Scaling of flux pinning with the thermodynamic critical field

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A systematic study of flux pinning and the thermodynamic critical field H_c has been undertaken to determine whether H_c is a central factor determining the critical current J_c. Materials that have a fairly wide temperature interval of thermodynamic reversibility are selected so that the thermodynamic critical field can be confidently extrapolated into the irreversible regime. J_c is found to scale with H_c. For a given sample, the J_c/H_c vs H/H_c curves are close to a universal function as temperature changes. In addition, the peak in the pinning force curve also scales with H_c^2 for a wide variety of samples having quite different transition temperatures.
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I. INTRODUCTION

Scaling laws for critical current densities J_c are frequently used to determine the fundamental physics involved in the pinning of the flux line lattice of a given superconductor.[1] For example, in practical low-temperature superconductors such as Nb_3Sn and NbTi, the volume pinning force approaches the upper critical field H_{c2}, with magnetic field dependences that are different depending on the types of pinning involved. As pointed out by Campbell and Evetts[1] and Kramer,[2] one might expect the pinning to go to zero at H_{c2}, as either $b^{1/2}(1-b)$ for fine precipitates or as $b^{1/2}(1-b)^2$ if shear in the flux line lattice dominates the pinning. Here, $b = B/B_{c2}$. In addition to the functional dependence of J_c on b, the reduced magnetic field where the volume pinning force is a maximum often can be used to determine which mechanism is operating for a given superconductor.[1] Shalk *et al.*[3] and Flukiger *et al.*[4] have extended these types of analysis to the high-temperature superconductors. By determining which scaling law applies for a given conductor, insight can be gained into the mechanism that controls the pinning.

For the low-temperature superconductors, H_{c2} is an easily measured quantity and theories of pinning tend to work well close to H_{c2} where the order parameter is small. Hence it is a very useful scaling parameter. For the high-temperature superconductors, fluctuations in both the amplitude and phase of the order parameter occur over a wide range of temperature and field, and H_{c2} becomes a much more difficult quantity to measure. In addition, the high-temperature superconductors show flux creep, thermally activated flux flow, flux line lattice melting, and a much richer phase diagram in the H-T plane. Because the flux pinning goes to zero at the irreversibility line H_{irr} rather than H_{c2}, it does not make sense to use H_{c2} as the scaling variable. In sorting out the fundamental mechanisms responsible for pinning, some variable other than H_{c2} needs to be used for scaling.

The new physics reported here is a systematic study of the possibility of using the thermodynamic critical field H_c as a scaling variable for flux pinning. To do this, first it must be possible to measure H_c, and then H_c must be shown to be a good scaling variable. The nickel-boride materials have been selected to carry out this study because they meet many of the needed criteria. Excellent single crystals are available. They are easy to alloy and have a rather wide range of κ values, where κ is the ratio of the penetration depth to the coherence distance for the material. Probably most important, there is a wide range of thermodynamic reversibility in the magnetization curves in the H-T plane, so H_c can be measured with confidence. Our goal here is to focus on flux pinning in the midrange of temperatures and magnetic fields from zero to 5 times H_c where the superconducting penetration depth and coherence distance do not vary too rapidly with temperature. More specifically, the goal is to (1) determine the role of the thermodynamic critical field and the vortex core energy as a factor in the mechanism controlling the pinning, (2) determine whether the magnitude of the peak

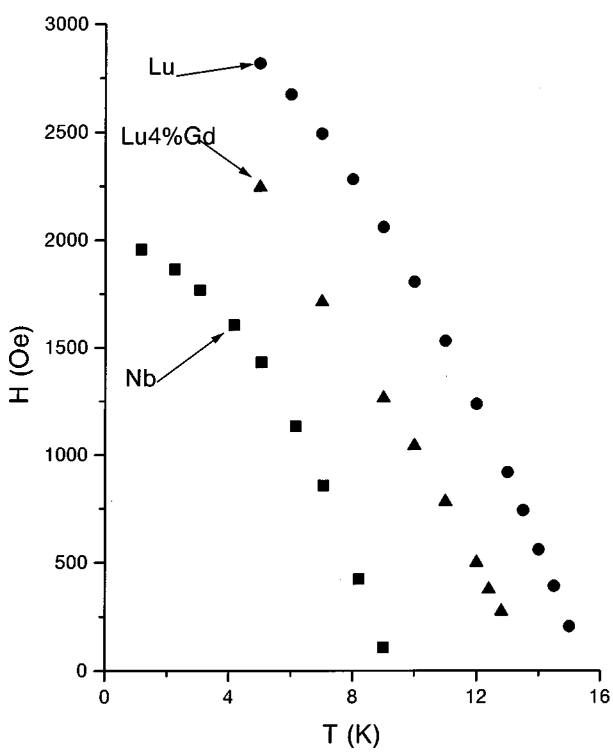

FIG. 1. Comparison of the thermodynamic critical field for two of the nickel-borocarbides with Nb to show a law of corresponding states.

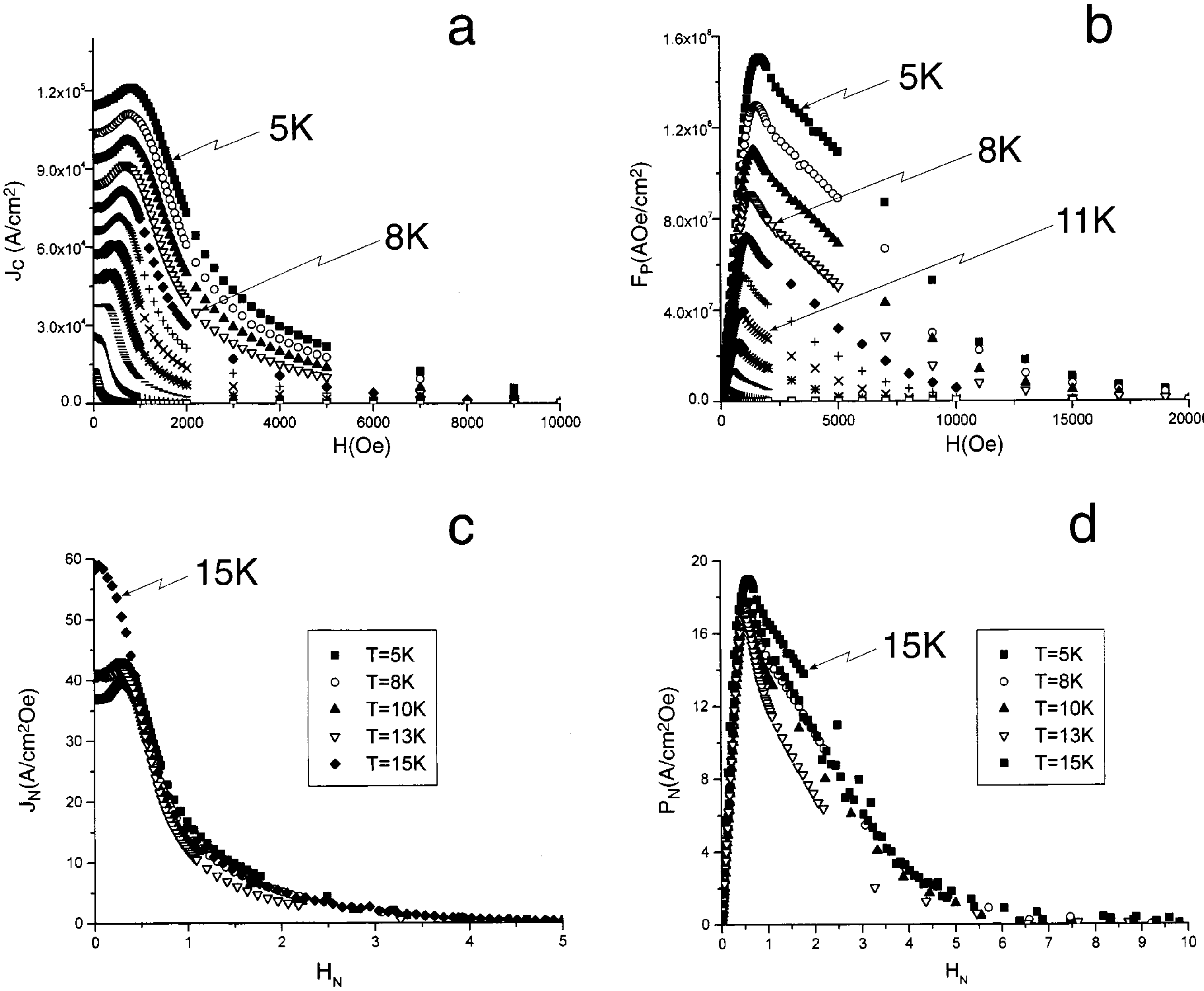

FIG. 2. (a) Critical current density plot for $H \| ab$ for Lu(1221) showing a factor of 10 change in J_c as T varies from 5 to 13 K for Lu(1221). (b) Volume pinning force measured every degree from 5 to 15 K. (c) Normalized J_c/H_c plot showing scaling of J_c with H_c. (d) Normalized volume pinning force plot, F_p/H_c^2 vs H_N.

in the volume pinning force is proportional to the H_c^2, and (3) relate the position of the peak in volume pinning to the mechanism causing the pinning.

There are several experiments that have shown in a rough way that the critical current density J_c of a superconductor is related to the thermodynamic critical field curve H_c. Because H_c is related to the condensation energy and thus to the line energy of a vortex, it is natural to expect some connection between J_c and H_c. The detailed dependence, however, is complicated because there are collective effects and summation problems that contribute to the depinning effects. One series of experiments that points to this connection between J_c and H_c involved the thermal depinning of a single vortex trapped in a variety of Pb and Nb thin films.[5,6] It was found that the vortex spontaneously depins whenever the superconducting order parameter Δ is reduced to about 20% of the value at $T=0,\Delta_0$. Because Δ is directly related to the thermodynamic critical field H_c by the BCS (Ref. 7) relation

$$\Delta = H_c[\pi k^2 V/6\gamma]^{1/2}, \quad (1)$$

it seems clear that there is some connection between the pinning strength of an isolated vortex and H_c. Here, γ is the electronic specific heat coefficient, V is the molar volume, and k is the Boltzmann constant. This is an elementary pinning force effect. In a rather different kind of measurement involving a full flux line lattice, J_c was shown to be proportional to H_c in Fe-doped $YBa_2Cu_3O_{7-\delta}$ [Y(123)].[8] As Fe is added to Y(123), the J_c and H_c values both drop very quickly, but the ratio of J_c/H_c remains relatively constant as J_c falls by more than an order of magnitude. The single vortex depinning and the J_c changes with Fe content are rather different experiments, the first depending on the elementary pinning force of a defect and the latter depending on both defect pinning and on collective shear modulus effects in the flux line lattice. Both point toward H_c being an important variable.

The purpose of this study is to explore the role that the free energy, and hence H_c plays as a factor contributing to the strength of flux pinning in a variety of materials. Because thermodynamic reversibility is required to measure H_c, and

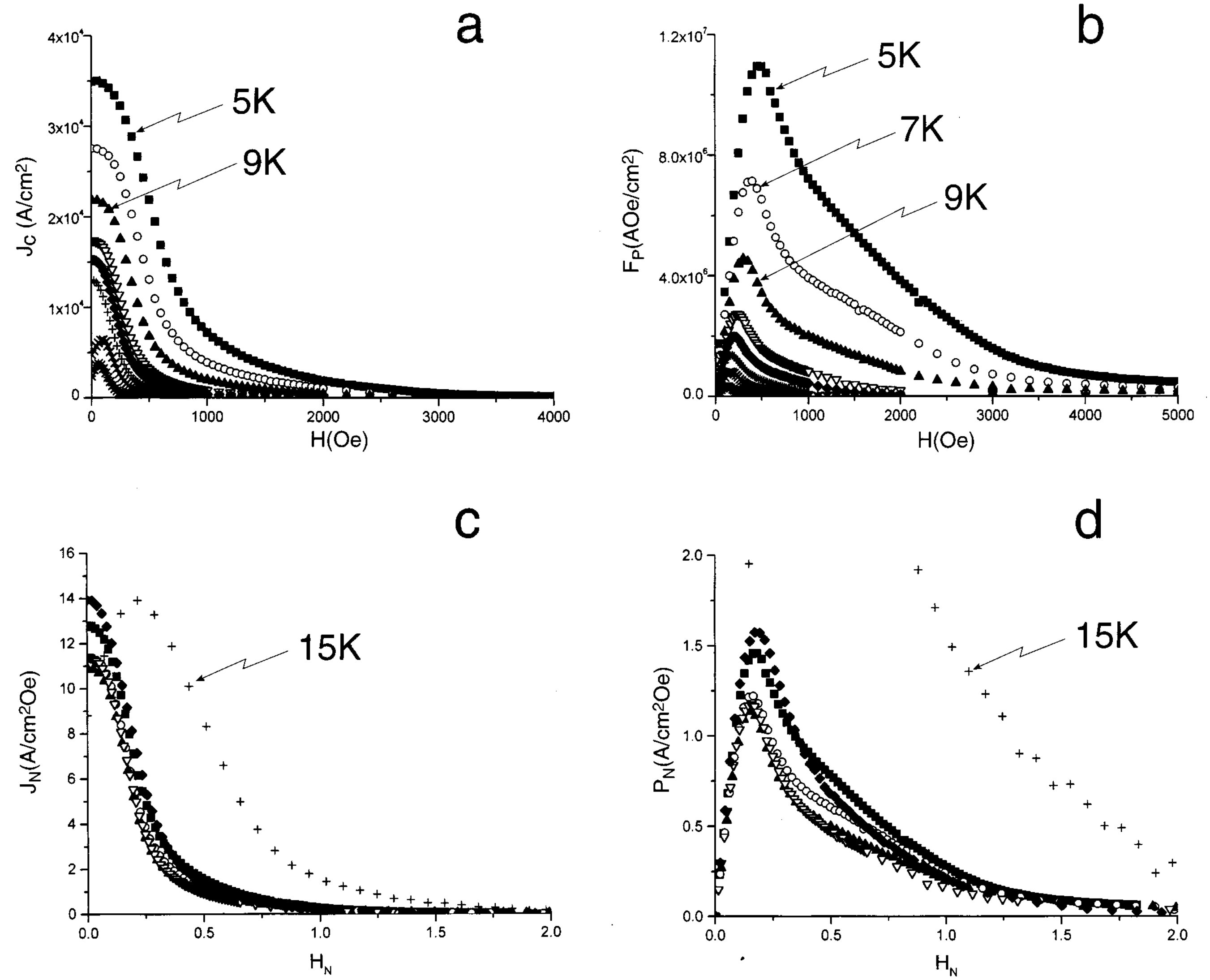

FIG. 3. Plots similar to Fig. 1 for $h \| c$ for Lu(1221).

because flux pinning is inherently irreversible, there might appear to be a contradiction in the design of the experiment. You cannot measure J_c and H_c at the same point in the H-T plane. If, however, the sample shows thermodynamic reversibility from the transition temperature T_c to about 70% of T_c, then one can extrapolate to lower temperatures using a law of corresponding states. A very general feature of superconductivity is that the functional dependence of the thermodynamic critical field curve is approximately the same for all superconductors,[7,9] so this extrapolation can be made with some confidence. The onset of pinning does not change the free energy and thus the H_c vs T curve. Samples are chosen to have at least 30% of the superconducting region reversible, so that the extrapolation of the H_c vs T curve can be made.

II. EXPERIMENTAL TECHNIQUE

The free energy curves are determined from reversible magnetization curves measured with a Quantum Designs superconducting quantum interference magnetometer with a sample motion length of 4 cm. The magnetic field is homogeneous to 0.05% for this motion. Samples of the nickel-borocarbides were grown by a flux growth technique described elsewhere.[10] Typically, the samples were flat plates about $2\times2\times0.1$ mm^3 in dimension. Critical currents were determined in the irreversible part of the magnetization curves from the Bean relation[11]

$$J_c = 17\Delta M/r, \tag{2}$$

where r is the average dimension perpendicular to the magnetic field and ΔM is the difference in magnetization for the field increasing and field decreasing cases. Here, ΔM is measured in emu/cm^3 and r is measured in cm.

Close to T_c, the magnetization curves are thermodynamically reversible over the entire magnetic field range and the thermodynamic critical field values are determined by integrating to find the area under the magnetization curves via $\int -m\,dH = H_c^2/8\pi$. For these samples, the range of reversibility extends from T_c to $0.7T_c$. In the irreversibility regime, the Bean model predicts that the equilibrium magnetization is the average of the field-increasing and field-decreasing magnetization values. Recently, this has been

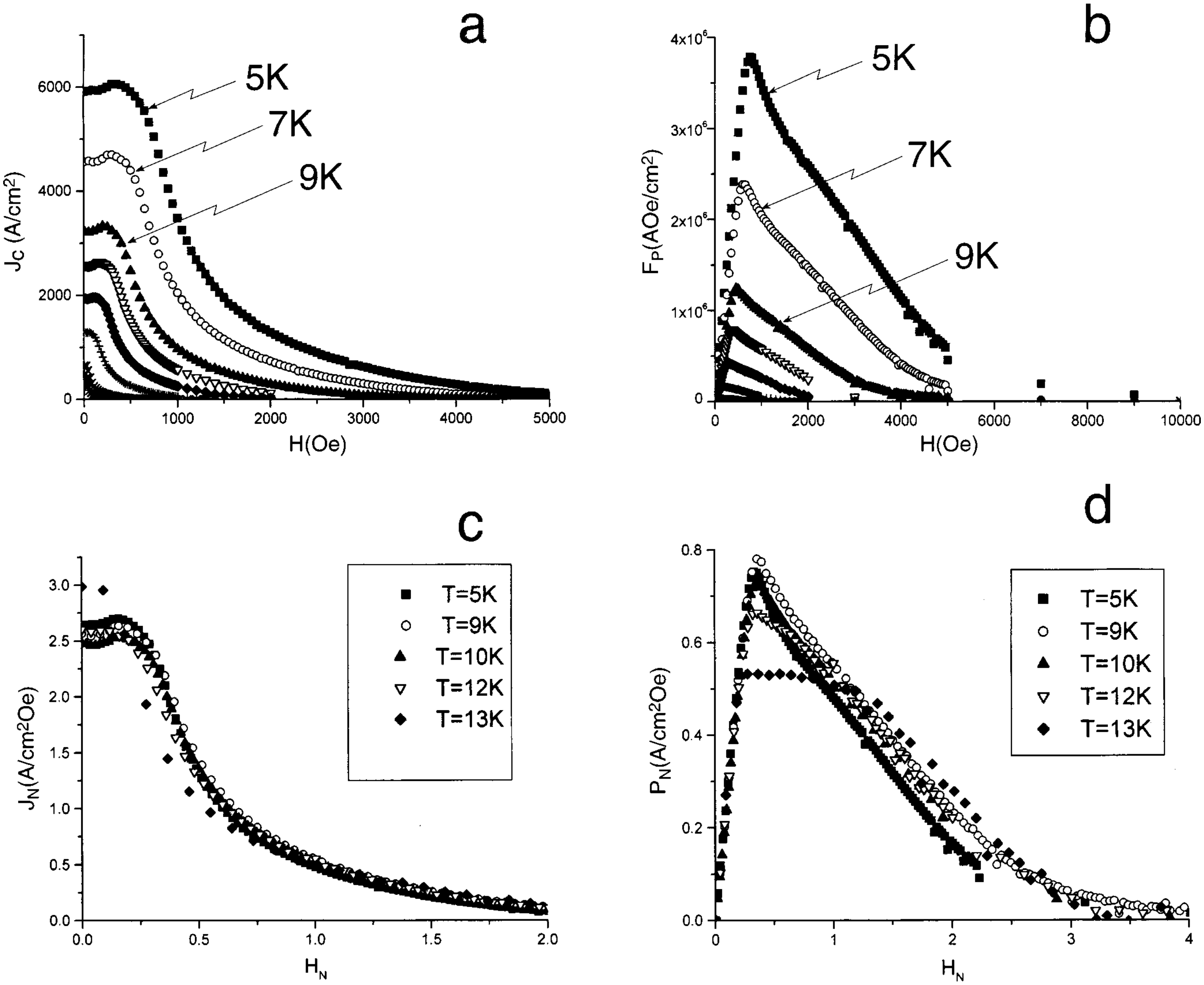

FIG. 4. Plots similar to Fig. 1 for $Lu_{0.96}Gd_{0.04}$ and for $H\|ab$.

confirmed by Willemin and co-workers[12] who have shown that the equilibrium magnetization is indeed close to the average of the increasing field and decreasing field values. They show that a small ac field perpendicular to the main field will quickly move the flux line lattice from the hysteretic to the equilibrium configuration. Using this Bean model assumption, H_c values can be determined over a much wider field range. The data show that H_c data thus derived give critical field curves very similar to the classic superconductor, Nb, as shown in Fig. 1. A BCS (Refs. 7 and 10) law of corresponding states is then used to extrapolate H_c to lower temperatures.

III. RESULTS AND DISCUSSION

The H_c vs T curves for these nickel-borocarbides are similar the behavior of the classical superconductor, Nb, as shown in Fig. 1. The slope dH_c/dT at T_c is about 350 Oe/K and the H_0/T_c ratio is about 200 Oe/K. Here, H_0 is the value of H_c at $T=0$. The close similarity of these curves gives confidence that a law of corresponding states much like classical superconductors and the BCS (Ref. 7) theory is obeyed.

A family of J_c vs H measurements at temperatures ranging from 5 to 15 K is shown in Fig. 2(a) for the lutetium nickel borocarbide, $LuNi_2B_2C$ [Lu(1221)] for $H\|ab$. The data show a small peak effect in the 20–200 mT range and then fall to zero at the irreversibility field H_{irr}. If these data are normalized by the thermodynamic critical field J_c/H_c vs H/H_c, the curves collapse onto a universal curve as shown in Fig. 2(c). In the figure, $H_N=H/H_c$. Only the highest-temperature data at 15 K deviate from the curve significantly from the universal curve. At 15 K, the peak effect at fields less than half of H_c is not present, so there is a real change in the kind of pinning center that controls J_c as T approaches T_c.

If these same data are cast in terms of the volume pinning force $F_p=J_c\times B$, the results are shown in Fig. 2(b). The peak in the F_p curve lies at about $0.1H_{irr}$, a value substantially lower than the corresponding value for NbTi or Nb_3Sn. Again, these curves have very similar shape. Because the line energy of a vortex goes as H_c^2, the data are plotted as P_N vs H_N where $P_N=F_p/H_c^2$ in Fig. 2(d). This presentation shows good scaling of the magnitude of the peak in P_N of about 18, but there are some differences in the scaled curve in the region of $H/H_c=2$.

If the direction of the applied magnetic field is rotated from the a-b plane to the c axis, the pinning decreases by about a factor of 10, but the scaling is retained as shown by Figs. 3(a) and 3(c). On the reduced scale of J_c/H_c vs H/H_c all of the data except the 15 K data fall close to the same curve as shown in Fig. 3(c). When these data are cast in terms of the volume pinning force, as in Fig. 3(b) and in normalized form as F_p/H_c^2 in Fig. 3(d), there is rough scaling except for the 15 K data. The peak in the $P_N = F_p/H_c^2$ curve is from 1.3 to 1.6 for the data up to 13 K data. Again the 15 K data are quite different. Very close to T_c, the character of the pinning changes dramatically.

Repeating the experiment with an alloy $Lu_{0.96}Gd_{0.04}Ni_2B_2C$ gives essentially the same sort of scaling as shown by the $J_c \| ab$ data of Fig. 4. The addition of Gd decreases the values of J_c by a factor of 10, and the peak in the normalized P_N is about 0.8.

In this family of materials, the strength of the pinning can be changed substantially by introducing new pinning centers and by changing the direction of the vortices relative to the crystalline axis of the sample. With these factors in place, the pinning force then scales very well with the magnitude of the thermodynamic critical field as the temperature is changed.

To show how the maximum value of the volume pinning force depends on the thermodynamic critical field, we plot $F_{p(max)}$ vs H_c on a log-log scale as shown in Fig. 5 for the $H \| ab$ data for both the Lu sample and the $Lu_{0.96}Gd_{0.04}$ data. The slope of the two parallel lines is 2 on this log-log plot, indicating that F_p is proportional the H_c^2

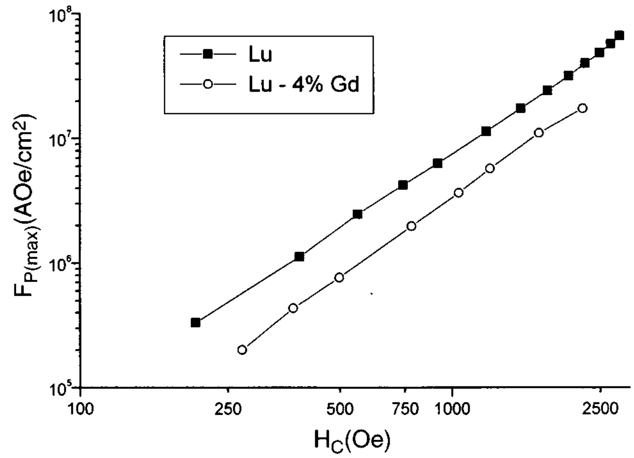

FIG. 5. Plot to show $F_{p(max)}$ proportional to H_c^2.

IV. CONCLUSIONS

In the region of thermodynamic reversibility, the H_c vs T curves for all of the nickel-borocarbides studied here are similar to the classic superconductors. Both the slope of the thermodynamic critical field curve at T_c and the ratios of H_0/T_c are very similar to Nb and hence to the predictions of the BCS theory. In the irreversible magnetization region, the critical current densities are found to change in a very systematic way with temperature and magnetic field. On a reduced plot of J_c/H_c vs H/H_c curves collapse onto a common curve in the midrange of magnetic fields up to a few times H_c. In addition, the normalized volume pinning force $P_N = F_p/H_c^2$ scales remarkably well with a clear peak at $H/H_c \sim 0.3$. Furthermore, the maximum pinning force $F_{p(max)}$ is proportional to H_c^2 which in turn is proportional to the line energy of the vortex. In some materials, H_{c2} is not useful as a scaling variable because flux line lattice melting and thermally activated flux flow intervene. For these materials, the thermodynamic critical field provides a very useful scaling variable if there is a sufficiently wide range of thermodynamic reversibility to permit measurement of H_c.

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