IFUSP/P-35

ABSENCE OF THE INFLUENCE OF PAULI SPIN PARAMAGNETISM ON H_{c2} FOR A Ti-11 at.%Nb ALLOY*

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Submitted to Physica Status Solidi.

Setembro de 1974

Subject Classification: 14.2

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Absence of the Influence of Pauli Spin Paramagnetism on H_{c2} for a Ti-11 at.%Nb Alloy

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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 τ is the electronic relaxation time) and for $\tau/\tau_s \ll 1$, where τ_s is the spin-orbit relaxation time, the two theories give essentially identical results for $H_{c2}(T)$. WHH introduced τ_s as an adjustable parameter to fit experimental data. Subsequently Neuringer and Shapira [(3)] introduced experimental evidence to show that τ_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 $1.68\ K \leq T \leq 5.40\ K\ (=T_c)$. 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 $\sim 1A/cm^2$. The critical field

H_{c2} was found to be indenpendent 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 ± 2) $\mu\Omega$ - cm.

The relative importance of PSP is characterized by the parameter $\alpha = \frac{\sqrt{2}\, H_{c2}^{*}(0)}{H_p}$, where $H_p = 18400\, T_c$ 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 $H_{c2}^{*}(0) = -0.69 \left(\frac{dH_{c2}}{dt}\right)_{t=1} \equiv 0.69\, H_o$, 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 $H_o = 83.8$ kOe. Thus, we find $\alpha = 0.82$. Near T_c, the resistive transitions had a width of $\lesssim 800$ G. Therefore, we expect that the use of another experimental criterion for H_{c2} would give essentially the same results for H_o and α.

To describe the effects of spin-orbit scattering, WHH have introduced the parameter $\lambda_{so} = \hbar/3\pi k_B T_c \tau_s$. In Fig. 2, we plot the reduced field $h = H_{c2}/H_o$ 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 α when $\lambda_{so} = \infty$. Thus it is impossible to obtain a fit to the data with any value of λ_{so}, although the best fit is with $\lambda_{so} = \infty$. Such discrepencies 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 $H_{c2}(0)/H_o$ 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 λ_{so} for Ti-11 at.%Nb , using the value of λ_{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 λ_{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.

The authors wish to acknowledge the financial support of FAPESP.

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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 $h = H_{c2}/H_{o}$ on reduced temperature $t = T/T_{c}$. Theoretical curves were obtained from WHH Eq. (28).

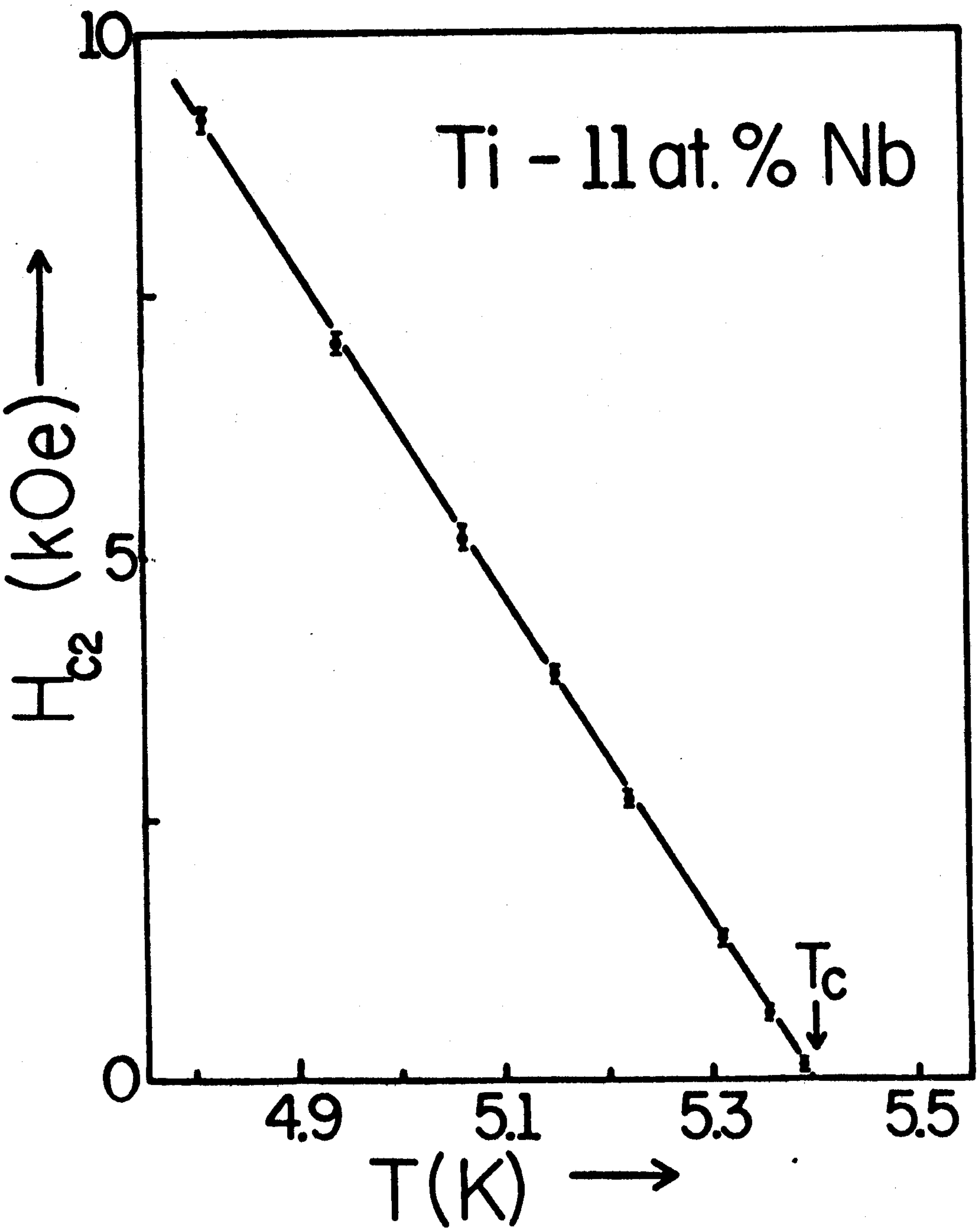
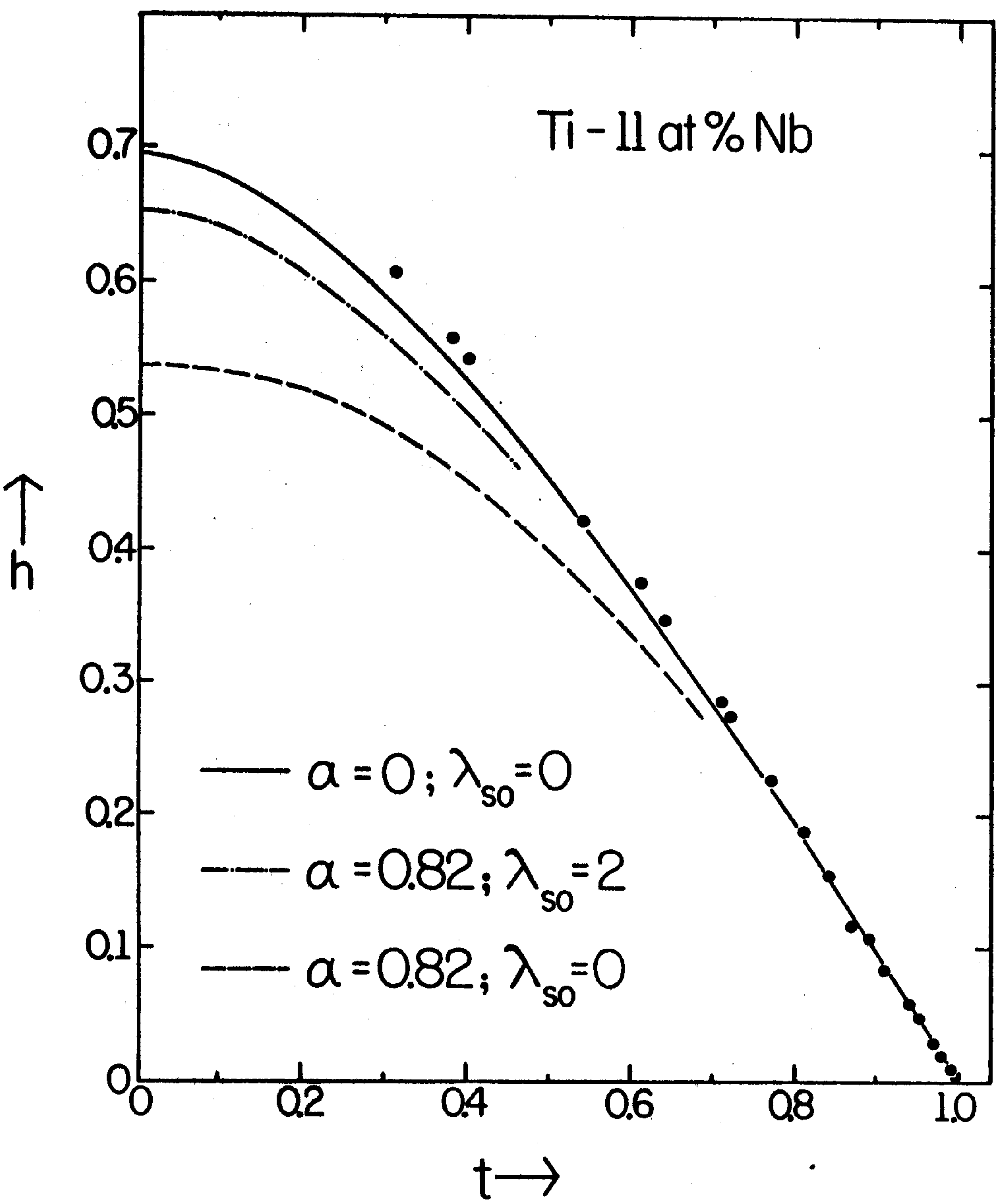


FIG. 1



Ti - 11 at % Nb
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
h
0
0.2
0.4
0.6
0.8
1.0
t
α = 0 ; λso = 0
α = 0.82 ; λso = 2
α = 0.82 ; λso = 0

FIG. 2