EVIDENCE THAT THE TRANSITION AT H_{c2} IN NIOBIUM MAY NOT BE SECOND ORDER NEAR ABSOLUTE ZERO TEMPERATURE

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The anisotropy of H_{c2} for single crystal niobium has been measured for $0.4^{\circ}\mathrm{K} \leqslant T \leqslant 4.2^{\circ}\mathrm{K}$. A continuation of the observed trend to lower temperatures would imply that the transition near absolute zero is not second order for all field directions.

The idealized bulk transition of a type-II superconductor at $H_{c2}(T)$ is generally considered to be second order in the Ehrenfest sense [1]. Experiments on niobium have shown that $H_{c2}(T)$ may be anisotropic [2,3] for sufficiently pure single crystal specimens and that this anisotropy increases as T decreases from $9.2^{\circ}\mathrm{K}$ ($T = T_c$) to $1.2^{\circ}\mathrm{K}$ [3.4]. The continuation of this trend in the limit $T \rightarrow 0$ would in fact indicate that the transition should more properly be classified as third or higher order at absolute zero, at least for certain orientations of the applied magnetic field. As has been discussed by Gorter [5], such a transition would be indicated by a non-zero slope in $H_{c2}(T)$ at $T = 0$. This letter presents evidence that this may indeed be the case for pure niobium. Previous investigations of H_{c2} in niobium in the liquid ^{3}He temperature range led to different conclusions because either the bulk transition at H_{c2} of pure niobium was not observed [6] or the nature of the anisotropy was not taken into account [7].

The single crystal specimen of Nb was prepared by electron beam zone refining and high vacuum annealing. It had the form of a cylinder of length 1.5 cm and diameter 0.2 cm; with the axis parallel to the $[1\bar{1}0]$ direction and had a residual resistance ratio of 750. One end was soldered with indium to a copper disc held firmly against a copper ^{3}He chamber of a "single-cycle" cryostat. The disc could be rotated to obtain the orientation dependence of H_{c2}, the field of a superconducting solenoid being aligned perpendicular to the sample axis. The applied field was monitored with a Hall probe located near the sample in the surrounding ^{4}He bath. A set of modulation coils in the ^{4}He bath produced a small a.c.field at 400 Hz parallel to the sample's axis, and a sharp transition at H_{c2} was observed by phase sensitive detection of the signal from a pickup coil surrounding and coaxial with the sample. That this was a bulk transition was verified at $1.2^{\circ}\mathrm{K}$ by a thermal conductivity measurement on the sample in situ. The relative precision in determining H_{c2} for each orientation was better than 0.1%, although the absolute accuracy was only perhaps 1% owing to the finite transition width and variations in the Hall probe with thermal cycling. The orientation dependence of H_{c2} of this sample at $1.2^{\circ}\mathrm{K}$ was identical to that of the sample studied in ref. 3 which had a resistance ratio of 1600.

The temperature was obtained from the vapor pressure of ^{3}He at the room temperature end of a 0.3 cm diameter stainless steel tube communicating with the ^{3}He chamber. Pressure readings were interpreted according to the 1962 ^{3}He vapor pressure scale and the thermomolecular pressure ratios of Freddi and Modena [8]. The temperature so derived agreed to better than 4% with the magnetic temperature of powdered cerous magnesium nitrate packed into the form of a right circular cylinder of height equal to diameter.

Fig. 1a shows the T-dependence of H_{c2} along the principal axes for liquid ^{3}He temperatures; H_{111} is the maximum value of H_{c2} in the $[1\bar{1}0]$ plane and H_{001} the minimum *. No anomalies were observed in the temperature region where specific heat is reported to become dominated by the effects of a small energy gap [12], in agreement with the results of ref. 7. Fig. 1b displays the anisotropy $H_{111} - H_{001}$ over the range $0.40^{\circ}\mathrm{K} \leqslant T \leqslant 4.0^{\circ}\mathrm{K}$.

* see footnote on next page

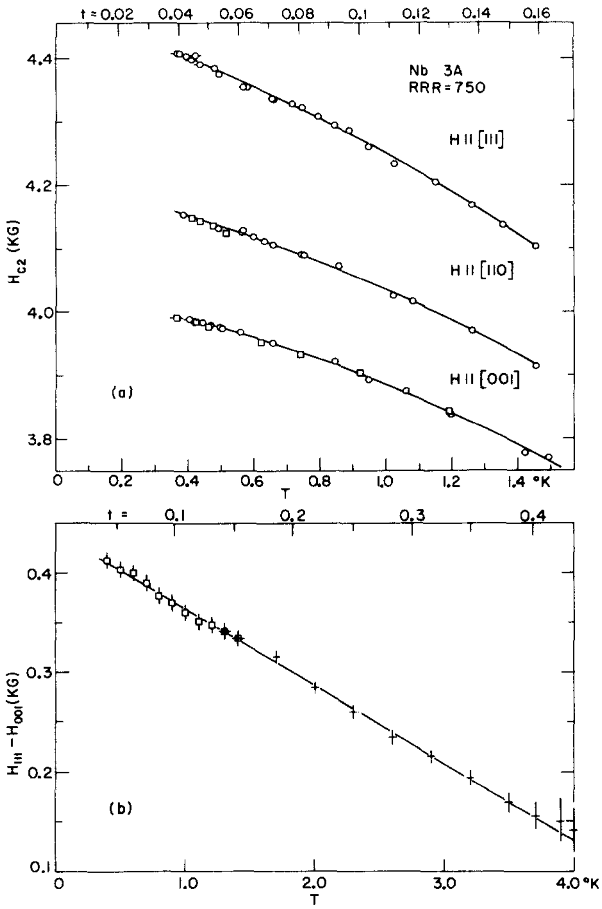

Fig. 1. (a) Temperature dependence of H_{c2} for the applied field aligned along each of three principal crystallographic directions, (b) Temperature dependence of the difference in the critical fields along [111] and [001].

* A surface critical field H_{c3} could also be determinded, but with substantially reduced precision. No attempt was made to insure that the surface was free of contaminations, except for an acid etch before mounting. The measured value of H_{c3}/H_{c2} along the [111] and [001] for $0.4^{\circ}\mathrm{K} \leq T \leq 1.6^{\circ}\mathrm{K}$ was not anisotropic or temperature-dependent and had the value 1.71 with a relative scatter in the data points of ± 0.03. This contrasts with the low-temperature limiting value of 1.9 reported by Webb [9], but is in agreement with other measurements at 4.2°K [10]. The agreement of our value with 1.695 predicted by the local theory of Saint-James and de Gennes [11] for dirty superconductors suggests that this ratio for niobium is independent of the physics determining H_{c2}.

Clearly, the high temperature linear trend is continued smoothly to the lowest temperature attained. Since this low temperature corresponds to a very small value of the natural dimensionless parameter $t = T/T_c$, it is plausible that the data in fact represent the limiting low-temperature behavior of H_{c2}. Fig. 1b demonstrates that even if H_{001} is quadratic in t in the low temperature regime, H_{111} is not. In fact, H_{001} can be represented by a t^2 dependence only for $T < 0.8^{\circ}\mathrm{K}$, corresponding to $t^2 < 0.008$, but because the interval $0.4 < T < 0.8^{\circ}\mathrm{K}$ is relatively small, it is not clear whether the fit is significant. Thus the available evidence demonstrates that H_{c2} near $T = 0$ cannot be described by a rapdily converging power series in t which commences with the t^2 term. If the trend in fig. 1b continues to lower temperatures, the transition near absolute zero is third or higher order, at least for the field parallel to [111].

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