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Mean-free-path dependence of κ_2 in clean superconductors*

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The slope of the magnetization curve near the upper critical field H_{c2} has been measured for *Nb*Ta alloys in order to study systematically the deviations from the Eilenberger theory in the clean limit. κ values determined from these slopes, κ_2, agree well with the theory for κ greater than 1.0, but the measurements lie well above the theory for $\kappa < 1.0$. A study of pure V, as well as these alloys, shows that λ/ξ rather than ξ/l_{tr} is the important parameter governing the magnitude of the deviation.

I. INTRODUCTION

There has been a long-standing discrepancy between theory[1,2] and experiment[3–5] for the slope of the magnetization curve at H_{c2} in clean Type-II superconductors. Experimental values of κ_2 derived from

$$4\pi\frac{dM}{dH}=[1.18(2\kappa_2^2-1)]^{-1}$$

for pure Nb by Finnemore, Stromberg, and Swenson[3] (FSS) are about 50% higher than the Eilenberger theory[1] predicts, and the values for pure V as determined by Haas,[4] by Sekula and Kernohan,[5] and by Radebaugh and Keesom[6] are about 25% higher than theory predicts. In an attempt to clarify the origin of this discrepancy, we have measured the dependence of κ_2 on the transport mean free path l_{tr} in the Nb-Ta system to measure systematically the magnitude of the discrepancy as the clean limit is approached.

II. EXPERIMENTAL

Samples were prepared by outgassing cylindrical alloy specimens about 0.06 cm in diameter and 2 cm in a vacuum of 10^{-9} Torr near the melting point, as described previously.[7] After the outgassing process, samples were sealed in Pyrex capillaries without exposure to air for long-term (months) storage. Just before the magnetization measurements were to be made, the samples were removed from the Pyrex tubes and anodized for 20 min at 20 V in a 0.2N H_2SO_4 electrolyte. As discussed elsewhere,[8] this anodized surface inhibits further deterioration of the surface.

Magnetization measurements were made with the sample immersed in the ^{4}He bath by a sample motion technique.[3] Magnetic fields were homogeneous to better than 0.1% over the volume of the sample, and temperatures were stabilized to ± 3 mK at worst and usually to ± 1 mK. The important sources of error in the experiment were related to sample quality and were not related to temperature control or field inhomogeneity.

III. RESULTS AND DISCUSSION

The 1000-, 5000-, and 10 000-ppm Ta samples showed excellent reversibility near H_{c2}, as shown by one of the better transitions on Fig. 1. For these samples, the field-decreasing curve was typically 3% below the field-increasing curve; so there was no difficulty defining a slope. The data were analyzed in terms of a critical-state model worked out by Clem,[8] in which equilibrium magnetization is half way between the field-increasing and field-decreasing values. The Nb–20 000-ppm-Ta sample was not so well behaved. The field-increasing curve was similar to the 10 000-ppm sample, but the field-decreasing curves followed $B=H$ for fields down to 0.7 H_{c2} before it began to expel flux. In addition, the trapped flux was about 50% of H_{c1}. Hence the data for this sample are much less reliable than for the others. κ_2 values for this sample were determined from the field-increasing slope.

Values of κ_2/κ for all the samples at three different temperatures are shown on Fig. 2. Here the values of κ are determined from the resistivity by the formula[9] $\kappa=\kappa_0+(7.53\times10^3)\rho\gamma^{1/2}$, where $\kappa_0=0.78$ for pure Nb, ρ is the resistivity in Ω cm, and γ is the electronic specific heat in erg/cm^3. Experimental values of κ also were determined from the

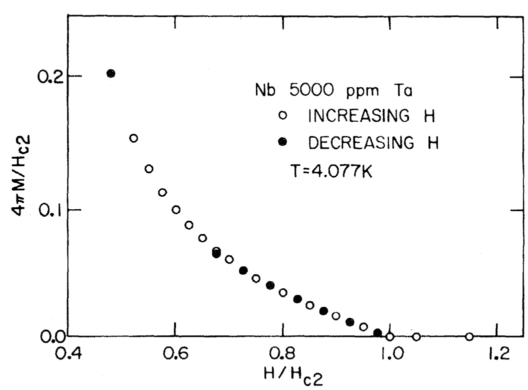

FIG. 1. Magnetization curve near H_{c2}.

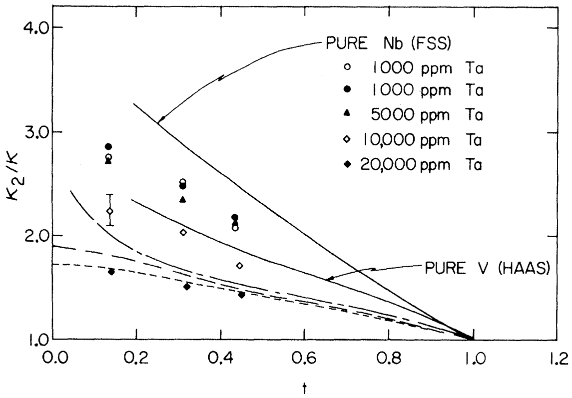

FIG. 2. Temperature dependence of κ_2. Dashed curves show the predictions of the Eilenberger theory for values of ξ/l_{tr} ranging from zero for the top curve (long-short dash) to 0.25 for the bottom curve (short dashes).

ratio of H_{c2}/H_c in the limit T goes to T_c. The values are 0.83, 1.0, and 1.1 for the 5000-ppm, 10 000-ppm, and the 20 000-ppm Ta samples, respectively, in good accord with the values in Table I. The agreement between these two methods of determining κ would indicate an accuracy of about ± 0.05. The primary source of error in determining κ_2 is the slight curvature of the $4\pi M$ vs H data near T_c. For these samples, the data above $H/H_{c2} = 0.85$ were straight lines within the accuracy of the data; so the slope has been defined by the best straight-line fit to the data in this range. The error bars shown on the 10 000-ppm sample at $t = 0.14$ are typical for the 1000, 5000, and 10 000-ppm samples. Reproducibility from sample to sample is illustrated by the difference between the two 1000-ppm samples. A second 5000-ppm sample was also measured, and the scatter is similar to the 1000-ppm sample. Values of ξ/l_{tr} for the samples were derived from the resistivity and critical-field curves, as described elsewhere.[7] A summary of the sample parameters is given in Table I.

The primary result of these experiments is that the measured κ_2/κ values begin to deviate from the theoretical predictions for κ values of about 1.0. The *Nb*Ta samples reported here have κ values ranging from 0.78 for pure Nb to about 1.1 for the 20 000-ppm Ta sample, and the data of Fig. 2 indicate a steady progression of the data toward the theoretical values as κ approaches 1. It is interesting to note that pure V with $\kappa = 0.85$ fits very nicely with the *Nb*Ta samples. Several samples of V with ξ/l_{tr} ranging from 0.2 (Ref. 6) to 0.02 (Ref. 4) all have the same ratio of κ_2/κ; so ξ/l_{tr} does not seem to be the important parameter which determines the magnitude of the deviation from the theory. Rather, the ratio of the penetration depth to the coherence distance λ/ξ is the important factor governing the magnitude of the deviation from the theory.

Several factors could contribute part of the observed increase of κ_2 over the predictions of the basic theory.[1] Strong-coupling effects,[10–13] for example, lead to κ_2 values above the weak-coupling theory,[1] but the magnitude of this effect in Nb and V would be expected to be much smaller than the discrepancies shown here. Both Nb and V are intermediate-coupling superconductors, so the κ_2/κ values should not rise above 1.7 because of this effect, as indicated by the Fearday-Rollins[11] experiments. Anisotropy of the Fermi surface can also contribute, but the magnitude of this effect is not well established.

In summary, there is excellent agreement between theory and experiment for the regime where $\lambda/\xi > 1$. In the regime where nonlocal effects are very important, however, there is a steady divergence of the experimental values from the theory as λ/ξ approaches 0.707.

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TABLE I. Sample parameters.

Sample	κ	ξ/l_{tr}	$\kappa_2^{\text{experiment}\,a}/\kappa_2^{\text{theory}}$
Pure Nb	0.78	0.01	1.6
Nb–1 000-ppm-Ta	0.79	0.04	1.5
Nb–5 000-ppm-Ta	0.82	0.08	1.4
Nb–10 000-ppm-Ta	0.9	0.12	1.2
Nb–20 000-ppm-Ta	1.1	0.16	1.0
Pure V[b]	0.85	0.02	1.2

[a]Taken at $t = 0.3$. [b]Reference 4.

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