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EXPERIMENTAL DETERMINATION OF THE TEMPERATURE-DEPENDENT PENETRATION DEPTH IN V_3Si

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Small angle neutron diffraction from the flux-line lattice (FLL) in a high quality, single crystal of superconducting V_3Si has been used to deduce the low-field penetration depth $\lambda(T)$. An absolute determination is possible because the FLL form factor F_{hk} is essentially single-valued in the scattering vector magnitude $|K_{hk}|$, as well as nearly London-like at low field. We obtain $\lambda(0)=102\pm 1$ nm, 20% to 30% larger than previous determinations of the London penetration depth $\lambda_L(0)$. The temperature dependence of $\lambda(T)$ is found to deviate from that of the BCS theory. An assessment of the data indicates the most prominent source of the discrepancy is due to strong electron-phonon coupling, and we find $2\Delta(0)/k_B T_C = 3.82 \pm 0.07$, in reasonable agreement with values found in the literature.

The temperature-dependent penetration depth $\lambda(T)$ is the fundamental length that describes the spatial variation of a static magnetic field within a superconductor, and has been the subject of extensive investigation in a number of superconducting pure materials and alloys (1). Almost exclusively it has been determined by detecting the near-surface penetration of a weak magnetic field into bulk or very thin samples in the Meissner state. Few techniques enable an absolute determination of λ ; usually one may obtain only relative changes with temperature. The penetration depth also characterizes the field decay from the core of an isolated flux-line (FL) in a type-II superconductor in the mixed state. Here we report measurements of $\lambda(T)$ in the A-15 compound V_3Si . The data are extracted by analyzing the small-angle neutron scattered intensity from the flux-line lattice at low-field (2). The technique permits an absolute determination of $\lambda(T)$, thereby enabling a direct comparison to the predictions of microscopic theory. In the following we briefly describe the experimental principles; and compare $\lambda(T)$ to the predictions of BCS theory and its modification due to many-body effects.

The measurements were made on an exceptionally high-quality single crystal (volume ~ 0.8 cm³) grown at Oak Ridge. The sample was characterized to have a superconducting transition temperature $T_C = 16.8$ K, a residual resistance ratio $R(298 \text{ K})/R(20 \text{ K}) = 30$, a cubic-to-tetragonal structural transition below $T_m = 21$ K, and was found (by TEM) to be free of second-phase precipitates larger than 1 - 2 nm. The neutron scattering measurements were performed on the 30-m SANS facility at Oak Ridge with the applied magnetic field horizontal and parallel to a $\langle 110 \rangle$ crystal axis. Over a wide range of temperature and field intensity, the FLL for this sample is observed to be single crystal. The microscopic field profile of the FLL can be

obtained from the form factor F_{hk} , found by measuring the integrated intensity I_{hk} in the peaks of the various order (hk) Bragg reflections,

$$|F_{hk}|^2 = C |K_{hk}|^{-2} I_{hk}. \quad (1)$$

Here, K_{hk} is the FLL reciprocal space vector for the (hk) reflection, B is the flux density, and C contains well-defined constants of the experiment. Two observed features of the form factor in V_3Si lead to a straight-forward determination of a penetration depth: First, at low flux densities (e.g. $B < 1.1$ T at 4.8 K) the form factors for the various reflections lie on a universal curve as a function of K_{hk} . This means the total microscopic field is comprised of a linear superposition of isolated FL fields. Second, the observed functional form of the low-field (e.g. $B < 0.6$ T at 4.8 K) form factor is London-like,

$$|F_{hk}| = (1 + \lambda^2 K_{hk}^2)^{-1/2}. \quad (2)$$

Thus, at sufficiently low field, the parameter λ multiplying the quadratic K -dependence can be associated with the field decay about an isolated FL. We performed the SANS measurements of the lowest order (10) Bragg reflection at a fixed $B = 0.15$ T for various reduced temperatures $t = T/T_C$, and used Eqs. (1) and (2) to find $\lambda(t)$.

The above empirical observations imply a local electrodynamic response in V_3Si , which is consistent with the following independent check. ECS have calculated the ratio $\lambda(t)/\lambda_L(t)$ vs the ratio $\xi_0/\lambda_L(t)$ in Figure 7 of their original paper (3). Using data for the BCS coherence length ξ_0 and the London penetration depth $\lambda_L(0)$ (4, 5), we anticipate $\lambda(0)/\lambda_L(0) = 1.0 \pm 0.05$ in the clean limit. Therefore we compare our data with theoretical results of the local, London limit.

Figure 1 shows the absolute penetration depth

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FIGURE 1. The measured penetration depth as a function of reduced temperature. The dashed curve is the BCS London limit fit to the data at high T. The solid curve is the same theory matched to the low-T results.

as a function of t compared to the BCS theory. The dashed curve was fit to the data in the high-temperature Ginzburg-Landau regime where $\lambda(t)^{-2} = \lambda_L(0)^{-2}(1-t)$; the fit yields an apparent $\lambda_L(0) = 97$ nm. The solid curve was normalized to the low-temperature data that indicate $\lambda_L(0) = 102$ nm. It is known that both impurity scattering and strong-coupling effects can result in deviations such as those apparent here (6).

We have estimated the impurity contribution using the resistivity, and the best available data for ξ_0 and the free Fermi surface area (5, 6), to obtain the impurity parameter $\alpha = 0.882\xi_0/\lambda = 0.20$, where λ is the electron transport mean free path. Within the context of BCS the deviations cannot be explained by the impurity correction alone. This is shown with increased sensitivity in Figure 2, where the data are plotted as a normalized deviation function from the temperature dependence of the two-fluid model (1). In fact, to obtain a reasonable fit to the data via the scattering mechanism alone requires $\alpha = 3.5$, well outside the range of possible error in its estimate.

We have included the effects of strong electron-phonon coupling by the familiar technique of scaling the temperature-dependent gap where it appears in the BCS expressions. This procedure is a good approximation if the strong-coupling correction factor $\eta_\Delta(t)$ for the gap parameter $\Delta(t)$ is only weakly temperature-dependent (5). The result of such a fit is shown in Figure 2, where we have included the combined effects of strong-coupling and impurity scattering. From this we obtain, $\Delta(0)/\Delta(0)_{\text{BCS}} = \eta_\Delta(0) = 1.10 \pm 0.02$, or $2\Delta(0)/k_B T_c = 3.88 \pm 0.07$. This new value seems to

FIGURE 2. The results plotted as a normalized deviation function with respect to the two-fluid model. Solid curve: BCS London limit. Dashed curve: BCS theory corrected for the observed impurity scattering. Dash-dot curve: BCS theory corrected for strong coupling as well as impurity effects.

agree with, but lie near the upper range of, previous determinations found by a variety of experimental techniques (4-6).

From the measured value at low-temperature (see Figure 1), we obtain the London penetration depth $\lambda_L(0) = \lambda(0)(1+1.283\alpha)^{-1/2} = 91.6 \pm 2.5$ nm, slightly larger than that calculated from normal state properties, which yield $\lambda_L(0)$ in the range 75 nm to 86 nm (4,5). The value $\lambda_L^{\text{BCS}}(0) = 57$ nm, found using unrenormalized properties calculated from band theory (6), would imply an anomalously large electron-phonon coupling constant $\lambda_{ep} = 1.6$. This observation is consistent with a previously recognized problem in vanadium-based compounds, and may possibly be reconciled by more subtle effects such as spin-fluctuations, anisotropy, or a sharply-peaked density of states at the Fermi level (5,6).

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