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

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In a recent article, Harshman *et al.* [Phys. Rev. B **69**, 174505 (2004)] claim that our μSR measurements [Phys. Rev. Lett. **83**, 4156 (1999)] of the effective in-plane magnetic penetration depth $\lambda_{ab}(T,H)$ in high-quality single crystals of $YBa_2Cu_3O_{6.95}$ are dominated by flux pinning effects, and hence are inconsistent with *d*-wave superconductivity. The purpose of this Comment is to point out that the phenomenological *s*-wave pinning model applied by Harshman *et al.* to $YBa_2Cu_3O_7$ is invaild. The model does not account for the finite size of the vortex cores or the field-induced vortex-lattice transformation, and hence yields inaccurate information on the magnetic penetration depth. We also comment on the criticism of zero-field microwave measurements that show excellent agreement with our μSR results for the limiting low-temperature behavior of $\lambda_{ab}(T)$.

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Finite size of the vortex cores. Yaouanc, Dalmas de Réotier, and Brandt[1] have shown that the second moment due to an ideal hexagonal VL is given by

$$\sigma_L^2 = \frac{0.00371\Phi_0^2}{\lambda^4} f_v(b), \tag{1}$$

where $b = B/B_{c2}$ is the reduced field and $f_v(b)$ is a universal function that accounts for the finite size of the vortex cores. In Ref. 2 the assumption is made that $f_v = 1$. However, this assumption actually has limited validity. As explained in Refs. 1,3, f_v is strongly dependent on b, and the strength of this field dependence is greatest at low b. Brandt[3] has shown that the often used approximation $f_v = 1$ is good only for $\kappa \geqslant 70$ and only for a very narrow field range. Neither of these conditions are satisfied in Ref. 2. Both the determined value $\kappa = 43.8 \pm 1.8$ and the lowest field ($H = 0.05$ T) considered in Ref. 2 are too small for Eq. (1) with $f_v = 1$ to apply. We note that the smaller value of the second moment σ at $H = 0.05$ T shown in Fig. 2 of Ref. 2 is in fact expected, because at this field σ_L is more appropriately described by Eq. (12) of Ref. 3

$$\sigma_L^2 = \frac{b\kappa^2}{8\pi^2} \frac{\Phi_0^2}{\lambda^4}. \tag{2}$$

The authors of Ref. 1 warn that failure to account for the finite size of the vortex cores in single crystal $YBa_2Cu_3O_{7-\delta}$, which exhibits a distinctively anisotropic μSR line shape, can lead to erroneous values and behavior for $\lambda_{ab}(T,H)$. The large low-field value of the vortex core size reported in our work on $YBa_2Cu_3O_{6.95}$ (Ref. 4) does not imply a gross error in modeling the μSR data. The same modeling procedure applied to $La_{1.85}Sr_{0.15}CuO_4$ single crystals[5] yields values of the vortex core size fully consistent with the coherence length estimated from the Ginzburg-Landau expression for the upper critical field H_{c2}. Even so, the temperature and field dependence of λ_{ab} in $La_{1.85}Sr_{0.15}CuO_4$ is qualitatively similar to what we observe in $YBa_2Cu_3O_{6.95}$. We note that recent calculations by Atkinson[6] show that large vortices can arise from proximity-induced superconductivity in the chain layers.[6]

Pinning effects. Despite these shortcomings, Harshman *et al.*[2] determine $\lambda_{ab}(T,H)$ by fitting the total second moment $\sigma^2(T,H)$ of the μSR line shape to a model containing *two independent* parameters for pinning-induced distortions of the VL—whereas we maintain that a single Gaussian convolution of an appropriate theoretical magnetic field distribution for the VL is sufficient to account for disorder.[7] The major difference is that in Ref. 2 the vortex lines are assumed to wander significantly along their length, whereas we assume the dominant effect of pinning in $YBa_2Cu_3O_{7-\delta}$ is random displacement of fairly straight vortex lines from their ideal positions in the VL. In this way we strongly disagree with the assertion of Harshman *et al.*[2] that point distortions of the vortex lines in ultraclean $YBa_2Cu_3O_{7-\delta}$ are as important as in $Bi_2Sr_2CaCu_2O_{8+\delta}$. The dimensionality of the vortices is dependent on the ratio $\gamma s/\lambda_{ab}$, where $\gamma = (m_c/m_{ab})^{1/2}$ is the mass anisotropy and s is the spacing between CuO_2 planes. It is well known that γ is nearly two orders of magnitude smaller in optimally doped $YBa_2Cu_3O_{7-\delta}$ than in $Bi_2Sr_2CaCu_2O_{8+\delta}$. Consequently, while the vortices in $Bi_2Sr_2CaCu_2O_{8+\delta}$ are weakly coupled two-dimensional "pancakes" of flux that are highly susceptible to point disorder, the vortices in optimally doped $YBa_2Cu_3O_{7-\delta}$ resemble rigid rods of flux.[8] By applying a "field-shifting" procedure, we have demonstrated (see Fig. 13, Ref. 7 and Fig. 1, Ref. 9) that the vortices in our $YBa_2Cu_3O_{6.95}$ single crystals remain firmly pinned up to temperatures well above 0.5 T_c. This itself is strong evidence against thermally activated depinning of vortices as the source of the observed linear temperature dependence of λ_{ab}.

The validity of the *s*-wave flux pinning model proposed by Harshman *et al.*[2] is argued to be its ability to simultaneously fit the second moment $\sigma^2(T,H)$ for data taken at different applied fields. This fails to account for the gradual hexagonal-square VL transformation that occurs near H

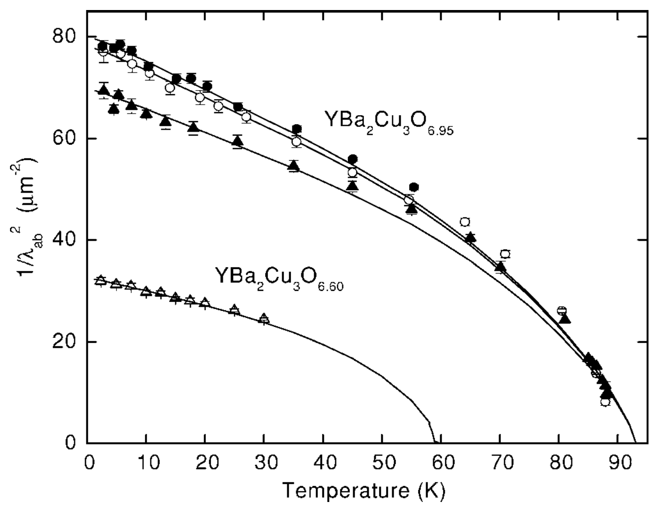

FIG. 1. μSR results from Refs. 4,12,13 for the temperature dependence of $1/\lambda_{ab}^2$ in $YBa_2Cu_3O_{6.95}$ at 0.2 T (solid circles), 0.5 T (open circles), and 1.5 T (solid triangles), and in $YBa_2Cu_3O_{6.60}$ at 0.5 T (open triangles). The solid curves represent the microwave measurements (Refs. 11,14) of $\Delta\lambda_{ab}$, converted to absolute values λ_{ab} using the μSR values for $\lambda_{ab}(T=0)$.

=4 T for a field applied parallel to the $\hat{c}$ axis.[10] Since the VL is highly distorted from hexagonal geometry at the highest field considered in Ref. 2 (i.e., $H=6$ T), it is clear that a reasonable simultaneous fit to $\sigma^2(T,H)$ was achieved only because of the freedom allowed for by the two pinning parameters in their model. The values of these parameters are certainly questionable, since they cannot be independently confirmed.

Comparison of μSR and microwave data. Harshman *et al.*[2] argue that the excellent agreement between our μSR results for $\lambda_{ab}(T)$ at $H=0.5$ T[4] and zero-field microwave cavity perturbation measurements[11] is merely a coincidence, and that this is the only matching data of its kind. However, Harshman *et al.*[2] make no mention of the excellent agreement between microwave and μSR data for underdoped single crystals of $YBa_2Cu_3O_{6.60}$ (Ref. 12) (reproduced here in Fig. 1). This is extremely important, because the $YBa_2Cu_3O_{6.60}$ crystals studied in Ref. 12 exhibited VL melting effects,[13] qualitatively similar to highly-anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ at lower temperature and magnetic field. If temperature-dependent reordering of the VL was indeed responsible for the low-temperature linear T dependence of $\lambda_{ab}(T)$ observed by μSR, a clear departure from the microwave data[14] for $YBa_2Cu_3O_{6.60}$ should have been observed—since vortex fluctuations would result in a stronger decrease of σ^2 with increasing T. Instead the agreement between μSR data well below the VL melting transition and the microwave measurements is comparable to that found for near-optimally doped single crystals. This is not surprising, since it has been shown experimentally that in clean materials melting of the VL is a *first-order* phase transition.[15]

We take strong exception to the assertion by Harshman *et al.*[2] that the linear temperature dependence of $\Delta\lambda$ observed by microwaves "may be due to defects, interrupted weak links or other obstacles to supercurrent flow," or that "divergent surface currents" may be playing a role. This amounts to an arbitrary and unjustified dismissal of a large body of careful measurements on what are acknowledged to be the best crystals available. First, the measurements in question were always taken in a geometry with negligible demagnetizing effects, so that "divergent surface currents" are irrelevant.[16] Second, the effects of currents in the $\hat{c}$ direction have been systematically studied via crystal cleaving procedures—for the measurements in question, the $\hat{c}$-axis effects *are* negligible.[14,17] Third, the linear temperature dependence of $\Delta\lambda$ has been observed by microwaves over many years of measurements, on a large number of samples from different crystal growths and with different shapes.[18] This could not possibly be the case if the effects were due to crystal imperfections. In fact, the linear term has become more obvious at low temperatures as greater purity and crystalline perfection has been achieved.[18] Finally, the linear changes in superfluid density have been quantitatively confirmed by integration of the temperature dependent broadband microwave conductivity,[19] whose shape is consistent with Born scattering in a d-wave superconductor.

Absolute value of λ_{ab}. Harshman *et al.*[2] remark that the zero-field, zero-temperature value of λ_{ab} determined in Ref. 4 for $YBa_2Cu_3O_{6.95}$ is significantly smaller than the established value of 120 to 140 nm, and that this is evidence that we have inaccurately determined the behavior of $\lambda_{ab}(T,H)$. In fact this is not true. The small absolute values of the penetration depth obtained in our studies, $\lambda_{ab}(T\to 0,H\to 0)=112$ nm for $YBa_2Cu_3O_{6.95}$ and $\lambda_{ab}(T\to 0,H\to 0)=170$ nm for $YBa_2Cu_3O_{6.60}$, have recently been confirmed by precise measurements of the absolute values of the $\hat{a}$-axis and $\hat{b}$-axis penetration depths using a zero-field ESR spectroscopy technique.[20] We consider this a remarkable confirmation of our modeling procedure. On the other hand, the large value $\lambda_{ab}(T\to 0,H\to 0)=127.6\pm 1.5$ nm determined in Ref. 2 for fully doped $YBa_2Cu_3O_7$ is significantly larger than the value of 91 ± 6 nm reported in Ref. 20.

In summary, the phenomenological s-wave pinning model introduced by Harshman *et al.*[2] does not accurately describe the μSR data as claimed. The model has been applied to $YBa_2Cu_3O_7$ outside its limits of validity, and does not yield accurate absolute values of the magnetic penetration depth.

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