

Dedicated to Professor Valentin I. Vlad's 70th Anniversary

MAGNETIC BEHAVIOUR OF COBALT IN $(\text{Gd}_x\text{Y}_{1-x})_{n+1}\text{Co}_{3n+5}\text{B}_{2n}$ COMPOUNDS

E. BURZO^{1,2}, P. VLAIC¹

¹“Babes-Bolyai” University, Faculty of Physics, M. Kogalniceanu No.1, 400084, Cluj-Napoca, Romania E-mail: emil.burzo@phys.ubbcluj.ro, E-mail: petrica_vlaic@yahoo.com

²Romanian Academy of Science, Cluj-Napoca Branch, Republicii No. 9, 400015, Cluj-Napoca, Romania

Received June 6, 2013

Abstract. The magnetic measurements performed on $(\text{Gd}_x\text{Y}_{1-x})_{n+1}\text{Co}_{3n+5}\text{B}_{2n}$ compounds with $n = 1, 2, 3$ and ∞ evidenced the sensitivity of saturation cobalt moments on gadolinium content, exchange interactions, respectively. The effective cobalt moments are only little influenced by composition. The ratio between the number of cobalt spins determined from Curie constants and that obtained from saturation magnetization follows a $T_C^{-2/3}$ dependence, as expected from a spin fluctuations behaviour. The cobalt moments for compounds having $T_C > 340$ K, are linearly dependent both on exchange fields as well as on the exchange splitting of their subbands. The above data are analysed in the model of induced magnetism.

Key words: rare-earth compounds, magnetization, magnetic susceptibility, electronic structure.

1. INTRODUCTION

The $\text{R}_{n+1}\text{Co}_{3n+5}\text{B}_{2n}$ compounds, where R is a rare-earth or yttrium are known to exist for $n = 0$ (RCO_5), $n = 1$ (RCO_4B), $n = 2$ ($\text{R}_3\text{Co}_{11}\text{B}_4$), $n = 3$ ($\text{R}_2\text{Co}_7\text{B}_3$) and $n = \infty$ (RCO_3B_2). These are formed from CaCu_5 type structure in which crystallizes the RCO_5 compounds by alternative stacking of one layer of RCO_5 and n layers of RCO_3B_2 unit cells. They crystallize in hexagonal type structures. The cobalt atoms are located in one type of site in RCO_3B_2 , two types of sites in RCO_5 and RCO_4B and three sites in $\text{R}_3\text{Co}_{11}\text{B}_4$ and $\text{R}_2\text{Co}_7\text{B}_3$ compounds.

In the above compounds, the 4f electrons of rare-earth have a small spatial extent and generally can be assumed that their moments are well localized. Yttrium is non-magnetic. The cobalt in the above system shows a wide spectrum of magnetic behaviours. A well established magnetism with high ordering temperatures has been found in RCO_5 series, while YCo_3B_2 is paramagnetic, by

crossing the situation when there is a collapse (or inset) of the ordered cobalt moments [1–5]. The cobalt moments are generally dependent on the lattice sites where they are located. By magnetic measurements only their mean values can be obtained. A somewhat related behaviour was reported in RCO_2 compounds. A T^2 dependence of the magnetic susceptibility, at low temperatures, was shown in YCo_2 , as expected for an exchange enhanced paramagnet, while at high temperatures a Curie-Weiss type dependence can be evidenced [6]. The above behaviour is characteristic for a spin fluctuations system [7]. An ordered cobalt moment can be induced by replacing yttrium by a magnetic rare-earth, by increasing the exchange field, respectively or under the action of high magnetic field, above a critical value [8]. Two models were proposed to analyse the above features. The first, called collective electron metamagnetism has been based on a theoretical study which analysed the possibility of making certain paramagnetic substances ferromagnetic, by the application and subsequent removal of sufficiently strong magnetic fields [9]. The model has been used by Bloch *et al.* [10] to analyse the magnetic behaviour of RCO_2 compounds. Other reports have been also based on this model in describing some properties of R-Co compounds.

The second model, called induced magnetism or epimagnetism, has been also used to describe the magnetic behaviour of RCO_2 -based compounds [11]. In this case the effect of internal or external fields on the exchange splitting of Co3d band has been considered. The critical field for exchange splitting of Co3d band was estimated by analysing the magnetic properties of $\text{Gd}(\text{Co}_x\text{Ni}_{1-x})_2$ system [12]. At higher field than the critical one, a linear dependence of cobalt moment with the exchange field was shown with a slope of $(3 \cdot 10^2)^{-1} \mu_B/T$ [8]. A similar behaviour has been reported in RCO_4B based systems [2, 13].

The exchange interactions between rare-earth and cobalt in R-Co or R-Co-B compounds are of 4f-5d-3d type [14]. The 4f electrons of rare-earth polarize their 5d bands and there are also 5d-3d short range exchange interactions. The part played by R5d band polarization in analysing the exchange interactions, is a fundamental question. The R5d band polarizations are determined by two effects [15]. The first, due to local 4f-5d interactions, can be described by J_{4f-5d} exchange integral

$$J_{4f-5d} = \int g(\rho(r)) \phi_{4f}^2(r) \phi_{5d}^2(r) dr, \quad (1)$$

where $\phi_{4f}(r)$ and $\phi_{5d}(r)$ are the partial wave functions and $g(\rho(r))$ is a function of the electronic density [16]. For a given series, this contribution is proportional to De Gennes factor [15]. The R5d band polarization induced by 5d-3d short range exchange interactions, $M_{5d}(0)$ [15,17], is proportional to the number of magnetic 3d atoms, z_i situated in the neighboring of an R atom and their moments, M_i ,

$$M_{5d}(0) \propto \sum_i z_i M_i$$

In this paper we analyse the magnetic behaviour of $(\text{Gd}_x\text{Y}_{1-x})_{n+1}\text{Co}_{3n+5}\text{B}_{2n}$ compounds. The $\text{Y}_{n+1}\text{Co}_{3n+5}\text{B}_{2n}$ series are ferromagnetic. A ferrimagnetic type ordering can be shown in the corresponding gadolinium systems. Since gadolinium is in S-state and yttrium is not magnetic, the mean cobalt moments in (Gd,Y)-Co-B-compounds can be obtained with a better accuracy. The analyses of the magnetic behaviour of cobalt in the above series evidence that they can be described in spin fluctuations model. Also their dependence on exchange or external fields can be correlated with exchange splitting of their 3d bands.

2. EXPERIMENTAL AND COMPUTING METHOD

The magnetic properties of $(\text{Gd}_x\text{Y}_{1-x})_{n+1}\text{Co}_{3n+5}\text{B}_{2n}$ series with $n = 1, 2, 3$ and ∞ were previously reported [1, 2, 5, 18–20]. The following works were, in general, in agreement with the above data [21–28].

The present studies were made in the temperature range 4(2)-800 K and in external fields up to 7 T. The spontaneous magnetization, M_s , has been determined from magnetization isotherms according to the approach to saturation law. The mean cobalt moments, in ferrimagnetic compounds, were obtained considering a two sublattices model.

In order to obtain reliable data above the Curie temperatures ($T > T_c$), the magnetic susceptibilities, χ , have been determined from their field dependences according to Honda-Arrortt plot [29], $\chi_m = \chi + cM_s'H^{-1}$, by extrapolating the measured values χ_m to $H^{-1} \rightarrow 0$. By c is denoted a presumed magnetic ordered impurity content and M_s' is their saturation magnetization. By this method any possible alteration of magnetic susceptibility as result of the presence of magnetic ordered phase is avoided. Generally, no magnetic ordered phases were evidenced at $T > T_c$. The reciprocal susceptibilities follow a Curie-Weiss type dependence in Y-Co-B compounds and of Néel type for (Gd,Y)-Co-B ones.

The ground state electronic structure calculations were performed by using tight-binding linear muffin-tin orbital (TB-LMTO) method in the atomic sphere approximation (ASA) [30]. The self-consistent spin-polarized calculations were performed at the experimental values of the lattice parameters [1] and carried out for 793 k points in the irreducible wedge of the Brillouin zone (BZ) corresponding to 13824 k points in the full Brillouin zone (BZ). The overlaps of the muffin-tin spheres, for RCo_4B (R = Gd, Y) compounds, are below 10% and the standard combined correction terms were included in order to compensate the errors due to ASA [30]. The local spin density approximation (LSDA) has been used for the exchange and correlation potential within Vosko-Wilk-Nussair parameterization [31]. The valence basis consists of s-, p- and d-type orbitals, whereas the 4f orbitals

of Gd were considered as open core states that do not hybridize with the conduction electrons but having the population calculated self-consistently. Relativistic corrections were taken into account without spin-orbit coupling.

3. MAGNETIC PROPERTIES

The magnetic measurements performed on $(\text{Gd}_x\text{Y}_{1-x})_{n+1}\text{Co}_{3n+5}\text{B}_{2n}$ compounds evidenced a wide range of magnetic behaviors. The YCo_3B_2 , at low temperatures, has a Pauli-type paramagnetism (Fig. 1). The magnetic susceptibility increases up to $T \cong 150$ K. At $T > 200$ K, a Curie-Weiss dependence is evidenced with an effective moment of $1.34 \mu_B/\text{Co}$ atom. The above behaviour can be described by the spin fluctuations model [7, 17]. The average amplitude of local spin fluctuations

$$\langle S_{\text{loc}}^2 \rangle = 3k_B T \sum_q \chi_q \quad (2)$$

is a temperature dependent quantity, increasing until it reaches an upper limit determined by charge neutrality conditions, at a temperature $T^* \cong 200$ K. At $T > T^*$ the YCo_3B_2 compound behaves as having local cobalt moment. The effective cobalt moment, smaller than that of Co^{2+} ion, suggests a strong hybridization of Co3d with B2p and Y4d bands. As yttrium is replaced by gadolinium, an ordered cobalt moment is induced, which increases when Gd content is higher, and for GdCo_3B_2 a value of $0.2 \mu_B$ was shown (Fig. 2). The effective cobalt moments in $(\text{Gd}_x\text{Y}_{1-x})\text{Co}_3\text{B}_2$ series are little dependent on composition and near the same as that determined in YCo_3B_2 .

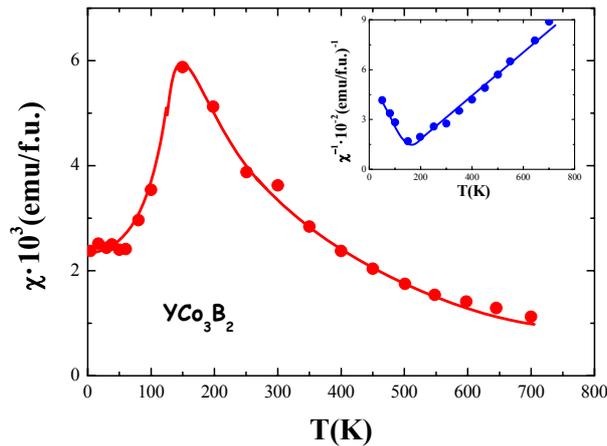


Fig. 1 – Thermal variation of the magnetic susceptibility in YCo_3B_2 compound. In inset is plotted the temperature dependence of the reciprocal susceptibility.

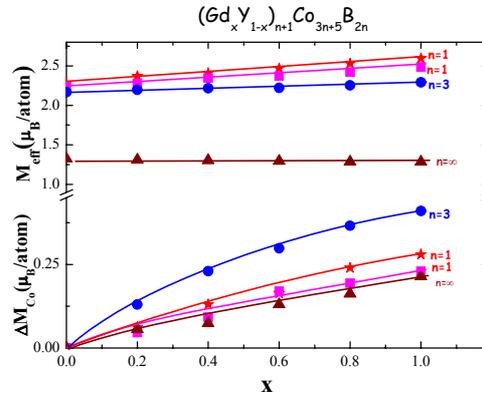


Fig. 2 – The evolutions of mean induced cobalt moments as function of gadolinium content in $(\text{Gd}_x \text{Y}_{1-x})_{n+1} \text{Co}_{3n+5} \text{B}_{2n}$ compounds with $n = 1, 2, 3$ and ∞ . The effective cobalt moments are only little dependent on composition.

The mean cobalt moments in $(\text{Gd}_x \text{Y}_{1-x})_{n+1} \text{Co}_{3n+5} \text{B}_{2n}$ increase as the $(3n+5)/2n$ ratio as well as the gadolinium content is higher. The variations of mean cobalt moments as result of Y substitution by Gd, in the studied series are plotted in Fig. 2. Their increase is the result of increasing exchange interactions mediated by Gd5d band polarizations.

By using the two sublattices molecular field model, the exchange interactions inside and between magnetic sublattices were determined and the exchange field, H_{exch} , acting on cobalt atoms, respectively. There is a relatively low increase of mean cobalt moment up to a value $H_{\text{exch}} \cong 50$ T (Fig. 3). Then, there is a sudden change of M_{Co} from 0.2 μ_B/atom to $\cong 0.42$ μ_B/atom . At higher exchange fields a linear dependence was shown with a slope of $b = (3 \cdot 10^2)^{-1} \mu_B/\text{T}$ (Fig. 4). Finally, the cobalt moments saturate.

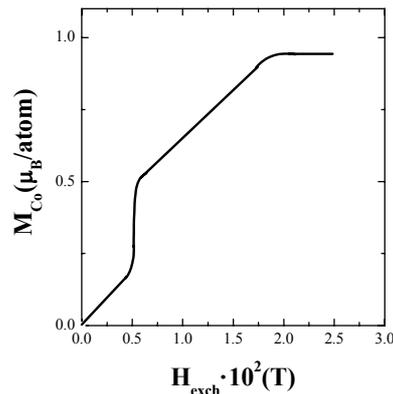


Fig. 3 – The dependence of mean cobalt moments as function of exchange fields in R-Co-B compounds, as a general feature of induced magnetism.

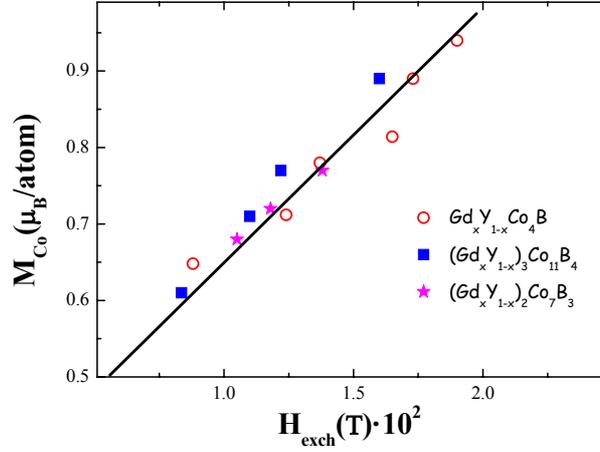


Fig. 4 – Variation of mean cobalt saturation moments as function of exchange fields. The data for $M_{\text{Co}} \geq 0.5\mu_{\text{B}}$ are only plotted.

The mean effective cobalt moments, for a given series, are nearly composition independent (Fig. 2).

The above features can be analysed in spin fluctuations model [7]. The theoretical analysis of the model predict: 1) for ferromagnetic compounds the magnetic susceptibilities obey a Curie-Weiss type behavior; 2) the Curie constant is independent on saturation 3d moments at $T = 0$, but depends on the band structure around the Fermi energy. Therefore, the Curie constants are not changed when one change the effective exchange constant, keeping the same band structure, even though the saturation moments and Curie temperatures have been modified; 3) the Curie-Weiss law holds even for paramagnetic alloys (or compounds) when they are close to the ferromagnetic instability. These predictions are in good agreement with features evidenced by cobalt moments, experimentally determined, in $(\text{Gd}_x\text{Y}_{1-x})_{n+1}\text{Co}_{3n+5}\text{B}_{2n}$ series.

The spin fluctuations model can describe the transition metal moments having different degree of localization, as evidenced by the ratio $r = S_p/S_0$ between the number of spins, S_p , determined from Curie constants, and those obtained from saturation magnetization, S_0 , respectively. In the local moment limit there is $S_p/S_0=1$. In the opposite weakly ferromagnetic limit there is a divergence as $S_0 \rightarrow 0$ or $T_C \rightarrow 0$. The r values can be distributed almost continuously between the two limits. According to Wohlfarth [32, 33], the application of itinerant electron model of ferromagnetism, gives the ratio r proportional to T_C^{-1} , a hyperbolic increase of r values as the Curie temperatures diminish, respectively. When the spin fluctuations model is considered, the mathematical approach gives $r \propto T_C^{-2/3}$ [33]. In this case, the approximate hyperbolic form, suggested by Rhodes-Wohlfarth [22], is distorted.

The r values as function of T_C^{-1} and $T_C^{-2/3}$ are plotted in Fig. 5 for compounds with $n = 1, 2, 3$ and having mean saturation cobalt moments higher than $\cong 0.50 \mu_B$. These correspond to a range of values where M_{Co} are linearly dependent on the exchange field. We note that for smaller M_{Co} values, the r values can be strongly influenced by small deviations from expected values, even if these are in the limit of experimental errors; the trends given in Fig. 5 are followed even for the above range of values, but with higher dispersion of data.

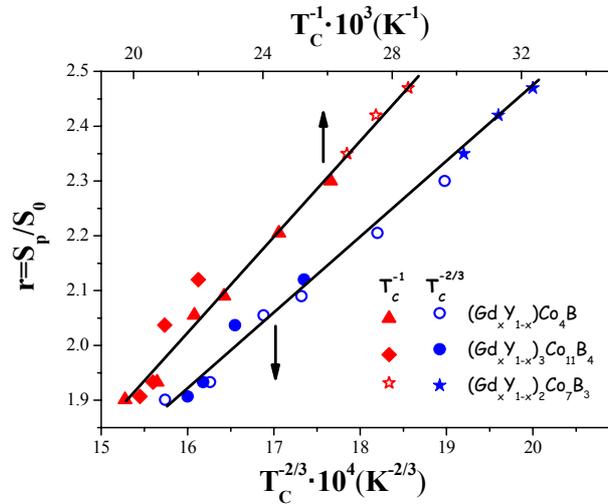


Fig. 5 – The $r = S_p/S_0$ values as function of $T_C^{-2/3}$ and T_C^{-1} in $(Gd_xY_{1-x})_{n+1}Co_{3n+5}B_{2n}$ compounds for $S_0 \geq 0.25$.

Linear variations of r values both as function of $T_C^{-2/3}$ or T_C^{-1} were shown. The dispersion of the data are greater when T_C^{-1} dependence is considered, suggesting that the model of spin fluctuations is most adequate to describe the experimental data. A variation of r values as function $T_C^{-2/3}$ was also evidenced in $(Gd_xY_{1-x})Co_4Si$ compounds [34] or $Ni_{100-x}Y_x$ amorphous alloys [35].

4. BAND STRUCTURES

The site decomposed density of states (DOS) of cobalt atoms at 2c and 6i sites in RCo_4B ($R = Gd, Y$) compounds, are plotted in Fig. 6. The computed magnetic moments per formula unit are in good agreement with experimental data (Table 1). We note that the saturation magnetization obtained by the present measurements on YCo_4B was little higher than the previously reported value [1]. A higher external field was now used. The computed magnetic moments in YCo_4B are close to those previously reported [36, 37].

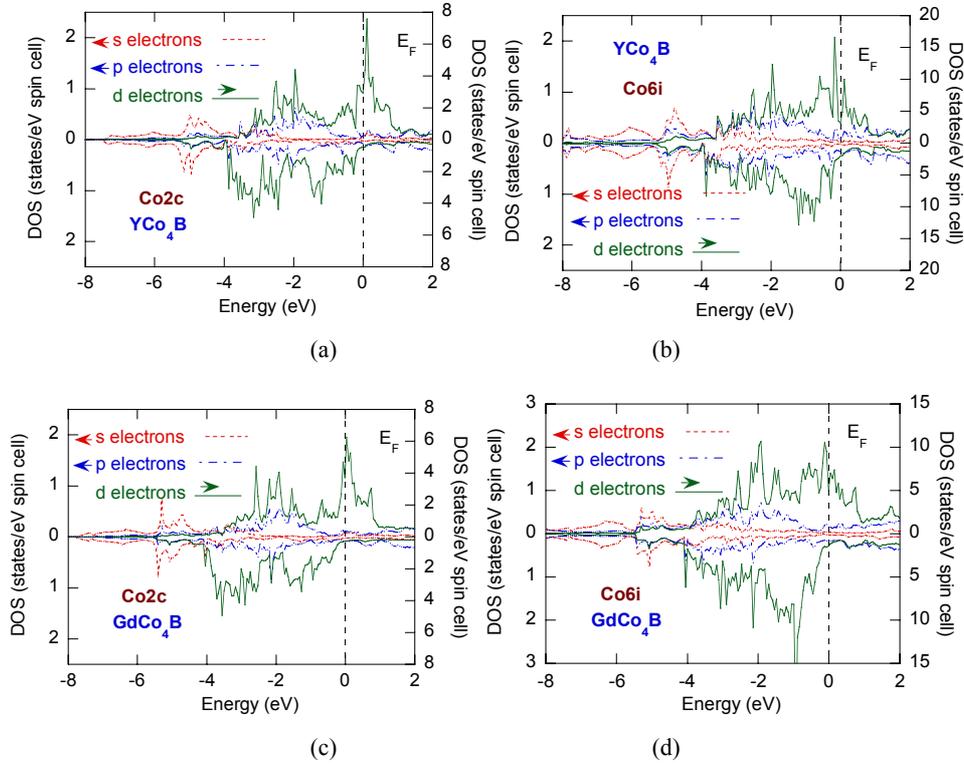


Fig. 6 – Site decomposed DOS of YCo_4B (a,b) and GdCo_4B (c,d), at Co2c (a,c) and Co6i(b,d).

The forms of partial DOS of cobalt atoms in GdCo_4B and YCo_4B are rather similar although their bands are somewhat shifted. The Fermi level, E_F , in GdCo_4B at Co2c site for spin up states is situated in a peak of the density of states, while in YCo_4B is located close to the corresponding peak. For both GdCo_4B and YCo_4B , in case of 6i sites, the E_F are situated close to a maximum in the state density. The densities of states of spin down subbands are rather small for GdCo_4B and YCo_4B , both at Co2c and Co6i sites.

The increase of the exchange interactions, when substituting Y by Gd is followed by an increase of the exchange splitting of Co3d subbands. This is illustrated in Fig. 7 where the cobalt moments at 2c and 6i sites are plotted as function of the exchange splittings energy, ΔE_{exch} , of their 3d bands. A linear dependence is obtained, suggesting that these parameters are strongly correlated. The determined slope $s = 0.96 \text{ eV}/\mu_B$ is in good agreement with those obtained from band structure calculations in some RCo_4A ($A = \text{Co}, \text{Al}, \text{Si}$) compounds [34] or Zr-A ($A = \text{Fe}, \text{Co}, \text{Ni}$) amorphous alloys or crystalline compounds [38].

Table 1

Magnetic moments determined in RCO_4B ($R = Y, Gd$) compounds

| Compound | Site | 1 | M_1 (μ_B /atom) | M_{total} (μ_B /atom) | M_{total} (μ_B /f.u.) | |
|---------------------|------|---|---------------------------|---------------------------------|------------------------------|------|
| | | | | | computed | exp. |
| GdCo ₄ B | Gd1a | 0 | -0.037 | -7.41 | 3.36 | 3.27 |
| | | 1 | -0.063 | | | |
| | | 2 | -0.306 | | | |
| | Gd1b | 0 | -0.023 | -7.47 | | |
| | | 1 | -0.127 | | | |
| | | 2 | -0.311 | | | |
| | Co2c | 0 | 0.020 | 1.65 | | |
| | | 1 | -0.037 | | | |
| | | 2 | 1.654 | | | |
| | Co6i | 0 | 0.002 | 0.80 | | |
| | | 1 | -0.02 | | | |
| | | 2 | 0.818 | | | |
| | B2d | 0 | -0.004 | -0.009 | | |
| | | 1 | -0.004 | | | |
| | | 2 | -0.001 | | | |
| YCo ₄ B | Y1a | 0 | -0.021 | -0.16 | 3.20 | 2.92 |
| | | 1 | -0.029 | | | |
| | | 2 | -0.106 | | | |
| | Y1b | 0 | -0.001 | -0.24 | | |
| | | 1 | -0.074 | | | |
| | | 2 | -0.159 | | | |
| | Co2c | 0 | 0.021 | 1.48 | | |
| | | 1 | -0.021 | | | |
| | | 2 | 1.476 | | | |
| | Co6i | 0 | -0.001 | 0.65 | | |
| | | 1 | -0.013 | | | |
| | | 2 | 0.670 | | | |
| | B2d | 0 | -0.006 | -0.05 | | |
| | | 1 | -0.038 | | | |
| | | 2 | 0.001 | | | |

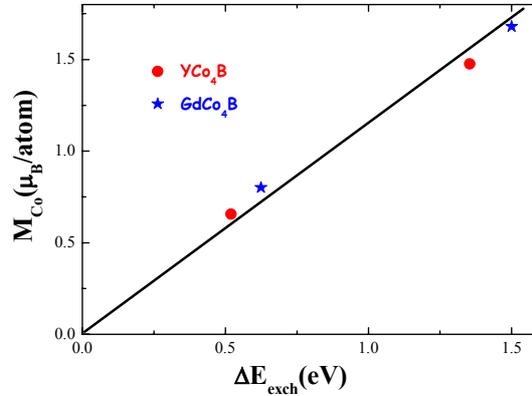


Fig. 7 – The cobalt moments at 2c and 6i sites in RCo_4B ($\text{R} = \text{Gd}, \text{Y}$) as function of exchange splitting energy of their 3d bands.

There seems to be not a sensitive change in the distribution of Co3d electrons in spin up and spin down states, respectively as function of exchange field, as expected in the model of itinerant electrons metamagnetism. Even if it exist, the above mechanism can have only a minor contribution to the increase of cobalt moments, as suggested by the relatively close density of states, at E_F , of cobalt spin down subbands both in GdCo_4B or YCo_4B compounds.

The dominant mechanism involved in the variation of cobalt moment can be attributed to the exchange splitting of 3d subbands when exchange or external fields are increased, starting from a critical value, estimated at $H_{cr} \cong 50$ T. After the transition to a magnetic ordered states, the mean cobalt moments increase linearly with the exchange (or external) field with a slope of $(3 \cdot 10^2)^{-1} \mu_B/\text{T}$. Taking into account also the data from Fig. 7, the exchange splitting of Co3d subbands can be correlated with the internal/external fields. A slope of the order of $3 \cdot 10^{-3} \text{ eV/T}$ has been obtained. In a field of $\cong 50$ T there is a sudden increase of cobalt moment from $0.20 \mu_B$ to $0.42 \mu_B$ (Fig. 2). This transition corresponds to an exchange splitting of $\cong 0.15 \text{ eV}$ for Co3d band. We note that a critical exchange splitting for the appearance of the nickel moment, of the order of $3 \cdot 10^{-3} \text{ eV}$, was estimated in $\text{Gd}_x\text{La}_{1-x}\text{Ni}_5$ compounds [39].

The analysis of magnetic properties of R-Fe compounds [40] suggested also that the changes of iron moments were mainly due to the variation of exchange splitting of Fe3d band.

5. PRESSURE EFFECTS

The pressure studies can give additional information on the magnetic behavior of transition metals in rare-earth compounds [41–49]. In order to characterize the magnetic properties, at high pressures, the quantity Γ was defined:

$$\Gamma = \frac{1}{\kappa T_C} \frac{dT_C}{dp} = - \frac{d \ln T_C}{d \ln v} \quad (3)$$

By κ is denoted the compressibility, v is the volume and p the pressure.

Two types of dependences of Γ values, as function of Curie temperatures, were reported. These were based on Stoner-Wohlfarth itinerant model of ferromagnetism and a model considering more localized 3d electrons, respectively.

Starting from weak itinerant model of ferromagnetism, for a large number of cobalt and iron-rare-earth compounds, was shown a Γ dependence on T_C of the form [42]:

$$\Gamma = -\frac{5}{3} + B T_C^2 \quad (4)$$

with

$$B = \frac{5}{6} \frac{1}{I_b} \bar{I}^2 \quad (5)$$

and

$$T_C = T_F (\bar{I} - 1)^{1/2} \quad (6)$$

In the above expressions, I is the effective intra-atomic exchange integral which is reduced from its bare value I_b by many-body correlation effects, $\bar{I} = I \eta(E_F)$ with $\eta(E_F)$ the density of states at the Fermi level and T_F is the effective degeneracy temperature.

The dependence of Γ values on Curie temperatures has been also analysed [43] starting from Stearns model [50]. In this model only a small fraction of the iron 3d electrons (5 %) were considered as fully itinerant while the remaining occupy sufficiently narrow bands to be considered as localized. In the above model the Γ values as function of Curie temperatures are described by the relation:

$$\Gamma = \frac{5}{3} + 2 \frac{d \ln \eta_{eff}}{d \ln v} + \frac{5}{8} \frac{k_B N_0 g^2 I^2}{S(S+1) J_{eff}^2 I_b} T_C \quad (7)$$

where N_0 is the Avogadro number, g is the Landé factor and J_{eff} characterizes the coupling of the localized spin to itinerant one.

The Γ values for RCo_4B ($R=Ce, Y, Gd$) have been determined from pressure studies up to $p = 1.2$ GPa [46]. These values are plotted in Fig. 8 as a function of T_C^{-2} and T_C , respectively. The experimental data fit better the relation (4). When Γ values are plotted as function of T_C , deviation from linearity can be shown. These data suggest that the cobalt magnetic behaviour, in RCo_4B compounds, is more close to a description involving itinerant magnetism than that considering localized features.

When using an effective intr-atomic exchange integral $I = 0.9$ eV widely accepted in literature [15], and a density of states at the Fermi level, as determined in YCo_4B compound, according to relation (6) a Fermi temperature $T_F \cong 820$ K has been obtained. The T_F value is somewhat smaller than that reported in R-Fe system ($T_F \cong 1000$ K) [42]. According to the relation (5) a ratio $I/I_b \cong 0.9$ has been estimated, evidencing relatively high correlation between Co3d electrons.

Admitting a linear dependence of Γ on the Curie temperature, as denoted in Fig. 8 by dashed line, the Γ values can be described by a relation $\Gamma = a - bT_C$, where $a = 13.4$ and $b = -0.022 \text{ K}^{-1}$. These data can be compared with those obtained by pressure studies on R_2Fe_{17} compounds ($a = 34.5$, $b = -0.054 \text{ K}^{-1}$) [47] or in $\text{Y}_2\text{Fe}_{17}\text{C(N)}$ system ($a = 37.5$, $b = 0.063 \text{ K}^{-1}$) [45]. According to relation (7) a value $\text{dln}J_{\text{eff}}/\text{dln}v = 6$ has been estimated in R-Co-B compounds. This is more than two times smaller than those obtained in R-Fe compounds. A higher volume variation with pressure, in cobalt compounds than in iron ones, can take into account the observed difference. The discussion considering a localized model is somewhat speculative since we neglected the deviation from linearity of the $\Gamma=f(T_C)$ plot.

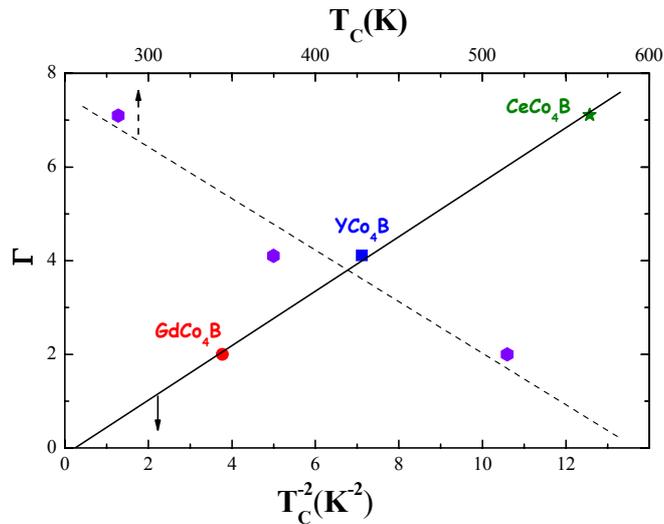


Fig. 8 – The dependence of $\Gamma = \text{dln}T_C/\text{dln}v$ as a function of T_C^{-2} and T_C , respectively.

The pressure studies on RCo_4B compounds evidenced that cobalt moments have a magnetic behaviour more close to that described by itinerant electron model. Some degree of localization is also suggested, in agreement with spin fluctuations model.

6. CONCLUSIONS

The analysis of magnetic properties of $(\text{Gd}_x\text{Y}_{1-x})_{n+1}\text{Co}_{3n+5}\text{B}_{2n}$ compounds with $n = 1, 2, 3$ and ∞ evidenced that the mean saturation cobalt moments are sensitive to gadolinium content, exchange interactions, respectively. In addition, the effective cobalt moments, for a given series, are little dependent on composition. The ratio r between the number of cobalt spins determined from Curie constants and saturation magnetization follows a $T_C^{-2/3}$ dependence. These features suggest that the cobalt magnetic behaviour can be better described by a spin fluctuations model.

A linear relation was shown between the cobalt moments at 2c and 6i sites in RCo_4B ($\text{R} = \text{Gd}, \text{Y}$) and the exchange splitting energy of their 3d subbands, with a slope $0.96 \text{ eV}/\mu_B$. The cobalt induced moments, for compounds where $M_{\text{Co}} > 0.5 \mu_B/\text{atom}$ (or $T_C > 340 \text{ K}$) are also linearly dependent on exchange field with $(3 \cdot 10^2)^{-1} \mu_B/T$. Thus, the exchange splitting of the 3d bands seems to be mainly determined by the internal or external magnetic fields acting on cobalt atom. Thus, a model of induced magnetism seems to describe better the transition of cobalt to magnetic ordered state, at a critical field, H_{cr} , and then, their linear increase with the exchange field.

The spin fluctuations model can describe the wide range of cobalt magnetic features starting from an exchange enhanced paramagnet to weak ferromagnetism and finally to a strong ferromagnet. On the above scale of magnetic behaviour, the cobalt in $(\text{Gd}_x\text{Y}_{1-x})_{n+1}\text{Co}_{3n+5}\text{B}_{2n}$ compounds with $n = 1, 2, 3$ and ∞ series is more close to a description starting from itinerant electron magnetism as suggested by pressure studies, although some localized features are present.

REFERENCES

1. A. T. Pedziwiatr, S. Y. Jiang, W. E. Wallace, E. Burzo and V. Pop, *J. Magn. Magn. Mater.*, **66**, 69 (1987).
2. E. Burzo, I. Creanga, N. Plugaru, V. Pop and I. Ursu, *Rev. Roum. Phys.*, **33**, 57 (1988).
3. E. Burzo, N. Plugaru, I. Creanga and I. Ursu, *J. Less Common Met.*, **155**, 281 (1989).
4. E. Burzo, H. R. Kirchmayr and A. Chelkowski, *Landolt Börnstein Handbook*, Spinger Verlag, Vol. **19d2**, 1990.
5. R. Ballou, E. Burzo and V. Pop, *J. Magn. Magn. Mater.*, **140-144**, 945 (1995).
6. E. Burzo, E. Gratz and V. Pop, *J. Magn. Magn. Mater.*, **119**, 59 (1992).
7. T. Moriya, *J. Magn. Magn. Mater.*, **14**, 1 (1979); **100**, 261 (1991).
8. E. Burzo, *Solid State Commun.*, **14**, 1295 (1974);
E. Burzo, *Rom. J. Phys.*, **57**, 82 (2012).
9. E. P. Wohlfarth and P. Rhodes, *Phil. Mag.*, **7**, 1817 (1962).
10. D. Bloch, D. M. Edward, M. Shimizu and J. Voiron, *J. Phys. F.: Metal Phys.*, **5**, 1217 (1975).
11. E. Burzo, *Rev. Roum. Phys.* **23**, 689 (1978); *J. Less Common. Met.*, **77**, 251 (1981).
12. E. Burzo, D. P. Lazar and M. Ciorascu, *Phys. Stat. Solidi (b)*, **65**, K145 (1974).
13. N. P. Thuy, N. M. Hong, N.H. Nghi and D. C. Thanh, *Phys. Stat. Sol. (a)*, **127**, 201 (1991).

14. J. Campbell, J. Phys. F.: Metal. Phys., **2**, L47 (1972).
15. E. Burzo, L.Chioncel, R. Tetean and O. Isnard, J. Phys.: Condens. Matter, **23**, 026001 (2011) and references.
16. U. von Barth, and L. Hedin, J.Phys. C.: Solid State, **5**, 1629 (1972).
17. E.Burzo, S. G. Chiuzaian, M. Neumann, M. Valeanu, L. Chioncel and I. Creanga, J. Appl. Phys., **92**, 7362 (2002).
18. R. Ballou, E. Burzo, V. Pop and A. Pentek, J. Appl. Phys., **73**, 5695 (1993).
19. E. Burzo, V. Pop, C. Borodi and R. Balou, IEEE Trans Magn., **30**, 628 (1994).
20. E. Burzo, J. Magn. Magn. Mater., **140-144**, 2018 (1995).
21. H. Ido, M. Nanjo and M. Yamada, J. Appl. Phys., **75**, 7140 (1994).
22. A Kowalczyk and A. Stefanski, IEEE Trans. Magn., **30**, 648 (1994).
23. A. Kowalczyk, Acta Phys. Polonica, **85**, 623 (1994).
24. A. Kowalczyk, J. Magn. Magn. Mater., **175**, 279 (1997).
25. Y. Suzuki, T. Ito, T. Uchida, O.Nashima, N.M.Hong and H. Ido, J. Appl. Phys., **81**, 5141 (1997).
26. F. Maruyama, N.Nagai, Y. Amato, H. Yoshie, K. Adachi, Japan J. Appl. Phys., **37**, 1825 (1998).
27. C. Zlotea, C. Chacon and O. Isnard, J. Appl. Phys., **92**, 7382 (2002).
28. M. Maruyama, J. Alloys. Comp., **320**, 7 (2001).
29. L. F. Bates, Modern Magnetism, Cambridge University Press, Cambridge 1951, p. 133.
30. O. K. Andersen, Phys. Rev., **B12**, 3060 (1975);
O. K. Andersen and O. Jepsen, Phys. Rev. Lett., **53**, 2571 (1984).
31. S.H. Vosko, L. Wilk and M. Nussair, Can. J. Phys., **58**, 1200 (1980).
32. P. Rhodes and E. P. Wohlfarth, Proc. Roy. Soc., **A273**, 247 (1968).
33. E. P. Wohlfarth, J. Magn. Magn. Mater., **7**, 113 (1978).
34. E. Burzo, P. Vlaic and I. Creanga, J. Alloys Comp., **509**, 8289 (2011);
E. Burzo, Rom. Repts. Phys., **64**, 1195 (2012).
35. A. Lienard and J. P. Rebouillat, J. Appl. Phys., **49**, 1680 (1978).
36. A. Szayek, J. Magn. Magn. Mater., **185**, 322 (1998).
37. P. Vlaic and E. Burzo, Mold. J. Phys. Sci., **1**, 40 (2002).
38. I. Turek, Ch. Becker and H. Hafner, J. Phys.: Cond. Matter, **4**, 7257 (1992).
39. E. Burzo, L. Chioncel, I. Costina and S. G. Chiuzaian, J. Phys.: Condens. Matter, **18**, 4861 (2006).
40. J. Azoulay and L. Ley, Solid State Commun., **31**, 131 (1979).
41. M. Brouha and K. H. J. Buschow, J. Appl. Phys., **64**, 1813 (1978).
42. M. Brouha and K.H. J. Buschow, J. Phys. F.: Metal. Phys., **5**, 543 (1975).
43. S. Jaakkola, S. Parviainen and S. Penttila, J. Phys. F.: Metal. Phys., **13**, 491 (1983).
44. J. P. Liu, K. Bakker, F. R. De Boer, T. H. Jacobs, B. D. de Mooij and K. H. J. Buschow, J. Less Common Met., **170**, 190 (1991).
45. M. Valeanu, N. Plugaru and E. Burzo, Phys. Stat Solidi (b), **184**, K77 (1994).
46. Z. Arnold, J. Kamarad, Y. Skorokhood, N.M. Hong, N.O.Thuy and C. V. Thang, J. Magn. Magn. Mater., **262**, 382 (2008).
47. E. Burzo and C. Djega-Mariadassou, *Nanoscale Devices-Fundamentals and Applications*, Springer Verlag, 2006, p. 371.
48. N. Plugaru, M. Valeanu and E. Burzo, IEEE Trans. Magn., **30**, 663 (1994).
49. E. Burzo, P. Vlaic, D. P. Kozlenko, S. E. Kichanov, N. T. Dang, E. V. Lukin, B. N. Savenko, J. Alloys. Comp., **551**, 702 (2013).
50. M. B. Stearns, Phys. Rev. **B8**, 4383 (1978); Physica, **91B**, 37 (1988).