The temperature dependence of E_0/E_i comes from the factor C_vT. The line in Fig. 1 represents the fit of (E_0/E_i) to the product of T and a Debye specific-heat function. This is a two-parameter fit; the Debye temperature is found from the fit to be 14.8°K and the low-temperature limit of (E_0/E_i) to be $E_0/E_i = 1.6\times10^{-7}T^4$. At very low temperatures all of the thermally excited phonons interact with the electrons and C_v is the total lattice specific heat of the crystal. Thus, the right-hand side of Eq. (3) involves no adjustable parameters in the low-temperature limit. Using values measured on our specimen for μ, n, and t, and Bryant and Keesom's[5] value for C_v, in Eq. (3) gives $E_0/E_i = 1.1\times10^{-7}T^4$, about two thirds of the measured value. value.

The value of θ, the effective Debye temperature of the interacting phonons, is a measure of q_m, the maximum wave vector of the interacting phonons, or of the number of phonon modes which interact with the electrons. The observed value, $\theta = 14.8$°K, corresponds to 8×10^{18} modes per cm^3, in other words, about one mode per electron. Although calculation of the number of phonons which drift with the electrons is difficult because of the anisotropy of the electronic energy bands, we would have expected that the electronic motion would impart the drift velocity to a large number of phonons. In the case of a spherical Fermi surface, phonons with wave vector less than twice the Fermi wave vector can scatter electrons directly. The sphere of such directly interacting phonons in wave-number space contains 12 phonon states (including the three polarization branches) per electron. Since each of the electron valleys contain 1/4 of the electrons, the number of directly interacting phonons might be reduced to three per electron. However, because not all valleys interact with the same phonons, the number should be somewhat larger than three. The number might be reduced if the higher energy scattered phonons had short momentum-loss relaxation times, so that they remained in equilibrium even though scattered by the electrons.

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EXPERIMENTAL EVIDENCE FOR DELAYED ENTRY OF FLUX INTO A TYPE-II SUPERCONDUCTOR*

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Null-deflection torque magnetometer studies[1,2] have been carried out on annealed homogeneous Pb-Tl alloys (4.3-12.3 at.% Tl) in the form of thick films (1.4-4.2 μ) and foils (25-100 μ) over the interval $1.1 \leq T \leq 4.2$°K, with the applied field H very nearly in the plane of the specimen. By this method, the measured field dependence of the torque τ defines a characteristic field H_τ at which τ/H departs from its initially linear dependence on H. The departure from linearity can be ascribed to flux penetration, in accord with our measurements on thick annealed pure Pb films which exhibit linear τ/H behavior until nearly H_c(bulk), whereupon τ/H drops rapidly to zero. Furthermore, a residual value of τ/H (negative) at $H = 0$ is interpreted as evidence of flux trapping. For alloy films (4.2°K), direct comparison can be made between H_τ and the bulk lower critical field H_{c1}(bulk), where the latter is deduced from the data of Bon Mardion, Goodman, and Lacaze.[3] Foils exhibited H_τ values approximately equal to H_{c1}(bulk), and flux trapping was observed only when H_τ was exceeded. In addition, H_τ varied parabolically with reduced temperature,[4] a behavior similar to that observed for H_{c1} in the In-Bi system by Kinsel, Lynton,

and Serin.[5] In marked contrast, the as-deposited and annealed alloy films exhibited linear τ/H characteristics to fields which always exceeded H_{c1}(bulk) and which in some instances were as great as three times H_{c1}(bulk). Furthermore, when τ/H did deviate from linearity, it did so in a gradual manner. Flux trapping was not detectable until after H was raised well above H_τ, nearly to H_{c2}(bulk). If, however, a film was scored to form an array of small isolated squares (edge length 0.015-0.060 cm), it then displayed a value of H_τ nearly equal to H_{c1}(bulk). Flux trapping at $H = 0$ was observed only when H_τ was exceeded. For the scored films the dependence of H_τ on reduced temperature was parabolic.[4] Scoring a film seems to induce H_τ behavior similar to that of a bulk foil. These observations appear to be qualitatively consistent with certain features of the surface barrier theory recently proposed by Bean and Livingston,[6] although quantitatively, flux entry into the unscored films appears to be delayed to substantially higher fields than anticipated. Simple estimates indicate that even the thinnest film studied was still sufficiently thick to accommodate several layers of flux threads (supercurrent vortices) above H_{c1}(bulk). Thus the observed delay of flux entry is probably not attributable to the inability of the sample to accommodate flux threads within its thickness.

Films were prepared by vacuum evaporation onto glass substrates at room temperature with residual pressures in the range $(2\text{-}7)\times10^{-7}$ mm Hg. Compositional homogeneity was monitored by analysis of films formed by the exposure of glass substrates during only a fraction of the total evaporation period. Thicknesses were calculated from wet chemical mass determinations utilizing specimens of known area, and assuming the bulk mass density of Pb, a good approximation for this alloy system at the present thicknesses and concentrations. Foils were manufactured by vacuum casting and subsequent rolling. Initial purity of both Pb and Tl was 99.999%. All chemical compositions were determined by standard polarographic techniques. All specimens were annealed in residual pressures less than 3×10^{-6} mm Hg. Extraneous magnetic fields were compensated to the extent that it was possible to cool the specimens in residual fields no larger than 0.1 G. Fields applied subsequent to cooling were parallel to the plane of the specimen to within 0.05°.

Figure 1, curve A, depicts τ/H vs H for an unscored 6.5 at.% Tl film (1.4 μ) at 1.1°K. For this particular specimen, τ/H remained linear to at least 730 G (no flux penetration). Flux trapping at $H = 0$ was not detected until after the applied field was increased to roughly 1500 G, a value well above H_τ and approaching H_{c2}(bulk). After the film was scored, forming an array of isolated squares, its behavior changed to that shown by curve B, which also corresponds to 1.1°K. Curve C depicts τ/H vs H for the scored film at 4.2°K, and it is seen that the corresponding H_τ value is in good agreement with H_{c1}(bulk) at 4.2°K. Figure 1 also illustrates reasonable accord between the scored-film H_τ(1.1°K) value and an estimated value for H_{c1}(1.1°K) obtained using the experimental H_{c1}(4.2°K) value[3] and an assumed parabolic temperature dependence. The hysteretic τ/H vs H plot shown in Fig. 2 for the same scored film is indicative of flux trapping at $H = 0$ which occurs when H is decreased from

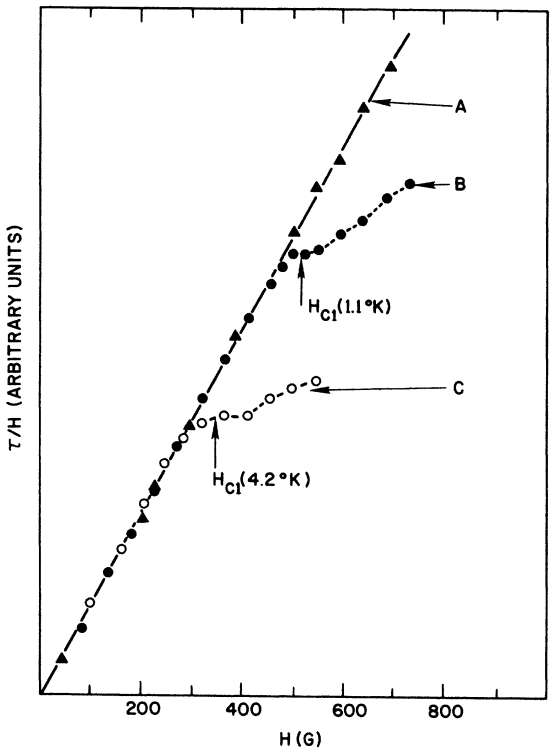

FIG. 1. Plot of τ/H vs H for a Pb-6.5 at.% Tl film (1.4 μ) illustrating the difference in behavior between the unscored and scored condition. Curve A for the unscored condition (1.1°K) remains linear to a field of at least 730 G which is considerably greater than the bulk H_{c1}(1.1°K) value. Curves B and C for the scored film at 1.1°K and 4.2°K, respectively, depart from linearity at field values H_τ in reasonable accord with the corresponding bulk lower critical fields indicated by the arrows.

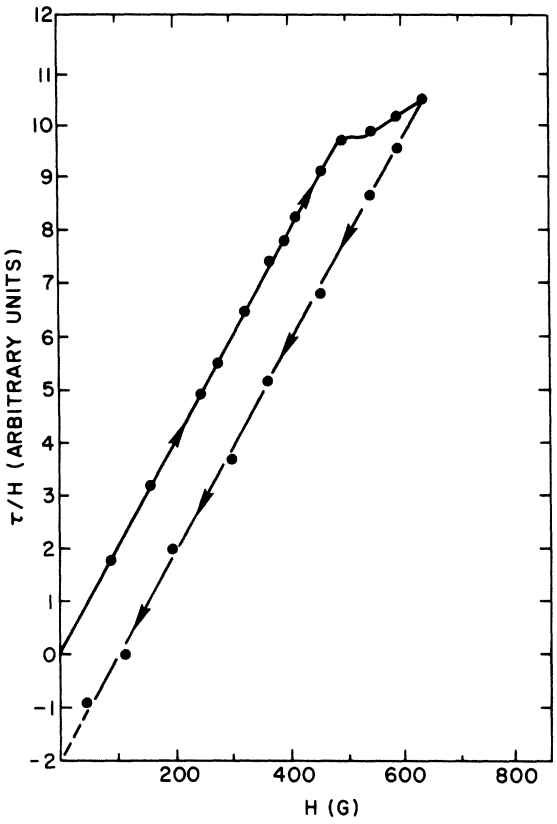

FIG. 2. Plot of τ/H vs H at 1.1°K for the scored film of Fig. 1. The hysteresis which occurs when H is decreased from fields greater than H_τ is taken to be indicative of flux trapping. Such evidence of flux trapping was not detected if field cycling was confined to fields less than H_τ.

a field value greater than H_τ.

The effects of scoring a film, as illustrated in Figs. 1 and 2, have also been observed in three other specimens as summarized in Table I.

It appears that the notable difference in τ/H for foils and unscored films with regard to evidencing flux penetration near H_{c1}(bulk) can be understood if it is assumed that, for the unscored film, flux penetration is inhibited by a surface barrier in accord with a model recently proposed by Bean and Livingston.[6] They consider the effects of attractive image forces experienced by flux threads (supercurrent vortices) near a surface, and indicate that a plane surface can provide an energy barrier to flux thread motion into or out of a specimen. Furthermore, they point out that field concentrations at corners or other irregularities may be sufficient to overcome this barrier and hence serve as centers for the injection of flux threads. These same regions of field concentration, however, actually inhibit the efflux of threads as the applied field is reduced. It is believed that the high values of H_τ observed for unscored films are due to the low concentration of surface irregularities, and that scoring the film creates flux injection centers which facilitate flux entry once H_{c1}(bulk) has been exceeded and formation of the mixed state is favored energetically. The observed flux trapping is compatible with the notion that the same centers do not allow threads to escape easily as H is decreased. By way of contrast, the unscored films do not exhibit flux trapping at $H = 0$ until the field is raised almost to H_{c2}(bulk). This is consistent with the Bean and Livingston statement that for a sufficiently perfect surface, the barrier to flux escape disappears at $H = 0$ and hence, there should be no residual trapped flux. For foils, the absence of delayed flux entry and the presence of substantial trapped flux at $H = 0$ when the field exceeds H_τ is probably due to the presence of surface irregularities introduced during manufacture.

We wish to thank T. G. Berlincourt for valuable

Table I. Comparison of H_τ for scored films with H_{c1}(bulk).[a]

Composition (at.%)	Thickness (μ)	H_τ(4.2°K) (G)	H_{c1}(4.2°K)[b] (G)	H_τ(1.1°K) (G)	H_τ(1.1°K) (calc)[c] (G)
4.3	4.2	440	420	645	670
6.0	2.6	312	360	484	475
6.5	1.4	350	350	506	524
12.3	2.0	255	250	405	390

[a]Uncertainties in H_{c1} and H_τ are approximately ±15 G.

[b]Bulk values obtained by interpolation from data of reference 1.

[c]The calculated values for H_τ(1.1°K) were obtained using H_τ(4.2°K) and assuming a parabolic temperature dependence.

suggestions and for noting the possible relevance of the Bean and Livingston theory and also R. R. Hake for helpful comments. We are indebted to C. P. Bean and J. D. Livingston for making available the results of their theoretical investigation prior to publication. We wish to thank R. R. Hargrove for aid with specimen preparation, R. E. Gile for help with the measurements, and E. P. Parry for the chemical analyses.

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POLARIZATION IN THE ELASTIC SCATTERING OF 22-MeV PROTONS FROM DEUTERONS*

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The measurement and interpretation of the polarization in the scattering of low-energy nucleons by deuterons should have an important bearing on the understanding of nucleon-nucleon interactions in nuclear matter. Even though the two-body interaction may not be completely known, one would hope to predict the results of nucleon-deuteron scattering in terms of measured nucleon-nucleon scattering parameters, and to determine whether or not any specifically three-body interaction would be required to explain the results. Unfortunately, at low energies, where the results are of greatest interest with respect to their bearing on nuclear structure, the interactions among the three particles during the scattering are roughly equally strong, and thus the analytic solution of the problem becomes difficult. The maximum polarization is known to be small in p-p scattering ($<1\%$)[1,2] and in n-p scattering ($\approx 5\%$)[3,4] near 20-MeV bombarding energy. On the other hand, the polarization in the scattering of protons from complex nuclei reaches values of up to 100% at energies as low as 6 MeV. In scattering from the lightest nuclei, in particular, the maximum polarization is approximately 100% in p-^{4}He scattering at 6 to 14.5 MeV,[5,6] and about 55% in p-^{3}H and p-^{3}He scattering at 14.5 MeV.[6] The former is understandable in terms of the splitting of the $j = l + 1/2$ and $j = l - 1/2$ phase shifts due to the strong spin-orbit forces acting in the p-^{4}He (^{5}Li) system. Such an explanation might be considered for the p-^{3}H and p-^{3}He results, treating the target as a spin-zero nucleus and thereby ignoring any tensor interaction. However, an extension of this argument to the p-d system does not seem warranted since measurements of the polarization in p-d scattering have been consistent with zero or very small values at energies below 17 MeV.[7] Thus, determinations of polarization in p-d or n-d scattering at energies below 50 MeV should provide information useful to the understanding of this remarkable difference between the polarization induced in nucleon-nucleon scattering and that resulting from the scattering of the nucleon from a few-nucleon system.

A general theory of nucleon-deuteron scattering, including tensor forces but neglecting the distortion of the deuteron, has been developed,[8] but calculations based on this formalism are not presently available. An approximate calculation has been made which includes, also, the effect of deuteron distortion in n-d scattering below 3.5 MeV.[9] This calculation predicts a rapid variation of the neutron polarization with energy at 90° c.m., reaching a maximum of 12% near 1 MeV. Experimental results to date are not in