

## Magnetic behavior of $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$ and $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$ compounds

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The results of magnetic and Mössbauer-effect studies on  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  and  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds between 4.2 and 1300 K are reported. The ferrimagnetic structure evidenced in the ordered range for  $x > 0.1$  is confirmed by the measurements above the Curie points. The thermal variation of the reciprocal susceptibilities obeys a Néel-type law. Using the molecular-field model, we deduce the magnitude of the magnetic interactions in the compounds. The effective iron moments and  $^{57}\text{Fe}$  hyperfine-field values decrease by increasing the nickel content. The deviation of these values from the simple dilution behavior are attributed to the variation of magnetic interactions in the system. Finally, we analyze the magnetic behavior of iron in the rare-earth compounds.

### I. INTRODUCTION

The investigation of the magnetic properties of  $R'\text{Fe}_x$  compounds (where  $R' = \text{Gd to Tm}$ ) evidenced that the iron moments are in antiparallel orientation to those of rare-earth compounds.<sup>1</sup> The iron magnetic contributions decrease with the increase of  $R'$  content.<sup>2,3</sup> This behavior is generally attributed to the progressive filling of the iron 3d band by the conduction electrons contributed by rare-earth atoms. The iron moments in  $R''T_2$  compounds, where  $R''$  is a rare-earth atom or yttrium, are situated between  $1.62\mu_B$  ( $\text{GdFe}_2$ ) and  $1.44\mu_B$  ( $\text{YFe}_2$ ).<sup>2,4</sup> Nickel is nonmagnetic in isomorphous compounds.<sup>5,6</sup>

Generally, we refer to the mean values of the iron moments, since their magnetic contributions in the compounds with complex crystalline structure differ according to their position.<sup>7</sup> Because of the high symmetry of the crystalline cell, the Laves phase compounds  $R''T_2$  ( $T = \text{Fe, Co, or Ni}$ ) are an exception. The point symmetry of  $T$  atoms is trigonal ( $\bar{3}m$ ), while that of  $R''$  atoms is cubic ( $\bar{4}3m$ ). Thus the study of pseudobinary Laves compounds, where a two-sublattice magnetic model seems to be appropriate, may offer interesting information on the magnetic behavior of 3d transition metals.

Various types of pseudobinary  $R''(T'_{1-x}T''_x)_2$  compounds were studied. By magnetic measurements only the gadolinium compounds or the compounds with nonmagnetic rare-earth elements (or yttrium) may supply useful information on the saturation transition-metal moments. In compounds with a non-S-state rare-earth element, the transition-metal magnetic moments cannot be determined precisely because of the reduction of rare-earth ionic moment by crystal-field effects or the difficulties in saturating the system as result of its high anisotropy.

Several models have been used to analyze the magnetic behavior of the transition metal in these systems. For example, Taylor<sup>8</sup> used an itinerant model for the transition-metal moments in  $\text{Gd}(\text{Co}_x\text{Ni}_{1-x})_2$  compounds. Burzo *et al.*<sup>9</sup> and later Cannon *et al.*<sup>10</sup> showed that the local environment model can describe correctly the magnetic behavior of the transition-metal atoms in these systems. The magnetic behavior of  $\text{Y}(\text{Fe}_x\text{Co}_{1-x})_2$  compounds was analyzed in the Mott model or by considering the localized moments in the band model.<sup>11,12</sup> Generally, little work has been done on the  $R'(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds. Cristopher *et al.*<sup>13</sup> reported that  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds crystallize in  $\text{MgCu}_2$ -type structure in the composition range  $x < 0.3$  and  $x > 0.7$ . Recently, an x-ray and Mössbauer-effect study on  $\text{Ce}(\text{Fe}_x\text{Ni}_{1-x})_2$  was reported.<sup>14</sup>

We prepared a number of  $R''(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds, namely,  $R'' = \text{Y, Gd, Dy, and Ho}$ . The  $\text{Y}(\text{Fe}_x\text{Ni}_{1-x})_2$  and  $\text{Gd}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds have not been obtained in pure state. In the case of gadolinium compounds an amount up to 10% of a second phase was evidenced. The  $\text{YFe}_2$  and  $\text{YNi}_2$  compounds are little soluble in each other. The  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  and  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds have been obtained in a single phase, the  $R\text{Fe}_2$  and  $R\text{Ni}_2$  ( $R = \text{Dy or Ho}$ ) compounds being soluble during the whole concentration range.

The analysis of the magnetic behavior of  $R(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds may supply information concerning the influence of the variable magnetic interactions—by replacing iron by nickel—on the iron moments. In this case, the influence of the variable electron concentration is eliminated by maintaining constant the rare-earth content.

Because of the high anisotropy of Dy and  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds we may obtain data on the iron moments only independently by Mössbauer-effect measurements. It is to be noted that although all the  $R\text{Fe}_2$  compounds crystallize in

$\text{MgCu}_2$ -type structure, various Mössbauer spectra were observed.<sup>15</sup> This behavior is attributed to the different orientations of the easy axis of magnetization relative to the crystallographic axis. When the system magnetizes along the [001] direction, all the iron atoms are magnetically equivalent and only a six-line spectrum is observed as in case of  $\text{DyFe}_2$  and  $\text{HoFe}_2$  compounds. Resulting from the Mössbauer spectra, for all the  $R(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds the [001] axis is the easy direction of magnetization, the hyperfine spectra presenting one six-line pattern.<sup>16</sup>

## II. EXPERIMENTAL

The  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  samples were prepared by melting the constituents in an induction furnace previously described.<sup>17</sup> The  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds were obtained in an arc furnace. In both cases the meltings were made in helium gas. The samples were thermally treated at 950 °C for one week. The crystallographic purity was checked by x-ray analysis and metallographic study. Only one phase is evidenced. The compounds crystallize in  $\text{MgCu}_2$ -type structure. The lattice parameters are presented in Fig. 1.

The magnetic measurements were made between 4.2 and 1300 K. The saturation data were obtained in fields up to 50 kOe. For paramagnetic measurements a translation balance was used. The samples were sealed in quartz ampoules under vacuum. The measurements were made at the two values of the external field (4 and 8 kOe) both by heating and cooling the samples. The results were the same, evidencing that the samples above the Curie temperatures had neither ferromagnetic impurities nor oxidation phenomena during the measurements. The nuclear  $\gamma$ -ray measurements were performed with Austin Science Associates equipment between 4.2 K and the Curie temperatures, the experimental facilities being previously presented.<sup>16</sup>

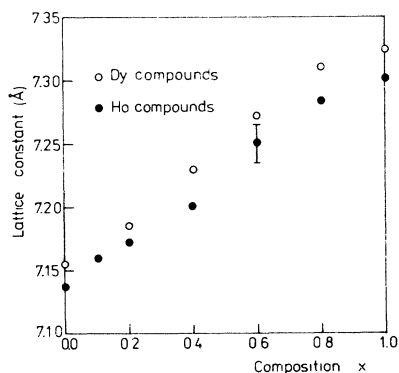


FIG. 1. Lattice parameters of  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  and  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds.

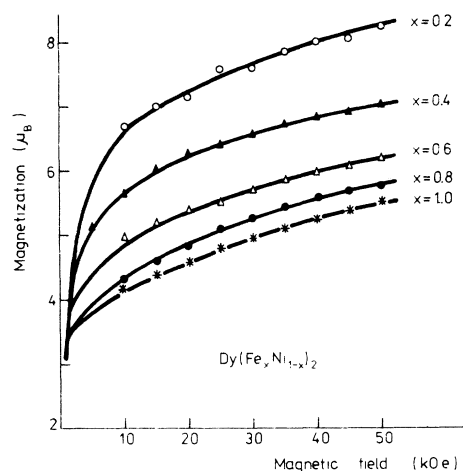


FIG. 2. Magnetization isotherms at 4.2 K in  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds.

## III. EXPERIMENTAL RESULTS

The studied compounds are highly anisotropic. This is observed from Fig. 2, where some magnetization isotherms obtained from  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds at 4.2 K are presented. The alloys are not saturated even in fields of 50 kOe. The approach to saturation is difficult and accordingly we determined the saturation magnetization by means of a standard approach of  $1/H$ . The values of the saturation magnetization were obtained with an accuracy of  $\pm 2\%$ .

The  $R(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds are ferrimagnetic if the 3d transition-metal atoms present a magnetic contribution. This may be evidenced by analyzing the thermal variation of the spontaneous magnetization. We present in Fig. 3 the experimental values obtained in case of  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds. Replacing iron by nickel the resultant magnetization increases as a result of the diminution

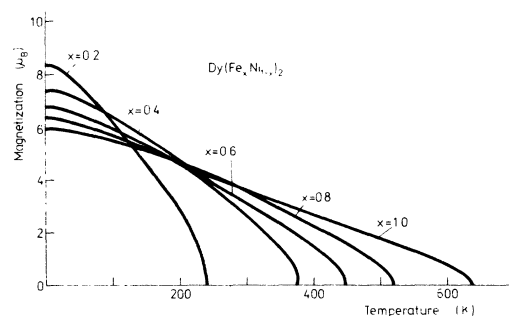


FIG. 3. Thermal variation of spontaneous magnetization for  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds.

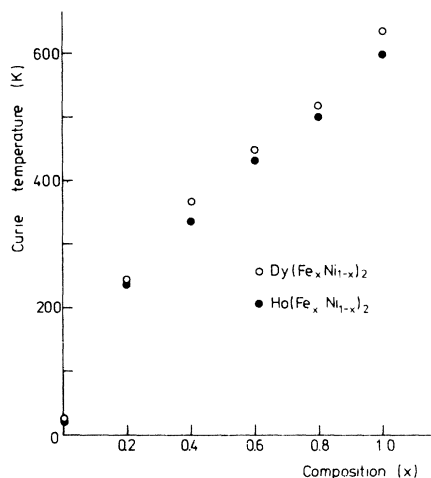


FIG. 4. Composition dependence of the Curie temperature in  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  and  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds.

of the 3d sublattice contribution. Probably, nickel has no magnetic moment in these systems, as in the case of  $R\text{Ni}_2$  compounds<sup>5,6</sup> or  $\text{Gd}(\text{Co}_x\text{Ni}_{1-x})_2$  ternary alloys.<sup>9,10</sup> Thus in analyzing the magnetic properties of  $R(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds we consider a magnetic model with two sublattices, corresponding to R and Fe atoms, respectively.

Clark<sup>18,19</sup> has studied comparatively the magnetic behavior of the  $\text{DyFe}_2$  compound—where [001] is the easy axis of magnetization—both as a single crystal and polycrystal. Even at 120 kOe it was impossible to saturate the polycrystal sample at 4.2 K. The polycrystal moment is reduced by ~17% below the single-crystal value. Assuming the same reduction of the moment for the  $\text{Dy-Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds, having [001] easy axis, we obtain from the saturation data an iron magnetic contribution  $(1.50 \pm 0.30)\mu_B$  for the entire concentration range.

Although the iron moment does not seem to vary

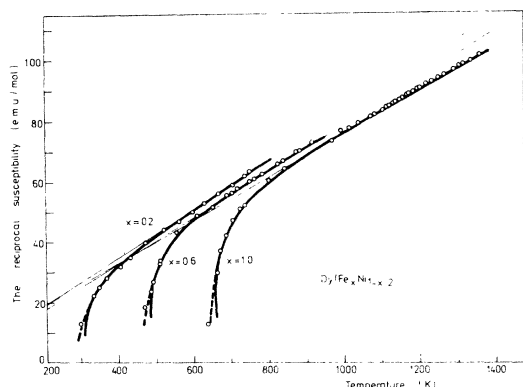


FIG. 5. Thermal variation of reciprocal susceptibility for  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds with  $x = 1.0$ ; 0.6, and 0.2.

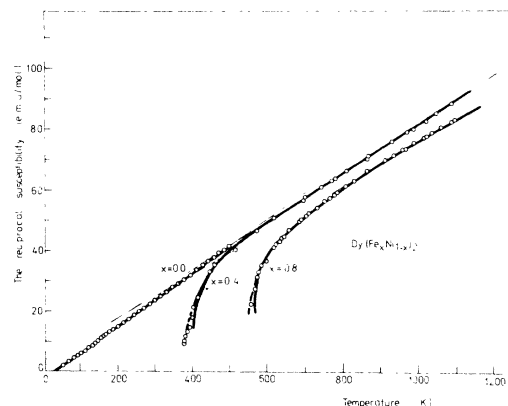


FIG. 6. Thermal variation of reciprocal susceptibility for the  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds with  $x = 0.8$ ; 0.4, and 0.

much in the studied composition range, the Curie temperatures,  $T_C$  of  $R(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds decrease continuously by substituting nickel for iron (Fig. 4). This evidence that the greatest contribution to the  $T_C$  values is given by the interactions involving the iron atoms. The Curie temperatures decrease up to  $x = 0.4$  almost linearly with  $dT_C/dx = -4.4$  K/at.% Ni).

The ferrimagnetic ordering evidenced by the saturation studies is also proved by measurements above the Curie points. As seen from Figs. 5–8 the inverse of paramagnetic susceptibility as a function of temperature follows the hyperbolic law of the Néel type, which can be expressed in the form<sup>20</sup>:

$$\frac{1}{x - x_P} = \frac{1}{x'_0} + \frac{T}{C'} - \frac{\sigma'}{T - \theta'} \quad (1)$$

We noted by  $C'$  the Curie constant, by  $x_P$  the Pauli paramagnetism due to the conduction electrons, and  $x'_0$ ,  $\sigma'$ , and  $\theta'$  are parameters related to the molecular-field coefficients. Since  $x_P/x < 10^{-4}$  we neglect the  $x_P$  term from relation (1). By fitting the experimental data we determined the parameters  $x'_0$ ,  $C'$ ,  $\sigma'$ , and  $\theta'$ . These values are listed in Table I.

We plotted by solid lines (Figs. 5–8) the calculated curves according to relation (1), using the parameters from Table I. A good agreement with the experimental data is observed, except for a region of 30–40 K above the Curie points. The discrepancy between the calculated curves and the experimental points in this temperature range is ascribed by Néel to the molecular-field fluctuations.<sup>20</sup>

Néel<sup>21</sup> pointed out that the thermal expansions will affect the strength of the exchange interactions, so that the molecular-field constants vary with temperature. On the assumption that the

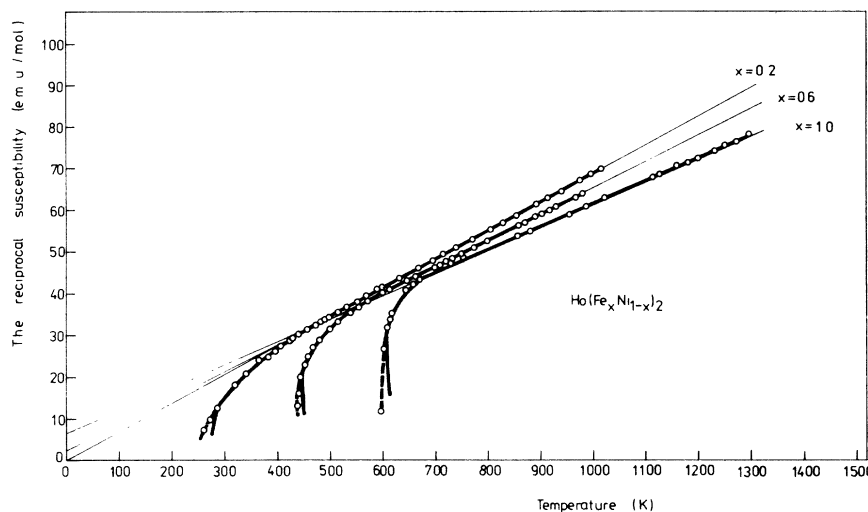


FIG. 7. Thermal variation of reciprocal susceptibility for the  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds with  $x = 1.0$ ,  $0.6$ , and  $0.2$ .

molecular-field coefficients vary linearly with temperature:  $J_{ij} = J_{ij}(0)[1 + \gamma T]$ , the apparent Curie constant  $C'$  is related to the true paramagnetic  $C$  by the relation<sup>21</sup>:

$$1/C = 1/C' - \gamma(1/x_0'). \quad (2)$$

Making use of the pressure studies on some  $R'\text{Fe}_2$  compounds,<sup>2</sup> we have estimated, in the manner previously described<sup>22</sup>  $\gamma = -(4 \pm 2) \times 10^{-4}$ . This is of the same order of magnitude as the values determined in the rare-earth garnets.<sup>23</sup> For the compounds where the  $3d$  transition metal has no moment, the  $T_C$  values are not pressure dependent<sup>24</sup> and thus the value is nil.<sup>22</sup>

In the case of  $\text{DyNi}_2$  and  $\text{HoNi}_2$  compounds, where nickel has no magnetic moment, a Curie-Weiss law is evidenced. The determined Curie constants—Table I—are almost the same with those of  $\text{Dy}^{3+}$  and  $\text{Ho}^{3+}$  ions.<sup>5,6</sup> Starting from the corrected Curie constants in accordance with the addition

law of susceptibilities we have determined the iron contribution to  $C$  values are iron effective moments  $M_{\text{Fe}}^P$ , respectively. A synthesis of these data is presented in Table II. A small decrease of the  $M_{\text{Fe}}^P$  values by increasing the nickel content is observed (Fig. 9). A similar composition dependence is observed for  $^{57}\text{Fe}$  hyperfine field values  $H_n$  at  $4.2\text{ K}$ .<sup>16</sup> A change of the slope is observed at  $x \leq 0.4$ . For the iron concentration  $x \approx 0.4$  the  $H_n$  values decrease more rapidly (Table II). The same composition dependence of the mean  $^{57}\text{Fe}$  hyperfine field is observed in  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_3$  compounds.<sup>25</sup>

Using the corrected parameters:  $C$ ,  $x_0^{-1}$ ,  $\sigma$ , and  $\theta$ , we calculate the molecular-field coefficients characterizing the magnetic interactions in the studied compounds. The results are presented in Fig. 10. The magnetic interactions between the iron atoms are the dominant ones. By increasing the nickel content, the magnetic interactions  $J_{R-R}$

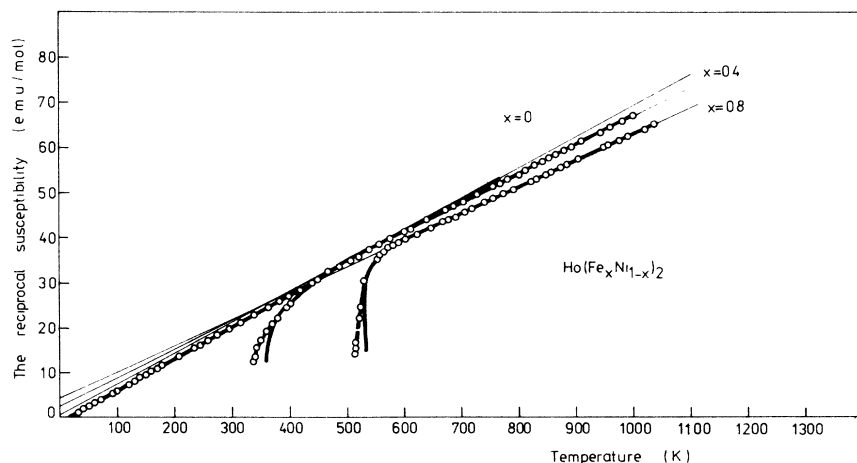


FIG. 8. Thermal variation of reciprocal susceptibility for the  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds with  $x = 0.8$ ,  $0.4$ , and  $0$ .

TABLE I. The  $C'$ ,  $1/x'_0$ ,  $\sigma'$  and  $\theta'$  parameters used for plotting the theoretical curves in Figs. 5–8.

Compound		$x = 1.0$	$x = 0.8$	$x = 0.6$	$x = 0.4$	$x = 0.2$	$x = 0$
$C'$ (emu/mol)	$R = \text{Dy}$	17.75	16.86	16.00	15.34	14.47	14.16
	$R = \text{Ho}$	18.47	17.06	16.15	15.50	14.66	14.10
$1/x'_0$ (emu/mol) <sup>-1</sup>	$R = \text{Dy}$	5.55	3.76	2.00	0.90	-0.25	...
	$R = \text{Ho}$	7.64	4.62	3.12	2.90	-0.90	...
$\sigma'$ (emu/mol)	$R = \text{Dy}$	351	322	237	164	193	...
	$R = \text{Ho}$	28	63	122	203	229	...
$\theta'$ (K)	$R = \text{Dy}$	660	558	470	398	290	28
	$R = \text{Ho}$	630	531	448	352	270	18.5

and  $J_{R-\text{Fe}}$  decrease, while  $J_{\text{Fe}-\text{Fe}}$  increases. The increase of  $J_{\text{Fe}-\text{Fe}}$  values by decreasing  $x$ , evidences their importance even in the case of compounds with low iron content. Using the determined interactions we calculated the exchange field at 0 K for the atoms of Dy(Ho) and Fe. As seen from Fig. 11, the exchange fields on both the iron sites and the  $R$  ones, decrease as the nickel content increases. This is reflected in the composition dependence of the Curie temperatures.

#### IV. DISCUSSION

The analysis of the magnetic data shows that the hyperfine field values and also the iron moments deviate from the simple dilution behavior. This deviation may be attributed to the variation of magnetic interactions in the system. Previously, in the case of compounds with a constant electron concentration we evidenced<sup>26</sup> that the induced iron or cobalt moments  $\Delta M_T$  are linearly dependent on the exchange fields  $H_e(T)$  acting on 3d transition-metal magnetization:

$$\Delta M_T = V_T H_e(T), \quad (3)$$

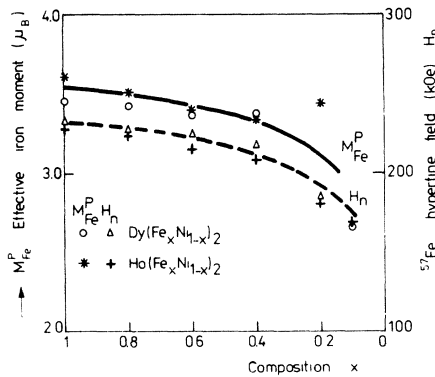


FIG. 9. Composition dependence of the iron effective moment and  $^{57}\text{Fe}$  hyperfine field values for  $R(\text{Fe}_x\text{Ni}_{1-x})_2$ .

where  $V_{\text{Fe}} = 1/(18 \pm 2)10^6 \mu_B/\text{Oe}$ , for the iron compounds, and  $V_{\text{Co}} = 1/(3 \pm 0.2)10^6 \mu_B/\text{Oe}$ , for the cobalt ones. The relation (3) seems to be independent of the crystal structure.

It is of interest to analyze to what extent the relation (3) describes the variation of the iron magnetization in  $R(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds. As we already observed, from the saturation measurements we cannot obtain accurate values for the iron moment. Consequently, we determine these data from the  $^{57}\text{Fe}$  hyperfine field values. We consider that the hyperfine fields are proportional to the iron moment; the proportionality constant is  $A = (145 \pm 3) \text{ kOe}/\mu_B$ . This value was deduced comparing the iron saturation moment and the  $^{57}\text{Fe}$  hyperfine field values in  $\text{YFe}_x$ ,<sup>27</sup>  $\text{Y}(\text{Fe}_x\text{Co}_{1-x})_2$ ,<sup>28</sup> and<sup>29</sup>  $(\text{Gd}_x\text{Y}_{1-x})\text{Fe}_2$  compounds.

From the differences in the exchange fields act-

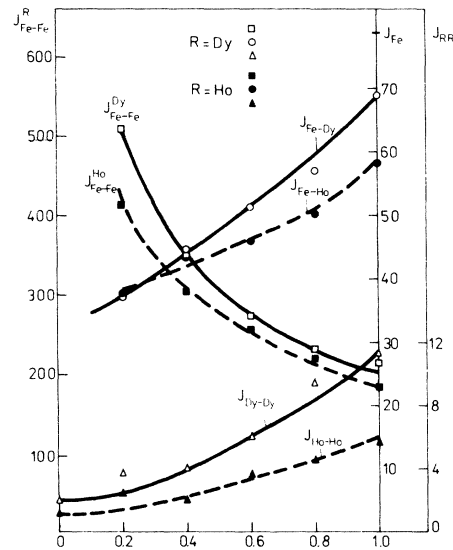


FIG. 10. Composition dependence of the molecular-field coefficients in  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  and  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds.

TABLE II. The corrected Curie constant  $C$ , the effective iron moments  $M_{\text{Fe}}^P$ , and the  $^{57}\text{Fe}$  hyperfine field values in  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  and  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$ .

Compound		$x = 1.0$	$x = 0.8$	$x = 0.6$	$x = 0.4$	$x = 0.2$	$x = 0.1$
$C$ (emu/mol)	$R = \text{Dy}$	17.08	16.44	15.80	15.25	14.68	...
	$R = \text{Ho}$	17.50	16.54	15.84	15.23	14.74	...
Effective iron moments	$R = \text{Dy}$	3.45	3.42	3.37	3.38	2.75	...
		$\pm 0.25$	$\pm 0.30$	$\pm 0.40$	$\pm 0.55$	$\pm 0.80$	...
$M_{\text{Fe}}^P(\mu_B)$	$R = \text{Ho}$	3.60	3.50	3.40	3.36	3.55	...
		$\pm 0.30$	$\pm 0.35$	$\pm 0.40$	$\pm 0.55$	$\pm 0.80$	...
Hyperfine field at 4.2 K (kOe)	$R = \text{Dy}$	232	227	224	218	185	...
	$R = \text{Ho}$	228	226	215	209	181	169

ing on the iron sites we compute the induced iron moments according to

$$\Delta M_{\text{Fe}}^0 = \Delta H_e(\text{Fe})V_{\text{Fe}}, \quad (4)$$

where  $\Delta H_e(\text{Fe}) = H_e(x=1) - H_e(x)$ . The relations (4) obtained for  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  and  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds are plotted in Fig. 12 by the hatching region, where the estimated errors in determining the exchange fields and the theoretical  $\Delta M_{\text{Fe}}^0$  values, respectively, are considered. As seen from Fig. 12, a reasonable agreement between the calculated values and those experimentally determined is evidenced. It can be noted that the iron moments are less sensible to the magnetic interactions than the cobalt ones.<sup>26</sup> The induced iron moments are rather small, being only somewhat greater than the experimental errors. As previously evidenced,<sup>26</sup> this explains that the agreement with the model is not so strong.

Probably, the iron magnetic behavior may be better considered in the model proposed by Stearns.<sup>30</sup> The model suggests that the greatest part of the 3d electrons of iron are in the narrow

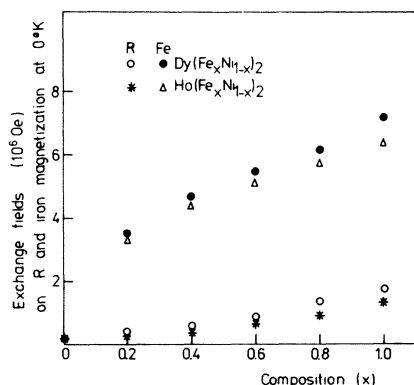


FIG. 11. Exchange fields at 0 K on Dy(Ho) and Fe atoms in  $R(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds ( $R = \text{Dy}$  or  $\text{Ho}$ ).

bands and they may be considered localized. The magnetic interactions between the iron moments take place through a small fraction of itinerant  $d$  electrons. This coupling is of Ruderman-Kittel-Kasuya-Yoshida type.<sup>31</sup>

The analysis of the composition dependence of the  $\delta$  isomer shifts, confirms that the deviation of the  $^{57}\text{Fe}$  hyperfine field values (and by assumption the iron moments) from the simple dilution behavior is mainly due to the variation of the magnetic interactions. The isomer shifts in  $R(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds are linearly dependent on the volume. This suggests that the variation of  $\delta$  is mainly due to the size effects and is not related to the increase of the electron concentration of the system, by substituting nickel for iron (Fig. 13).

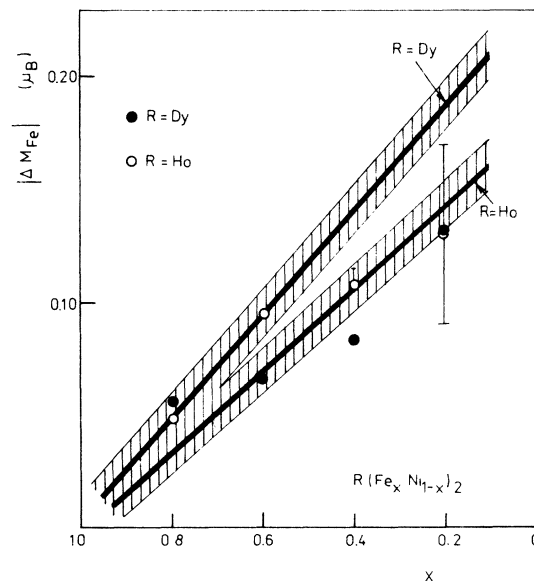


FIG. 12. Induced iron moments calculated from the exchange-field values and the experimental data.

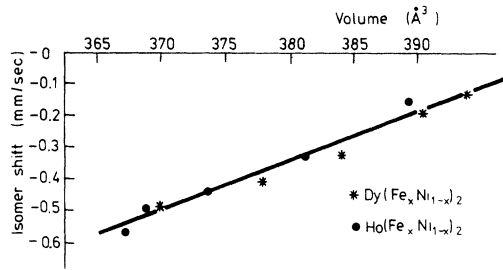


FIG. 13. Volume dependence of the isomer shift in  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  and  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds.

The Mössbauer spectra are formed by the six-line pattern for all the studied composition. We were not able to distinguish the local environment effects in the analysis of spectra. These effects may be observed only by the pulsed NMR technique whose resolution is about one order of magnitude greater.<sup>32,33</sup>

Information on the iron magnetic behavior may be also obtained from the temperature dependence of the  $^{57}\text{Fe}$  hyperfine field values. We present in Fig. 14 the thermal variation of hyperfine fields in  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds. The plot of  $H_n(x, T)/H_n(x, 0)$  as function of  $t/T_c$  evidences an increase of the radius of curvature by the decrease of the iron content. To compare the shapes of these curves we use the parameter  $h(x, t)$  previously defined<sup>34</sup> as

$$h(x, t) = \frac{H_n(x, t)}{H_n(x, 0)} - \frac{H_n(x=1, t)}{H_n(x=1, 0)}. \quad (5)$$

The  $h(x, t)$  values are represented in Fig. 15. These values are negative and increase in absolute magnitude as  $x$  decreases. The temperature dependence of  $h(x, t)$  is characteristic for the localized moments, evidencing the diminution of the exchange coupling felt by the iron moment.<sup>34</sup>

Another test which may give information on the

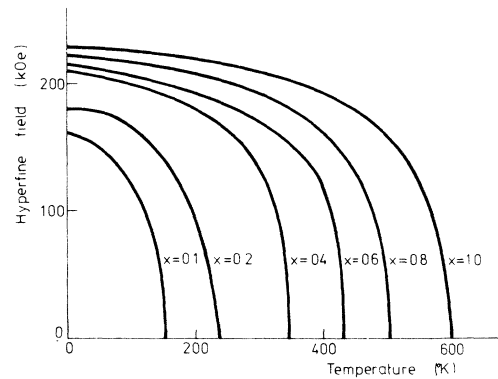


FIG. 14. Thermal variation of the hyperfine fields in  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds.

localization degree of the iron moment is to what extent the Néel model<sup>20</sup> may describe the magnetic behavior of the analyzed compounds. This model was developed in order to describe the magnetic properties of the systems with localized moments as magnetic insulators.

Using the values of the magnetic interactions deduced from the paramagnetic range, we computed the thermal variation of spontaneous magnetization. Previously, we evidenced that the two-sublattice model describes rather well the magnetic behavior of  $\text{DyFe}_2$  and  $\text{HoFe}_2$  compounds.<sup>35</sup> Although the errors in determining the molecular-field coefficients from paramagnetic data may influence the results, the agreement between the calculated values and the experimental data is rather good (Fig. 16).

A measure of the localization of the iron moments is given by the ratio  $r = q_c/q_s$ , between the number of magnetic carriers per atom deduced from the Curie constant  $q_c$ , and the number of carriers deduced from the saturation data. For a localized moment  $r=1$ . In the case of Fe, Co, and

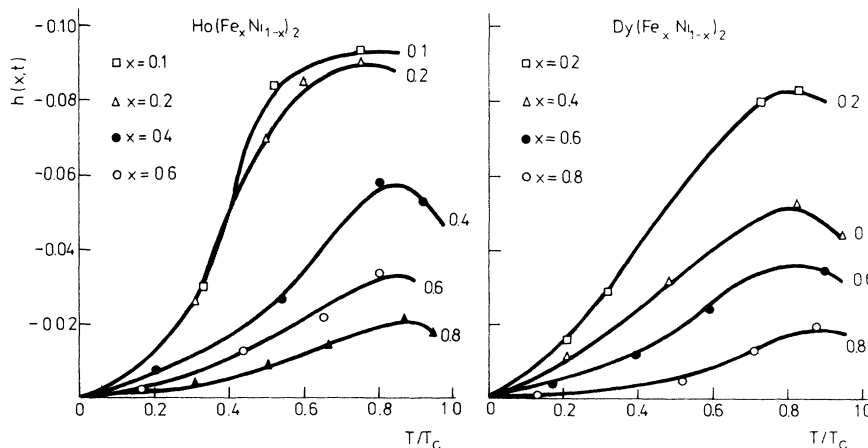


FIG. 15. Thermal variation of  $h(x)$  values [Eq. (5)] for  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds and  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds.

TABLE III. The effective transition-metal moments  $M_T^P$ , the saturation moments  $M_T^0$ , the ratio  $r = q_p/q_s$ , and the Curie temperatures in rare-earth (yttrium) compounds.

Compound	$M_T^0$ ( $\mu_B$ )	$M_T^P$ ( $\mu_B$ )	$r = q_p/q_s$	Curie temperature (K)	Reference
GdFe <sub>2</sub>	1.62	2.97	1.32	793	3, 4
TbFe <sub>2</sub>	1.60	3.45 ± 0.25	1.60 ± 0.20	697	4, 37
DyFe <sub>2</sub> <sup>a</sup>	1.60	3.45 ± 0.25	1.60 ± 0.20	635	4, 19
Dy(Fe <sub>0.8</sub> Ni <sub>0.2</sub> ) <sub>2</sub> <sup>a</sup>	1.57	3.42 ± 0.30	1.60 ± 0.20	520	
Dy(Fe <sub>0.6</sub> Ni <sub>0.4</sub> ) <sub>2</sub> <sup>a</sup>	1.55	3.37 ± 0.40	1.60 ± 0.35	448	
Dy(Fe <sub>0.4</sub> Ni <sub>0.6</sub> ) <sub>2</sub> <sup>a</sup>	1.50	3.38 ± 0.55	1.65 ± 0.35	368	
Dy(Fe <sub>0.2</sub> Ni <sub>0.8</sub> ) <sub>2</sub> <sup>a</sup>	1.28	2.75 ± 0.80	1.56 ± 0.50	242	
HoFe <sub>2</sub> <sup>a</sup>	1.57	3.60 ± 0.30	1.70 ± 0.20	597	4, 19
Ho(Fe <sub>0.8</sub> Ni <sub>0.2</sub> ) <sub>2</sub> <sup>a</sup>	1.54	3.50 ± 0.35	1.70 ± 0.25	500	
Ho(Fe <sub>0.6</sub> Ni <sub>0.4</sub> ) <sub>2</sub> <sup>a</sup>	1.48	3.40 ± 0.40	1.70 ± 0.30	432	
Ho(Fe <sub>0.4</sub> Ni <sub>0.6</sub> ) <sub>2</sub> <sup>a</sup>	1.44	3.36 ± 0.55	1.70 ± 0.40	334	
Ho(Fe <sub>0.2</sub> Ni <sub>0.8</sub> ) <sub>2</sub> <sup>a</sup>	1.25	3.55 ± 0.80	2.15 ± 0.50	240	
ErFe <sub>2</sub>	1.54	3.40 ± 0.25	1.60 ± 0.20	574	4, 35
TmFe <sub>2</sub>	1.50	3.40 ± 0.25	1.60 ± 0.20	566	4, 35
LuFe <sub>2</sub>	1.45	3.04	1.44	583	2, 3
YFe <sub>2</sub>	1.44	3.02	1.50	535	2, 3, 4
GdFe <sub>3</sub>	1.83	3.82	1.61	733	2, 38
HoFe <sub>3</sub>	1.67	3.63	1.65	566	7
YFe <sub>3</sub>	1.67	3.43	1.54	539	2, 3
Y <sub>6</sub> Fe <sub>23</sub>	1.91	3.73	1.49	478	2, 3
Gd <sub>2</sub> Fe <sub>17</sub>	2.16	4.25	1.56	479	2, 38
Y <sub>2</sub> Fe <sub>17</sub>	2.04	3.97	1.50	310	2, 3
GdCo <sub>2</sub>	1.02	2.16 ± 0.50	1.35 ± 0.40	395	22
GdCo <sub>3</sub>	1.57	2.90 ± 0.10	1.31 ± 0.10	611	22
Gd <sub>2</sub> Co <sub>7</sub>	1.63	3.00 ± 0.10	1.32 ± 0.10	767	22
GdNi <sub>3</sub>	0.16	0.97	2.46	118	39
Gd <sub>2</sub> Ni <sub>7</sub>	0.19	1.07	2.45	119	39
Gd <sub>2</sub> Ni <sub>17</sub>	0.30	1.38	2.35	190	39, 40

<sup>a</sup> Present measurements.

Ni moments the  $r$  values are 1.05, 1.34, and 1.46.

A synthesis of the magnetic data on Fe, Co, or Ni in the rare-earth compounds—which have been studied both by the saturation and the paramagnetic measurements—is presented in Table III. In case of compounds with non-S-state rare-earth atoms, the saturation iron moment was obtained from the <sup>57</sup>Fe hyperfine field value at 4.2 K.

The values listed in Table III are plotted as a function of the Curie temperatures (Fig. 17). The points are approximately arranged on the unique curve. The degree of localization of the 3d transition-metal moments is a function of the Curie temperatures of the compounds. The same behavior was observed for some 3d transition-metal alloys.<sup>36</sup> The results summarized in Fig. 17 suggest that in the analysis of the degree of localization of the 3d transition-metal moments we have to consider the magnetic interactions, as reflected in the Curie temperature.

For the  $\text{Dy}(\text{Fe}_x\text{Ni}_{1-x})_2$  and  $\text{Ho}(\text{Fe}_x\text{Ni}_{1-x})_2$  com-

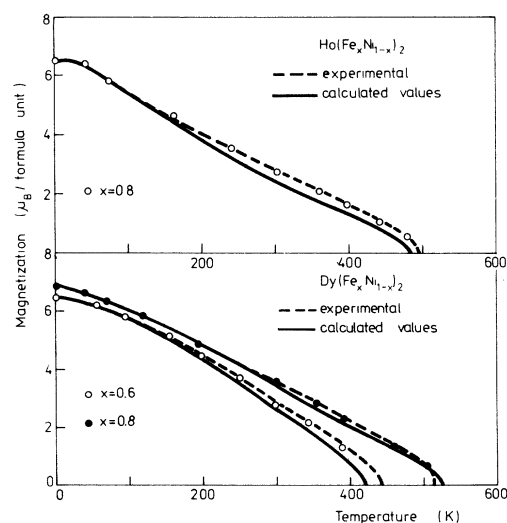


FIG. 16. Thermal variation of spontaneous magnetization for  $R(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds with  $x = 0.6$  and  $0.8$ . By solid lines we plotted the calculated curves.



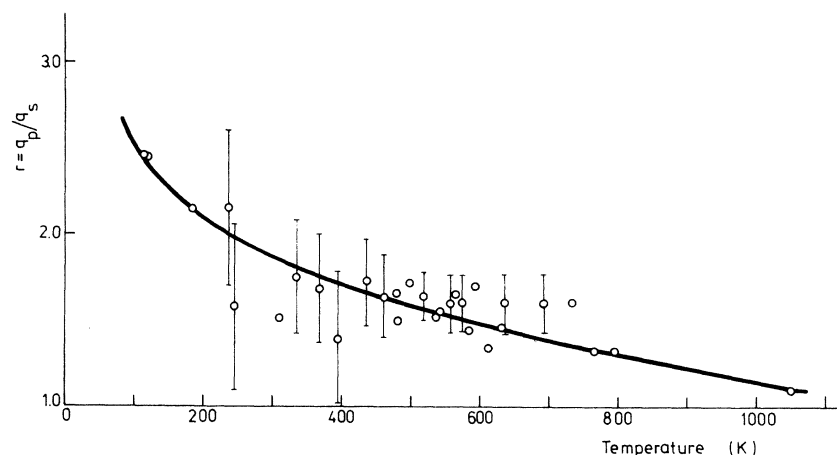


FIG. 17. The dependence of the ratio  $r = q_p/q_s$  between the number of magnetic carriers determined from Curie constant  $q_p$  and those determined from the saturation data  $q_s$  as function of the Curie temperatures (see Table III).

pounds, the ratio  $r$  does not show very much degree of itinerancy of iron.

#### V. CONCLUSIONS

The magnetic measurements performed on  $R(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds ( $R = \text{Dy}$  or  $\text{Ho}$ ) give evidence that these systems are ferrimagnetic, if the  $3d$  transition-metal atoms carry a magnetic moment. The  $^{57}\text{Fe}$  hyperfine-field values (and by assumption the iron moments) are dependent on composition. This is the result of diminishing the magnetic interactions consequence of replacing iron by nickel. A correlation between the exchange fields on the iron sites and the iron magnetic contribution is evidenced.

The iron atoms present both localized and band behavior, as reflected in all the magnetic data. These features seem to be better considered in the

model proposed by Stearns.

By plotting the ratio between the number of magnetic carriers deduced from the Curie constant and the saturation data, respectively, for iron, cobalt, or nickel in rare-earth compounds, as a function of the Curie temperature, a unique curve is evidenced. In the case of  $R(\text{Fe}_x\text{Ni}_{1-x})_2$  compounds we do not evidence a large degree of itinerancy for the iron moments. The above conclusion is also confirmed by Mössbauer effect studies.

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