Below this temperature, we have been able to fit the data by scaling the low-frequency formula with the gap $2\Delta(0)$ adjusted to $(3.4 \pm 0.3)kT_C$.

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[2] The highest frequency previously reported is that at 9.16 GHz on polycrystalline mercury [$h\nu/\Delta(0) \sim 0.07$] by R. B. Ferguson, Bull. Am. Phys. Soc. 12, 330 (1967). There is also the work of H. E. Bömmel on indium at ≈10 GHz reported informally in the discussion at the Cambridge Colloquium on Superconductivity, June 1959, and variously quoted since. E. A. Lynton [Phys. Today 12, No. 11, 26 (Nov. 1959)] incorrectly gives the frequency in Bömmel's experiment as 30 GHz. This error was unfortunately repeated in a theoretical paper by I. A. Privorotskii, Zh. Eksperim. i Teor. Fiz. 43, 133 (1962) [translation: Soviet Phys.—JETP 16, 945 (1963)], who compared Bömmel's presumed results with the theoretical high-frequency absorption curve. It seems unlikely that this comparison is valid.

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MEISSNER EFFECT FOR SUPERCONDUCTORS WITH MAGNETIC IMPURITIES*

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Th-Gd alloys show a full Meissner effect and magnetization curves which are reversible to 0.6 % of H_C. Critical field curves agree with the Abrikosov-Gor'kov theory to an accuracy of about 3 %.

A special interest has centered around superconductors with magnetic impurities since Abrikosov and Gor'kov (AG)[1] first predicted that they might exhibit gapless superconductivity. Thermodynamic properties,[2] the thermal conductivity,[3,4] and the acoustic attenuation[5] have been calculated for this theory and many aspects have been qualitatively confirmed by critical-temperature (T_C),[6-9] electron-tunneling,[10] specific-heat,[11] and microwave-absorption[12] experiments. An accurate confirmation of the theory for bulk materials, however, has been difficult because there are serious sample preparation problems. The measurement of critical field curves has heretofore been complicated by severe hysteresis and almost perfect flux trapping.[11] For the Th-Gd alloys which are reported here, however, the magnetization curves confirm a full Meissner effect and establish that the bulk properties of superconductors doped with paramagnetic impurities obey the AG theory to an accuracy of approximately 3 %.

Isothermal magnetization measurements were made by the ballistic induction technique which was developed by Finnemore and Mapother.[13] Above 1.1°K, the T-58 vapor pressure scale[14] was taken as the primary standard, and below 1.1°K, temperatures were determined from the susceptibility of cerium magnesium nitrate. The sixth order Garrett[15] solenoid which was used to produce the magnetic fields was calibrated by the nuclear magnetic resonance of protons in glycerine. To prepare the alloy samples, appropriate quantities of Th and Gd were arc melted four or five times, sealed in Ta containers and annealed at 1200°C for 1 week, pressed into a block, swaged to 0.040-in. diam wire, and annealed at 800°C for 1 h to allow recrystallization and the relief of strain. As a final step, the samples were electropolished in a perchloric acid and methanol solution. Samples prepared in this way have an electrical resistivity at 4.2°K which is proportional

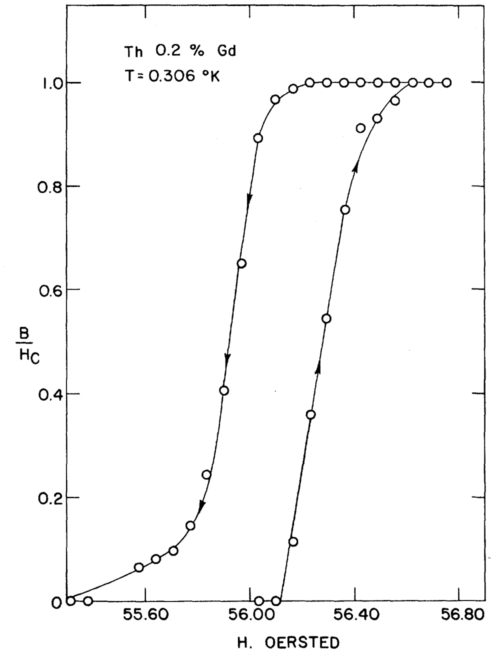

FIG. 1. A superconducting-to-normal and a normal-to superconducting phase transition for Th-0.2 at.% Gd sample at 0.306°K. Hysteresis is approximately 0.6% of H_c.

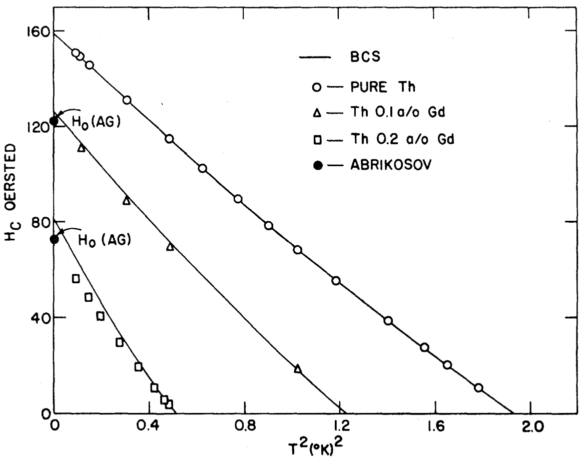

FIG. 2. Critical field curves for pure Th and Th-Gd alloys.

to Gd concentration. The pure Th sample reported here was prepared by an electrotransport[16] process so it has a much lower normal-state resistivity and a resistivity ratio ($R_{300}/R_{4.2}$) of 1200.

An isothermal magnetization curve for Th-0.2 at.% Gd at 0.306°K is shown in Fig. 1. The phase transition which takes place at 56.45 Oe is approximately 0.40 Oe wide or about 60% broader than would be expected from the geometry of the specimen alone.[13] This is very sharp for an alloy and it indicates that the material is homogeneous on the scale of the superconducting coherence length. For the transition shown here, the hysteresis is 0.35 Oe or about 0.6 % of H_c. All the alloys show some hysteresis and the magnitude of the effect is approximately proportional to H_c. At fields less than 98 % of H_c, the Meissner effect is complete for both of these alloys.

Critical field curves for pure Th and the two alloys are shown in Fig. 2. Pure Th seems to be an excellent example of a weak-coupling superconductor in that the critical field curve follows the BCS[17] prediction (solid line of Fig. 2) to an accuracy of 0.1 % over the entire temperature range. This particular sample also shows a temperature-dependent supercooling of 0.68 % of H_c. On the basis of the St. James and de Gennes theory,[18] this would give a kappa value less than 0.51 for pure Th. If the standard approximations are made,[13] the data for pure Th give a critical temperature of 1.390°K, a critical field at $T=0$ (H_0) of 159.1 Oe, an electronic specific-heat coefficient (γ) of 4.34 mJ/mole °K^2, an energy gap at $T=0$ $[2\Delta_p(0)]$ of $3.53kT_c$ where k is the Boltzmann constant, and a jump in specific heat of $1.43\gamma T_c$. These are in rather good agreement with earlier measurements[19] and in excellent agreement with BCS.

The addition of Gd depresses both H_0 and T_c but the shape remains fairly close to the parabolic law, $H_c = H_0(1-t^2)$ where $t = T/T_c$. There is good evidence that there is no spin ordering in this concentration and temperature range[20] so the results should provide a good test for the AG paramagnetic theory. A very important parameter for each sample is the spin scattering time or the lifetime broadening (Γ).[2] This is not directly measured in the experiment but it can be determined with the help of the theory[2] from the measured T_c to be $\Gamma/\Delta_p(0)=0.32$ for Th-0.20 at.% Gd. Hence, this sample shows 64 % of the broadening required to completely destroy superconductivity. A theoretical value for the critical field at $T=0$ $[H_0(\mathrm{AG})]$ has[2] been calculated to be 72.8 Oe. As can be seen from Fig. 2 (large solid dot on the ordinate), this is in excellent agreement with an extrapolation of the data at higher temperatures.

For comparison, the critical-field curves which

Table I. Characteristics for Th and Th-Gd alloys.

	T_c (°K)	H_0 (Oe)	$\Delta C/\Delta C_p$ Measured	$\Delta C/\Delta C_p$ Calculated	$\Gamma/2\Delta_p(0)$
Pure Th	1.390 ± 0.002	159.1 ± 0.2	1.00	1.00	...
Th-0.10% Gd	1.107 ± 0.007	122.6[a]	0.71	0.717	0.142
Th-0.20% Gd	0.714 ± 0.002	72.8[a]	0.35	0.362	0.317

[a] Calculated from the AG theory.

BCS would predict for a pure metal with the same T_c as the alloys and a γ value equal to that of pure Th is shown by the solid-line curve of Fig. 2. The critical-field curves lie well below BCS but very close to the AG predictions. Another way to compare with the theory is to calculate the specific-heat jump at T_c $[\Delta C]$ from the slope of the magnetization curve. For the Th-0.20 at.% Gd sample, the ratio of the jump for the alloy to the jump for pure Th $[\Delta C/\Delta C_p]$ is 0.35 compared to the theoretical value of 0.362.[2] Again the agreement is excellent.

Similar calculations have been carried out for the Th-0.10 at.% Gd sample and the appropriate parameters for both samples have been collected in Table I. The theory of Abrikosov and Gor'kov[1] and of Skalski, Betbeder-Matibet, and Weiss[2] seems to apply for Th-Gd alloys and it predicts the bulk properties to an accuracy of about 3 %.

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