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PARAMAGNETISM ON  $H_{c2}$  FOR A Ti-11 at.%Nb  
ALLOY\*

by

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Absence of the Influence of Pauli Spin Paramagnetism on  $H_{c2}$   
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Werthamer, Helfand and Hohenberg (1) (WHH) and Maki (2) have proposed theories to account for the effects of Pauli spin paramagnetism (PSP) and spin-orbit scattering on the temperature dependence of  $H_{c2}$  in type-II superconductors. Qualitatively, the PSP tends to depress  $H_{c2}$  at low temperatures  $T$ , whereas spin-orbit scattering tends to counteract the effect of PSP. In the dirty limit (i.e.,  $2\pi\tau k_B T_c / \hbar \ll 1$ , where  $\tau$  is the electronic relaxation time) and for  $\tau/\tau_s \ll 1$ , where  $\tau_s$  is the spin-orbit relaxation time, the two theories give essentially identical results for  $H_{c2}(T)$ . WHH introduced  $\tau_s$  as an adjustable parameter to fit experimental data. Subsequently Neuringer and Shapira (3) introduced experimental evidence to show that  $\tau_s$  is, in fact, related to the spin-orbit interaction and that it is in order of magnitude agreement with  $\tau/\tau_s \sim \left(\frac{Ze^2}{\hbar c}\right)^4$ , given by Abrikosov and Gor'kov (4).

We have measured the temperature dependence of  $H_{c2}$  for the superconducting alloy Ti-11 at.%Nb in the temperature range  $1.68 \text{ K} \leq T \leq 5.40 \text{ K} (=T_c)$ . Resistive transitions were observed by standard four-wire techniques in a superconducting solenoid with the magnetic field parallel to the current direction. The criterion for  $H_{c2}$  was chosen to be the zero-voltage intercept of the linear portion of the transition on a voltage-versus-field curve (5) for a current density of  $\sim 1\text{A/cm}^2$ . The critical field

$H_{c2}$  was found to be independent of current density below this value. Samples were cut from a boule, kindly provided by Dr. L. J. Neuringer, which had been arc-melted and vacuum annealed. The resistivity at 4.2 K, for  $H > H_{c2}$ , was found to be  $(56 \pm 2)$   $\mu\Omega$  - cm.

The relative importance of PSP is characterized by the parameter  $\alpha = \frac{\sqrt{2} H_{c2}^*(0)}{H_p}$ , where  $H_p = 18400 T_c \text{ Oe}$  and  $T_c$  is the transition temperature in K. In the dirty limit,  $H_{c2}^*(0)$ , the upper critical field which would be obtained in the absence of PSP, is given by  $H_{c2}^*(0) = -0.69 \left( \frac{dH_{c2}}{dt} \right)_{t=1} \equiv 0.69 H_0$ , where  $t = T/T_c$ . In Fig. 1, we show  $H_{c2}$  as a function of temperature near  $T_c$ . The zero field intercept of the solid line gives  $T_c = (5.40 \pm 0.02)$  K, the error being related to the thermometer calibration. Our  $H_{c2}(T)$  data near  $T_c$  give  $H_0 = 83.8$  kOe. Thus, we find  $\alpha = 0.82$ . Near  $T_c$ , the resistive transitions had a width of  $\approx 800$  G. Therefore, we expect that the use of another experimental criterion for  $H_{c2}$  would give essentially the same results for  $H_0$  and  $\alpha$ .

To describe the effects of spin-orbit scattering, WHH have introduced the parameter  $\lambda_{so} = \hbar/3\pi k_F T_c \tau_s$ . In Fig. 2, we plot the reduced field  $h = H_{c2}/H_0$  versus  $t$  for comparison with theory. Shown in the figure is a curve obtained from WHH Eq. (28) for  $\alpha = 0.82$  and  $\lambda_{so} = 0$ , which corresponds to the absence of spin-orbit scattering. The data points lie above this curve and, as well, lie slightly above the curve for  $\alpha=0$ . The latter is also the curve for any finite  $\alpha$  when  $\lambda_{so} = \infty$ . Thus it is impossible to obtain a fit to the data with any value of  $\lambda_{so}$ , although the best fit is with  $\lambda_{so} = \infty$ . Such discrepancies with theory have been noted previously by Neuringer and Shapira

for Ti-52 at.%Ta and by Williamson (6) for Nb rich Nb-Zr alloys. Helfand and Werthamer (7) have shown that  $H_{C2}(0)/H_0$  is about 0.73 for clean materials in the absence of paramagnetic effects. However, we estimate  $\tau \lesssim 10^{-15}$  sec, so that the dirty-limit condition should be well satisfied.

We note finally that Neuringer and Shapira found their data for Ti-44 at.%Nb to lie well below the  $\alpha = 0$  curve. It is curious that for Ti-11 at.%Nb, where the effective value of  $Z$  should be smaller than for Ti-44 at.%Nb, the data lie above the  $\alpha = 0$  curve, seemingly indicating a greater influence of spin-orbit scattering. To obtain an idea of how much below the  $\alpha = 0$  curve we might expect our data to lie, we have tried to estimate  $\lambda_{so}$  for Ti-11 at.%Nb, using the value of  $\lambda_{so}$  which Neuringer and Shapira obtained for Ti-58 at.%V. This procedure seems appropriate since Ti-11 at.%Nb and Ti-58 at.%V should have roughly the same effective  $Z$  value. Noting that  $\lambda_{so} = 0.7$  for Ti-58 at.%V and that  $\lambda_{so}$  is proportional to  $1/T_c$ , we estimate that  $\lambda_{so} \sim 1$ , and almost certainly  $\lambda_{so} < 2$ , for Ti-11 at.%Nb. Thus, in Fig. 2 we have plotted the curve corresponding to  $\alpha = 0.82$  and  $\lambda_{so} = 2$ . As can be seen, the experimental data still lie well above this curve.

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## FIGURE CAPTIONS

Fig. 1: Temperature dependence of  $H_{c2}$  as determined from resistive transitions. Bars on points represent experimental uncertainty in determination of  $H_{c2}$ . The solid line represents a least squares fit to the experimental points.

Fig. 2: Dependence of reduced magnetic field  $h = H_{c2}/H_0$  on reduced temperature  $t = T/T_c$ . Theoretical curves were obtained from WHH Eq. (28).

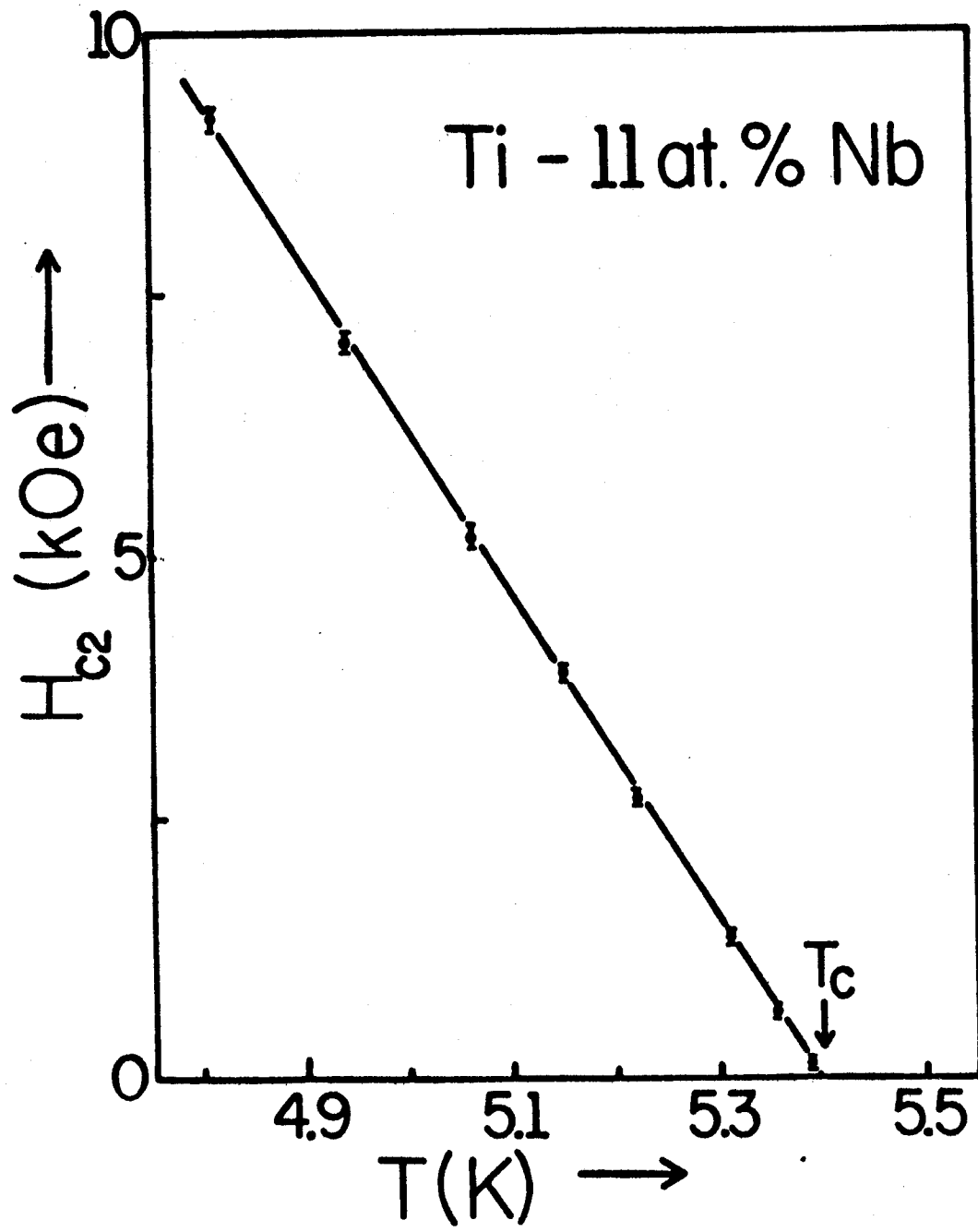


FIG. 1

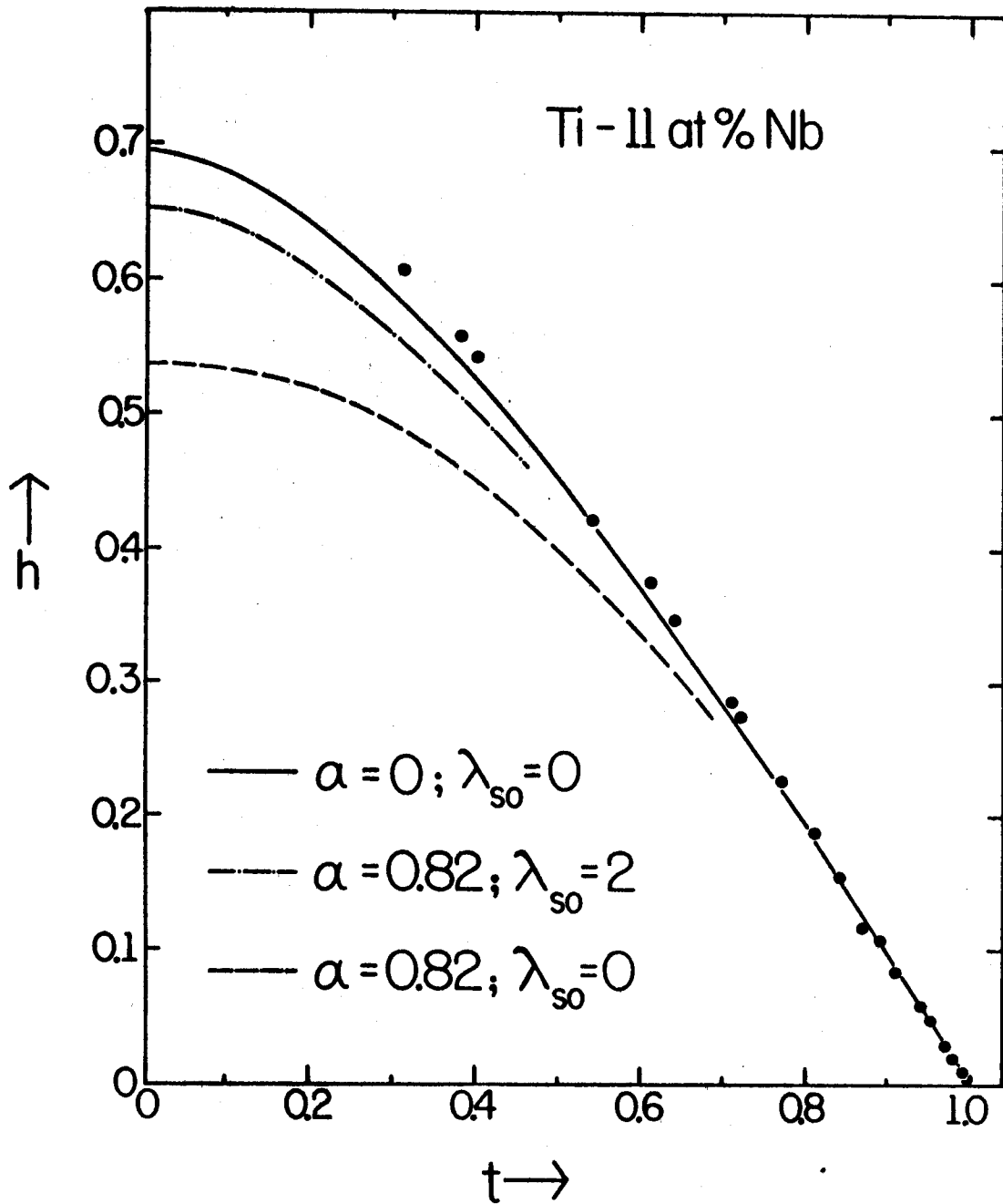


FIG. 2