

Irreversibility Lines of Rb_3C_{60} Fullerene†M. F. Tai¹ and M. W. Lee²¹*Institute of Physics, National Chung Cheng University,
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The irreversibility line $H_{irr}(T)$ of isotropic superconducting Rb_3C_{60} fullerene ($T_c = 30.5 \pm 0.1$ K) was obtained from $M(T)$ curves for low fields and $M(H)$ curves for high fields, respectively. It can be described by a simple power-law equation, $H_{irr}(T) = H_{irr}(0)[1 - T/T_0]^\gamma$. Based on experimental data the best fitting results to this scaling relation are determined as: $\gamma = 2.04 \pm 0.16$, $H_{irr}(0) = 47.0 \pm 5.2$ T, and $T_0 = 30.4 \pm 0.2$ K for $H_{irr} \leq 1$ T ($T \leq 0.8T_c$); and $\gamma = 1.50 \pm 0.03$, $H_{irr}(0) = 89.8 \pm 1.6$ T, and $T_0 = 30.9 \pm 0.4$ K for $1 \text{ T} \leq H_{irr} \leq 5$ T ($T < 0.2T_c$). The characteristic crossover field of $H \sim 1$ T separates the two regions of different γ values. The existence of γ value near 2 suggests that the irreversibility line close to T_c is possibly due to thermally activated vortex-lattice melting that may have occurred in our Rb_3C_{60} sample. The other value of $\gamma = 1.5$ may be attributed to a vortex-glass phase transition in low temperatures.

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Numerous experiments on high- and low- T_c superconductors (HTS's and LTS's) have revealed the presence of the irreversibility lines $H_{irr}(T)$ [1,2]. When the temperature is close to T_c , i.e., in the low H_{irr} region, these lines can be well fitted to a simple power-law equation: $H_{irr}(T) = H_{irr}(0)[1 - T/T_0]^\gamma$. γ values so obtained are dependent on the transition mechanisms from irreversible to reversible magnetization, and they vary from 1.3 to 5.5 [1-5]. Many theoretical models [1-5] have been proposed to explain different γ values of this power-law relationship. They include flux-line (vortex) lattice melting model that requires $\gamma = 2$, and vortex-glass transition model that calls for $\gamma = 3/2$. Other models, e.g., thermal depinning or vortex creep, give other γ values.

It was found that when T is lower than $0.8T_c$, the irreversibility lines may deviate significantly from the above described power-law behavior [1,2]. Such deviations indicate that other temperature-dependent forms in the high field and low temperature region exist. There are some proposed more general equations that may describe H_{irr} . For example, it was found that in an aligned sample [3] and randomly oriented sample of $(\text{Bi,Pb})_2\text{Ca}_2\text{Sr}_2\text{Cu}_3\text{O}_y$ [4] $H_{irr} \sim (1 - T/T_c)^\gamma$ for $H_{irr} < 200$ G and $H_{irr} \sim \exp(-T/T_c)$

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for $H_{irr} > 200$ G. Recently, Huang *et al.* [1] studied the $H_{irr}(T)$ lines for $\text{HgBa}_2\text{CaCu}_2\text{O}_y$ oxides, and Song *et al.* [2] did for $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_y$ superconductors. They found that the temperature dependencies of $H_{irr}(T)$ for both samples deviate from the power-law relationship. They also proposed a two-dimensional exponential function, $H_{irr}(T) = a \exp(-T/T_c)$, for low-temperature high-field range. They based their theory on the breakdown of the interlayer coupling in the conduction channel. It seems that the deviation of H_{irr} from the power relationship is strongly dependent on the nature of materials. For example, ≥ 5 T for Y-based HTS' s, ~ 0.2 T for Hg-based HTS' s, ~ 0.02 T for Bi-based HTS' s, and ~ 0.01 T for Tl-based HTS' s [1,2].

In this work, we study the irreversibility line of superconducting Rb_3C_{60} polycrystalline sample over the magnetic fields up to 5.5 T. This result is compared with the various functional forms for the $H_{irr}(T)$ line reported in all HTS' s.

The sample preparation procedures for a well-characterized Rb_3C_{60} fullerene with $T_c = 30.5$ K were described in detail elsewhere [5-8]. All *dc* magnetic data were measured by a Quantum Design superconducting quantum interference device (SQUID) magnetometer. The temperature dependencies of zero-field-cooled (ZFC) and field-cooled (FC) magnetization, $\mathbf{M}(\mathbf{T})$, were performed at various magnetic fields from 1 mT to 5 T. The field-dependent magnetization curves; $\mathbf{M}(\mathbf{H})$, were measured in fields ranging up to ± 5.5 T at different temperatures from 5 K to 25 K. The irreversibility temperature/field (T_{irr}/H_{irr}) can be determined by the merging point of ZFC and FC $\mathbf{M}(T)$ curves at a constant field. Alternatively, they can be obtained from the merging point of the $\mathbf{M}(\mathbf{H})$ curves measured at a fixed temperature for both the increasing- and decreasing-field branches.

Fig. 1 shows the $H_{irr}(T)$ line of superconducting Rb_3C_{60} fullerene with fields up to 5.5 T. Except for open circles all symbols shown in Fig. 1 are determined from $\mathbf{M}(T)$ curves. The H_{irr} for $1 - T/T_c > 0.1$ are also obtained by $\mathbf{M}(\mathbf{H})$ curves, which is represented as open circles in Fig. 1. The irreversibility fields obtained from both methods showed the same temperature-dependent behavior except with a difference of magnitude of $H_{irr}(0)$. Because large background noises were produced from the Pyrex sample holder in higher field, the measured signals of high-field FC $\mathbf{M}(T)$ were vague and hard to recognize. Hence high-field H_{irr} determined by $\mathbf{M}(T)$ curves is less accurate than that by $\mathbf{M}(\mathbf{H})$ curves.

The irreversibility lines as functions of temperature are expressed by the simple power-law equations: $H_{irr}(T) = H_{irr}(0)[1 - T/T_c]^\gamma$ with $\gamma \sim 2$ for $1 - T/T_c < 0.2$ and $\gamma \sim 3/2$ for $1 - T/T_c > 0.1$. Here $H_{irr}(0)$ is the irreversibility field at $T = 0$ K. T_o is considered to be the irreversibility temperature at zero applied field, $T_{irr}(H = 0)$, which approaches the zero-field superconducting critical temperature, $T_c(H = 0)$. Experimental data are used to determine $H_{irr}(0)$, T_o and γ . The best fitting results are obtained as follows: in low-field ($H_{irr} < 1$ T, i.e. $1 - T/T_c < 0.2$) region $\gamma = 2.04 \pm 0.16$, $H_{irr}(0) = 47.0 \pm 5.2$ T, and $T_o = 30.4 \pm 0.2$ K; whereas $\gamma = 1.50 \pm 0.03$, $H_{irr}(0) = 89.8 \pm 1.6$ T, and $T_o = 30.9 \pm 0.4$ K in $1 \text{ T} \leq H_{irr} \leq 5 \text{ T}$ ($1 - T/T_c > 0.1$). The fitting parameters of T_o in both lines are close to the superconducting critical temperature of Rb_3C_{60} at zero field, $T_c(H = 0)$. The temperature dependence of exponential form, $H_{irr}(T) = a \cdot \exp(-T/T_c)$, as the above description in introduction, is not applicable to our Rb_3C_{60} sample, even for field up to 5.5 T. The absence of exponential forms in irreversibility lines may be attributed to the isotropic structure in alkali-metal-doped C_{60} and no interlayer decoupling effect as described in HTS' s.

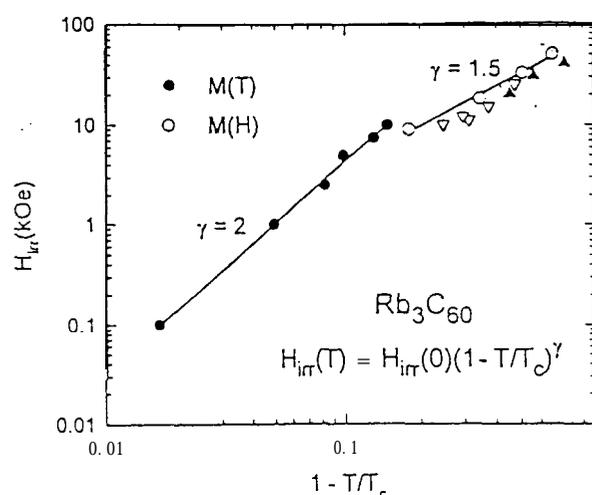


FIG. 1. Irreversibility line $H_{irr}(T)$ as a function of reduced temperature $(1 - T/T_c)$ of Rb_3C_{60} polycrystalline sample. Except that open circles are obtained from $M(H)$ curves at various temperatures, all symbols are determined from $M(T)$ curves at various temperatures. The two real lines are the fitting curves to power-law equations: $H_{irr}(T) = H_{irr}(0)[1 - T/T_c]^\gamma$ with $\gamma \sim 2$ for $1 - T/T_c < 0.2$ and with $\gamma \sim 3/2$ for $1 - T/T_c \geq 0.1$.

The much extensive work on the irreversibility line has been carried out on various HTS' s and LTS' s. This simple power-law relation with different γ has also been observed in these superconductors. Different γ value, e.g., $\sim 3/2$ for Y1:2:3, $\sim 2/5$ for Hg 1:2:1:2, $\sim 11/2$ for the Bi- and Tl-based HTS' s, and ~ 2 for Nb and Sb-based LTS' s, seem to correlate well with the degree of the anisotropy and crystalline of these superconductors [1,2]. Many models, including thermal depinning, vortex lattice melting ($\gamma = 2$), and vortex-glass transition ($\gamma = 3/2$), have been proposed to explain the power-law relationship of $H_{irr}(T)$ and γ values in HTS' s and LTS' s.

Based on the nonlocal elasticity theory of the Lindemann criterion, $\gamma = 2$ for the irreversibility line at near T_c is likely due to the occurrence of thermally activated vortex-lattice melting in our Rb_3C_{60} sample [5]. Such interpretation has been adapted to account for vortex melting in Nb_3Sn [9], Nb-Ti [9], and Nb [10]. On the other hand, the irreversibility line in low temperature region with $\gamma = 3/2$ may be attributed to the occurrence of a vortex-glass phase transition, which has been used to explain the $H_{irr}(T)$ of Y1:2:3 superconductors.

The irreversibility line of powdered Rb_3C_{60} fullerene was obtained from the measurements of both $M(T)$ and $M(H)$. It obeys simple power-law equations: $H_{irr}(T) = H_{irr}(0)[1 - T/T_c]^\gamma$ with $\gamma \sim 2$ for $1 - T/T_c < 0.2$ and $\gamma \sim 3/2$ for $1 - T/T_c > 0.1$.

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