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Irreversibility line and the hierarchy of weak links in $Bi_2Sr_2CaCu_2O_{8+\Delta}$

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The irreversibility line for $\mathbf{H}\|c$ in a single crystal specimen of $Bi_2Sr_2CaCu_2O_{8+\Delta}$ (Bi2212) has been determined via vanishing of hysteresis in isothermal dc magnetization measurements. The hysteresis loops ($\mathbf{H}\|c$) in Bi2212 appear to show signatures of two-component magnetic response in several temperature regions where the temperature dependence of irreversibility field charges sharply. It is proposed that the observed behavior may be a consequence of existence of weak links of varying strength in Bi2212.

I. INTRODUCTION

The fact that the flux pinning has to vanish at a temperature below the superconducting transition in a hard type-II superconductor inevitably leads to the existence of pinning-depinning transition [or an irreversibility line (IRL)] above which the value of macroscopic critical current density J_c is zero. Ever since the determination of an IRL in a specimen of copper oxide superconductor by Mueller, Takashige, and Bednorz,[1] a variety of techniques and procedures have been employed to determine IRL in all types of conventional and high-temperature superconductors. The irreversibility line data obtained by different techniques on the same specimen do not appear to exactly overlap,[2-4] however, there does appear to exist a definite hierarchy amongst IR lines obtained via different ac and dc magnetization methods. The beautiful electron holograph pictures of Harda *et al.*[5] have vividly demonstrated that the rigid flux lattice indeed melts in a single-crystal specimen of $Bi_2Sr_2CaCu_2O_{8+\Delta}$ (Bi2212) for $\mathbf{H}\|c$ at a temperature which correlates well with the irreversibility temperature $T_r(H)$ value determined from temperature-dependent magnetization data. The Bi2212 system is an archetypal of highly anisotropic layered superconductors and the IRL in this compound for $\mathbf{H}\|c$ has been most widely investigated. Schilling *et al.*[6] have recently argued that a qualitative change in the temperature dependence of IRL occurring in the specific field/temperature region ($T=50-60$ K and $H=800-1000$ Oe) can be understood in terms of a transformation in the *dimensionality of the fluctuations* associated with Josephson coupled layered superconductors. The fluctuations are shown to have two-dimensional (2D) character below about 50 K and 3D character above about 60 K. We have reinvestigated IRL over the entire *H-T* range in our single-crystal sample of Bi2212 and we note that change in the character of IRL occurs at two other field/temperature regions and the transformations in both these regions correlate well with a qualitative change in the character of a isothermal hysteresis curve. The hysteresis loops in Bi2212 ($\mathbf{H}\|c$) show signatures of two-component magnetic response in the temperature regions of sharper change in the temperature dependence of irreversibility field values. The purpose of this paper is to present this new correlation and argue that the observed behavior may be related to the existence of weak links of varying strength in the Bi2212 system. We feel that these weak links are of inter-unit-cell variety and are a material characteristic. In layered superconductors, such as Bi2201, Bi2212, Bi2223, etc., there also exists[4,7] an intrinsic intra-unit-cell weak link corresponding to intrinsic Josephson coupling between a pair of CuO_2 planes (or CuO_2 bilayers or CuO_2 trilayers). It may be recalled here that a unit cell of $Bi_2Sr_2Ca_{n-1}Cu_nO_{6+2(n-1)}$ comprises two formula units per tetragonal unit cell. The single-crystal samples of Bi2212 are never perfectly stoichiometric.[8-11] In addition to the inevitable presence of stacking faults, edge dislocations, etc.[12,13] the high-resolution electron micrographs (HREM) of single crystals of Bi2212 have often revealed the presence of intergrowth of unit cells of Bi2201.[9,10] The faults, dislocations, intergrowths, etc., can lead to inter-unit-cell weak links having a certain hierarchy. The intrinsic intra-unit-cell weak link is expected to be stronger than all the inter-unit-cell weak links. Rapid changes in the strength of different inter-unit-cell weak links may occur over different temperature intervals and this phenomenon probably can give rise to observed noticeable changes in the curvature of IRL across corresponding temperature intervals. It was recently demonstrated from magnetization studies[4,7,14] that the onset of rapid weakening in the strength of intra-unit-cell weak links in a sample of Bi2212 occurs at the dimensional crossover temperature $T^* \approx 85$ K, which lies only a little below its nominal $T_c(0)$ value of 88 K. The existence of a similar dimensional crossover line in Bi2212 has also been independently claimed by Wan, Harris, and Garland[15] from transport studies, and confirmed by Rastogi *et al.*[16] by nonresonant microwave absorption studies.

II. EXPERIMENTAL

The single-crystal sample at nominal composition Bi2212 used for the present study is the same on which the 3D to 2D crossover phenomenon just below T_c had been vividly elucidated by magnetization studies.[7] The new dc magnetization data over the entire H-T range (for $\mathbf{H}\|c$) have been obtained using low-field (up to 10 kOe) and high-field (up to 55 kOe) Quantum Design superconducting quantum interference device magnetometers. Figures 1–5 show the isothermal M-H curves obtained at several temperatures lying between 5 and 88 K. Figures 2–4 also show the selected portions of M-H curves at a few chosen temperatures on an expanded scale. The objective of expanded plots is to search and to highlight the presence of two-component magnetic response in dc magnetization data.[4,17–19] The magnetization hysteresis loops from 5 to 15 K (see Fig. 1) appear to be nominally one component (i.e., superposition of magnetic responses from two independent/interdependent sources is not necessary). The loop at 5 K [Fig. 1(a)] does, however, contain the presence of flux jumps[20] between ±35 kOe and ±40 kOe and also, the loops from 5 to 15 K show the phenomenon of dip in magnetization values as the field approaches zero value on the reverse and the forward hysteresis cycles. The hysteresis loops at 25 K [Figs. 2(a)–2(c)], at 75 K [Fig. 4(d)], at 85 K [Fig. 5(a)], and at 86.7 K [Figs. 5(b) and 5(c)] clearly have signatures of two-component magnetic response (see, discussion ahead). Irrespective of the observation that hysteretic magnetic behavior is one- or two-component-like, we can

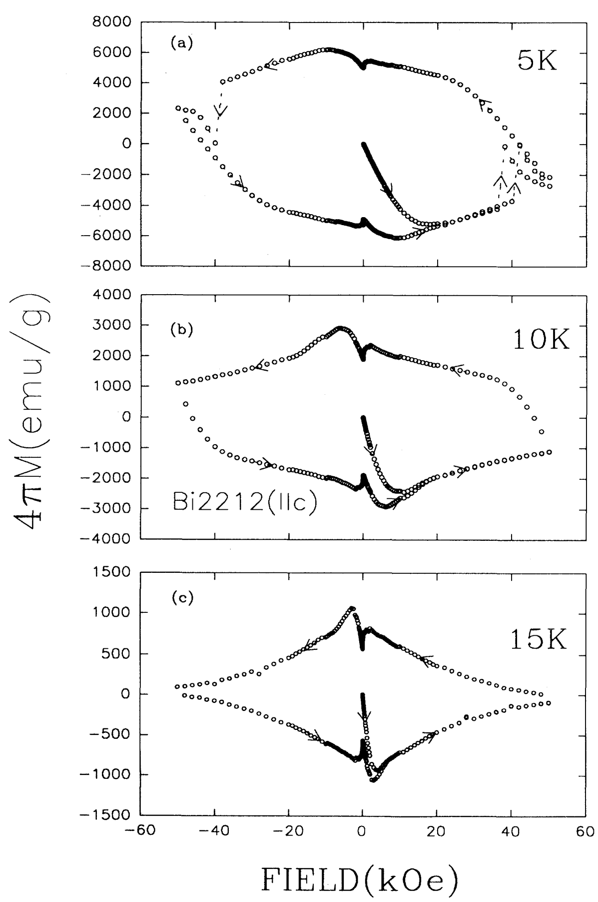

FIG. 1. Magnetization hysteresis loops for $\mathbf{H}\|c$ in Bi2212 at 5 K, 10 K, and 15 K, respectively.

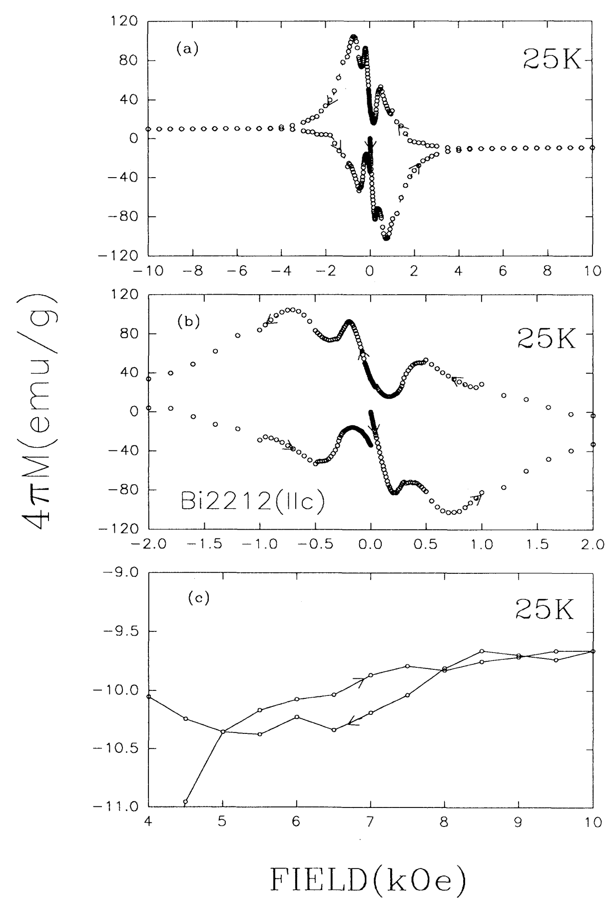

FIG. 2. Magnetization hysteresis curves in Bi2212 for $\mathbf{H}\|c$ at 25 K. (b) and (c) show the details on the expanded scales across the $H=0$ region and on reversal from H_{max} of 10 kOe, respectively.

identify from any hysteresis loop a field value at which the hysteresis vanishes. Such a field can be taken to identify the irreversibility field $H_r(T)$. Figures 6(a) and 6(b) show the variation of $H_r(T)$ vs T on linear and logarithmic scales, respectively. The general shape of the $H_r(T)$ line up to 85 K in Fig. 6(b) is similar to that of Schilling *et al.*[6] Following Schilling *et al.*,[6] we show semilog plots of H_r vs $(T_c/T-1)$ and H vs T_c/T in Figs. 7(a) and 7(b), respectively. It is apparent that the data in the lower-temperature region fit to $1/T$ behavior [see Fig. 7(b)], whereas at higher-temperature values they fit to power-law behavior, H_r proportional to $(T_c/T-1)^n$, with exponent $n \approx 1.2$, as compared to $n \approx 1.8$ observed by Schilling *et al.*[6] It may be noted that the measured values of $H_r(T)$ undergo drastic change at the dimensional crossover temperature of 85 K;[7] the three data points in Fig. 6(b) identify this change which has been described in some detail earlier by Nishihara *et al.*[14] We shall not dwell more on this discontinuous change occurring at 85 K in the present paper.

III. DISCUSSION

The arrows at 30 K and at 75 K in Fig. 6(a), approximately mark the temperatures across which visible changes in the character of the IR line occur. The *M-H* curve at 25 K in Figs. 2(a) and 2(b) has an unusual shape (two-peaked structure). Such unusually shaped *M-H* loops in the temperature interval 15–35 K have been found for Bi2212(**H**$\|c$) in numerous studies.[9,12,21,22] The hysteresis loop at 25 K may be viewed as a superposition of two superconducting hysteresis loops. Such a behavior is reminiscent of well documented two-component magnetic response in ceramic samples of oxide superconductors,[23–25] multifilament wires of conventional alloy superconductors,[26] two-phase alloys,[27] etc. Further, the ex-

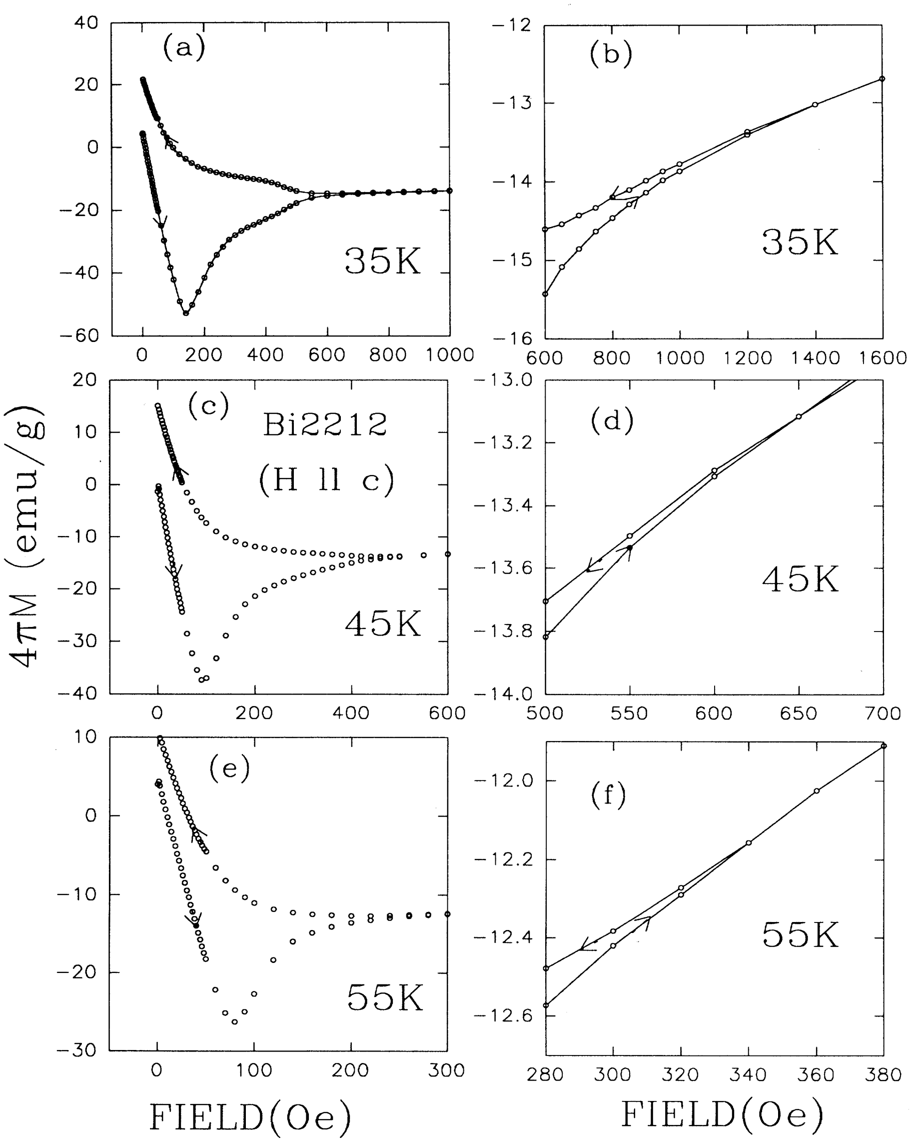

FIG. 3. Magnetization hysteresis curves in Bi2212 for **H**$\|c$ at 35 K, 45 K, and 55 K, respectively. For each temperature, the behavior near the corresponding $H_r(T)$ value has also been shown on an expanded scale.

panded portion of the M-H curve at 25 K in Fig. 2(c) shows that the virgin [zero-field-cooled (ZFC)] magnetization curve lies above the reverse magnetization curve between 5.5 and 8 kOe. This type of behavior would be viewed as anomalous if the irreversibility is resulting only from macroscopic currents flowing in the bulk of the sample as per the description of irreversible magnetic response in terms of the critical-state model.[27] However, it may be possible to understand this so-called anomalous response in terms of irreversibility arising from surface barrier effects as proposed recently by Zeldov et al.[28] in the context of studies for $\mathbf{H}\|c$ in the Bi2212 system. Such a behavior was noted[4,7] at $T > 85$ K [see, for instance, Fig. 5(b)], where the two-component nature of magnetic response has also been clearly visible [see Fig. 5(c)]. We may, therefore, take the existence of the observation, $|M_{ZFC}(H)| < |M(H\downarrow)|$ (over a limited field interval near H_{max}), also to be a signature of the presence of two-component magnetic response. The M-H loops below 25 K and above 35 K appear to be nominally one component. However, a careful examination of an expanded portion of the M-H loop at 75 K in Fig. 4(d) reveals the presence of the behavior described above, i.e., the virgin magnetization curve lies above the reversed magnetization hysteresis curve (obtained on reversal of field from a given H_{max}) in the field interval, 70 Oe $< H <$ 260 Oe. We also note that the irreversibility field value at 75 K depends on the maximum field H_{max} up to which we ramp the field during the virgin forward run. The $H_r(T)$ value of 84 Oe at 75 K in Fig. 6 corresponds to H_{max} of 150 Oe. No anomalous behavior is evident at 75 K if the H_{max} value is limited to 150 Oe (data not shown here). However, the $H_r(T)$ value at 75 K from the data of Fig. 4(d) would be reckoned to be greater than 260 Oe. The dependence of the $H_r(T)$ value on H_{max} appears to be

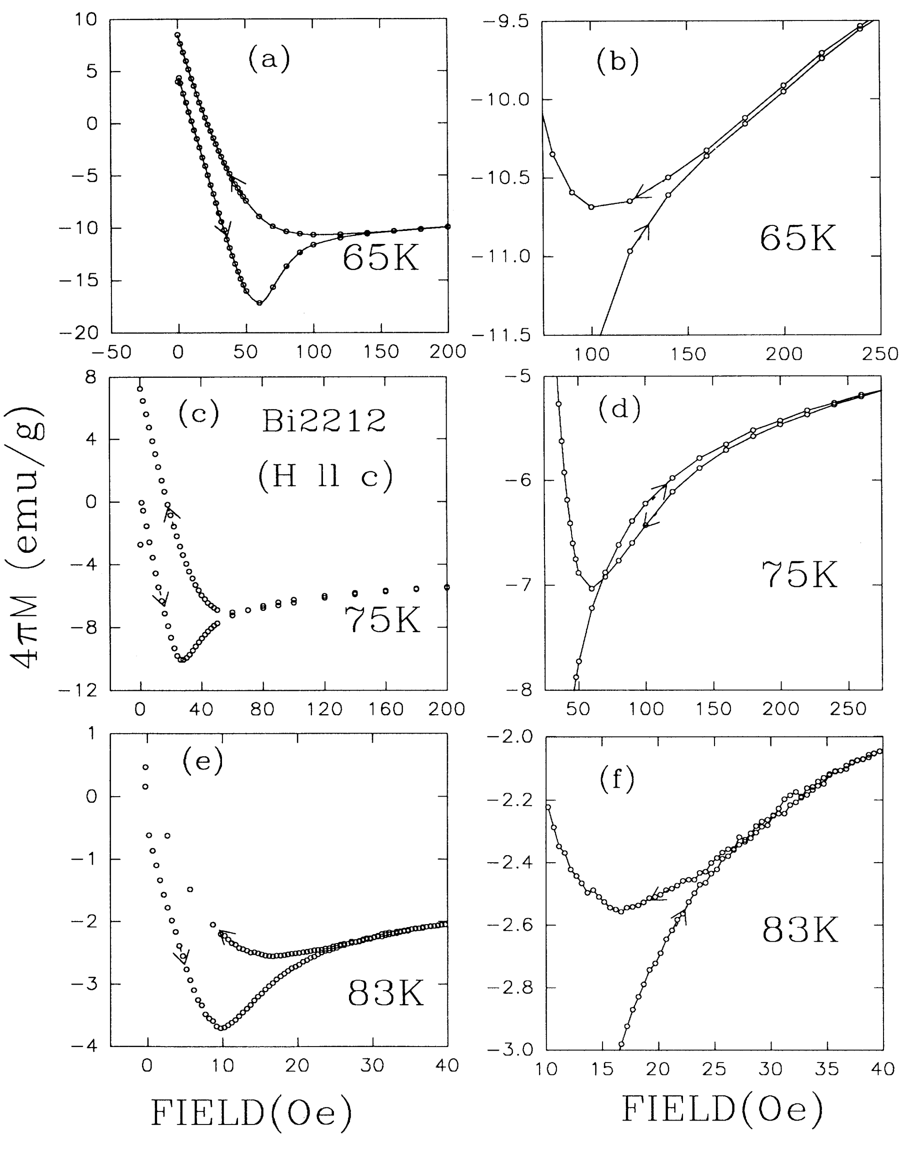

FIG. 4. Magnetization hysteresis curves in Bi2212 for $\mathbf{H}\|c$ at 65 K, 75 K, and 83 K, respectively. For each temperature, the behavior near the corresponding $H_r(T)$ value has been shown on an expanded scale. An anomalous behavior may be noted at 75 K in (d) where the ZFC magnetization curve lies above the reversed magnetization curve for $H > 75$ Oe.

another curious facet associated with two-component magnetic response, as has also been pointed out earlier from the examination of data at $T > 85$ K.[4,7] This kind of curious behavior is not observed between 5 and 15 K, between 35 and 65 K, and between 78 and 83 K. To summarize the scenario in terms of one-component and two-component magnetic responses, it may be stated that we have observed the following transformations (for $\mathbf{H}\|c$) in our Bi2212 sample: 5–15 K (one component) $\rightarrow$25 K (two component) $\rightarrow$35–73 K (one component) $\rightarrow$75 K (two component) $\rightarrow$78–83 K (one component) $\rightarrow$85 K (dimensional crossover temperature) $\rightarrow$85–88 K (two component). A very rapid increase in $H_r(T)$ values sets in below about 25 K, and a somewhat sharper increase in $H_r(T)$ values also appears to occur below about 75 K. Around both these temperatures, 25 and 75 K, vivid signatures of two-component magnetic response are evident.

In the case of ceramic samples of high-T_c cuprates, the two-component magnetic response is considered to arise from intragrain and intergrain regions. In ceramic samples, intergranular links decide the transport critical current density, J_c^t. $J_c^t(H)$ at a given field H has been observed to be lower during the virgin ramp up of the field, as compared to that during the reverse cycle.[29] $J_c^t(H)$ is a single-valued function of H; the history dependence in the measured value of $J_c^t(H)$)arises from the influence of grain magnetization on the field value in the intergrain regions. The history-dependent transport current density data in ceramic samples are usually explained[30] in terms of an idea of Evetts and Glowacki.[31] It is argued[30,31] that intergrain region experiences more field (than the applied field) during the virgin run, and lesser field (than the applied field) during the first reverse run due to a larger pinning effect within the grain. The magnetization counterpart of the above observation may be stated as, the magnitude of the (intergranular) magnetization value at an applied field H will be lower during the virgin run when compared to that during the reverse cycle. There is, however, an additional complication in the case of magnetization values as compared to measured field dependence of $J_c^t(H)$. As stated above, magnetization data in a ceramic sample comprises superposition of hysteretic responses from both intergrain and intragrain regions. The two hysteretic responses are dictated by the respec-

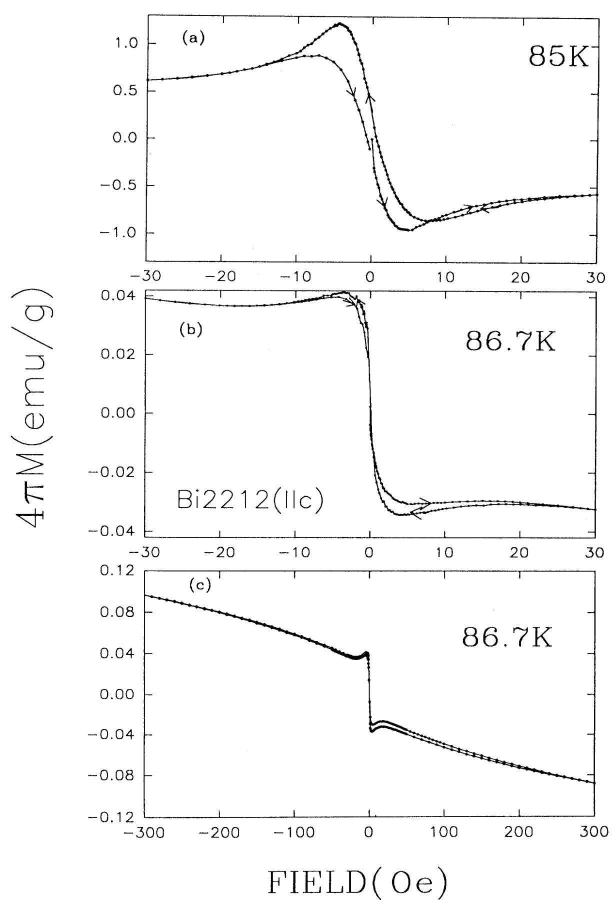

FIG. 5. Magnetization hysteresis loops in Bi2212 for $\mathbf{H}\|c$ at 85 K and 86.7 K. The ZFC magnetization leg lies above the reversed magnetization leg over the entire field region ($0<H<30$ Oe) at 86.7 K (b), whereas at 85 K, the anomalous behavior is evident only for $H>8$ Oe. The magnetization loop between ± 300 Oe at 86.7 K (c) has an unusual shape, corresponding to a two-component magnetic response as described in Ref. 7.

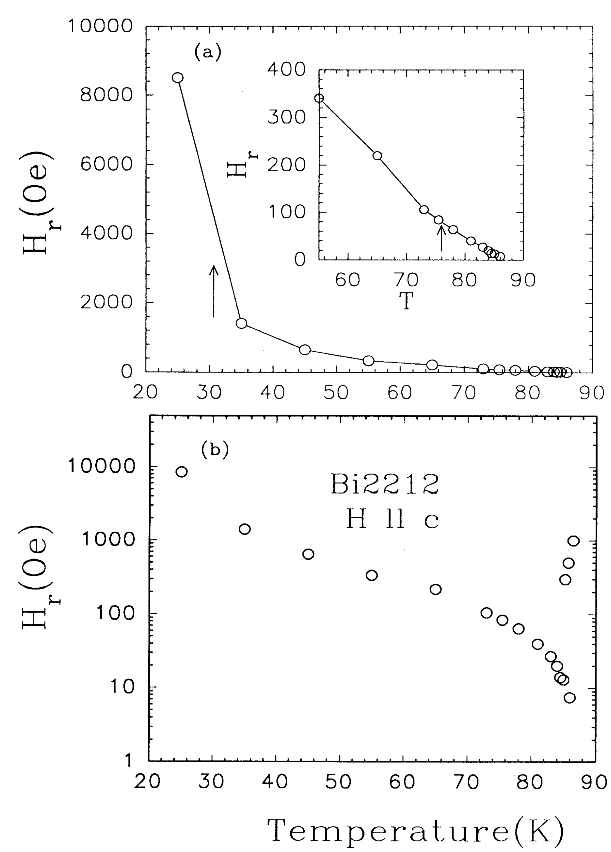

FIG. 6. The variation of irreversibility field (H_r) values with temperature on (a) linear and (b) log scales, respectively. The arrows in (a) mark the temperatures around which signatures of the two-component magnetic response are visible.

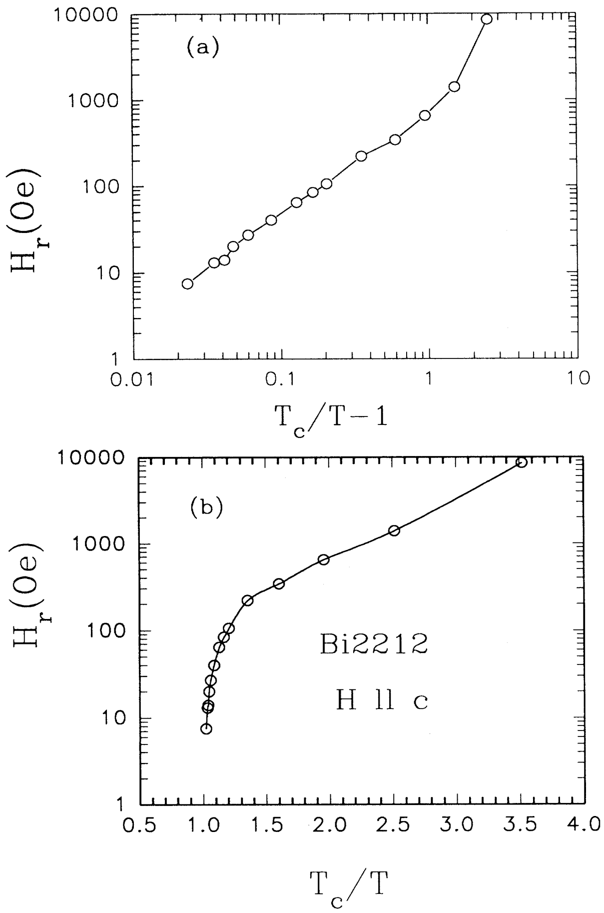

FIG. 7. Plot of H_r values vs (a) $(T_c/T-1)$ and (b) T_c/T, respectively.

tive current densities and the intergranular contribution has an additional complexity due to the history dependence of $J_c^I(H)$.

In the present case of a single-crystal specimen of Bi2212, we would like to argue that at $T=0$ K, the single-crystal sample comprises aligned microcrystallites strongly Josephson coupled to each other across inter-unit-cell weak links. Each microcrystallite further comprises submicrocrystallites, Josephson coupled to each other across inter-unit-cell weak links of higher strength. This subdivision can, in principle, go on (depending on different types of inter-unit-cell weak links present) till we reach submicrocrystallites of thickness equal to only a few unit cells. It is pertinent to recall here that on the basis of transport data in superlattices of Bi-Sr-Ca-Cu-O, Geballe[32] has asserted that a pair of CuO_2 bilayers, i.e., one unit cell of Bi2212, is adequate to give the $R=0$ state at a temperature of about 80 K. If the scenario state above is plausible, two-component magnetic response in a single-crystal sample of Bi2212 ($\mathbf{H}\|c$) can arise from (sub)microcrystallites and the weak coupling across (sub)microcrystallites, somewhat analogous to the responses from grains and intergranular regions in a ceramic superconducting sample. We wish to reemphasize here that so long as Josephson coupling between microcrystallites is relatively strong, the strongly coupled microcrystallites appear to behave as a single-component type-II superconductor. As the coupling weakens, we observe two-component magnetic response, and when the coupling becomes completely ineffective, we again observe only one-component magnetic response attributable only to individual microcrystallites.

Following Clem,[33] a vortex line (for $\mathbf{H}\|c$) in a Josephson-coupled cuprate superconductor is often viewed as a stacking of pancake vortices localized in CuO_2 planes (or bilayers or trilayers). In a perfectly stoichiometric case, the pancakes will be equispaced. However, if we allow for the possibility of inter-unit-cell weak links, in addition to the inevitably present intra-unit-cell weak links, the distance between a neighboring pair of pancakes would be more across inter-unit-cell weak links. In the vortex-solid-like phase (the so-called pinned state or the vortex glass state) with $R=0$,[34] the vortex lines are expected to be rigid entities with pancake vortices nearly perfectly stacked on top of each other for each vortex line. In the vortex-liquid-like phase, the freely moving vortex lines either comprise, easily cutting and joining, smaller lines or completely decoupled pancake vortices in different layers. Since the decoupling (or cutting) across different types of weak links in a vortex line is expected to happen in stages such that the decoupling across intra-unit-cell weak links occurs at the highest temperature resulting in a true dimensional crossover phenomenon, we expect the transformation from the vortex-solid phase to the vortex molten phase to occur in a number of repetitive cycles as temperature and field values are varied. The electrical transport data in the dissipative state of the Bi2212 system[35] allow for the possibility of an intermediate phase (in between the vortex glass and the vortex liquid phases) in which the motion of vortices is partially collective (or thermally activated across a barrier), i.e., not completely uncorrelated or diffusive. To conceive this intermediate phase, we are tempted to schematically view the vortex solid phase as a columnar phase (see Fig. 8) of disc-shaped objects (a kind of *discotic* liquid crystalline phase made up of disclike molecules or polymers[36]). To continue with this speculation further, the breakage of vortex lines across inter-unit-cell weak links may be viewed as analogous to transformation from quasicolumnar phase to a quasi-isotropic phase (molten phase) via a quasinematic phase as in *discotic* liquid crystals.[36] In liquid crystals parlance, the columnar phase is considered a two-dimensional solid and its melting will be effected by two-dimensional fluctuations, as desired by the analysis of Schilling *et al.*[6] The quasinematic phases may be viewed as sources of two-component magnetic response corresponding to a response from individual disclike entities and another response from the superconducting network made up of Josephson current flows across them. To summarize, if we have only one type of inter-unit-cell weak link (in addition to the inevitably present intra-unit-cell weak link), we expect to see the transformations as shown in the chart comprising Fig. 9.

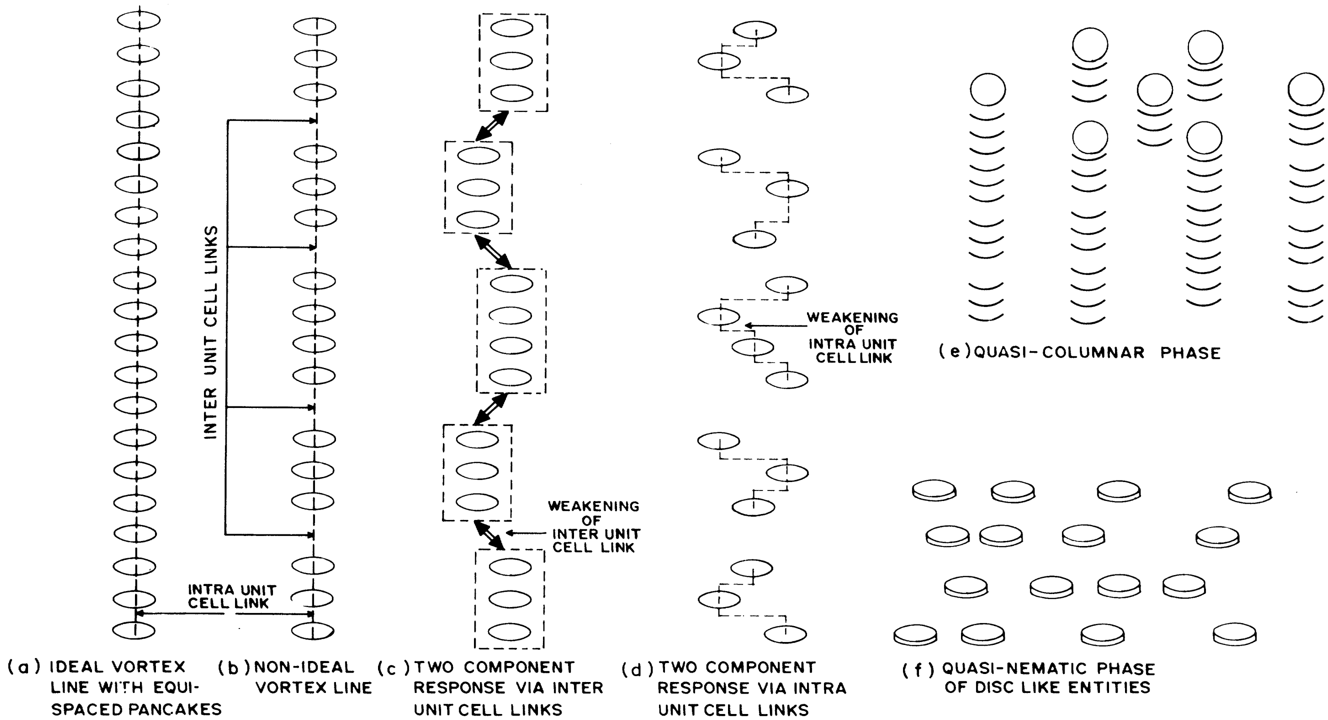

FIG. 8. Schematic plots showing (a) ideal vortex line made up of equispaced pancake vortices corresponding to existence of only intra-unit-cell link; (b) nonideal vortex line made up of pancake vortices which are not equispaced; it comprises inter- as well as intra-unit-cell links; (c) weakening of inter-unit-cell linkages at $T \ll T_c$; (d) weakening of intra-unit-cell linkages as $T \rightarrow T_c(0)$; (e) quasi-columnar vortex solid phase and (f) quasi-nematic phase of diskettes as in discotic liquid crystals (see Ref. 36).

IV. CONCLUSION

To conclude, we have presented a correlation between the occurrence of noticeable change in the irreversibility behavior with the appearance of two-component magnetic response in isothermal magnetic hysteresis data for **H**$\|c$ in a single-crystal specimen of Bi2212. We have attempted to identify the two-component magnetic behavior with the responses from inter-unit-cell linkages and the microcrystallites. The above correlation appears to imply that as the linkages get strengthened, the irreversibility increases. We have speculated that the transformation from vortex pinned state (which is like a columnar phase) to vortex molten state occurs via an intermediate state which may be like the vortex liquid crystalline discotic nematic phase.[36]

$T \ll T_c$:	SINGLE CRYSTAL VORTEX SOLID COLUMNAR PHASE (One Component Response in Magnetization Data)	Weakening of -------------> Inter-Unit Cell Linkages	VORTEX LIQUID CRYSTALLINE NEMATIC PHASE comprising disc like entities. Each diskette is probably like a sub-columnar phase (Two Component Response in Magnetization Data)	Complete Breakage ----------------> of Inter-Unit Cell Linkages	VORTEX MOLTEN PHASE of freely cutting and joining sub-columns. (One Component Response in Magnetization Data; Quasi- diffusive behaviour in electrical transport data)
$T \rightarrow T_c$:	MICROCRYSTALLITES QUASI-COLUMNAR PHASE (One Component Response in Magnetization Data)	Weakening of -------------> Intra-Unit Cell Linkages	VORTEX LIQUID CRYSTALLINE PHASE : Quasi-nematic phase of pancake vortices (Two Component Response in Magnetization Data)	Complete Breakage ----------------> of Intra-Unit Cell Linkages	VORTEX GAS LIKE PHASE of freely moving pancake vortices (One Component Response in Magnetization Data)

FIG. 9. A chart showing the transformation from "one-component response" to "two-component-like response" in magnetization data when one type of inter-unit-cell (extrinsic) and the intrinsic intra-unit-cell links are present. The inter-unit-cell links are expected to be weaker than the intra-unit-cell link and they would get severed at a relatively smaller temperature value. The intra-unit-cell link gets severed last at a temperature close to the nominally determined $T_c(0)$ value.

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