Table I. Values of Lorentz force parameter. The values of H and $H\sin\theta$, in kG, are shown for $V=0.1$ and 0.5 mV of Fig. 1.

	$V=0.1$ mV		$V=0.5$ mV	
θ	H	$H\sin\theta$	H	$H\sin\theta$
90°	0.80	0.80	1.94	1.94
65°	0.84	0.76	2.15	1.94
43°	1.17	0.80	2.84	1.94
20°	2.34	0.80	...	...

flux lines induces an emf

$$V=Hv/c=(\eta\varphi_0/c^2)JH, \tag{3}$$

which is linear in $\alpha=JH$. Because of the field dependence of η, V is not linear under the H variation (see Fig. 1). When J is varied at a fixed H, however, we do observe a linear dependence of V on J as expected from (3). At very small values of α the sample exhibits the flux-creep behavior, probably because of flux pinning by residual defects. Further studies are under way to determine if the resitive behavior between H_{c2} and H_{c3} can be explained by the superconducting sheath model.

We are indebted to A. R. Strnad for his collaboration in the experiments and to R. Epworth and J. Hasiak for their technical assistance. We are grateful to P. W. Anderson for his helpful discussions.

[1]D. Saint-James and P. G. de Gennes, Phys. Letters 7, 306 (1963).

[2]The values of H_{c2} obtained by resistance measurements are in agreement with those from magnetization measurements.

[3]D. P. Seraphim and R. A. Connell, Phys. Rev. 116, 606 (1959).

[4]J. I. Budnick, Phys. Rev. 119, 1578 (1960).

[5]S. H. Autler, E. S. Rosenblum, and K. H. Gooen, Phys. Rev. Letters 9, 489 (1962).

[6]W. F. Druyvesteyn, D. J. Van Ooijen, and T. J. Berben, Rev. Mod. Phys. 36, 58 (1964).

[7]Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. 131, 2486 (1963). More details on flux flow and flux creep are given in the papers by the present authors and by P. W. Anderson and Y. B. Kim, Rev. Mod. Phys. 36, 39 (1964).

EXPERIMENTAL EVIDENCE FOR A NEW SUPERCONDUCTING PHASE NUCLEATION FIELD IN TYPE-II SUPERCONDUCTORS*

W. J. Tomasch
Atomics International Division of North American Aviation, Incorporated, Canoga Park, California

and

A. S. Joseph
North American Aviation Science Center, Canoga Park, California

(Received 24 December 1963)

Utilizing a null-deflection torque magnetometer,[1,2] we have studied remnant superconductivity in thick films (4-10 μ) and bulk foils (51-127 μ) of Pb-Tl alloys in the field interval H_{c2} to $1.7\times H_{c2}$, where H_{c2} is the bulk upper critical field.[3] Measurements were made over the range 1.1-4.2°K on well-annealed homogeneous specimens of composition 4.2-10.0 at. % Tl. Our technique defines two critical fields H_l (longitudinal) and H_t (transverse) which mark, respectively, the cessation of superconductivity with the field applied parallel and perpendicular to the plane of the specimen. Numerically H_t correlates well with H_{c2}, the latter being deduced from the data of Bon Mardion, Goodman, and Lacaze.[4] Our results show that the ratio H_l/H_t is essentially constant, independent of composition, thickness, and temperature, hence implying a basic effect rather than one caused by specimen defects of various types. Recently Saint-James and de Gennes[5] have independently advanced a theory which predicts a new superconducting phase nucleation limit $H_{c3}>H_{c2}$ when H is applied parallel to the plane of a superconductor-vacuum interface. Furthermore, H_{c3}/H_{c2} is a calculable constant which they have evaluated numerically. Our observed values of H_l/H_t are in remarkable agreement with their theoretical value. The results of earlier tunneling studies[6] which prompted the present investigation are believed

Table I. Description of specimens used.

Specimen number	Form	Atomic percent thallium	Thickness in microns	Annealing[a] Time (hours)	Annealing[a] Temp (°C)
92-3	Film	4.2	5.69	113	312
F1-6	Foil	4.3	51	156	310
90-3	Film	6.5	4.12	65	305
69-5-2	Film	8	0.99	72	304
F2-5A	Foil	10.0[b]	51	152	310
F2-5B	Foil	10.0[b]	127	152	310

[a]Melting temperatures ranged between 327 and 335°C.
[b]Nominal composition determined from starting proportions.

to be consistent with the physical picture which follows from the Saint-James and de Gennes theory.

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 exposing additional glass substrates for 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.

It was initially thought that the substantial torques observed above H_{c2} were due to high-field superconducting regions associated with extended lattice defects and/or regions of local chemical inhomogeneity. Subsequent annealing was indeed able to reduce such behavior somewhat, but there remained an unannealable component which displayed regular and reproducible features. Annealed foils were then studied to see if films behaved in a basically different fashion compared to bulk specimens with regard to the cessation of superconductivity as evidenced by torque measurements. They did not. Specifically, the ratio H_l/H_t remained accurately the same for both film and foil.

A summary of experimental results is presented in Table I and Table II. Values of H_{c2} were interpolated for various compositions from the data of Bon Mardion, Goodman, and Lacaze.[4] The central features of interest in Table II are the correlation of H_t and H_{c2}, and the constancy of the ratio H_l/H_t at a value of 1.69 ± 0.02. Figure 1 depicts the angular dependence of the critical field between the limits H_l and H_t for a film and a foil. Near H_l $(\theta\approx0°)$, film and foil behave similarly. For $\theta\gtrsim40°$, there does appear to be a difference between the two.

Saint-James and de Gennes have examined the influence of a plane superconductor-vacuum interface on the solutions of the Ginzburg-Landau (G-L) equations with a field applied parallel to the interface. They conclude that there exists a super-

Table II. Critical field data.

Specimen number	$H_{c2}(4.2°K)$ (gauss)	$H_t(4.2°K)$ (gauss)	$H_l(4.2°K)$ (gauss)	$H_l(4.2°K)/H_t(4.2°K)$	$H_l(1.1°K)/H_t(1.1°K)$
92-3	920[a]	970	1650	1.70 ± 0.02	1.69 ± 0.02
F1-6	940[a]	950	1611	1.70 ± 0.02	
90-3	1270[a]	1300	2198	1.69 ± 0.02	1.69 ± 0.02
69-5-2		1245	2105	1.69 ± 0.02	
F2-5A	1680[a]	1575	2690	1.70 ± 0.02	1.69 ± 0.02
F2-5B	1680[a]	1575	2680	1.69 ± 0.02	

[a]Interpolated from data of Bon Mardion, Goodman, and Lacaze (reference 4).

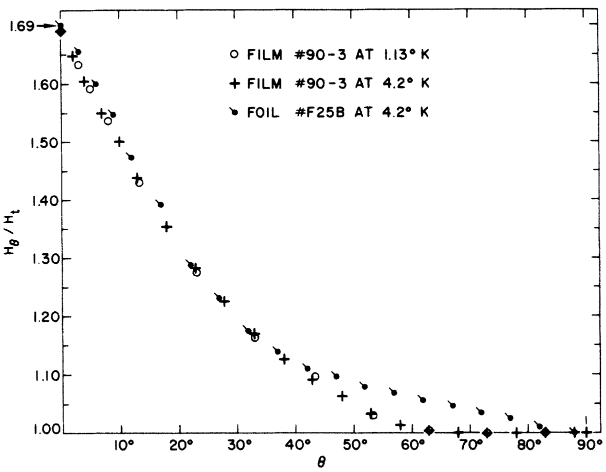

FIG. 1. The torque critical field ratio H_θ/H_t versus θ (the angle between H and specimen plane), where H_t corresponds to $\theta = 90°$. The arrow indicates the value H_{c3}/H_{c2} theoretically predicted by Saint-James and de Gennes (reference 5). For further information, consult Tables I and II.

conducting laminar region or sheath centered a distance $X_0 = 0.7682\xi$ below the interface, where ξ is the coherence length. Within this sheath, the local free energy is less than the bulk G-L value. According to their detailed calculations, the sheath will remain superconducting up to a limit $H_{c3} = 1.692H_{c2}$. For the case of a magnetic field applied normal to the interface, they conclude that the superconducting phase nucleation limit will equal H_{c2}. Also, at intermediate angles of applied field, they suggest that this limit is probably a smooth function of angle.

The numerical agreement between the calculated value of H_{c3}/H_{c2} and our observed values of H_l/H_t is striking. The observed correlation between H_t and H_{c2} is also in harmony with the theory. On the basis of this evidence it is suggested that $H_l = H_{c3}$ and $H_t = H_{c2}$, where H_l and H_t are defined operationally in terms of a torque measurement. In general, it is believed that our observations lend strength to the notion of a superconducting sheath which presists in the interval $H_{c2} < H < 1.692H_{c2}$.

We wish to thank Dr. T. G. Berlincourt for acquainting us with the theory of Saint-James and de Gennes and for suggesting its possible applicability. We are indebted to D. Saint-James and P. G. de Gennes 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.

---

*Work supported in part by the U. S. Atomic Energy Commission.

[1]A. S. Joseph and W. L. Gordon, Phys. Rev. 126, 489 (1962).

[2]B. K. Sevast'yanov and V. A. Sokolina, Zh. Eksperim. i Teor. Fiz. 42, 1212 (1962) [translation: Soviet Phys.—JETP 15, 840 (1962)].

[3]A. A. Abrikosov, Zh. Eksperim. i Teor. Fiz. 42, 1442 (1957) [translation: Soviet Phys.—JETP 10, 998 (1960)].

[4]G. Bon Mardion, B. B. Goodman, and A. Lacaze, Phys. Letters 2, 321 (1962).

[5]D. Saint-James and P. G. de Gennes, Phys. Letters 7, 306 (1963).

[6]W. J. Tomasch, Bull. Am. Phys. Soc. 8, 419 (1963). A more detailed account of this work is in preparation.

OBSERVATION OF DIFFUSION BROADENING OF RAYLEIGH SCATTERED LIGHT*

H. Z. Cummins, N. Knable, and Y. Yeh
Columbia Radiation Laboratory, Columbia University, New York, New York
(Received 10 December 1963)

Light which is Rayleigh scattered by dilute solutions of macromolecules is normally considered to be spectrally identical to the incident or exciting light. Although angular scattering intensity and polarization measurements have been employed for many years in the study of polymers and colloids,[1] the additional information carried by the spectral distribution of scattered light has been inaccessible because of the limited resolution of traditional spectroscopic apparatus.

We have utilized a cw optical maser in conjunction with optical heterodyne detection techniques to examine the spectrum of Rayleigh scattering with an instrumental resolution of 6 cps, corresponding to an equivalent optical resolving power of approximately 10^{14}. The observed spectrum is found to be broadened, and the broadening has been found to depend both on the size of the scat-