Thermal nucleation of the normal state in superheated superconducting tin grains

H. Dubos
Groupe de Physique des Solides (UA 17 CNRS), Universités Denis Diderot and Pierre et Marie Curie, 75251 Cedex 05, Paris, France and Centro de Física Nuclear, Universidade de Lisboa, 1699 Lisbon, Portugal

T. A. Girard
Centro de Física Nuclear, Universidade de Lisboa, 1699 Lisbon, Portugal and Groupe de Physique des Solides (UA 17 CNRS), Universités Denis Diderot and Pierre et Marie Curie, 75251 Cedex 05, Paris, France

G. Waysand
Groupe de Physique des Solides (UA 17 CNRS), Universités Denis Diderot and Pierre et Marie Curie, 75251 Cedex 05, Paris, France

P. Perrier and V. Jeudy
Groupe de Physique des Solides (UA 17 CNRS), Universités Denis Diderot and Pierre et Marie Curie, 75251 Cedex 05, Paris, France and Centro de Física Nuclear, Universidade de Lisboa, 1699 Lisbon, Portugal

D. Limagne
Groupe de Physique des Solides (UA 17 CNRS), Universités Denis Diderot and Pierre et Marie Curie, 75251 Cedex 05, Paris, France

J. Seco
Centro de Física Nuclear, Universidade de Lisboa, 1699 Lisbon, Portugal

J. I. Collar
PPE Division/CERN, 1211 Geneva 23, Switzerland; Groupe de Physique des Solides (UA 17 CNRS), Universités Denis Diderot and Pierre et Marie Curie, 75251 Cedex 05, Paris, France; and Centro de Física Nuclear, Universidade de Lisboa, 1699 Lisbon, Portugal

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Suspensions of superheated type-I superconducting Sn microspheres of 16–25 and 10–25 μm diameters were irradiated at temperatures below 1 K and above 2 K by decay electrons from $^{14}$C and $^{35}$S, respectively. Measurements of the radiation-induced gaps in the superheating transition curves indicate a full heating of the smallest grain volume of each suspension, contrary to a partial heating model based on the difference between quasiparticle relaxation and diffusion rates in Sn. The phonons are in thermal equilibrium with the quasiparticles when the normal state is nucleated. [S0163-1829(98)05834-2]

I. INTRODUCTION

The thermodynamic response of metastable type-I superconducting microspheres to irradiation has received considerable attention in recent years as a result of their possible applications in particle detection.\(^\text{1,2}\) Thermal nucleation of the normal state in the superheated material is induced by the interaction of radiation if the energy deposited is sufficient to raise its temperature across the phase boundary. How much of the volume is required to be heated in order to induce nucleation of the normal state has, however, been a point of some dispute.

There are essentially two possibilities: some or all. In ‘‘local-heating’’ descriptions, only a fraction of the volume is required; in a ‘‘global-heating’’ description, the entire volume is uniformly heated above the phase line before the normal state is nucleated.

To our knowledge, a complete description of ‘‘local heating’’ has never been satisfactorily elaborated. Generally, the volume fraction has been related to the heating of an equatorial surface area, or nucleation germ (surface defect, boundary, or impurity). The significance of defects was demonstrated by single-microsphere (hereafter referred to as ‘‘grain’’) experiments in which a variation of the superheated-to-normal transition field was observed for variation of the grain orientation relative to the applied field.\(^\text{3,4}\) Similar results were obtained on single-grain rotations under irradiation;\(^\text{5}\) the effect is more pronounced at increasingly lower temperatures.

On the basis of a series of irradiation measurements with single grains, Frank \textit{et al.}\(^\text{6}\) recently advanced a ‘‘unified’’ heating model that combines both ‘‘local’’ and ‘‘global’’ heating behaviors by whether or not an equatorial defect is heated above the phase line before or with the uniform heating of the grain, which in turn depends on (1) the location of the interaction site relative to that of the defect, and (2) the difference between the materials-dependent thermal relaxation and diffusion rates of the excited quasiparticles. For materials in which the diffusion time is significantly less than the phonon relaxation time, no local temperature can be es-
established: the defect is uniformly heated with the grain volume, resulting in a global-heating behavior. In contrast, for materials in which the relaxation is sufficiently faster than the diffusion, such as Sn/In, only a ‘‘warm spot’’ is created, which if sufficiently near a defect provokes its nucleation before the remainder of the volume, resulting in a local-heating behavior.

The model of Ref. 4 comes closest to including the detailed microscopic aspects of the involved energy transport. As appealing as it may appear, and independent of questions regarding the applicability of the near-equilibrium relaxation rates of Kaplan et al.5 in such nonequilibrium situations, the experimental basis given for the model must, however, be discounted in toto: neither the Sn grains of Refs. 3 and 4 nor the In grains of Ref. 4 exhibited the full superheating field (Hsh). A partial compilation3,4,6,7 of recent Hsh measurements for Sn is shown in Fig. 1. The fact that the transition fields of Refs. 3 and 4 are near the bulk thermodynamic critical field8 (Hc) suggests that the observed transitions occurred from intermediate states,9 which would both lower the transition fields and generate the low-energy tail in the irradiation-induced transition spectra that are observed.

Nonetheless, the possibility of any local-heating behavior for Sn has a significant impact on the current development of Sn-based devices for particle-detection applications, since only those materials exhibiting a global-heating behavior can generate a well-defined energy threshold. The experiments of Ref. 4 were performed on relatively large (34–46 μm) diameter grains using heavily ionizing 4-MeV α particles that are generally stopped within about 10 μm of the grain surface. We here report a series of experiments on suspensions of smaller diameter, fully metastable Sn grains, under irradiation by the decay electrons of 14C and 35S in which the energy depositions are distributed across the grain volumes, which clearly demonstrate a global heating in their normal-state nucleation. Although single-grain measurements in principle yield more precise results, uncertainties arising from size distributions and local-field effects can be reduced by working with well-separated suspensions of grains. This approach does not require the extreme sensitivity necessary in single-grain measurements, and has generally yielded more accurate and reliable determinations of the Ginzburg-Landau parameter in type-I superconductors.2,7

In Sec. II, we describe in further detail the distinction between global- and local-heating models, indicating their different manifestations in single-grain and multigrain experiments. Section III describes our experiments, the results of which are given in Sec. IV.

II. THEORETICAL CONSIDERATIONS

A. Single grain

The phase diagram of a single superheated grain is shown in Fig. 2. The precise location of a grain within the diagram is ideally at 1/2 the applied field (Hsh), corresponding to its maximum local surface field as a result of demagnetization. The presence of a nucleation germ effectively raises this position nearer the phase line as a result of its ability to scatter quasiparticles.10

The temperature distance (ΔT) to the phase boundary is fixed by the grain location (Ta, Hsh). Thermal nucleation of the normal state depends only on the magnitude of the deposited energy (∆E):

\[
ΔE \leq V_{\text{heated}} \int_{T_a}^{T_a+\Delta T} C_s \, dT,
\]

where \( V_{\text{heated}} \) is the heated volume of the grain; \( C_s \) is the volume specific heat of the superconductor, given by

\[
C_s = [a \gamma T_c e^{-b/T_c} / T_a + \alpha T_a^3],
\]

where \( \{a,b,\alpha,\gamma\} \) are materials-dependent parameters. The first and second terms of Eq. (2) describe the electron and phonon contributions, respectively. In Fig. 2, \( T_a+\Delta T \) is related to the superheated field by

\[
T_a+\Delta T = [T_{a}^{2} + \frac{1}{2} T_{a}^{2} (\Delta H/H_{sh}(0))]^{1/2},
\]

which is derived from the BCS temperature variation of the supercritical field.11

\[
H_{sh}^{\text{local}}(T) = H_{sh}^{\text{local}}(0) [1 - (T_a/T_c)^2].
\]

The lowest \( H_d \) at which a grain transition occurs, corresponding to the largest induced \( \Delta T \), is given by
\[ \int_{T_a}^{T_a+\Delta T_{\text{max}}} C_d dT = \Delta E_{\text{max}} / V_{\text{min}}, \]

where \( \Delta E_{\text{max}} \) is the maximum energy deposition in the grain, and \( V_{\text{min}} \) is the minimum \( V_{\text{heated}} \). For a sufficiently large energy of the incident electron, \( \Delta E \) in a grain is approximately linear with the electron range. This implies that \( \Delta E_{\text{max}} \) is proportional to the grain radius (\( R \)). In a global-heating model, the grain is uniformly heated, such that \( V_{\text{min}} = V_{\text{grain}} \), and \( \Delta E_{\text{max}} / V_{\text{grain}} = \int_{T_a}^{T_a+\Delta T_{\text{max}}} C_d dT = R^{-2} \) is a scaling with the coherence length (\( \xi \)). Since \( \xi(T) \approx \xi_0 (1 - T/T_c)^{-1/2} \),

\[ \Delta E_{\text{max}} / V_{\text{grain}} = [3 \Delta E_{\text{max}}/4 \pi \xi_0^2] [1 - T/T_c] \]

where \( \xi_0 \) is the Pippard coherence length of the pure metal (Sn: 0.2 \( \mu \)m). For energy depositions further away from the defect site, \( V_{\text{heated}} \approx 0.5 V_{\text{grain}} + V_{\text{defect}} \approx 0.5 V_{\text{grain}} \). In any event, the transition occurs at a lower \( H_a \) than expected from \( \Delta E_{\text{max}} / V_{\text{grain}} \).

In the model of Ref. 4, the local-heating behavior of Sn results from the short time scale (\( \approx 1 \) ns) for quasiparticle relaxation to the energy gap by phonon emission, relative to the longer spreading time (\( \approx 100 \) ns) of the quasiparticles across the grain diameter. In this case, \( V_{\text{heated}} = V_{\text{grain}} \); the quasiparticles quickly relax to phonons, creating a “warm spot” within the grain volume which then spreads diffusively. Although the warm quasiparticles continue to exchange energy with cold phonons during the diffusion process, the normal-state nucleation in these materials is initiated prior to a full warming of the phonon system; for the Sn results of Ref. 4, only 20–50% of the deposited energy is in the phonon system.

### B. Multigrains

The situation for an ensemble of grains is a priori more complicated than for a single grain, owing to the inherent variation of the individual local fields resulting from the distribution of sizes, defects, and diamagnetic interactions between the grains.\(^{14} \) These yield an apparent spreading of the transition fields of the ensemble, as shown in the typical unirradiated experimental differential superheating curve of a test suspension of Fig. 3, which was recorded during a ramp of \( H_a \) from zero to well above \( H_{sh} \) at fixed temperature. The width of the curve results from the local-field variations, and for small filling factors corresponds to the distribution of local magnetic-field states populated by the grains. The last grains to undergo a transition are those more metallurgically perfect, and they experience virtually no diamagnetic effects since the majority of the previously superconducting ensemble has already become normal.

Reduction of the filling factor reduces the effects of the diamagnetic interactions.\(^{15} \) Nonetheless, given the nonuni-

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**FIG. 3.** Superposition of differential superheating curves (dN/dH) at 480 mK, with (○) and without irradiation (■).

**FIG. 4.** An effective phase diagram of a grain’s suspension. As indicated, electrons from the lower part of the energy-loss spectrum are capable of flipping only grains with small \( \Delta T \). Sufficiently long irradiation times or intense radiation fields establish an effective hot border at \( H_a \); grains introduced into the region between the superheated phase boundary and the “hot border” via increase of the applied magnetic field can transition only by thermal nucleation.
Eq. (5) is satisfied. This is observed in Fig. 3; the gap in the differential superheating curve of the suspension under irradiation results from the transiting of grains to the normal state during a pause at \( H_p = 300 \, \text{G} \) inserted into the field ramping, which has been recorded separately. The slope of the high-field region of the gap results from the transition of grains introduced into the hot border zone by increasing \( H_p \) following the pause.

The return of the suspension’s superheating curve to its unirradiated behavior occurs when \( H_p \) has been raised to \( H_{sh}(T_a) \). The maximum gap width \( (\Delta T_{\text{max}}) \) thus provides a measure of \( \Delta T_{\text{max}} \) induced by the maximum energy loss of the irradiation, which is defined by the minimum \( V_{\text{heated}} \) of the suspension at \( H_p \). Despite the many-body complications, the energy loss remains proportional to the electron range, and \( \Delta E_{\text{max}} / V_{\text{grain}} \) varies as \( R^{-2} \). In a global-heating description, \( \Delta H_{\text{max}} \leftrightarrow \Delta H = H_{sh} - H_{\text{step}} \) of Ref. 4, \( V_{\text{min}} \) corresponds to the smallest grain of the suspension and \( \Delta E_{\text{max}} / V_{\text{min}} = \text{const} \) for all temperature. For local-heating models, \( \Delta H_{\text{max}} \gg \Delta H \): \( V_{\text{min}} \) continues to correspond to that of a defect, so that \( \Delta H_{\text{max}} \) scales with \( V(\xi) \) and must therefore exhibit a temperature dependence.

### III. EXPERIMENT

Measurements of \( \Delta H_{\text{max}} \) were conducted for two different suspensions of Sn grains, of 10–25 \( \mu \text{m} \) diameters for \( T_a > 2 \, \text{K} \) and 16–25 \( \mu \text{m} \) diameters for \( T_a < 1 \, \text{K} \). In each case, data acquisition was accomplished using fast-pulse electronics.\(^{16}\) The normal-state nucleation of a grain creates discontinuities in the flux cut by a detecting loop, which is connected via two transformers to a LeCroy HQV810-based preamplifier. Only irreversible flux entry is detected: reversible flux changes are outside of the bandwidth of the preamplifier. The input signal is shaped with a fast LeCroy amplifier and discriminated with a LeCroy MVL407 ultrafast voltage comparator. Computer control synchronizes the magnetic step rise with the opening of a gate during which flux pulses are detected. Owing to the transformer presence, the current timing resolution of the system is limited to about 10 \( \mu \text{s} \).

#### A. Temperatures \( > 2 \, \text{K} \)

The grains were of spherical geometry, varying in diameter from 10–25 \( \mu \text{m} \), and were part of a sample made by sonic dispersion of the molten metal in an oil bath, size filtration using calibrated sieves, and uniform folding\(^{17}\) into a paraffin dielectric. The suspension consisted of three disks, each 5 mm in diameter and 0.3 mm thick. Each disk was estimated to contain \( 1.4 \times 10^5 \) tin grains based on a volume filling factor of 20\%. The disks were spaced along a 100-\( \mu \text{m} \)-diameter U-shaped copper wire loop of 225 \( \mu \text{m} \) width imprinted on an epoxy board.

Each disk was covered with one equal-diameter, tissue paper foil containing 5 \( \mu \text{Ci} \) of evaporated \( ^{35} \text{S} \), a pure beta-decay source with an end-point energy of 167 keV, and a half-life of 82 days. Owing to the width of the sense coil, only about 7\% of the total grains were sensitive to measurement.

The sensor was operated in a pumped \(^4\text{He} \) refrigerator; the temperature was pressure regulated, providing a nominal stability of \( 10^{-3} \, \text{K} \). The applied magnetic field, generated perpendicular to the loop by a niobium Helmholtz coil of 10 cm diameter and 1 cm separation, provided a field stability of 0.01 G and homogeneity of 3\% over the detector region.

Measurements\(^{18} \) were conducted at 2.30, 3.10, and 3.44 K with the radiation source installed. For each measurement, the detector was tuned by first cooling the suspension at zero field. The applied field was then raised until the last grain has transited to the normal state; the threshold level of the discriminator was adjusted to the minimum level at which no noise effect was observed in the curve.

Following electronic tuning, the applied field was then ramped in increments of 0.29 G in time intervals of 0.02 s at 2.30 K, 0.04 s at 3.10 K, and 0.09 s at 3.44 K to a mean value in the linear part of the superheating curve (well above the region in which intermediate states may exist) and a 3-s “pause” effect before the ramping was again continued until the last grain had transited to the normal state. This protocol, shown schematically in Fig. 5(a), was followed by a return of the field to zero; it was repeated many times.

#### B. Temperatures \( < 1 \, \text{K} \)

Sn grains of 16–25 \( \mu \text{m} \) diameter were also part of a sample made by sonic dispersion of the molten metal in an
s. This measurement field is only due to irradiation. The measurement period, 50 s, was selected on the basis of the observed transition rate of the superconducting grains, which as seen in Fig. 6 is typically exponential.

Following measurement, the field was raised until all grains were in the normal state, then recycled to zero and the procedure repeated many times. The variation in $\Delta H$ was 1 G.

The pause at $H_p + \Delta H$ resulted from systematic tests without irradiation in which the field was raised by an amount $\Delta H$ just after reaching 300 G and before the measurement, as shown in Fig. 5(c). In this case, for $\Delta H < \Delta H$, no transitions were recorded; for $\Delta H > \Delta H$, transitions occurred because of the delay in the magnetic-field response as a result of the field coil damping. Because of this damping, an additional 1-s delay at 300 G + $\Delta H$ was required in order for the field to reach its command value.

IV. RESULTS AND DISCUSSION

The maximum magnetic gap widths measured in each temperature range are presented in column 2 of Table I, together with the corresponding $\Delta T_{\text{max}}$ in column 3. For the $T > 2$ K measurements, $\langle \Delta T_{\text{max}} \rangle$ was obtained via Eq. (3) with $H_{\text{sh}}^0(0) = 570$ G. The $T < 1$ K measurements, however, required a different treatment since Eq. (4) is not well established for $T_a \ll T_c$. Moreover, because of the slow variation in the determination of $H_{\text{sh}}$ with temperature for this region, a small error in the determination of $H_{\text{sh}}(T)$ induces a large error in $\Delta T$. In this case, $\langle \Delta T_{\text{max}} \rangle$ was determined from the $\Delta H$ measurement and from a separately measured $H_{\text{sh}}(T)$ curve.

The last column of Table I is calculated from the integral of Eq. (1) with the $\{ \langle \Delta T_{\text{max}} \rangle \}$ column entries using Eq. (2) with \{a, b, c, $\gamma$\} = \{7.85, 1.42, 0.101 keV/K $^4$ $\mu m^3$, 0.6718 keV/K$^2$ $\mu m^3$\} for Sn. As evident, the integral is constant within errors for each suspension over its respective temperature range.

A. Variation of $\Delta E_{\text{max}}/V$ with temperature

The last column of Table I indicates no variation in $\Delta E_{\text{max}}/V$ for either temperature range, especially for $T > 2$ K, where the effects of a $V_{\text{heated}}(\xi)$ would be expected to appear. We show in Fig. 7 these results together with the

<table>
<thead>
<tr>
<th>$T$ (K)</th>
<th>$\Delta H_{\text{max}}$ (G)</th>
<th>$\Delta T_{\text{max}}$ (K)</th>
<th>$\int_r^\infty \Delta T_{\text{max}} C_s dT$ (keV/$\mu m^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;1$ K</td>
<td>16–25-$\mu m$ $\otimes$ suspension, $^{13}$C irradiation</td>
<td>0.85±0.04</td>
<td>10.0±0.12</td>
</tr>
<tr>
<td></td>
<td>0.48±0.02</td>
<td>14.0±0.12</td>
<td>0.51±0.08</td>
</tr>
<tr>
<td></td>
<td>0.20±0.02</td>
<td>16.0±0.12</td>
<td>0.75±0.08</td>
</tr>
<tr>
<td></td>
<td>0.10±0.01</td>
<td>17.0±0.12</td>
<td>0.86±0.08</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt;2$ K</td>
<td>10–25-$\mu m$ $\otimes$ suspension, $^{35}$S irradiation</td>
<td>3.44±0.04</td>
<td>3.2±0.1</td>
</tr>
<tr>
<td></td>
<td>3.10±0.02</td>
<td>3.6±0.1</td>
<td>1.24±0.17</td>
</tr>
<tr>
<td></td>
<td>2.30±0.02</td>
<td>6.3±0.1</td>
<td>2.93±0.23</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The temperature variation of $\Delta E_{\text{max}}/V(\xi)$ anticipated from the lowest temperature result in each temperature range. For $T < 1$ K, where $\xi = \xi_0$, the results are insufficiently sensitive to be conclusive; however, the normalization implies $R_{\text{heated}} \approx 35\xi_0$, suggesting a $V_{\text{heated}}$ much larger than would be expected by any local-heating description. For the $T > 2$ K results, the sensitivity is significantly better than the predicted temperature variation.

**B. Heating of the phonon system**

Analysis of the phonon system warming, corresponding to Figs. 4 and 5 of Ref. 4, is shown in Fig. 8, together with the measured $\{\Delta H_{\text{max}}\}$ from Table I. The contours are obtained by computing the $T + \Delta T_{\text{max}}$ in the integral of Eq. (1), which is necessary to provide the same value of $\Delta E_{\text{max}}/V_{\text{min}}$ to within 1%. The area defined within the solid lines represents the results for $C_v = C_{\text{electron}} + C_{\text{phonon}}$, with $R_{\text{min}} = R_{\text{measurement}} \pm 1\mu$m; the area within the dotted lines, $C_v = C_{\text{electron}}$ only. For the $T > 2$ K data, the theoretical contours overlap and the data supports either hypothesis; the $T < 1$ K results, however, lie well within the area anticipated from a full specific heat (electron + phonon), in contrast to the corresponding Fig. 5 of Ref. 4: nucleation of the normal state proceeds with a fully warmed phonon system.

**C. Heated volumes**

The $\Delta E_{\text{max}}$ of each decay for different grain radii was computed using a simulation that randomly emits electrons from a distributed source consistent with the energy distribution of the decay, and tracks them through both the paraffin and grains in accordance with Moliere scattering; the energy loss in each medium is computed using the Bethe-Bloch equation. Figure 9 shows the results for the $^{14}$C decay electrons. For the minimum radius of the $T > 2$ K and $T < 1$ K ensembles, $\Delta E_{\text{max}} = 45 \pm 1$ and $65 \pm 1$ keV, respectively. Divided by the respective mean values of the last column of Table I, these yield $R_{\text{heated}}$ of 8.0 ± 2.1 and 5.0 ± 0.086 $\mu$m for the $T < 1$ K and $T > 2$ K measurements, respectively, equivalent to the smallest grain radius in each suspension and well above $\xi_0$.

According to the discussion of Sec. II A, the local-heating behavior observed in Ref. 4 for Sn and In is characterized by a low-energy tail in the differential superheating curves extending 30–50 G below $H_{\text{step}}$ (see Fig. 3 therein); in principle, the lowest recorded transition field of this tail should correspond to the nearest-defect energy deposition, and $V_{\text{heated}} \approx V(\xi)$. In fact, these lowest transition fields imply $R_{\text{heated}} \approx 8.5$ $\mu$m, well above $\xi_0$ but sufficiently less than $R_{\text{grain}}$ to further suggest the intermediate-state presence.
V. CONCLUSIONS

In order to investigate the local-heating conclusion of Ref. 4 for Sn, we have performed a series of electron irradiation experiments on two different, fully metastable, suspensions of Sn grains in two different temperature ranges below \( T_c \).

Measurements for \( T < 1 \) K with a suspension of Sn grains 16–25 \( \mu \)m in diameter irradiated by the decay electrons of \(^{14}\)C clearly demonstrate that nucleation of the normal state proceeds with a fully warmed phonon system; measurements for \( T > 2 \) K with a suspension of Sn grains 10–25 \( \mu \)m in diameter irradiated by \(^{35}\)S decay electrons clearly deny both the temperature variation of \( \Delta E_{\text{max}} / V(\xi) \) and \( V_{\text{heated}} = 0.5V_{\text{min}} \). In each case, the heated volume derived from the maximum gap width induced in the respective superheating curves by the irradiation, combined with the calculated maximum energy deposition in the material, is in good agreement with the smallest grain of its suspension.

We thus conclude that the electron-induced thermal nucleation of a suspension of superheated superconducting Sn grains is consistent with a global heating of the grain volume, contrary to the model of Ref. 4.

The energy of the \( \alpha \) irradiation of Ref. 4 experiments is generally deposited within 10 \( \mu \)m of the grain surface. Although the electrons of these experiments have a maximum range of some 70 \( \mu \)m in Sn, about 40\% of the incident activity is also stopped within 10 \( \mu \)m, with energy sufficient to raise a defect volume by several K throughout the measurement range. However, the distinction between local- and global-heating behavior of the Ref. 4 model is based on whether or not the material-dependent quasiparticle relaxation rate is less than the diffusion rate, independent of the energy deposition mechanism. The defect presence is signaled by the step at \( H_{\text{step}} \) in the measurements of Ref. 4, but the local-heating behavior is manifested by the low-field tail below \( H_{\text{step}} \). According to Ref. 4, the presence of this tail in Sn is explained by the more rapid quasiparticle relaxation rather than diffusion rate. This tail is also observed in the In irradiations, and a local-heating behavior is similarly concluded for the same reason; for Al and Zn, no tail is observed and these transitions are designated as "global" because the relaxation rate is slower than the diffusion. Observation of the local-heating tail in the Sn/In experiments of Ref. 4 is, however, most likely due only to the significant presence of intermediate states, evidenced by the fact that the grains never reached the theoretical limit of superheating as seen in the experimental superheating fields. Since this can be determined in advance by measurement of the associated differential superheating curve, we strongly recommend that this curve be examined prior to the future reporting of any such experiments.

Curiously, the model of Ref. 4 would seem to "make sense" physically. Since it constitutes a reasonable first attempt at explaining the heat transport in a type-I superconducting material, why it fails to manifest itself in our experiments is perhaps a greater question. Further experimental investigations are clearly needed.

ACKNOWLEDGMENTS

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13. This expression is customarily stated as valid only for \( T \approx T_c \); a more general validity over the phase space near the transition boundary follows from the work of Gorkov and others. Moreover, high-field calculations of \( H_{c2} \) (treated in, for example, Refs. 9 or 11) yield \( H_{c2} \approx \xi^{-2}(t) \); measurements of this field over \( 0 < t < 1 \) (for example, Refs. 2, 6, and 7) yield \( H_{c3}/H_{c} \approx (1-t)^{1/2} \approx \xi(t)^{(1-t)} \).
15. Several groups have reduced this spreading order of magnitude by resorting to ordered arrays [for microspheres, see, for example, M. Le Gros, A. da Silva, B. G. Turrell, A. Kotlicki, and A. K. Drukier, Appl. Phys. Lett. 56, 2234 (1990); for microdots, see, for example, R. Leoni, G. Shirripa Spagnola, P. Carelli, M. G. Castellano, and M. Cirillo, in Low Temperature Detectors for Neutrinos and Dark Matter, edited by N. Booth and G. L. Salmon (Editions Frontieres, Paris, 1992), p. 57]. None have, however, been able to eliminate it.