i.e., the curves in Fig. 1 of the Comment[1]) represent *measurements at nearly zero field* ($H \rightarrow 0$) which are *arbitrarily offset and scaled* in order to appear to match the μ^+SR data at strong fields $H \geqslant 0.2$ T; this comparison is a poor substitute for a theoretical calculation based on known parameters being compared with the muon data, as presented in Fig. 1 of Ref. 2. Third, microwave measurements probe the *dynamic* response to *diamagnetic surface screening in the Meissner state*, at fields H much weaker than H_{c1}, the lower critical field; the μSR measurements probe the *bulk distribution* of quasistatic magnetic field penetration in the vortex state ($H > H_{c1}$). The microwave and muon measurements thus probe two completely different thermodynamic states of the sample. Even Amin *et al.*,[6] in their conclusion, caution against any comparison between microwave data and μ^+SR data, with explicit reference to data of Sonier *et al.* Given these facts, the microwave to μ^+SR comparison is of little value. Not surprisingly, the microwave finding of a linear in temperature variation of changes in the penetration depth (shown in Fig. 1 of Ref. 1 as evidence of *d*-wave behavior) is not in agreement with data from other microwave measurements.[10,11]

As was shown in the *d*-wave analyses of earlier data of Sonier *et al.*,[6] the external field used in most μ^+SR experiments is sufficient to quench the linear-in-T form for the temperature dependence of the magnetic penetration depth. Further, according to the *d*-wave analysis of Li *et al.*,[12] weak magnetic fields ($H \sim H_{c1}$) produce a significant nonlinear-T effect on the penetration depth at low temperature. It is, therefore, impossible that Sonier *et al.* could have observed (in the fields applied) a linear-in-T dependence associated with the pairing-state symmetry. Interest in the theoretical linear-T dependence that is found at $H=0$, for example, in the works of Annett, Goldenfeld, and Renn[10] and Yip and Sauls,[13] stems in part from the recognition that a linear-T dependence extending to $T=0$ would violate both Nernst's theorem and the second law of thermodynamics.[14,15] Hence considerable theoretical effort in the context of *d*-wave pairing has been devoted to examining various mechanisms of superconductivity that are likely to quench the linear-T behavior, such as nonlocal and nonlinear effects[12] and impurity scattering.[16]

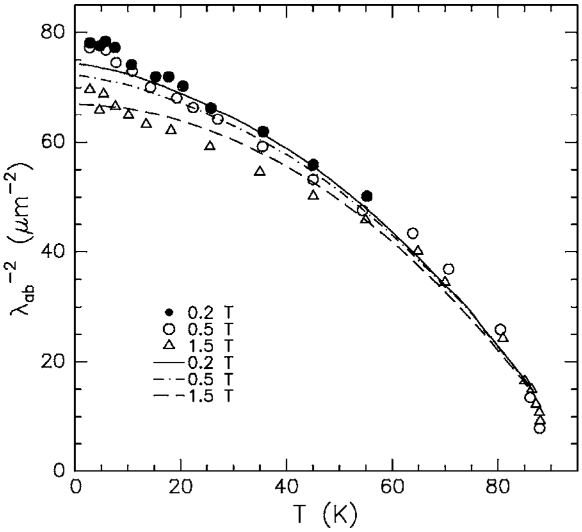

FIG. 1. Experiment (data from the Comment, Ref. 1) and *d*-wave theory (curves, after Ref. 6) for the temperature- and magnetic-field dependence of the inverse-square effective penetration depth of $YBa_2Cu_3O_{6.95}$. Values of the applied magnetic field H are given in the legend.

The μ^+SR data for $YBa_2Cu_3O_{6.95}$ from the Comment by Sonier *et al.* are reproduced here in our Fig. 1. The curves through the data are *d*-wave model functions for the effective penetration depth that we determined from calculations by Amin *et al.*,[6] where a gap parameter ($\Delta_0=2.65\ k_BT_c$) similar to that in other literature was used.[17] No corrections for fluxon depinning have been made, following the practice of Sonier *et al.* The experimental parameters of $T_c=93$ K and $\lambda_{ab}(T=0,H=0)=0.112$ nm given in the Comment[1] were used to construct the theory curves. The decrease in λ_{ab}^{-2} with increasing H is determined by the Amin theory,[6] where λ_{ab} is treated as the effective penetration depth. In contrast to the procedure used in the Comment, each curve here for a given field H is a *calculated theoretical function,* not an *arbitrarily scaled curve.*

The disagreement between *d*-wave theory and the μ^+SR experiment is obvious in our Fig. 1. The theoretical curves contain pronounced curvature in the temperature dependence at low temperatures, and the experimental data tend to deviate upwards at such low temperatures. The comparison of the data shown here in our Fig. 1 reveals that the shapes of the temperature dependences in the μ^+SR data and in *d*-wave theory are clearly different at low temperature. In fact, Amin *et al.*[6] had earlier noted a similar disagreement between theory and experiment. Thus the anomalous behavior exhibited in the μ^+SR data (and by inference in the microwave data) shown in the Comment's Fig. 1 is insufficient to support a claim of *d*-wave pairing.

IV. RESPONSE TO CRITICISMS OF THE PINNING MODEL

Even though flux trapping inhibits macroscopic thermal equilibration of the magnetic induction (because B remains essentially frozen by pinning[7]), vortex movement can occur on microscopic length scales (distances less than the intervortex spacing d, which for the fields under discussion range from 2000 Å to 200 Å. [A triangular lattice has $d = 1.075(\Phi_0/B)^{1/2}$; a square lattice has $d=(\Phi_0/B)^{1/2}$.[8,9]] Small vortex displacements are connected with weaker local pinning forces in high-quality crystal specimens, and have a tendency to be greatest at magnetic fields near the phase boundary ($H\sim 1$ T) that separates the Bragg glass and the vortex glass behavior.[18,19] Properties of small-amplitude vortex displacements have been determined independently from the microwave impedance in external magnetic fields.[20] Pinning frequencies obtained by microwave measurements[20] show pronounced increases in pinning strength below 30 K, indicative of pinning-activation energies in the range $E_A \sim (10\text{ K to }14\text{ K})k_B$. In addition, anomalies in the microwave surface resistance at 35 K to 45 K (Refs. 21,22) confirm that $YBa_2Cu_3O_{6.95}$ is not a perfectly stable system at low temperatures. The upturn in the μ^+SR data at low temperatures is consistent with an activated increase in local pinning, with $E_A \approx (20\text{ K})k_B$, as shown quantitatively in Ref. 2. This activation energy for de-pinning was obtained for μ^+SR at constant magnetic field. Pinning forces are also dependent upon specimen preparation. Thus the microwave results[20] and the μ^+SR results[2] provide mutually consistent evidence of temperature-dependent vortex pinning at or below ~20 K.

In fitting the μ^+SR data to obtain the *s*-wave result, we used[2] a complete representation of local magnetic field distributions in vortex states perturbed by pinning. The physical model for the vortex state includes the field dependence of the effective penetration depth and its implicit variation with the vortex core.[23] The coherence distance is determined from the Ginzburg-Landau parameter κ. The temperature dependence of the gap is represented by the Gorter-Casimir two-fluid model. Brandt's earlier treatments of the second moment of the local magnetic field distribution[24] was found to give a better fit than more recent calculations,[25] possibly indicating that conventional Ginsburg-Landau theory[26] (the theory of Ref. 25 and Eq. (1) of the Comment[1]) may not be the best model for describing the microscopics of the high-T_c pairing mechanism.

The analogous treatment of the same μ^+SR data with *d*-wave pairing theory, including *d*-wave treatment of the coherence distance and vortex core,[23] yields a poor fit of theory to data. This comparison is what leads to the conclusion that the bulk pairing state in $YBa_2Cu_3O_{6.95}$ is dominantly nodeless (e.g., *s*-wave) exhibiting *no evidence* of a noded (e.g., *d*-wave) component. One should also note that the variation of the vortex cores in *s*-wave and *d*-wave pairing theory are too much alike to be of much use in distinguishing pairing mechanisms.[23] The fact that the fitted ξ_0 (as reported by Sonier *et al.*) appears proportional to the vortex lattice spacing indicates correlation among the fitting parameters rather than an intrinsic effect somehow related to the pairing state.

The variation of the vortex lattice symmetry over the field range tested does not significantly affect our results. The formulation for the square root of the second moment of the local field distribution of the unperturbed triangular flux lattice, $\sigma = 0.069\Phi_0/\lambda^2$, is a good approximation for all fields when used consistently, with λ treated as the effective penetration depth, λ_{ab}. We infer from the recent neutron diffraction measurements[9] and the variation in the numerical coefficient 0.069 in the above expression with vortex lattice symmetry[24] that the systematic error in the field dependence of σ could be 2%, which is below the resolution of the μ^+SR experiment, and hence negligible. At the four fields used in our experiment, $H=0.05$, 1.0, 3.0, and 6.0 T, Brandt's theory[26] predicts that σ (unperturbed by pinning) should decrease *monotonically* with increasing H, contrary to the data. Moreover, the deviation from the large-κ limit of σ at $H = 0.05$ T is only 3% and therefore does not explain the nonmonotonicity in the experimental σ. Thus the low-field limit, represented by Eq. (2) of the Comment,[1] does not apply to the data of Ref. 2.

V. CONCLUSIONS

To summarize, the mere similarity of shape between selected μ^+SR and scaled microwave data at low temperatures is definitely not sufficient to prove *d*-wave superconductivity. Moreover, the μ^+SR data do not agree with any published *d*-wave theory or expectation. It is now clear that the Comment's authors[1] do not actually have any evidence of a noded gap function in $YBa_2Cu_3O_{6.95}$. In fact, Sonier *et al.*[27,28] have *never* had evidence of *d*-wave superconductivity, as they have repeatedly claimed.[2,6] They did, however, have evidence of anomalous behavior of a type which had been reported over ten years earlier[29] for single-crystal $Bi_2Sr_2CaCu_2O_8$ and explained as due to a *combination* of fluxon depinning (which Sonier *et al.* ignore) and a nodeless gap.

If one were to conjecture the possibility that the order parameter is composed of a superposition of components of *s* and (noded) *d* symmetry, then our results[2] indicate that the *s*-wave term is overwhelmingly dominant. The results of our recent study[2] confirm earlier work,[3–5,30] as well as a more recent finding of a modified two-fluid form for $\lambda_{ab}(T)$ in a sample comprised of a mosaic of $YBa_2Cu_3O_{6.95}$ crystals, where static vortex disorder (induced by strong pinning) was found to smear the local magnetic field distribution.[31] The approximations that we used and that were criticized by Sonier *et al.*[1] have no significant effect on our results; our original finding[2] of bulk nodeless pairing (consistent with *s*-wave or extended *s*-wave pairing) stands unchallenged.

Our finding of bulk superconductivity in $YBa_2Cu_3O_{6.95}$ that is nodeless in character suggests that the Cu *d* bands of the CuO_2 layers do not play a direct role in the hole pairing in the $YBa_2Cu_3O_{6.95}$ material. This result is consistent with the superconducting hole condensate in $YBa_2Cu_3O_{6.95}$ residing, not in the CuO_2 layers, but in the BaO layers.[29,32–34]

It is important to note that some high-T_c superconductors, such as Cu-doped Ba_2YRuO_6 or Sr_2YRuO_6 with (onset) T_c of ~93 K or ~49 K,[35–38] do not contain CuO_2 planes, while others, such as $GdSr_2Cu_2RuO_8$ and $Gd_{2-z}Ce_zSr_2Cu_2RuO_{10}$ (both with T_c's near 45 K) have CuO_2 planes that exhibit either weak ferromagnetism or antiferromagnetism, and hence those planes do not superconduct.[32–34] [This is also true of Co-doped $YBa_2Cu_3O_7$ (Ref. 39).] An examination of the major high-T_c materials suggests that their hole condensates all reside in the BaO, SrO, or interstitial oxygen regions.[32]

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