Magnetic relaxation, current-voltage characteristics, and possible dissipation mechanisms for high-T_c superconducting thin films of Y-Ba-Cu-O

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We propose a mechanism that may account for the temperature-insensitive relaxation of the magnetic-shielding current in epitaxial thin films of $YBa_2Cu_3O_{7-\delta}$. We show that such relaxation is related to the shape of the current-voltage (J-E) characteristic of the superconductor in its critical state. The weak temperature dependence of the relaxation implies a temperature-insensitive J-E characteristic that resembles that of conventional type-II superconductors when a spatial variation of critical current density (J_c) is present. We suggest such a distribution of J_c as an explanation for the apparently large and temperature-insensitive relaxation observed in $YBa_2Cu_3O_{7-\delta}$.

$YBa_2Cu_3O_{7-\delta}$ samples exhibit a relatively slow onset of dissipation when the critical current density (J_c) is approached, even for high-quality samples.[1] Such dissipation presents itself in two different but related forms. It causes the decay of the otherwise persisting magnetic-shielding current,[1-3] and it leads to a finite voltage rise when a transport current below the critical current density is driven through the superconductor by external electromagnetic forces.[4-6]

Transport studies of such dissipation on high-J_c samples are usually limited to the region near T_c because the large critical current density makes low-temperature studies difficult. Dissipation in this temperature region can be described by the conventional flux-creep model of Anderson and Kim.[4-6,7] Studies of the relaxation of the magnetic-shielding current, however, do not suffer from experimental difficulties arising from the large value of J_c and can be performed conveniently down to much lower temperatures. (On the other hand, studies of magnetic relaxation very close to T_c are difficult due to the diminishing value of J_c.) Relaxation measurements over a wide temperature range generally lead to a temperature-insensitive relaxation rate once the temperature is below approximately 80% of T_c.[8] Large relaxation was observed by us[9] to persist down to 4.2 K and has been reported to persist down to the millikelvin region,[10] contradicting the simple Anderson-Kim thermal-activation model. A temperature-insensitive relaxation rate would in the simple Anderson-Kim model lead to a pinning barrier U_0 that was linearly increasing with temperature so as to keep U_0/kT constant.[9] This unexpected temperature dependence of the derived barrier height, together with the fact that most of the transport measurements are performed near T_c and magnetic relaxation studies are not, has caused a significant amount of confusion in seemingly suggesting that magnetic-relaxation studies give much lower value for the U_0 than transport measurements.

Hagen *et al.*[3] and Griessen and co-workers[11] have suggested that such an anomalous temperature dependence of U_0 can be explained if one generalizes the simple Anderson-Kim model to include a distribution of pinning-barrier heights, and the appropriate distribution functions have been calculated to best describe the observed temperature dependence of the relaxation. A difficulty of their approach is the sensitivity of the resulting distribution function to the detailed temperature dependence of the measured relaxation. This approach also has difficulty in explaining the large residual relaxation in the millikelvin region,[10] since that would require a monotonically increasing distribution of pinning-barrier heights down to practically zero energy level. This is unlikely because the vortex-vortex interaction will provide a minimum-energy barrier.

We propose an alternative model in which the measured quantity U_0/kT can equivalently be viewed as the exponent of the current-voltage (J-E) characteristic that is empirically well approximated by a power-law form. The power-law-shaped J-E characteristic and the weak temperature dependence of the power-law exponent suggest that the dissipation may be caused by a spatial variation of the critical current density—a phenomenon well known in conventional type-II superconductors. The microstructural variation responsible for such spatially inhomogeneous J_c is not dealt with in this paper, although we point out that in principle any variation of the superconducting order parameter could cause such variations of the local critical current density.

At a given dissipation level, the same loss mechanism is responsible for both the magnetic relaxation and the transport J-E characteristics with the two related through simple electrodynamics on a macroscopic scale. When averaged over a length scale much larger than the vortex spacing, the sample dissipation can be described by a nonlinear phenomenological constitutive relation. At a given temperature,

$$E = E(J,B) \ . \tag{1}$$

Experimentally, relation (1) is a slowly varying function of the magnetic field B. For our thin-film measurments, the influence of the magnetic field generated by J (the self-field) on the J-E characteristic (1) can usually be ignored. This is because the self-field induced by the current in the thin film usually stays below a few hundred gauss—much lower than the applied magnetic field which is of the order of a few kilogauss. Thus a transport measurement on a microbridge can be viewed as a direct measurement of the spatially averaged current-voltage relation (1). Such direct-transport measurements indicate that the macroscopic J-E relation is fairly well approximated by a power-law form

$$E = \alpha J^n \tag{2}$$

with a large exponent ($n \sim 10$ to 60) as will be discussed later in this paper. Such a J-E characteristic is different from the Anderson-Kim flux-creep model which predicts an exponential-like curve that can be written as

$$E = \frac{v_0 H}{c} \exp\left[-\frac{U_0}{kT} \right] \sinh\left[\frac{JHVX}{ckT} \right] \tag{3}$$

to the lowest order when the nonlinearity of pinning potential height dependence on current density is ignored. In (3) H is the applied magnetic field, VX is the four-dimensional volume of the vortex bundle, and v_0 is the prefactor proportional to the attempt frequency of the vortex bundle in the pinning well. Notice that to distinguish a high-exponent power-law-shaped J-E curve (2) from that of an exponential curve (3), the two curves need to be compared over a range of a few decades in E.

The magnetic relaxation relates to the J-E characteristics (1) on a phenomenological level only and does not provide any new information about microscopic mechanisms of the dissipation. To see this we assume a simple thin-film geometry where the magnetic field is applied perpendicular to the surface of the film which is parallel to the Cu-O planes. In this case (1) can be considered to be isotropic and can be substituted by the scalar form (2). We may now relate (2) to the Maxwell equations $\nabla \times \mathbf{E} = -(1/c)\partial_t \mathbf{B}$ and $\nabla \times \mathbf{B} = (4\pi/c)\mathbf{J}$ to solve for the time-dependent relaxation of $J(t)$. To the lowest order, assuming that the sample is in its critical state, one obtains from such argument the time dependence of the current density[9]

$$\ln J(t) = \ln J(0) - \frac{1}{n-1} \ln\left[\frac{t}{\tau_0} + 1 \right] , \tag{4}$$

which can for large n be linearized to give a nearly logarithmic decay rate

$$J(t) \approx J(0) \left[1 - \frac{1}{n} \ln\left[\frac{t}{\tau_0} + 1 \right] \right] \tag{5}$$

with

$$\tau_0 \approx \frac{\pi l a^3 \Lambda}{3cJ^{n-1}(0)(n-1)} ,$$

where a stands for the sample radius and $\Lambda \approx 4\pi a^2/c^2$ is the self-inductance of the film.

A similar exercise with the Anderson-Kim J-E characteristics (3) leads to the usual flux-creep relation

$$J(t) \approx J(0) \left[1 - \frac{kT}{U_0} \ln\left[\frac{t}{\tau_0'} + 1 \right] \right] , \tag{6}$$

with

$$\tau_0' \approx \frac{2\pi a^2 kT}{H^2 v_0 VX} .$$

Comparing (5) and (6) in the long-time limit ($t \gg \tau_0$ and τ_0'), it is evident that the time dependence of systems with a large-n power law J-E and that of the Kim-Anderson flux-creep characteristic are very similar. The only difference between (5) and the Anderson-Kim expression (6) is that in (5) the power-law exponent n replaced the Anderson-Kim model's U_0/kT.

We now show that the experimental J-E characteristics can indeed be relatively well described empirically by a power-law form and that the magnetic relaxation measurement indeed correlates with that of the transport measured J-E characteristics. The existence of such a correlation allows us to use the magnetic relaxation measurement as a more convenient tool for the studies of the temperature dependence of the relaxation phenomenon down to liquid-helium temperatures. This approach avoids the difficulties associated with large current-density transport measurements.

Magnetic-shielding current relaxation was measured through the dipole moment generated by the shielding current. A Princeton Applied Research 155 vibrating sample magnetometer was used for the measurement of the dipole moment. The Bean critical-state model was used to relate the dipole moment $m(t)$ and the current density $J(t)$, which we assume to have a nearly constant spatial distribution. Transport J-E characteristics were measured on the same film after it was patterned down to 200-μm bridges. All films were c-axis textured, *in situ* grown on MgO (100) substrates with the off-axis sputtering technique developed at Stanford.[12] Typical film thickness is around 4000 Å. The films have $J_c \approx 3 \times 10^7$ A/cm^2 at 4.2 K in an applied magnetic field of a few kilogauss.

Figure 1 shows a representative magnetic hysteresis loop of such a film. An example of the relaxation of the magnetic-shielding current at 6 kilogauss is shown in Fig. 2. The magnetic relaxation measurements were performed after saturation of the sample into its critical state. This was done by first ramping the applied magnetic field up to the desired value and then holding the field steady when the relaxation data were taken. For our measurements in the time domain of between 5 and 500

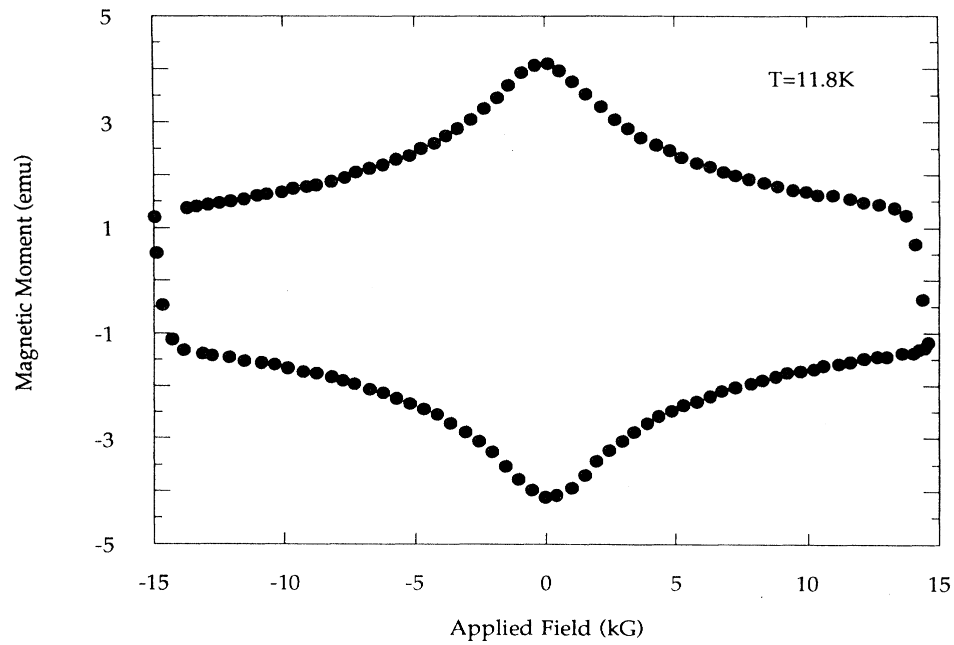

FIG. 1. Hysteresis loop of the $YBa_2Cu_3O_{7-\delta}$ film at 11 K measured by the vibrating sample magnetometer.

sec after the field ramping was stopped, the relaxation behavior appeared to be nearly logarithmic in time. Thus a limit of $t \gg \tau_0, \tau_0'$ was assumed. Processes on the time scale shorter than that involve a careful definition of the magnetic-field ramping process—a topic that will be further discussed in another publication.[13]

A typical set of transport J-E characteristics is shown in Fig. 3 measured with the magnetic field applied perpendicular to the film surface and the macroscopic direction of the transport current. The data follow approximately a power-law form over three orders of magnitude in voltage, indicating the deviation from the simple

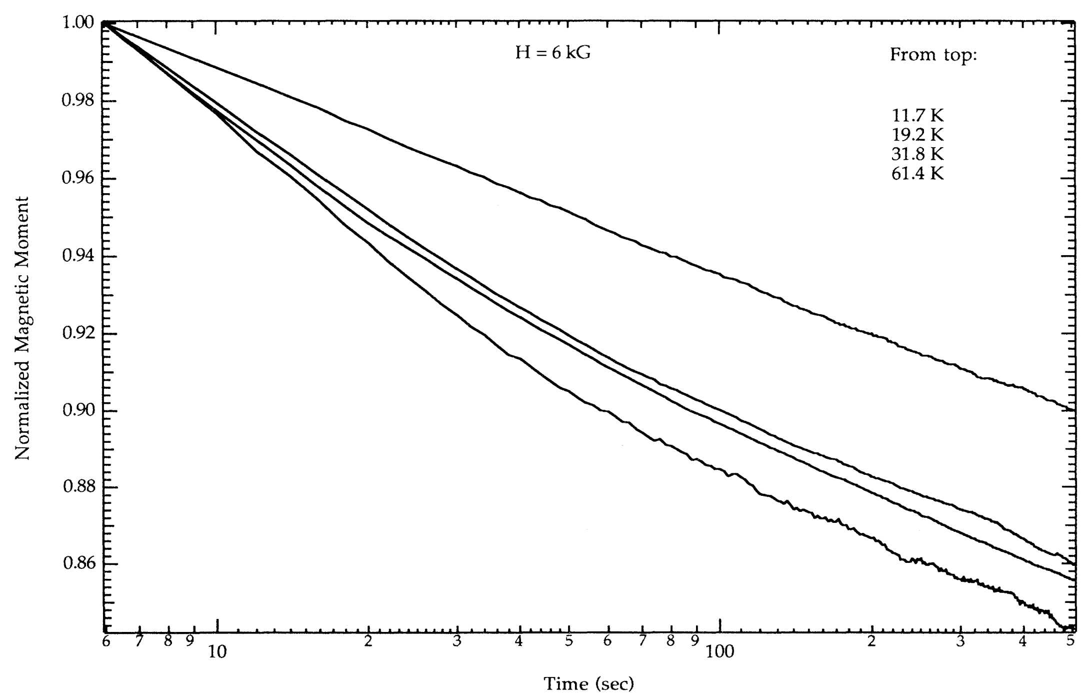

FIG. 2. Relaxation of the magnetic shielding current measured through the decay of the dimagnetic moment at different temperatures. Applied field: 6 kilogauss.

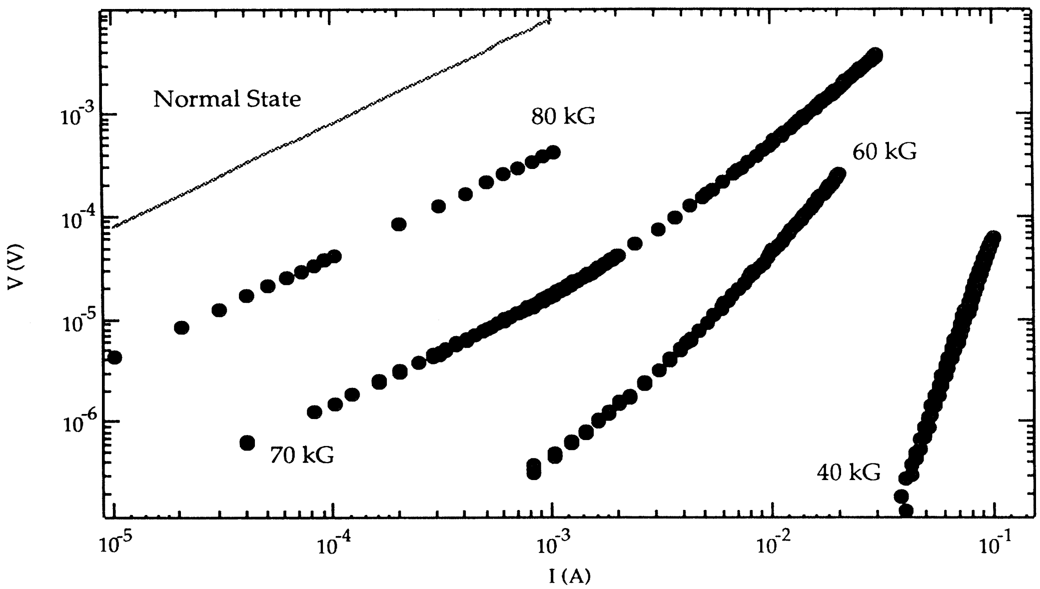

FIG. 3. Transport measurements of the current-voltage characteristic on a microbridge, 200 μm wide, 2 mm long between voltage leads. Data where taken at 75 and 11 K below T. The normal-state resistivity at T_c is indicated by the straight line.

Anderson-Kim relation (3). Relation (2) is therefore used to describe the data.

The power-law exponent n can be extracted by applying relations (2) and (5) to our transport and magnetic relaxation data, respectively. The results can be compared to provide a consistency check on the theory discussed so far. Magnetic relaxation data were taken over a wide temperature range, while the transport data for the 200-μm bridge are restricted to the region near T_c due to measurement current limits. The n value deduced from the two measurements are compared in Fig. 4. The high-temperature parts of the magnetic and transport data show a consistent trend in their temperature dependence, although the measurements do not exactly overlap in temperature. Transport measurements on a different film patterned into a 6-μm bridge are also shown in Fig. 4 for comparison; this gives consistent values for the exponent n. We thus believe that the theoretically derived correlation between magnetic relaxation and transport J-E characteristics does describe the actual behavior of our films. In what follows we proceed to use magnetic relaxation as a tool to study the J-E characteristics' power-law exponent n as a function of temperature. Note, however, that magnetic relaxation over hundreds of seconds corresponds to a dissipation level orders of magnitudes below that of the transport measurements. The fact that the transport and the relaxation measurements lead to similar n value suggests the same power-law-shaped J-E characteristic extends much farther down in dissipation level than has previously been measured by transport probes.

The weak temperature dependence of n in Fig. 4 over a large temperature region suggests that the sharpness of the J-E characteristic is rather temperature independent—a phenomenon inconsistent with the simple Anderson-Kim creep picture. However, such a temperature-insensitive power-law J-E characteristic is commonly observed in other type-II superconductors[14] and is considered, in general, to be a consequence of a spatially inhomogeneous distribution of the critical current density.

We suggest that such a distribution of J_c could be responsible for the weak temperature dependence of n observed in $YBa_2Cu_3O_7{-}\delta$. We take, for rough estimate purposes, a special limiting case worked out by Hampshire and Jones[15] in treating filamentary Nb_3Sn superconductors. By assuming that the inhomogeneous regions are electrically in series and by assuming a simple Gaussian distribution of local J_c, their relation leads to

$$n=\sqrt{\pi/2}\left[\frac{J_c}{\sigma}\right]^2 , \tag{7}$$

where σ stands for the standard deviation of the critical current-density distribution. Relation (7) describes the inhomogeneity-related broadening of the average J-E characteristic when measured on a length scale much larger than the size of the inhomogeneous domains. A schematic of such broadening is shown in Fig. 5. This relationship indicates that an n value of around 40 would follow from a spread of local J_c of only $\sigma/J_c\sim 16\%$. Variations of J_c on this order of magnitude are very likely to exist in our $YBa_2Cu_3O_{7-\delta}$ films, since our microstructural studies indicate the existence of significant densities of stacking faults and other types of defect structures on a length scale much finer than the sample radius. Strictly speaking, the distribution of our critical current is not one dimensional and therefore the inhomogeneous current is not simply in series. An inhomogeneous distri-

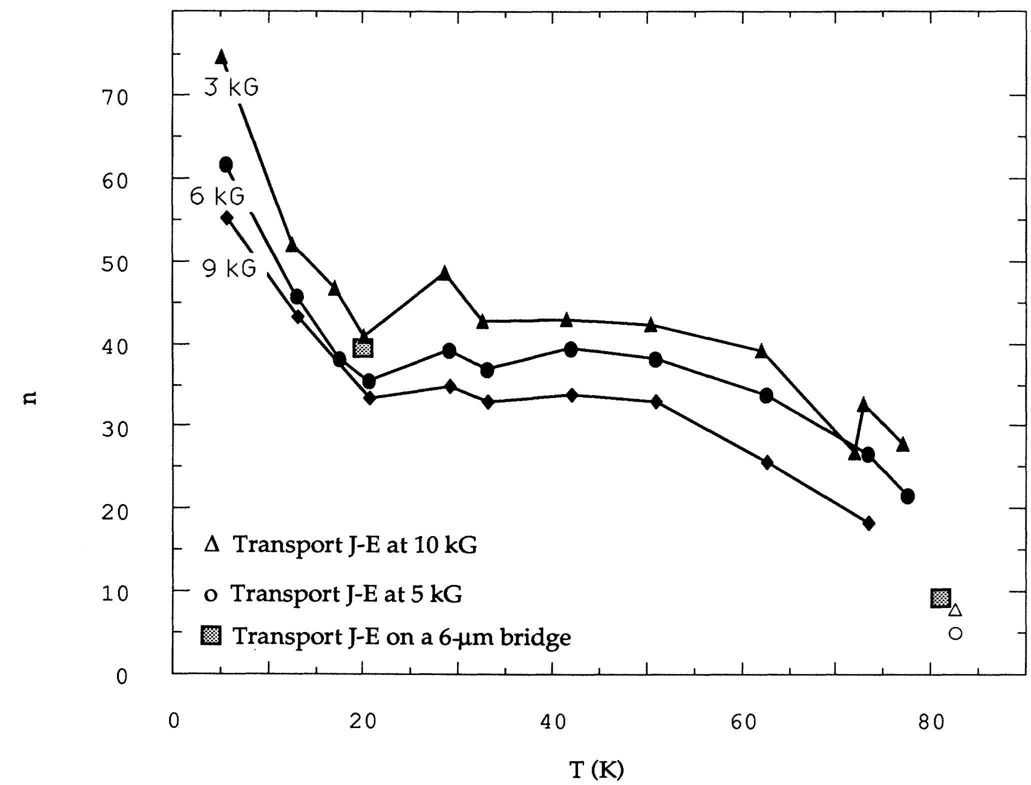

FIG. 4. Comparison of n values obtained from magnetic relaxation and from transport studies. Transport data on the 6-μm bridge were obtained on a film made *in situ* by laser ablation in zero applied magnetic field in a study of edge barriers (Ref. 17).

bution that is in parallel will also affect the I-V characteristics,[9] although a quantitative prediction depends on the local form of the I-V curve. The exact quantitative treatment of the problem is still to be worked out, but the similarities between the conventional superconductors and the high-T_c materials is suggestive.

It is of interest to compare the temperature dependence of n above 20 K with that of conventional type-II superconductors. Shown in Fig. 6 is the temperature dependence of the n value extracted from the measurements on Nb_3Sn by Hampshire and Jones.[15] When compared with Fig. 4, there is a clear resemblance. It is known for $YBa_2Cu_3O_{7-\delta}$ that, over a large temperature range, the functional form of the temperature dependence of the critical current is similar for samples with critical current densities which differ by orders of magnitude.[16] This is consistent with what we see here, because a rather constant temperature dependence of n implies a temperature insensitive distribution of J_c—in other words, sections of the sample must have a very similar temperature dependence in their local J_c, even though the value of J_c varies.

The temperature dependence of local J_c may not necessarily stay the same over the entire temperature range. The observed rise of n below 20 K as shown in Fig. 4 implies in the foregoing interpretation that the distribution there is changing with temperature. An increase of the order parameter in the weak-link region, for example, can directly cause an increase of local J_c and therefore affect the distribution. If we adopt this argument, then the distribution of J_c tends to narrow as the temperature is lowered below 20 K. However, the finite relaxation observed in the millikelvin region suggests that the distribution effect could still be dominating or else new physics such as quantum fluctuations becomes relevant.

In conclusion, we have determined a phenomenological relation between the magnetic relaxation and the shape of transport J-E characteristics. The J-E characteristic can

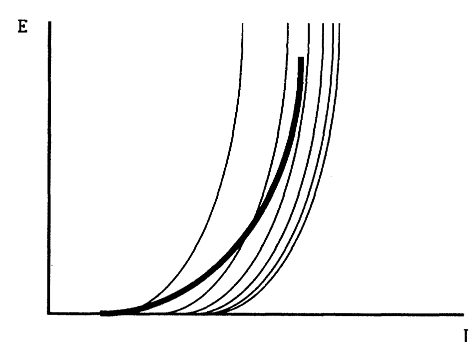

FIG. 5. Schematic representation of the inhomogeneity-related broadening of the overall current-voltage characteristic. The thin curves represent the local J-E characteristics while the dark curve represent the macroscopic current-voltage characteristic when measured on a length scale much longer than the inhomogeneity's domain size.

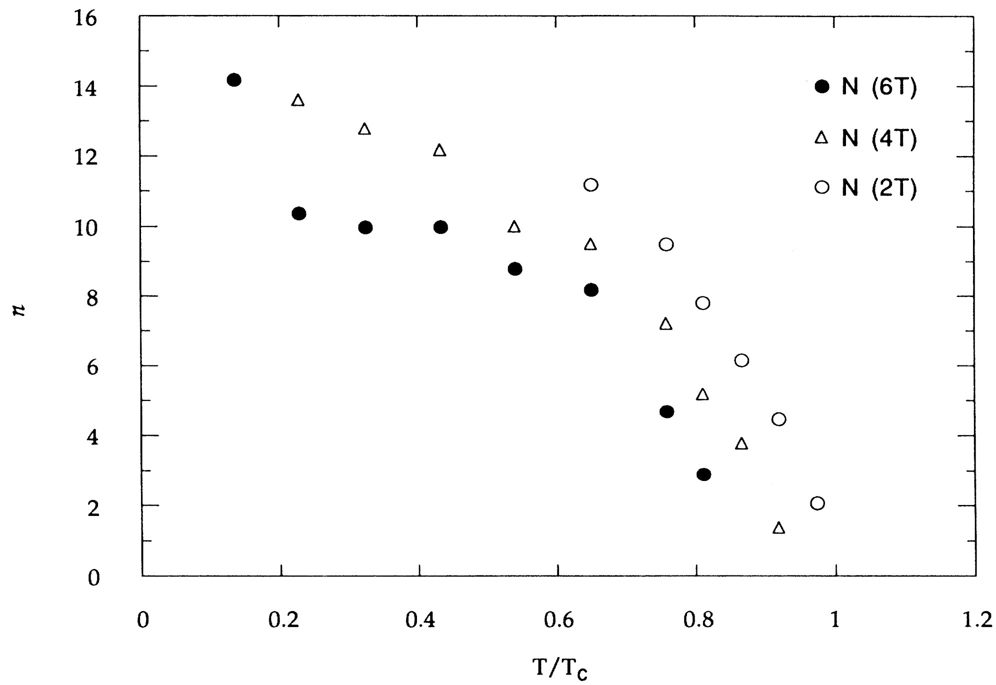

FIG. 6. Temperature dependence of the power-law exponent for Nb_3Sn wires. Data extracted from Ref. 15.

be well approximated by a power-law form. We suggest that the power-law exponent n is limited by a small spatial distribution of the local critical current density. Therefore, although results near T_c may show thermally activated behavior, the thermal effect may be overshadowed by a J_c distribution once the value U_0/kT exceeds a distribution limited power-law exponent n. As a result, caution should be used when comparing experimental results with models dealing with the properties of the intrinsic vortex state, since sample inhomogeneity effects discussed in this paper can complicate the analysis.

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