magnetite in the same temperature range, we obtain

$$A(\mathrm{Fe_3O_4}) = 0.232 \times 10^{-6} \text{ erg/cm}.$$

Suhl[5] has shown that in a sphere, $z$-directed spin waves having a wave number given by $k_0$ in

$$k_0^2 = 2\pi M_s^2/3A$$

are degenerate in frequency with the uniform precessional mode ($k = 0$). We expect[6,7] maximum coupling of the uniform precessional mode to transverse phonons via the $z$-directed spin waves when the frequency is given by

$$f_c = v_t k_0/2\pi,$$

where $v_t$ is the velocity of transverse phonons. Using our value of $A$ and the value $v_t = 3.87 \times 10^5$ cm/sec obtained in polycrystalline YIG at 25°C by McSkimin,[8] we find

$$|k_0| = 4.60 \times 10^5 \text{ cm}^{-1}$$

and

$$f_c = 2.83 \times 10^{10} \text{ sec}^{-1} \quad \text{or} \quad \lambda_c = 1.05 \text{ cm}.$$

It is our pleasure here to record our debt to Professor C. Kittel who suggested the investigation and to M. K. Jack of Hughes Research Laboratories who kindly supplied us with the specimen of YIG.

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## SUPERCONDUCTIVITY VERSUS FERROMAGNETISM IN LANTHANUM-GADOLINIUM ALLOYS

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The differential paramagnetic susceptibility of samples of LaGd alloys containing from 0.60 to 5.00 % Gd has been measured in the temperature range from 4.22 to 0.10°K. Matthias et al.[1] have shown that the addition of small amounts of Gd to La produces solid solutions with unusual magnetic properties. Alloys containing up to 0.90 % Gd are superconductors with transition temperatures ($T_c$) which decrease linearly with increasing Gd content. Alloys containing 3.0 or more percent Gd are ferromagnetic with Curie temperatures which increase with increasing Gd content. The alloy containing 3.0 % Gd becomes ferromagnetic at 1.3°K, the lowest temperature they could attain. Extrapolation of these data suggests that the $T_c$ vs percent Gd curve and the Curie temperature vs percent Gd curve would intersect for an alloy of 1.25 % at a temperature of 0.5°K. Thus two possibilities are suggested: (1) the curves meet and terminate, indicating the possibility of a ferromagnetic superconductor for one specific composition, or (2) they intersect in such a way that there would exist a range of compositions for which a given alloy would exhibit (in zero magnetic field) both superconductivity and ferromagnetism, but at different temperatures. The primary purpose of the work reported here was to investigate the validity of these extrapolations.

Temperatures below 1°K were produced by the magnetic cooling method. The sample to be investigated was cemented in a copper holder which was in thermal contact with the paramagnetic salt via a copper rod 12 cm long and 3 mm in diameter. A carbon resistor cemented directly on the sample indicated that it was in intimate

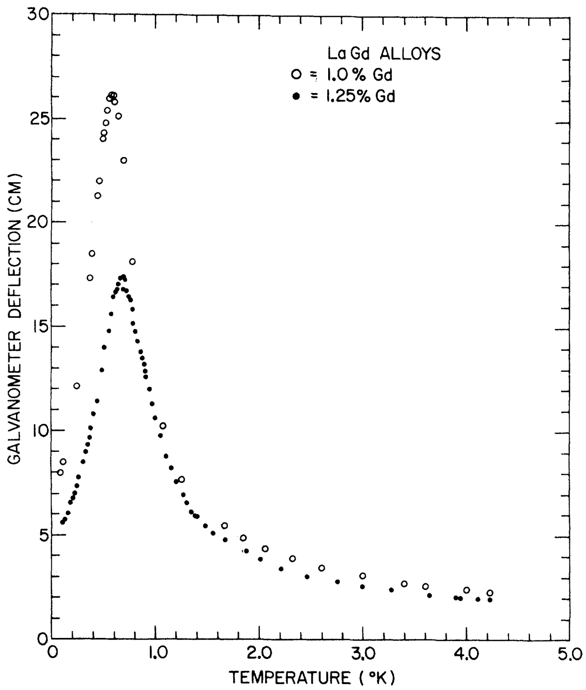


FIG. 1. Galvanometer deflection as a function of temperature obtained in zero applied magnetic field for the alloys containing 1.25 and 1.00 % Gd.

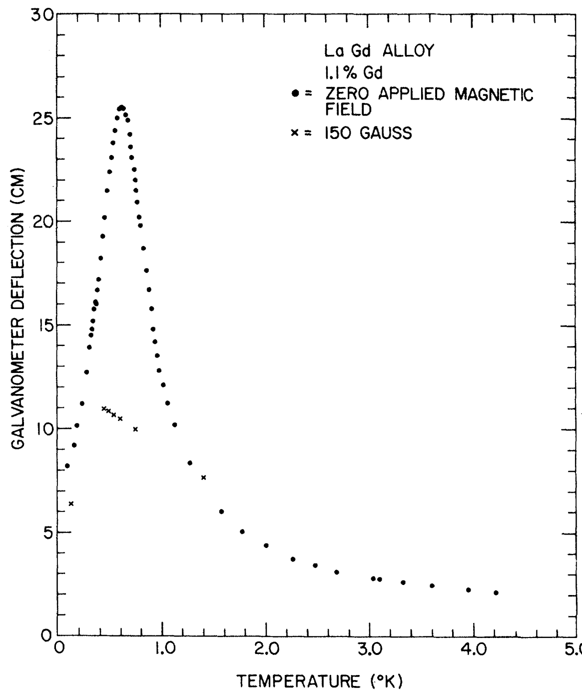


FIG. 2. Galvanometer deflection as a function of temperature and magnetic field for the alloy containing 1.10 % Gd.

thermal contact with the salt.[2] The differential magnetic susceptibilities of the salt and sample were independently observed by means of a dc mutual inductance technique described in detail elsewhere.[3]

In Fig. 1 galvanometer deflections obtained in zero applied magnetic field with the 1.25 and 1.00 % Gd alloys are plotted as a function of temperature. Such a plot represents susceptibility in arbitrary units vs temperature. These curves suggest the occurrence of a magnetic transition of some kind.

One possible interpretation of the curves in Fig. 1 is that the decrease in the susceptibility at the lower temperatures is due to superconductivity in parts of the sample. The entire sample could not be superconducting as the susceptibility was still paramagnetic at the lowest temperatures. If the decrease in susceptibility were caused by the diamagnetism of superconducting inclusions, the application of a magnetic field less than critical would have no effect on the susceptibility while a field greater than critical would cause an increase in the susceptibility. Application of a magnetic field actually caused the susceptibility to decrease, as shown in Fig. 2. Therefore, these alloys (1.00, 1.10, and 1.25 % Gd) do not become superconducting in the earth's magnetic field down to a temperature of 0.1°K.[4]

The maxima in the curves of Figs. 1 and 2 can be interpreted as evidence of antiferromagnetic or ferromagnetic transitions. Although pure Gd is ferromagnetic, Thoburn et al.,[5] on the basis of magnetic moment measurements at low temperatures, reported antiferromagnetic transitions in LaGd alloys containing 47 to 90 % Gd. On the other hand, Matthias et al.[1] observed large remanent moments for LaGd alloys containing 3 to 10 % Gd, and concluded that these alloys are ferromagnetic below 6.0°K.[1] In keeping with this latter conclusion the temperatures of the maxima in the susceptibility have been taken, in this report, to be approximations to ferromagnetic Curie temperatures.[6] Curie temperatures so defined are plotted as a function of Gd content in Fig. 3.

The 0.60 % Gd alloy becomes superconducting at 2.6°K.[1] Extrapolation of the Curie temperature curve in Fig. 3 indicates that this alloy might also become ferromagnetic at 0.3°K. The susceptibility of a sample of this alloy was paramagnetic at 4.2°K and increased as the temperature was lowered. A superconducting transition was observed which, in zero applied magnetic

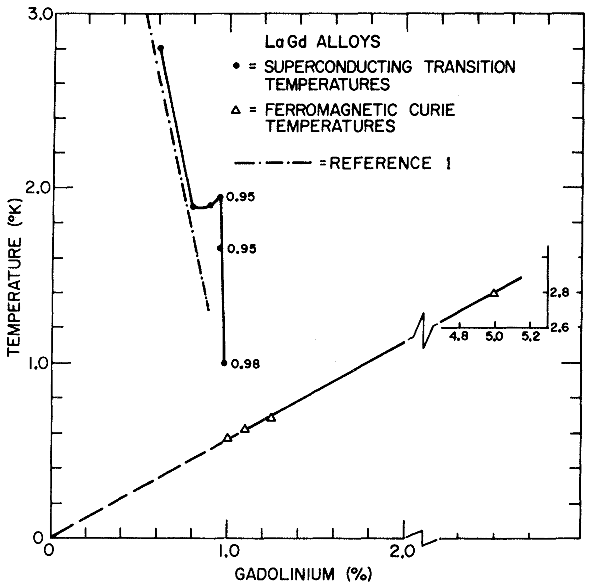


FIG. 3. Superconducting transition temperatures and ferromagnetic Curie temperatures of the La-Gd alloys as a function of Gd concentration.

field, was spread over the temperature interval from 2.8°K to 1.3°K. From 1.3°K down to 0.1°K the sample remained diamagnetic with a constant susceptibility. No evidence of ferromagnetism was observed in zero magnetic field.

Alloys in the range of 0.80 to 0.98% Gd were also studied. All samples were found to be superconducting. The zero field transitions ($T_c$) for the 0.60 and 0.80% Gd samples were in accord with the linear behavior previously reported.[1] However, departure from linear behavior was noted for a 0.95% sample. Its $T_c$ was higher than expected. The first reaction to this result was to question the Gd content of the sample. Further doubt about composition arose when a 0.98% sample was found to possess a $T_c$ which agreed with the linear dependence. To resolve this question of composition, a second 0.95% sample was fabricated. Its $T_c$ was higher than that of the first. In fact, its $T_c$ was even higher than that of the 0.80% sample. A 0.90% sample was then investigated and the results substantiated the deviation from linearity observed for the 0.95% samples. The dependence of $T_c$ on Gd concentration is depicted in Fig. 3. In drawing the curve in this figure, more weight was given to the second 0.95% sample as extra care was taken in its fabrication.

In Fig. 3 one notes rather strange behavior in the vicinity of 0.95% Gd. Increasing the Gd content from 0.95 to 0.98% causes $T_c$ to decrease by a factor of two. Increasing the Gd content from 0.98 to 1.00% causes the sample to exhibit ferromagnetism rather than superconductivity. On the other hand, decreasing the Gd content from 0.95 to 0.80% has relatively little effect on $T_c$. The sharp decrease in $T_c$ observed for those alloys between 0.95 and 0.98% is consistent with the ideas of Suhl and Matthias.[7] They predicted that the slope of $T_c$ vs percent Gd would approach infinity as $T_c$ approaches zero. The observed slope is 30°K per percent Gd. The behavior of $T_c$ in the region between 0.80 and 0.95% and the change from superconductivity to ferromagnetism between 0.98 and 1.00% are not yet understood.

Measurements of the susceptibility of the 0.95% sample in magnetic fields sufficient to destroy superconductivity suggest that this sample is ferromagnetic at the fields and temperatures involved. Critical magnetic field measurements, as well as magnetic moment measurements, will be included in a more comprehensive report.

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