Magnetic Resistivity and Magnetic Transitions in Rare-Earth Alloys

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(Received 28 October 1968; revised manuscript received 13 January 1969)

The spin-disorder resistivities and the magnetic phase transitions in gadolinium-dysprosium (Gd-Dy) alloys have been investigated experimentally, and the corresponding effects of pressure have been determined. The experiments involved measuring the change in the anomalies in the resistance of samples as a function of temperature and pressure. The resistivities of the metals provide evidence of magnetic transitions, through changes of slope in the resistivity-temperature curves at the critical temperatures. Therefore, the spin-disorder resistivities and the magnetic transitions both under atmospheric and hydrostatic pressures can be obtained from the resistance-temperature curves. The spin-disorder resistivity ρ_{mag} of these alloys is proportional to $3\pi Nm/(2\hbar e^2E_F)V^2(g-1)^2J(J+1)$, where g is the Lande g factor, J is the total angular momentum quantum number, V is an intra-atomic exchange integral, and E_F is the Fermi energy. The quantity ρ_{mag} was experimentally observed to increase with the increasing Gd composition and pressure. In the Rudermann-Kittel theory, the Curie temperature T_C of these alloys is proportional to the quantity $(g-1)^2J(J+1)V^2/(E_F)\sum_R\Phi(2k_FR)$, where $\Phi(2k_FR)=(2k_FR\cos 2k_FR-\sin 2k_FR)/(2k_FR)^4$. The quantity (T_C/ρ_{mag}) was experimentally observed to increase and then decrease as a function of composition with the peak value near 60 at.% Gd-40 at.% Dy, thus indicating that the quantity $\sum_R\Phi(2k_FR)$, which is proportional to (T_C/ρ_{mag}), passes through a similar maximum. With the application of pressure T_C for Gd-rich alloys decreased, whereas T_C for the Dy-rich alloys appeared to increase first, and then to decrease. The variations of T_C with pressure are explained by the relationship between $\sum_R\Phi$ and the c/a ratio of the crystal. It is thus concluded (tentatively) that the quantity $\sum_R\Phi$ passes through a peak value as a function of both pressure and composition.

I. INTRODUCTION

IN order to obtain a better understanding of the origin of ferromagnetism and antiferromagnetism in the rare earths, the magnetic resistivity of gadolinium-dysprosium (Gd-Dy) alloys has been investigated.

Prior to this present investigation, Bozorth and Suits[1] studied the magnetic transitions of these alloys at atmospheric pressure only, by means of resistivity and standard magnetic measurements. Milstein and Robinson[2] investigated the magnetic phase transition at atmospheric as well as at elevated hydrostatic pressure by means of the transformer method. Since the secondary voltage of a transformer is directly proportional to the susceptibility of the core materials, as the sample changes from a nonferromagnetic to a ferromagnetic state, a large increase in permeability, and hence in secondary voltage, is observed.

The present work is a study of various effects of pressure upon Gd-Dy alloys by means of the resistivity method. The following results are reported: (a) the experimental data of spin-disorder resistivity of Gd-Dy alloys at atmospheric pressure; (b) the experimental data of the effect of pressure on the spin-disorder resistivity of Gd-Dy alloys; (c) an interpretation of (a) and (b), in terms of the role of the lattice in the exchange interaction between conduction electrons and the magnetic shells, using spin-disorder resistivity equations; (d) the magnetic transition temperatures both under atmospheric pressure and hydrostatic pressure by the resistance methods; and (e) an interpretation of (d), in terms of the role of the lattice in magnetic coupling, within the framework of the Ruderman-Kittel theory and the resistivity data.

In the present investigation, resistivity measurements have been established as a fairly reliable technique for the determination of Curie and Néel temperatures of polycrystalline Gd-Dy alloys. This technique was employed before in studying magnetism in terbium.[3] By covering essentially the range of compositions as in Ref. 2, some check of the reliability of this present technique could be made. The technique will not be explained.

II. EXPERIMENTAL PROCEDURE

Gd-Dy alloys of 99.9% purity were supplied by the ALFA Inorganics, Inc., in the form of a 30-mil-thick foil. Samples of about 1.6 cm in length with cross-sectional area varying between 0.006 and 0.01 cm^2 were cut out from the foil. Variations in cross-sectional area were maintained below 0.0002 cm^2 over the entire length of the sample. The samples were annealed in vacuum for approximately 8 h at 800°C, then slowly cooled to room temperature. Sample resistance under pressure was measured using the standard four-probe method. A known dc current was passed through the sample and the voltage drop across the sample was measured. The resistivity of the sample was of the order of a $\mu\Omega$ cm.

In order to determine the resistivity of the sample under pressure, the sample was embedded in a pressure capsule; a cross section of the capsule is shown in Fig. 1. Solid silver chloride serves as a quasihydrostatic pressure-transmitting medium. Six wires (two current leads,

[1] R. M. Bozorth and J. C. Suits, J. Appl. Phys. 35, 1039 (1964).
[2] F. Milstein and L. B. Robinson, Phys. Rev. 159, 466 (1967).
[3] A. R. Wazzan, R. S. Vitt, and L. B. Robinson, Phys. Rev. 159, 400 (1967).

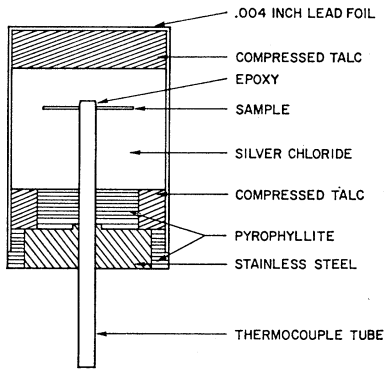

FIG. 1. Cross section of pressure capsule.

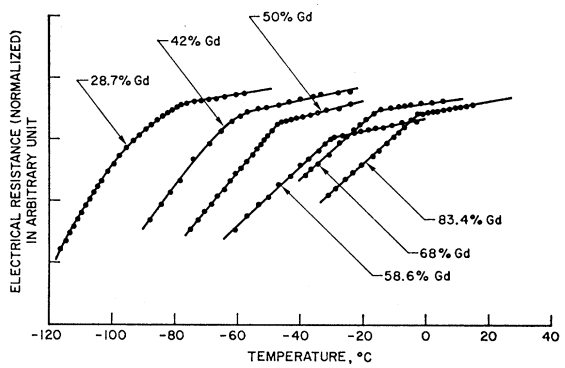

FIG. 2. Electrical resistance of Gd-Dy alloys as a function of temperature and compositions.

two voltage leads, and two thermocouple leads) were led out through a six-hole ceramic insulating tube. Pressures up to 19.5 kbar were obtained using a high-pressure vessel of the piston cylinder type. The sample was cooled by bringing the pressure capsule containing the sample in contact with liquid nitrogen. The sample was then allowed to warm up very slowly into the paramagnetic range. Resistance measurements were made during this warm-up period. The warm-up rate

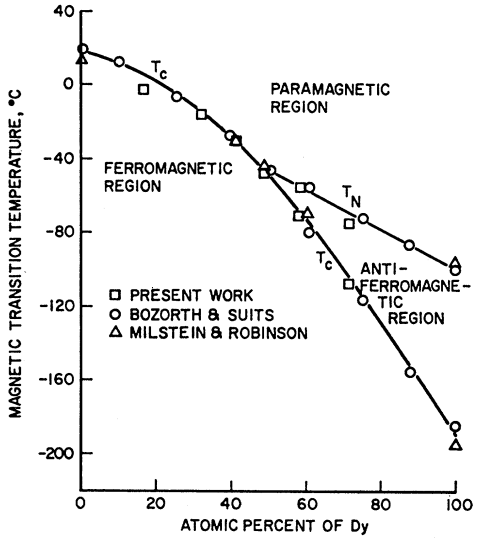

FIG. 3. Phase diagram for Gd-Dy alloys.

was always maintained below 1°K/min in the transition-temperature region. Resistance measurements were made at 2° intervals above and below the transition region. Each run was made at a constant pressure within the range 0–19.5 kbar. The sample was always allowed to warm up above 275°K before the pressure was increased to the next value.

III. RESULTS

A. Transition Temperatures

1. Atmospheric-Pressure Results

The Curie and Néel temperatures of the Gd-Dy alloys were first determined at atmospheric pressure. As expected, the Gd-rich alloys exhibited only a Curie temperature, while the Dy-rich alloys showed two ordering temperatures, Néel temperature and Curie

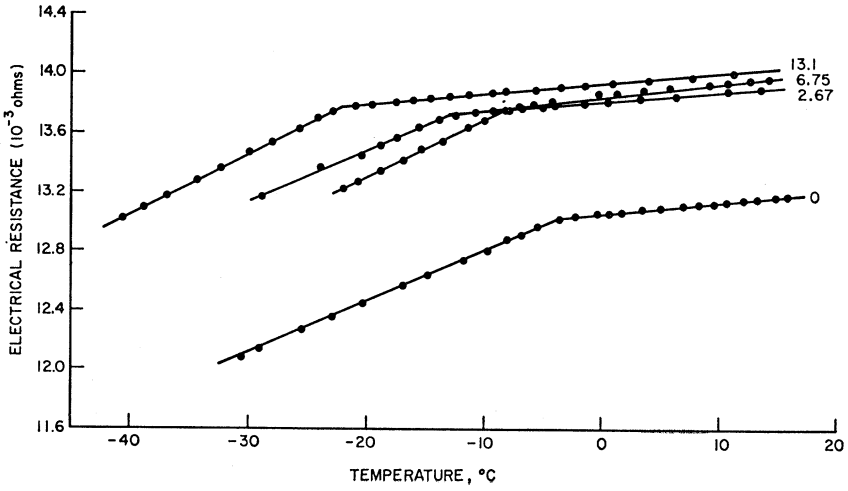

FIG. 4. Electrical resistance of Gd (83.4 at.%)-Dy (16.6 at.%) alloy as a function of temperature and pressure.

temperature. The resistance-versus-temperature curves for the Gd-Dy alloys are shown in Fig. 2.

In Fig. 2 for the Gd-rich alloys, a sharp decrease of resistance with decreasing temperature indicates a Curie temperature T_C, with T_C identified as the intersection point of two linear parts. As the amount of Dy increases, a nonlinear increasing of resistance was observed. The lower temperature at which the resistance begins to deviate from the linear behavior is taken as T_C, whereas the upper temperature is taken as T_N. The validity of this method of determining T_C and T_N is demonstrated by comparing the present values of T_C and T_N with the values of Bozorth and Suits,[1] and with the values of Robinson and Milstein.[2] The agreement is very good, as can be seen in Fig. 3. The detailed nature of the nonlinear region in the resistance-versus-temperature curve for Dy-rich alloys cannot be determined by these measurements. However, since Dy possesses a helical spin structure between T_N and T_C, it is expected that the Dy-rich alloys should have a similar structure. As the amount of Gd increases, the range of nonlinearity continues to decrease until it vanishes at about 50 at.% Gd.

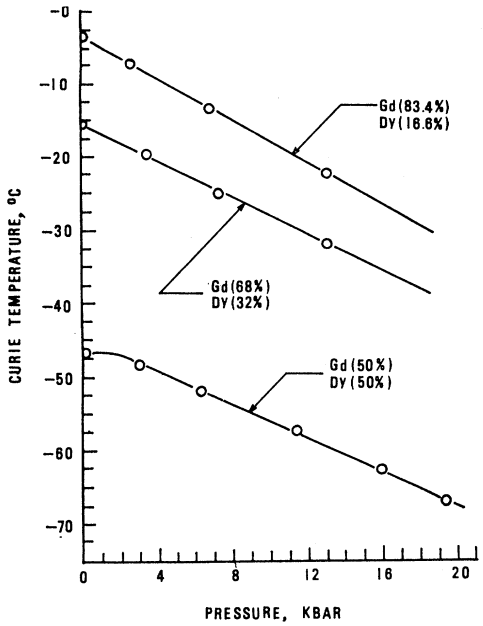

FIG. 5. Variation of Curie temperatures with pressure for Gd-Dy alloys.

2. *Pressure Results*

The five following alloys were selected for the pressure studies.

(a) The 83.4 at.% Gd-16.6 at.% Dy alloy undergoes a paramagnetic-ferromagnetic transition. The resistance curves as a function of pressure are shown in Fig. 4. The linear variation of the Curie temperature of this alloy with pressure is shown in Fig. 5; the pressure coefficient is found to be -1.45°C/kbar.

(b) The 68 at.% Gd-32 at.% Dy alloy also undergoes a paramagnetic-ferromagnetic transition. The resistance curves as a function of pressure are shown in Fig. 6. There exists only a single magnetic transition temperature up to 18.4 kbar. The variation of the Curie temperature of this alloy with pressure is also shown in Fig. 5; the pressure coefficient is -1.2°C/kbar.

(c) The 50 at.% Gd-50 at.% Dy alloy also has only one single transition temperature up to 19.5 kbar as shown in Fig. 7. As shown in Fig. 5, the Curie temperature stays almost constant in the range of 0 to 1 kbar, and then decreases linearly at the rate of 1.08°C/kbar.

(d) The 42 at.% Gd-58 at.% Dy alloy, which undergoes a transition from the paramagnetic state to an oscillatory state and then, with decreasing temperature, transforms to the ferromagnetic state, i.e., it possesses both Néel temperature and Curie temperature as

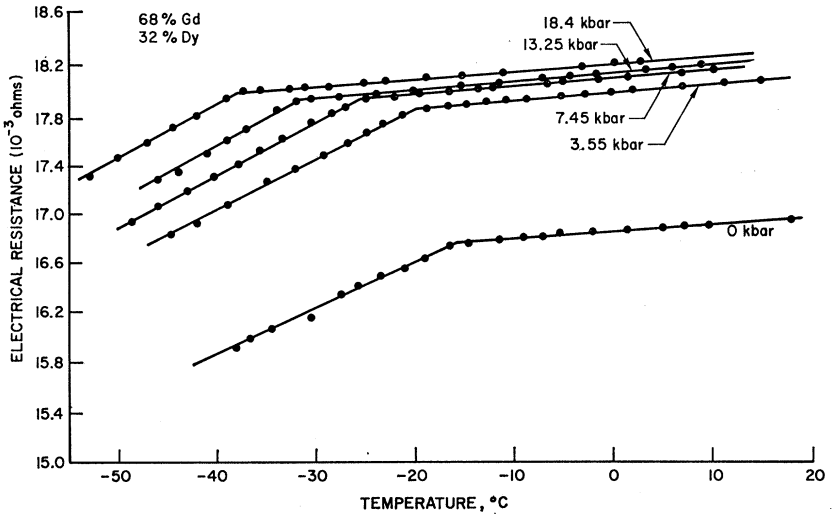

FIG. 6. Electrical resistance of Gd (68 at.%)-Dy (32 at.%) alloy as a function of temperature and pressure.

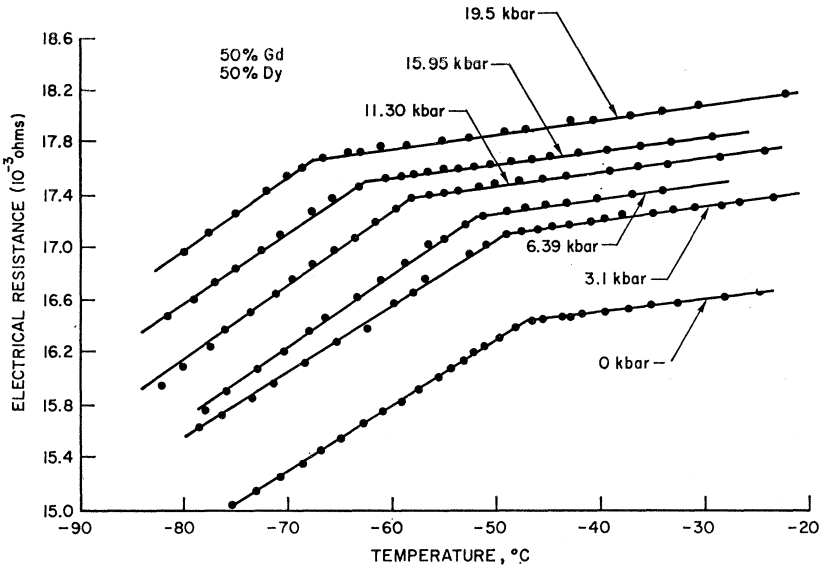

FIG. 7. Electrical resistance of Gd (50 at.%)-Dy (50 at.%) alloy as a function of temperature and pressure.

shown in Fig. 8. The shift of Curie temperature with pressure is shown in Fig. 9, where it appears to increase up to about the first 2 kbar, and then decreases linearly at the rate of 1.06°C/kbar. For the Néel temperature, Fig. 9 displays that it is decreasing linearly at the rate of 0.9°K/bar.

(e) In the case of the 28.7 at.% Gd-71.3 at.% Dy alloy the results of Fig. 10 indicate that the antiferromagnetic region is present to at least 10.65 kbar. Figure 11 shows that the Curie temperature increases in the first 3 kbar, and then decreases almost linearly (as the pressure increases) at the rate of 0.9°C/kbar, and shows that the Néel temperature is decreasing at the rate of 0.52°C/kbar.

The above results are summarized in Table I.

B. Spin-Disorder Resistivity

Since

$$\rho=\rho_{\rm res}+\rho_{\rm mag}(T)+\rho_{\rm ph}(T), \quad (1)$$

the spin-disorder resistivity in the region of $T\geq T_C$ (or T_N) can be obtained by extrapolating the electrical resistivity from the almost linear region above the transition temperature (T_C for the ferromagnetic-paramagnetic materials and T_N for the ferromagnetic-antiferromagnetic-paramagnetic materials) to the absolute temperature zero and subtracting the residual resistivity since we know that $\rho_{\rm ph}(0)=0$.

The electrical resistance R of Gd-Dy alloys of different composition as a function of temperature over the pressure range ~0–20 kbar is presented in Figs. 4, 6–8, and 10. To obtain the resistivity ρ of the sample of cross-sectional area A and length l, the following relation was applied:

$$\rho=R(A/l). \quad (2)$$

The spin-disorder resistivities of Gd-Dy alloys have been obtained by using Eq. (1) and the average values of residual resistivity of Bozorth and Suits.[1] The results are summarized in Table II and Fig. 12. We observe

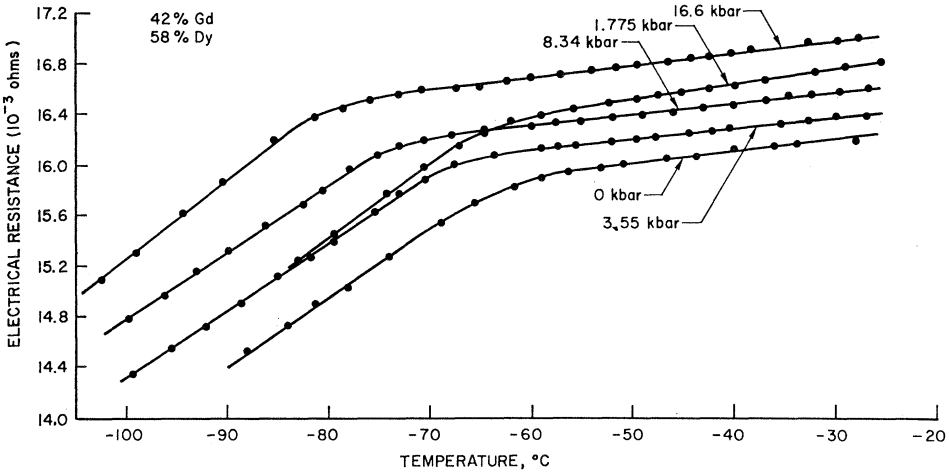

FIG. 8. Electrical resistance of Gd (42 at.%)-Dy (58 at.%) alloy as a function of temperature and pressure.

TABLE I. Transition temperatures and their variations with pressure for Gd-Dy alloys.

Gd (at. %)	T_C (°C)	Effect of pressure upon T_C	T_N (°C)	Effect of pressure upon T_N
83.4	−3.65	$dT_C/d_p = -1.45$ °C/kbar		
68	−15.75	$dT_C/d_p = -1.2$ °C/kbar		
50	−47	approx. const between 0 and 1 kbar; then $dT_C/d_p = -1.08$ °C/kbar		
42	−71	increases ~2.5 °C between 0 and 2 kbars; then $dT_C/d_p = -1.06$ °C/kbar	−56	$dT_N/d_p = -0.9$ °C/kbar
28.7	−108	increases ~3.2 °C between 0 and 3 kbar; then $dT_C/d_p = -0.9$ °C/kbar	−75.5	$dT_N/d_p = -0.52$ °C/kbar

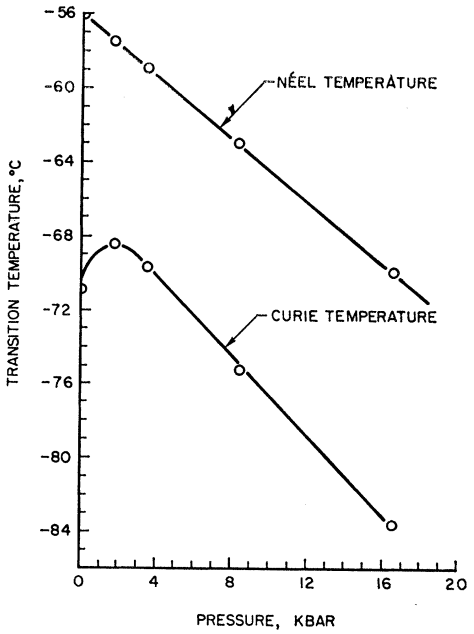

FIG. 9. Variation of transition temperatures with pressure for Gd (42 at.%)-Dy (58 at.%) alloy.

that the spin-disorder resistivity at high temperature ($T \geq T_C$ or T_N) of the Gd-Dy alloys increases with increasing Gd and with increasing pressure.

IV. ANALYSIS AND DISCUSSION OF RESULTS

A. Spin-Disorder Resistivity

The spin-disorder resistivity of Gd-Dy alloys was first obtained by Bozorth and Suits[1] under atmospheric pressure. The present results and the Bozorth-Suits results are given in Fig. 13 for comparison. The agreement is good, realizing that the resistivity may depend upon the history of the heat treatment of the sample. The present samples were annealed at 800°K for 8 h and cooled to room temperature in about 6 h. Therefore, the quantitative difference between the two sets of results is not very important. It has been shown theoretically by Kasuya,[4] by Dekker[5] and Van Peski-Tin-

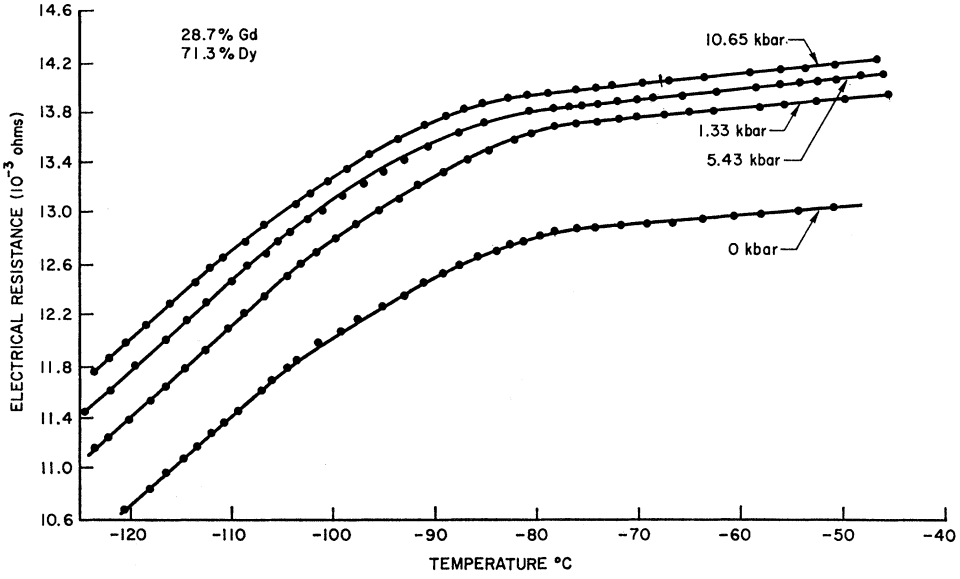

FIG. 10. Electrical resistance of Gd (27.8 at%)-Dy (71.3 at.%) alloy as a function of temperature and pressure.

[4] T. Kasuya, Progr. Theoret. Phys. (Kyoto) **22**, 227 (1959).
[5] A. J. Dekker, J. Appl. Phys. **36**, 906 (1965).

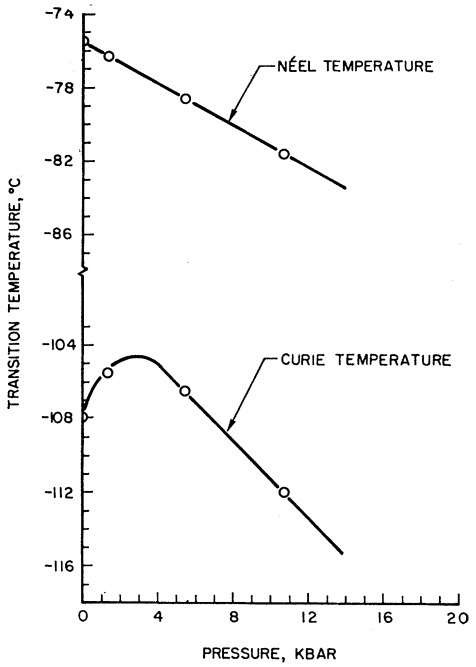

FIG. 11. Variation of transition temperatures with pressure for Gd (28.7 at.%)-Dy (71.3 at.%) alloy.

bergen, and by De Gennes and Friedel[6] and experimentally (in very dilute alloys) by Mackintosh and Smidt[7] that ρ_{mag} varies linearly with $(g-1)^2J(J+1)$

TABLE II. Resistivities, the Curie temperatures, the Tc/ρ_{mag}, and the influence of hydrostatic pressure upon them for Gd-Dy alloys.

Gd (at. %)	c/a	Pressure (kbar)	ρ_{mag}	T_C (°K)	T_N (°K)	Tc/ρ_{mag}
28.7	1.57799	0	74.74	165	197.50	2.2077
		1.33	75.41	167.5	196.75	2.2213
		5.43	76.57	166.5	194.50	2.1744
		10.65	77.31	162	191.50	2.0954
42.0	1.5803	0	78.8	202	217.0	2.5635
		1.78	79.49	204.5	215.50	2.5726
		3.55	80.2	203.25	214.00	2.5418
		8.34	81.26	197.5	210.00	2.4305
		16.6	82.78	189.25	203.0	2.2863
50.0	1.5817	0	82.55	226		2.739
		3.10	83.58	224.5		2.6888
		6.39	84.64	221.25		3.6141
		11.30	87.14	215		2.4644
		15.95	89.16	210.5		2.3610
		19.50	90.21	205.75		2.2807
68.0	1.58483	0	88.86	257.25		2.8951
		3.55	90.88	253.25		2.7847
		7.45	94.66	247.75		2.6173
		13.25	95.39	240.75		2.5238
		18.40	96.99	235.25		2.4254
83.4	1.5875	0	100.46	269.35		2.6814
		2.67	103.57	265.35		2.5621
		6.75	106.86	259.85		2.4317
		13.10	110.89	250.85		2.2620

[6] P. de Gennes and J. Friedel, J. Phys. Chem. Solids 4, 71 (1958).

[7] A. R. Mackintosh, and F. A. Smidt, Jr., Phys. Letters 2, 107 (1962).

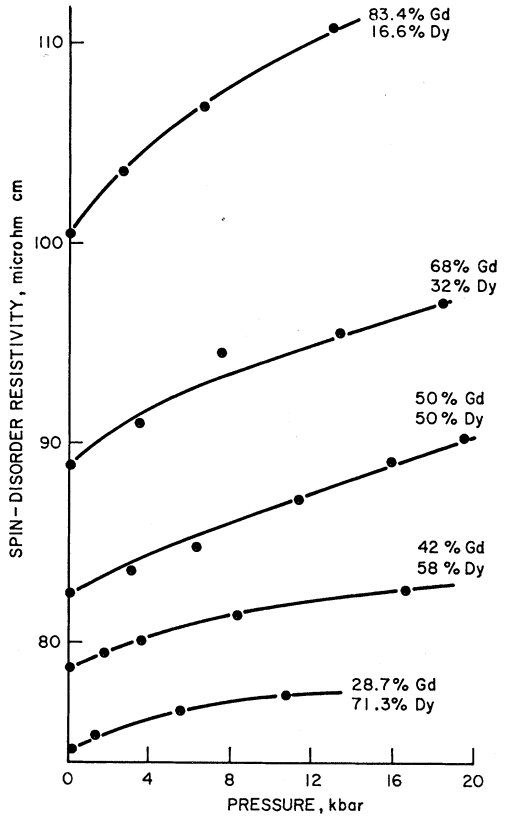

FIG. 12. Spin-disorder resistivity of Gd-Dy alloys versus pressure.

provided the electronic structure remains constant. Calculating the average values of S and J for pure Dy and Gd, one would expect ρ_{mag} in Fig. 13 to be linear. That the points cannot be fitted to a single straight line suggests that, as in other rare-earth alloys,[8] the electronic structure changes in going from Gd through Dy.

The effect of hydrostatic pressure upon the resistivity of metals may be attributed to[9] (a) a change in the interaction between the electrons and the lattice waves

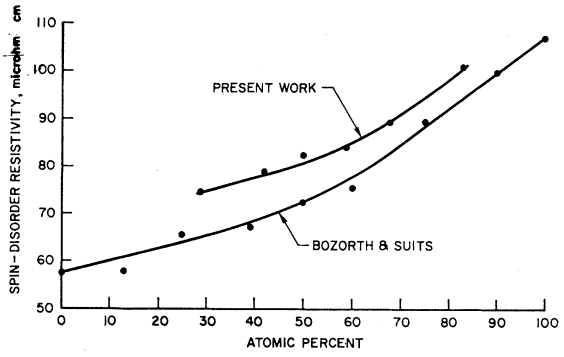

FIG. 13. Spin-disorder resistivity of Gd-Dy alloys versus at.% of Gd.

[8] F. A. Smidt, Jr., and A. H. Danne, J. Phys. Chem. Solids, 24, 361 (1963).

[9] H. D. Stromberg and D. R. Stephens, J. Phys. Chem. Solids 25, 1015 (1964).

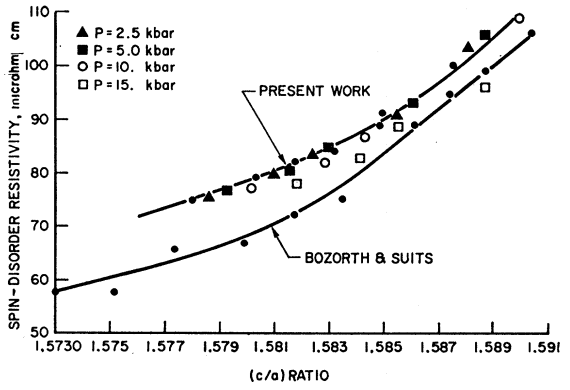

FIG. 14. Spin-disorder resistivity of Gd-Dy alloys versus c/a ratio.

caused by stiffening of the lattice, (b) a change of the lattice parameter and the associated change in the band structure and Fermi energy, and (c) crystallographic modifications and the accompanying changes in the band structure. These factors have an effect upon the spin-disorder resistivity which in the rare-earth metals may be concisely stated as[5]

$$\rho_{\text{mag}}=(3\pi Nm/2\hbar e^2E_F)V^2(g-1)^2J(J+1). \quad (3)$$

An exact analysis of the effect of pressure upon each parameter appearing in the above expression is almost impossible.

The effect of pressure upon the Fermi energy or the Fermi wave vector k_F may be computed for the free-electron model. Freeman *et al.*[10] however, recently computed the Fermi surface for thulium (Tm) and found it extremely complex and quite different from the free-electron model. Therefore, the effect of pressure upon the spin-disorder resistivity is discussed in the following approximate manner.

If one plots the spin-disorder resistivity data versus c/a of Gd-Dy alloys using an average value of c/a for pure Dy and Gd, he obtains the curve given in Fig. 14. It is clear that the ρ_{mag} increases with increasing c/a ratio. The lattice ratio c/a would be expected to change under pressure although the details are by no means certain. In view of this, the effect of pressure may be examined by interrelating the change of c/a and the change of ρ_{mag} under pressure. Danne[11] and Gschneider[12] determined c/a in Tm through Gd series and found that it increases in the series Tm through Gd. Furthermore, McWhan and Stevens[13] have observed that the c/a ratio of Gd, Tb, Dy, and Ho increases with pressure. In particular, for Dy at 75 kbar, they have found $\Delta(c/a)=(1.2\pm0.7)\%$. Jamieson[14] has observed the volume and the a lattice parameter of Dy to vary linearly with pressure up to about 100 kbar. Because of the scanty data available on the change of the c/a ratio of Gd with pressure, it was assumed that this change is equal to that of Dy. Thus, at x kbar, the change of the c/a ratio is estimated to be $(x/75)\times(1.2\pm0.7)\%$. The effect of pressure is now interpreted as follows.

(a) The change of c/a ratio [i.e., $\Delta(c/a)$ of Gd-Dy alloys] at a pressure of x bars is given by

$$\Delta(c/a)=(x/75)\times(1.2\pm0.7)\%(c/a).$$

(b) The resistivity of Gd-Dy alloys at pressure corresponding to (a) is taken from Fig. 12.

(c) The results of (a) and (b) are given in Fig. 14.

In Fig. 14, the data of five different compositions of Gd-Dy alloys at four different pressures are plotted. All points are located well in the neighborhood of present curve. Therefore, it is reasonable to conclude that the ρ_{mag} of Gd-Dy alloys increases with increasing pressure in the following manner.

(a) ρ_{mag} increases from the Tm through Gd.

(b) ρ_{mag} of Gd-Dy alloys increases with increasing concentration of Gd. Both (a) and (b) have been justified by the theoretical reasons and experimental results of Dekker[5] and of Bozorth and Suits,[1] respectively.

(c) The c/a ratio increases in the series Tm through Gd.

(d) The c/a ratio also increases with increasing Gd content if average values of c/a for Gd-Dy alloys are used.

(e) The c/a ratio increases with increasing pressure.

(f) Therefore, ρ_{mag} will be expected to increase with increasing pressure.

B. Magnetic Phase Transition

1. Atmospheric-Pressure Studies

The magnetic transition temperature of Gd-Dy alloys was first investigated by Bozorth and Suits[1] by electrical resistivity and standard magnetic measurements, and later by Robinson and Milstein[2] by an inductance method. The Curie and Néel temperatures for Gd-Dy alloys of present work, together with the data of Bozorth and Suits and of Robinson and Milstein, are shown in Fig. 3. Our results are in good agreement with their work. Bozorth and Suits also determined the crystal structure of Gd-Dy alloys, and found each to possess the hcp structure; i.e., through the whole range, the Gd-Dy alloys are solid solutions. However, a variation the electronic structure of these alloys was suggested in by them because of the nonlinearity of their spin-disorder resistivity data.

It is apparent that $\Delta T=T_N-T_C$ goes to zero when the Gd rises to about 50 at.%. Apparently the spiral structure does not exist in the Gd-rich alloys. The detailed structure of the spin arrangement in the tempera-

[10] A. J. Freeman, J. O. Dimmock, and R. E. Watson, Phys. Rev. Letters **16**, 94 (1966).
[11] A. H. Danne, in *The Rare Earths*, edited by F. H. Spedding and A. H. Danne (John Wiley & Sons, Inc., New York, 1961), Chap. 3.
[12] K. A. Gschneider, Jr., in *The Rare Earths*, edited by F. H. Spedding and A. H. Danne (John Wiley & Sons, Inc., New York, 1961), Chap. 14.
[13] D. B. McWhan and A. L. Stevens, Phys. Rev. **139**, A682 (1965).
[14] J. C. Jamieson, Science **145**, 572 (1964).

ture range of between T_C and T_N cannot be determined from the resistivity measurement.

2. Pressure Studies

The shift of magnetic phase transition under hydrostatic pressure of Gd-Dy alloy was first obtained by Milstein and Robinson[2] by using an inductance method. Good agreement exists between this work and the present work.

The variation of Curie temperature with pressure is almost linear for Gd-rich alloys as can be seen from Fig. 5. When the amount of Gd of the alloy decreases, the T_C-versus-pressure curves begin to depart from linearity; when the Gd content is lower than 50 at.%, the Curie temperature appears to increase first, and then decrease with increasing pressure (see Figs. 5, 9, and 11). However, the changes of Néel temperature under pressure are always almost linear in these alloys (see Figs. 9 and 11). Both results are expected if we examine the pressure coefficient of pure Gd and pure Dy.[15,16]

The magnetic transition temperature for the rare-earth metals is[17]

$$T_C \text{ (or } T_p) = \frac{Z\pi V^2}{E_F k} \sum_{R_n} \Phi(2k_F R_n)(g-1)^2 J(J+1), \quad (4)$$

where

$$\Phi(2k_F R) = \frac{k_F R \cos k_F R - \sin k_F R}{(k_F R)^4}.$$

Here J is the magnetic moment of the rare-earth ion, k is Boltzman's constant, E_F is the Fermi energy, k_F is the Fermi wave vector of conduction electrons, and V is the exchange coupling constant between the conduction electrons and the rare-earth ions. The sum in Eq. (4) is over the lattice vectors R_n.

An exact analysis of the effect of puresure upon the parameters in expression Eq. (4) is a rather formidable task. These difficulties may be attributed to the extreme complexity of the Fermi surface of rare-earth metals and the exact calculation of V and $\sum_R \Phi$. Therefore, the effect of pressure upon the magnetic phase transition will be examined in a qualitative way.

The spin-disorder resistivity given in Eq. (3) can be combined with Eq. (4) to give

$$\sum_{R_n} \Phi(2k_F R_n) = \left(\frac{3Nm}{2Z\hbar e^2}\right)\left(\frac{T_C}{\rho_{\text{mag}}}\right)k = C_1 m T_C/\rho_{\text{mag}}, \quad (5)$$

where $C_1 = \text{const} = 3Nk/2Z\hbar e^2$. *The present analysis is tentative and almost without doubt will be modified when the theory becomes more adequate; the rest of the interpretation of results must be understood in this light.*

Since the rare-earth elements all have same crystal structure, nearly the same lattice constants and the same number of valence electrons, one expects them to have approximately the same effective mass m. It will also be assumed that the variation of m with application of pressure will be negligible. Thus, Eq. (5) may be rewritten as

$$\sum_R \Phi_n(2k_F R_n) = C_2 T_C/\rho_{\text{mag}}, \quad (6)$$

where $C_2 = C_1 m$.

The sum $\sum_R \Phi$ is a fairly difficult expression to calculate since it converges rather slowly. And also $\sum_R \Phi$ is oscillatory function and is quite sensitive to the change of the values of k_F or to change of lattice properties. Because of the oscillatory and long-range nature of $\sum_R \Phi$, a small modification of $k_F R$ would probably lead to a large change in the numerical values of $\sum_R \Phi(2k_F R)$. With this computational difficulty in mind, the quantity T_C/ρ_{mag} on the left-hand side of Eq. (6) may be regarded as an experimental determination of $\sum_F \Phi(2k_F R)$. In view of this, it seems reasonable to attempt to relate the experimentally observed variation, with composition and with pressure, of the quantity T_C/ρ_{mag} to the variation of the $\sum_R \Phi(2k_F R)$, in terms of the effect of pressure and the effect of composition upon the properties of the lattice. The dependence of $\sum_R \Phi(2k_F R)$ upon the properties of the lattice is considered herein from an empirical point of view. The approach adopted is to attempt to relate empirically the $\sum_R \Phi$ to some parameter or ratio. The important parameter in the crystal appears to be the c/a ratio, that is,

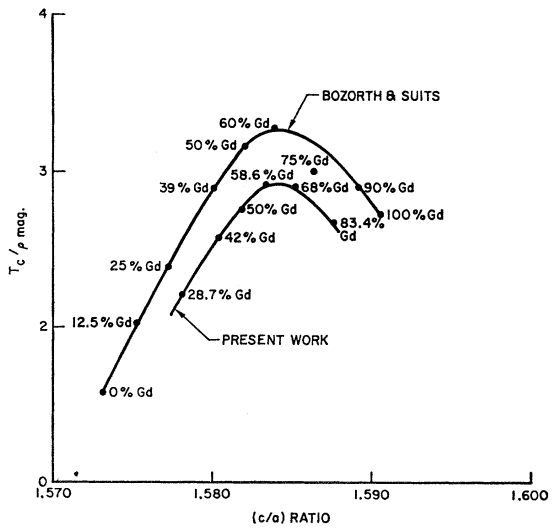

FIG. 15. T_C/ρ_{mag} [proportional to $\sum\phi(2k_F R)$] versus c/a ratio.

[15] L. B. Robinson, F. Milstein, and A. Jayaraman, Phys. Rev. 134, A187 (1964).
[16] L. B. Robinson, S. I. Tan, and K. F. Sterrett, Phys. Rev. 141, 548 (1966).
[17] R. J. Elliott, in *Magnetism*, edited by G. T. Rado and H. Suhl (Academic Press Inc., New York, 1965), Vol. IIA, p. 385.

(a) the c/a ratio of the heavy rare-earth metals increases with pressure, as reported by McWhan and Stevens[13] and by Jamieson.[14]

(b) The c/a ratio increases for the rare-earth metals in passing from Tm to Gd.

Figure 15 shows T_C/ρ_{mag} versus the room-temperature c/a values for the Gd-Dy alloys. The lower curve of T_C/ρ_{mag} is based on the experimentally determined values of the ferromagnetic Curie temperature and spin-disorder resistivity of Gd-Dy alloy of present results (see Table II). The upper curve of T_C/ρ_{mag} is based on the experimental results of Bozorth and Suits[1] (see Table III). Average values of the c/a ratio are used for the abscissa. The locations of the five Gd-Dy alloys investigated under pressure in the present study are indicated on the lower curve.

TABLE III. Resistivity of Gd-Dy alloys at atmospheric pressure.[a]

Dy (at. %)	Curie point T_C (°K)	Néel point T_N (°K)	ρ_{res}	ρ_{mag}	c/a	T_C/ρ_{mag}
Gd	292		4.4	106.4	1.5904	2.74
10	285		18.8	99.2	1.58866	2.87
25	266		24.8	89.1	1.58605	2.99
40	245		25.2	75.0	1.58344	3.27
50	228		25.4	72.2	1.5817	3.16
61	193	217	27.0	66.8	1.5798	2.89
75	156	210	21.3	65.7	1.57735	2.37
87.5	117	185	19.4	57.6	1.575175	2.03
Dy	90	174	2.4	57.6	1.5730	1.56

[a] See Ref. 1.

Since c/a increases with pressure, the ferromagnetic Curie temperature for those alloys to the left of peak (on the lower curve or upper curve) in Fig. 15 would be expected to increase with increasing pressure, until c/a reaches the value for which $\sum_R \Phi(2k_F R)$ is a maximum, and then T_C should decrease with further increase of pressure. Figure 15 will be used to interpret the present pressure results.

If one divides the Curie temperature of Gd-Dy alloys by spin-disorder resistivity at different pressure and then plots the results versus pressure, he obtains the curve given in Fig. 16. It is worthwhile to examine the five curves in Fig. 16.

Curve 1—T_C/ρ_{mag} for 28.7 at.% Gd-71.3 at.% Dy alloy. This curve shows that T_C/ρ_{mag} increases up to about 3 kbar and then decreases with increasing pressure.

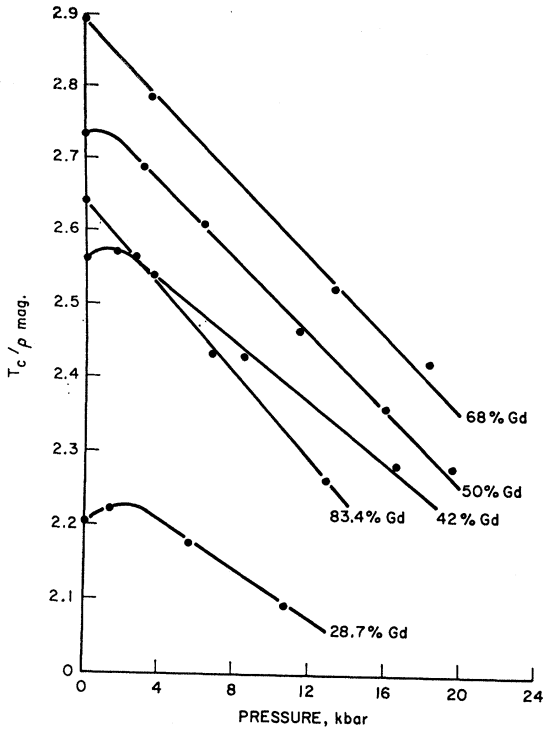

FIG. 16. The variation of T_C/ρ_{mag} with pressure for Gd-Dy alloy.

Curve 2—T_C/ρ_{mag} for 42 at.%Gd-58 at.% Dy alloy. This curve shows that T_C/ρ_{mag} increases up to about 1.5–2 kbar and then decreases with increasing pressure.

Curve 3—T_C/ρ_{mag} for 50 at.% Gd-50 at.% Dy alloy. This curve shows that T_C/ρ_{mag} stays almost constant up to about 1–1.5 kbar and then decreases with increasing pressure.

Curve 4—T_C/ρ_{mag} for 68 at.% Gd-32 at.% Dy alloy. This curve shows that T_C/ρ_{mag} decreases with increasing pressure.

Curve 5—T_C/ρ_{mag} for 83.4 at.% Gd-16.6 at.% Dy alloy. This curve also shows that T_C/ρ_{mag} decreases with increasing pressure.

The above results are in excellent agreement quantitatively with what was observed in Fig. 15, viz., for 28.7 at.% Gd-71.3 at.% Dy alloy and 42 at.% Gd-58 at.% Dy alloy, which are to the left of the peak of the curve in Fig. 15, T_C/ρ_{mag} increases and then decreases with increasing pressure; for 50 at.% Gd-50 at.% Dy alloy, which is close to the peak of $\sum_R \Phi(2k_F R)$, T_C/ρ_{mag} appears to remain unchanged in 0–1.5 kbar range, and then decreases; and for 68 at.% Gd-32 at.% Dy and 82.4 at.% Gd-16.6 at.% Dy alloys, which are to the right of the peak, T_C/ρ_{mag} decreases with increasing pressure.