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Explanation for the low-temperature behavior of H_{c1} in $YBa_2Cu_3O_7$

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We present magnetization curves $M(H)$ for $YBa_2Cu_3O_7$ crystals. The onset of deviation from linearity, δM, being analyzed in the framework of the Bean model, yields an "upturn" in the temperature dependence of the lower critical field $H_{c1}(T)$ at low T, similar to that observed by other groups. We propose a generalized Bean model, which takes into account the Bean-Livingston surface barrier. In this model the Abrikosov vortices start to penetrate into the sample at distinct points at the surface where the barrier is suppressed by surface defects. As a result δM appears to be proportional to $(H-H_{c1})^3$ rather than to $(H-H_{c1})^2$ as in the conventional Bean model. Our analysis shows the conventional BCS saturation of H_{c1} at low temperatures.

Determination of the lower critical field H_{c1} for high-temperature superconductors is still a challenge for experimentalists. Of particular interest is a reliable description of the temperature (T) dependence of H_{c1}, for which numerous studies have yielded conflicting results. At low temperatures, for example, several groups[1,2] have observed BCS-like saturating values, while others[3–8] have reported an anomalous "upturn," i.e., a sharp increase in H_{c1} as temperature decreases. This anomaly has been obtained by two techniques: (a) Measurements of the magnetization curves, $M(H_a)$, where H_a is the applied field; the onset of deviations from linearity (i.e., from full Meissner shielding), δM, points to flux penetration. (b) Measurements of the isothermal remanent magnetization $M_{\rm rem}$ (i.e., the field is decreased to zero at a controlled temperature); the appearance of $M_{\rm rem}$ signals the first field for flux penetration. In both techniques the onset is experimentally ill defined unless the field dependence of the measured feature is modeled. Usually the Bean model is invoked[2,6–8] and the onset is described by $(H-H_{c1})^2$; the anomalous upturn is interpreted by invoking surface barriers which cause retardation in flux entry.[6–8]

In this paper we present data for the $YBa_2Cu_3O_7$ crystal which, if analyzed in the framework of the Bean model, show the upturn at low temperature. We demonstrate, however, that the data is not consistent with this model. By an appropriate inclusion of the Bean-Livingston (BL) surface barrier into the Bean model, we achieve consistency with the data. Moreover, analysis of the data within the framework of the extended model yields $H_{c1}(T)$ without this anomalous upturn. We thus conclude that this anomaly is an artifact of an inappropriate modeling of the irreversible behavior.

The crystal under investigation is a $1000 \times 460 \times 4$ μm^3 untwinned $YBa_2Cu_3O_7$ described in Ref. 9. The sample is mounted at the center of a copper coil, and the magnetic measurements are carried out by using a miniature InSb Hall probe.[10] The applied magnetic field H_a is parallel to the c axis. One probe is placed on top of the sample and it measures the magnetic flux passing through the sample. The second probe is fully exposed to H_a, being placed far from the sample. The difference between the signals measured by the two probes is thus proportional to the magnetization M of the sample.

In order to identify the first critical field H_{c1} we measured the magnetization curves M as a function of H_a at various temperatures between 4.2 and 91 K. For each magnetization curve, $M(H_a)$, we fit the initial linear portion, extrapolate it to higher fields, and then evaluate the deviation δM of the actual data from linearity. At high temperatures, $T > 65$ K, where pinning is weak, a sharp kink defines the onset of δM. In Refs. 9 and 11 we have demonstrated that this kink corresponds to the first field for flux penetration, $H_p > H_{c1}$; this point will be further discussed below. In contrast, in the low-temperature region ($T < 65$ K) the kink is smeared by strong pinning. Typical data, at 40 K, are shown in Fig. 1. The inset to this figure describes the field dependence of the deviation δM from the initial linear slope. The onset of δM is conventionally expected to appear at $H = H_{c1}$ but, as one can see in Fig. 1, the onset is ill defined.

As mentioned above, this difficulty may be overcome by modeling the field dependence of the irreversible magnetization, for example, by the Bean model, which, in its simplest form, predicts $\delta M \sim (H-H_{c1})^2$ dependence. It has thus become common[2,7,8] to plot the square root of this irreversible magnetization, $(\delta M)^{1/2}$, as a func-

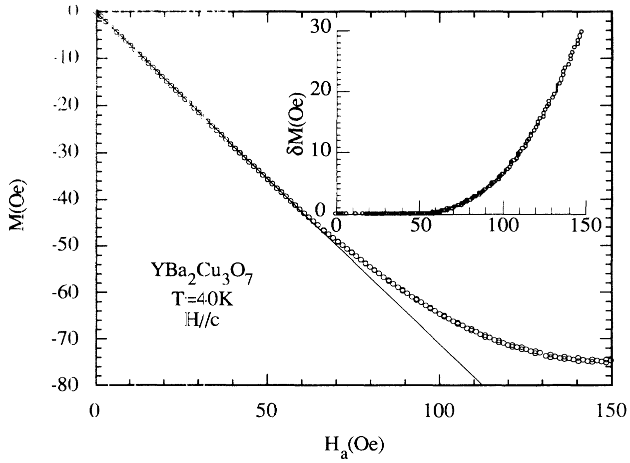

FIG. 1. Magnetization curve $M(H_a)$ at 40 K. The inset shows the field dependence of deviation from linearity, δM.

tion of H_a and to linearly extrapolate the data to zero in order to determine H_{c1}. This procedure is described by triangles in Fig. 2. The data presented in this form are indeed close to linear and yield the extrapolated field $H_{1/2} = 55$ Oe, before corrections for demagnetization. However, we note that small deviations are observed in the central field regime. Moreover, in the low-field limit, we observe stronger deviations from the linear regime and the deviated data are *above* the extrapolated line. In the other words, the field $H_{1/2}$, which is treated in the literature[7,8] as H_{c1}, appears to be *larger* than the actual first field for flux penetration. This circumstance by itself demonstrates the self-inconsistency which is built into this procedure. Similar self-contradicting deviations have been reported by other authors.[8]

As has already been shown,[6–9,11] the BL surface barrier plays an important role in vortex penetration into high-temperature superconductors. Taking this into account, we suggest that $M(H_a)$ data should be reanalyzed and we show that the new analysis results in the usual $H_{c1}(T)$ dependence which obeys the BCS predictions with saturation at low temperatures.

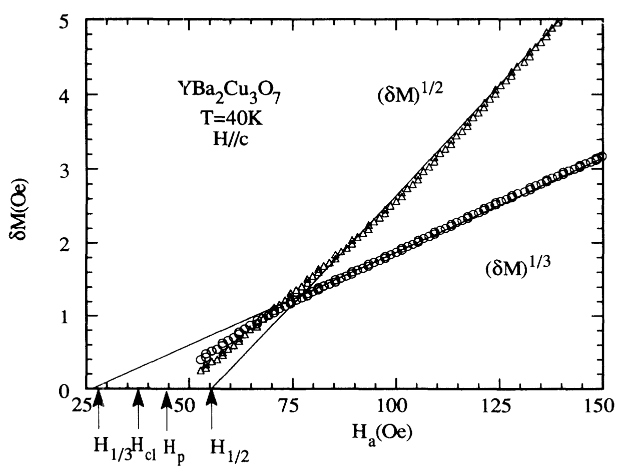

FIG. 2. Plots of $(\delta M)^{1/2}$ (triangles) and $(\delta M)^{1/3}$ (circles) vs H_a. The fields $H_{1/2}$ and $H_{1/3}$ are determined by the extrapolation of these two curves, respectively, to $\delta M = 0$. The field H_{c1} is determined as $mH_{c1} = H_{1/3}$ at $m = 0.7$ (see the text).

Consider a picture where the BL barrier prevents flux penetration into the bulk everywhere at the surface except at a few isolated points where the barrier is suppressed. Small defects in the surface (of order 100–300 Å) are good candidates for such points;[11] we refer to these defects as "gates" for flux penetration. Near such a gate one has

$$dH/dr = -(4\pi/c)\,j \equiv -\tilde{j}, \qquad (1)$$

where j is the critical current, which we consider to be field independent. Therefore, H decreases radially around the gate within a semicircle of radius r_0 (which is defined below), forming circular flux profiles around the gate (see Fig. 3), unlike the linear ones in the regular Bean model where flux penetrates through the whole surface.

It should be noted that H in Eq. (1) is the intensity of the magnetic field rather than the real density of flux, B. The relation between B and H is given by the equilibrium (Abrikosov) relation $B = B_{\rm eq}(H)$. This relation results in the well-known "dB/dH effect," which is discussed in detail in Refs. 12 and 13. Taking this circumstance into account, one immediately obtains from Eq. (1) the averaged induction $\overline{B}$, which is evidently proportional to the measured deviation from linearity, δM:

$$\overline{B} = 4\pi\delta M = \frac{n\pi}{A}\int_0^{r_0} r\,dr\,B_{\rm eq}(H_a - \tilde{j}r), \qquad (2)$$

where n is the number of the gates, A is the area of the sample in the ab plane, and $r_0 = (H_a - H_{c1})/\tilde{j}$ is the radius of the penetration semicircle, Fig. 3. We assume that r_0 is less than both the size of the sample and the typical distance between the gates, so the gates can be considered as isolated. This should hold if H_a does not exceed H_{c1} too much, in our case at $H_a \leq$ 4-5 H_{c1}.

It is clear from Eq. (2) that the choice of $B_{\rm eq}(H)$ dependence is of crucial importance for our analysis. The well-known asymptotes (see, for instance, Ref. 14 and also the discussion in Ref. 15) for $B_{\rm eq}(H)$, which hold for $(H - H_{c1}) \ll H_{c1}$ and for $H \gg H_{c1}$, cannot be used here because the experimental data are limited to the region $H_{c1} < H < 4\,H_{c1}$. In recent papers[1,8,16] the linear approximation for $B_{\rm eq}(H)$ was used:

$$\begin{aligned} B_{\rm eq} &= 0, \quad \text{at } H < H_{c1} \\ B_{\rm eq} &= H - m\,H_{c1}, \quad \text{at } H > H_{c1}. \end{aligned} \qquad (3)$$

Other possible models, like the "square-root" approxima-

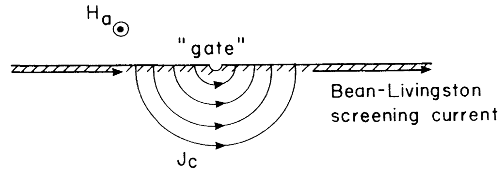

FIG. 3. Circular profiles of flux penetration through a "gate" at the surface (the gates are considered to be isolated). The radius of field penetration region is r_0.

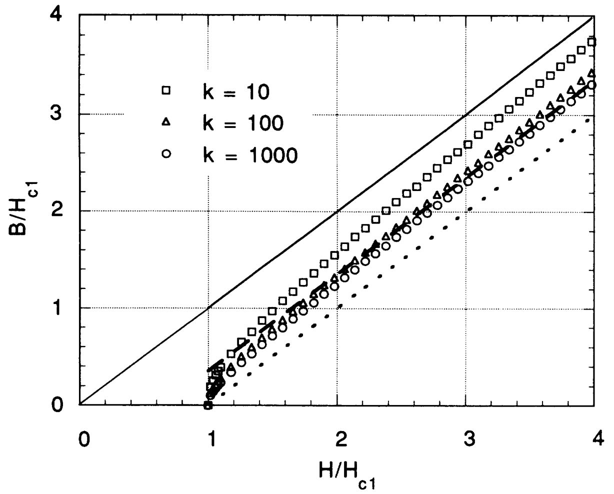

FIG. 4. The equilibrium Abrikosov $B_{eq}(H)$ curves. The squares, triangles, and circles correspond to $\kappa = 10$, 100, and 1000, respectively. The "linear" approximation (dashed line) with $m = 0.7$ gives a reasonable fit to the $B_{eq}(H)$ curve at $\kappa = 100$ ($YBa_2Cu_3O_7$). The dotted line corresponds to $m = 1$.

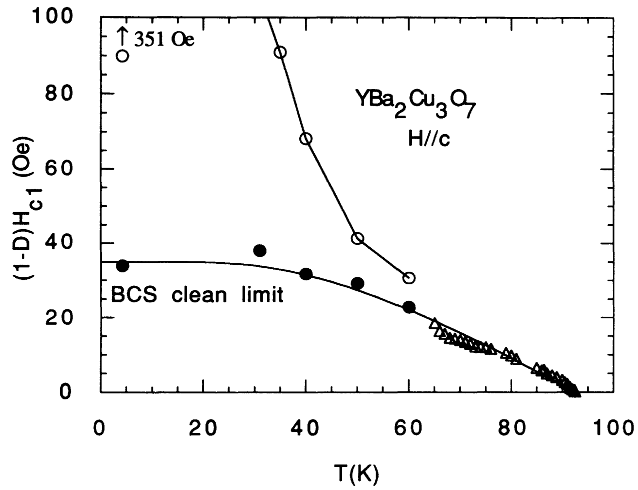

FIG. 5. H_{c1} vs temperature (filled circles) extracted from our model with "gates." Empty circles present $H_{1/2}$, which is treated as H_{c1} in terms of the conventional Bean model. Triangles show the position of the kink in $M(H_a)$ curves at $T > 65$ K.

tion, $H^2 = H_{c1}^2 + B_{eq}^2$, are described in detail in Ref. 13. In order to make a proper choice among the various possibilities, we performed a calculation of the $B_0(H)$ curve in the London approximation at $H_{c1} < H < 4H_{c1}$ just by minimizing the free energy of the vortex lattice.[14] The results are plotted in Fig. 4 at different values of the Ginzburg-Landau parameter $\kappa = \lambda/\xi$. It appears that for $YBa_2Cu_3O_7$, where[1] $\kappa_{ab} \approx 100$, the linear approximation (3) with $m \cong 0.7$ is appropriate.

By inserting Eq. (3) into Eq. (2) we obtain

$$\delta M = \frac{\pi}{A\tilde{j}^2}\left((1-m)\,H_{c1}\,\frac{(H_a - H_{c1})^2}{2} + \frac{(H_a - H_{c1})^3}{6}\right). \tag{4}$$

It is easy to see from Eq. (5) that δM grows as H^3 at $H \gg H_{c1}$; and that the extrapolation of the $(\delta M)^{1/3}$ from the region $H_a \gg H_{c1}$ to $\delta M = 0$ gives the value $H_{1/3} = m\,H_{c1}$ (see Fig. 2). As has already been discussed, the parameter m should be taken to be approximately 0.7, being dependent only on κ, i.e., practically temperature independent at low temperatures. Thus, by performing such an extrapolation we are able to obtain the $H_{c1}(T)$ dependence at $T < 65$ K temperatures (see filled circles in Fig. 5). In Refs. 1, 2, 7, and 8 the parameter m was chosen as 1, but really the exact value of m is not very important for us because it affects only the scale of H_{c1} and does not affect the form of the $H_{c1}(T)$ curve.

It is worth mentioning that the BL barrier is likely not to be completely destroyed but rather just diminished at the gate. As a result, penetration through the gate starts not at H_{c1} but at some first field for penetration, $H_p > H_{c1}$ (see Refs. 9 and 11). Nevertheless, this circumstance does not affect the part of the $\delta M(H_a)$ curve at $H_a > H_p$, so our analysis enables the extraction of the value of H_{c1} (and not H_p) from the data. Moreover, the difference between H_p and H_{c1}, which has been proved[9,11] to be dramatic in the vicinity of $T_c = 92.4$ K appears to be not so large at low temperatures. One can see it from (a) a good match at 65 K between the filled circles in Fig. 5, which represent H_{c1} below 65 K and triangles which show the kink position, i.e., H_p, above 65 K, and (b) from Fig. 2, where H_p is estimated by an eye-guided extrapolation of both $(\delta M)^{1/2}$ and $(\delta M)^{1/3}$.

In Fig. 5 it is clearly demonstrated that the upturn of H_{c1} reported in Refs. 3–8 is absent and the $H_{c1}(T)$ curve has the usual BCS "clean-limit" shape (see, for instance, Ref. 14) with saturation at low temperatures. This behavior is consistent with the measurements[17,18] of the London penetration depth $\lambda(T)$. The open circles in Fig. 5 present $H_{1/2}(T)$, which was treated in Refs. 7 and 8 as H_{c1} and does exhibit an upturn, but according to our analysis $H_{1/2}$ really has no relation to H_{c1}.

It can be shown that M_{rem} also grows as H_a^3 at large H_a in our model, but the corresponding expression is cumbersome and H_{c1} cannot be extracted from it so easily as in the case of δM. It is worth mentioning that the same analysis[2] performed for $La_{2-x}Sr_xCuO$, where $H_{1/2}$ is treated as H_{c1}, shows no upturn in the $H_{c1}(T)$ dependence. It could be an argument for less importance of the BL barrier in this compound than in $YBa_2Cu_3O_7$.

To conclude, the main feature of our model is that the penetration of the magnetic flux starts at distinct points at the surface, which we call "gates," where the Bean-Livingston barrier is suppressed by surface defects. In this model, the deviation from linearity, δM, and the remanent magnetization M_{rem} are proportional to $(H_a - H_{c1})^3$ instead of $(H_a - H_{c1})^2$ in the regular Bean model with penetration through the whole surface. Magnetization curves analyzed within the framework of this model yield the $H_{c1}(T)$ curve which exhibits saturation at low temperatures without any "upturn." We thus maintain that the upturn, which is reported by many groups, is an artifact of choosing an improper model.

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