Magnetic structures of quaternary intermetallic borocarbides \( \text{RCo}_2\text{B}_2\text{C} \) (\( R = \text{Dy}, \text{Ho}, \text{Er} \))

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Abstract
The magnetic structures of the title compounds have been studied by neutron diffraction. In contrast to the isomorphous \( \text{RNi}_2\text{B}_2\text{C} \) compounds, wherein a variety of exotic incommensurate modulated structures has been observed, the magnetic structure of \( \text{ErCo}_2\text{B}_2\text{C} \) is found to be a collinear antiferromagnet with \( \mathbf{k} = (1/2, 0, 1/2) \) while those of \( \text{HoCo}_2\text{B}_2\text{C} \) and \( \text{DyCo}_2\text{B}_2\text{C} \) are observed to be simple ferromagnets. For all studied compounds, the moments are found to be confined within the basal plane and their magnitudes are comparable to the values obtained from the low-temperature isothermal magnetization measurements. The absence of modulated magnetic structures in the \( \text{RCo}_2\text{B}_2\text{C} \) series (for \( \text{ErCo}_2\text{B}_2\text{C} \), verified down to 50 mK) is attributed to the quenching of the Fermi surface nesting features.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

One of the most striking features of the magnetism of the \( \text{RNi}_2\text{B}_2\text{C} \) series is the manifestation of a variety of incommensurate modulated antiferromagnetic-like structures, some of which coexist with a superconducting ground state [1–3]. There are three different types of modulations: \( \tilde{k}_1 \approx (0.55, 0, 0) \) as in \( R = \text{Gd, Tb, Ho} (T_N < T < 6.5 \text{ K}, \text{Er}) \); \( \tilde{k}_2 \approx (0.093, 0.093, 0) \) as in \( R = \text{Tm} \); and \( \tilde{k}_3 \approx (0, 0, 0.91) \) as in \( R = \text{Ho} (T_N < T < 8 \text{ K}) \). In addition, there are two commensurate antiferromagnetic (AFM) structures having \( \tilde{k}_4 = (0, 0, 1) \) as in \( R = \text{Pr, Dy, Ho} (T \leq T_N) \), and \( \tilde{k}_5 = (0.5, 0, 0.5) \) as in \( R = \text{Nd} \). For the case of \( R = \text{Ho} \), the \( \tilde{k}_1 \), \( \tilde{k}_3 \), and \( \tilde{k}_4 \) modes coexist within a narrow range of temperature [2].

The manifestation of such a variety of wavevectors is not uncommon in intermetallic magnets wherein the magnetic couplings are mediated by the indirect Ruderman–Kittel–Kasuya–Yosida (RKKY) interactions [4]: indeed, for the particular case of \( \text{RNi}_2\text{B}_2\text{C} \), the presence of these RKKY interactions is evidenced as a de Gennes scaling of both the superconducting and magnetic transition temperatures [1, 3].

As is generally the case, the type of the magnetic structure for the rare-earth moments in \( \text{RNi}_2\text{B}_2\text{C} \) is determined by the competition between these RKKY interactions, the crystalline electric field (CEF) forces, and the classic dipolar interactions [5–7]. The RKKY interactions (and thus the magnetic structure) of these borocarbides depend partially on the spatial separation of their \( R^{3+} \) ions as well as on their electronic band structures. The importance of the latter is highlighted by the observation that the \( \tilde{k}_1 \) mode is related to the electronic nesting features that give rise to a peak in the generalized susceptibility [8].

It is worth mentioning that the manifestation of a variety of wavevectors in the \( \text{RT}_2\text{B}_2\text{C} \) family is not forbidden by group theory arguments [9–11]. In fact, for these tetragonal borocarbides (I\( 4/mmm \)), where the magnetic moments reside...
at the Wyckoff site 2a, Wills et al [9] showed that there are 15 possible wavevectors; each (or a superposition) of them can be used to describe a distinct magnetic structure (see table 3 of [9]). As mentioned above, the stabilization of a specific structure depends critically on the energy balance among the CEF, dipolar, and exchange interactions. It is interesting to note that one of the possible magnetic states that are predicted by this representational analysis is ferromagnetic (FM): such an FM state has not been observed in RNi$_2$B$_2$C, but, as shown in a previous report [12] as well as in this work, an FM structure is manifested in a number of RCo$_2$B$_2$C compounds.

Based on electronic band structures of the RT$_2$B$_2$C (R = Lu, Y; T = Ni, Co) compounds [13, 14], their Sommerfeld specific-heat coefficients are almost equal. Furthermore, for the magnetic isomorphs, each Co- and Ni-based pair has almost equal lattice parameters and similar R$_3$+ single-ion crystalline electric field properties [15]. Then it is expected that the multi-$\mathbf{k}$-vector character should also be manifested in the isomorphous RCo$_2$B$_2$C series. Contrary to this expectation, the reported magnetic structures of RCo$_2$B$_2$C (R = Tb [12], Tm [16]) are found to be ferromagnetic, in distinct contrast to the modulated spin configuration of the Ni-based isomorphs. As this work shows, the magnetic structures of RCo$_2$B$_2$C (R = Dy, Ho, Er) are also different from their Ni-based isomorphs: while the structures of R = Dy, Ho are ferromagnetic, that of R = Er is commensurate antiferromagnetic.

The difference in the magnetic structure of these isomorphous RT$_2$B$_2$C (T = Ni, Co) series is attributed to the following: electronic band structure calculations [13, 14, 17–19] demonstrated that the density of states at the Fermi level, $N(E_F)$, of both series receives appreciable contribution from the 3d orbitals of the transition-metal atoms. Since the electronic properties of the RT$_2$B$_2$C family can be reasonably well described in terms of the rigid band model, the substitution of Co atoms (which have a lower number of 3d electrons) induces a downward shift in $E_F$ but with a new $N(E_F)$, which is almost equal to that of RNi$_2$B$_2$C (compare figures 1 and 4 of [13]). Such a shift entails a difference in the generalized susceptibilities and thus a difference in the character of the magnetic ground state.

2. Experiment

99.5% $^{11}$B enriched polycrystals of RCo$_2$B$_2$C were prepared by the conventional arc-melt method. Powder neutron diffraction measurements on as-prepared samples were carried out at the Institut Laue–Langevin (ILL), France (D1A $\lambda = 1.91$ Å, 1.3 K $\leq T \leq 30$ K) and the National Institute of Standards and Technology (NIST), USA (BT-9 triple-axis instrument with a pyrolytic graphite monochromator and filter, $\lambda = 2.359$ Å, 0.05 K $\leq T \leq 8.0$ K, and BT-1 high resolution powder diffractometer with $\lambda = 2.0787$ Å). Due to experimental difficulties, the neutron diffractograms within the mK range were measured only for ErCo$_2$B$_2$C (section 3.1). Similarly, detailed temperature dependent diffractograms were collected only for HoCo$_2$B$_2$C (section 3.2), though we were not able to study its diffractograms below 1.5 K.

Taking into account the well known properties of the crystal structures of borocarbides [2, 20] together with the successful indexation of the magnetic structures of the title compounds, the Rietveld powder analysis, using the FULLPROF package for ILL data and GSAS for the NIST data, was employed to refine the parameters of both crystallographic and magnetic structures. As we mentioned in an earlier report [12], the Co atoms are not polarized (if there were any moment it would be less than 0.25 $\mu_B$): accordingly, magnetic moments are admitted only on the R$^{3+}$ sites. The results of refining the main parameters (such as lattice unit cell, magnetic unit cell, thermal and occupation parameters) were satisfactory, yielding low $\chi^2$ (in the range of 2), $R_F$ (4–8), and $R_{wp}$ (4–9). The obtained values of the refined occupation and thermal parameters as well as the $\epsilon$-parameter of the B atoms were found to be the same (within the experimental errors) as the ones reported for the corresponding RNi$_2$B$_2$C isomorphs (see table 1 of Lynn et al [2]). In some of the refinements, no absorption corrections were taken into account; as a consequence, the obtained magnetic moments were found to be lower than the values deduced from the isothermal magnetization measurements (this is more evident in the case of DyCo$_2$B$_2$C).

Magnetization $M(T, H)$ measurements (sections 3.2 and 3.3) were carried out on a vibrating-sample magnetometer, which was operated within the range (0.5 K $\leq T \leq 30$ K, $H < 17$ T). During the analysis of the magnetization isotherms, we drew a distinction between the so-called spontaneous moment, $\mu_{(H=0)}$, and the saturation moment, $\mu_{(H\rightarrow\infty)}$. In contrast to most other compounds, wherein the difference between these limit moments is not appreciable enough to warrant such a distinction, the magnetization isotherms of some of the RCo$_2$B$_2$C compounds (particularly R = Dy, Er, Tm) do not show magnetic saturation even in magnetic fields of 15 T: this feature—analyzed as a high-field magnetic susceptibility, most evident in the single-crystal magnetization of TbCo$_2$B$_2$C [12]—is most probably due to a weak electronic polarization or a field-induced perturbation of the CEF interactions. Finally, it is expected that, for each compound measured at a specific temperature, the value of its magnetic moment determined from the powder zero-field magnetic diffractogram is comparable to its spontaneous magnetic moment determined from the magnetization isotherm.

3. Results

3.1. ErCo$_2$B$_2$C

Based on earlier zero-field ac susceptibility and specific-heat results [15], the magnetic order of ErCo$_2$B$_2$C sets in at $T_N = 4.0(1)$ K. Indeed, below $T_N$ the diffractograms of ErCo$_2$B$_2$C (figure 1) show additional intense magnetic-origin Bragg peaks, which can be indexed on the basis of the magnetic structure shown in figure 2: a commensurate, collinear, antiferromagnetic structure with the moments being coupled antiferromagnetically along both $a$ and $c$ axes and ferromagnetically along the $b$ axis, i.e. $k = (0 0 1/2)$. It is worth mentioning that this AFM character is also manifested in the magnetization isotherm of figure 3.
Figure 1. Representative neutron diffractograms of ErCo$_2$B$_2$C measured at 2 K (low panel) and 30 K (top panel). Symbols, solid line, and short vertical bars represent, respectively, measured intensities, calculated intensities based on Rietveld refinement, and positions of the Bragg reflections. The differences between the measured and calculated intensities are shown as difference curves. For the reliability factors of the refinements see section 2. The vertical arrows indicate the positions of the strongest contaminating peaks.

Evidently the above-mentioned AFM structure requires that the $a$- and $b$-parameters be distinct even though the crystal structure of the paramagnetic phase is tetragonal. In fact, a similar distinction in the basal plane parameters was already reported for the case of the ErNi$_2$B$_2$C [21–23] and NdNi$_2$B$_2$C [2] isomorphs: NdNi$_2$B$_2$C, in particular, orders antiferromagnetically with the same $\vec{k} = (\frac{1}{2} \frac{1}{2} 0)$. In these compounds, such a distinction is attributed to an orthorhombic distortion of the tetragonal cell, which is driven by magnetoelastic forces. In the present measurements this distortion is too small to be detected, as was the case for the initial neutron powder work on RNi$_2$B$_2$C systems [2].

Based on the refinement of the powder diffractograms (figure 1), the Er$^{3+}$ moment is found to be confined within the basal plane and reaches 6.8(2) $\mu_B$ at 2.0 K. This value is higher than the spontaneous moment ($\mu_{(H \rightarrow 0)} = 5.9 \pm 0.2 \mu_B$) but is in agreement with the saturation moment ($\mu_{(H \rightarrow 0)} = 7.1 \pm 0.1 \mu_B$), both obtained from the isothermal magnetization measured at 1.30(5) K (figure 3). Moreover, it compares favorably with the value reported for ErNi$_2$B$_2$C (7.2 $\pm$ 0.1 $\mu_B$) [2], suggesting a similarity in their single-ion properties; however, there are important differences: the Co-based isomorph does not superconduct and does not manifest an incommensurate magnetic structure; rather, it orders into a collinear AFM structure at a critical temperature which is 40% lower than that of the Ni-based isomorph.

It was reported earlier that both the specific heat and ac susceptibility curves of an ErCo$_2$B$_2$C sample exhibit a magnetic anomaly at $T_M = 0.37(2)$ K [15]. For the purpose of investigating the origin of this magnetic $T_M$ event, we collected neutron diffractograms at various temperatures: 50 mK (well below $T_M$), 700 mK (just above $T_M$ but well below $T_N$), and 8 K (above $T_N$). As can be seen in figure 4, there are no additional magnetic peaks (or any other features) that can be associated with this anomaly. In fact, the inset of figure 4 indicates that the magnetic patterns at 700 and 50 mK are identical. As there is no change in the diffractograms when the temperature is cooled through the reported $T_M$, it is concluded that the reported anomalous transition at $T_M$ may correspond to an ordered moment that is too small to be detected in powder diffraction, or it does not correspond to a new long-range ordered state. We also cannot rule out that it is a sample dependent effect, which would imply that it is not fundamental to the Er-sublattice magnetic order.

3.2. HoCo$_2$B$_2$C

The diffractograms of HoCo$_2$B$_2$C (figure 5) show that there are no additional satellite peaks when the sample is cooled below...
of [12]) and TmCo$_2$B$_2$C (see figure 6 of [16]).

Magnetization features were observed in TbCo$_2$B$_2$C (see figure 2)

Er, no saturation is attained even for a field of 15 T. Similar high-field

Rietveld analysis (see figure 6) confirms the conclusions drawn

cell which is of the same dimensions as the crystalline one. The

magnetic pattern is easily indexed on the basis of an FM unit

the intensities of the fundamental Bragg peaks. The resulting

lying within the basal plane. The thermal evolution of the

from the magnetic indexing: an FM structure with the moments

T$_C$ = 5.4(2) K; instead, there is a considerable enhancement in

the intensities of the fundamental Bragg peaks. The resulting magnetic pattern is easily indexed on the basis of an FM unit cell which is of the same dimensions as the crystalline one. The Rietveld analysis (see figure 6) confirms the conclusions drawn from the magnetic indexing: an FM structure with the moments lying within the basal plane. The thermal evolution of the Ho$^{3+}$ moments (figure 7) shows a tendency towards saturation to a moment of 7.2(2) $\mu_B$. This is in excellent agreement with the spontaneous moment ($\mu_{H\rightarrow0}$ = 7.3 ± 0.1 $\mu_B$) but slightly lower than the saturation moment ($\mu_{(\uparrow\rightarrow\downarrow)\rightarrow0}$ = 7.4±0.1) $\mu_B$, both obtained from the isothermal magnetization measured at 1.30(5) K (see figure 3). Furthermore, figure 7 indicates that the intensity monotonically decreases as T$_C$ is being approached from below, and that it decreases almost linearly above T$_C$ such that it becomes zero at 6.7 K. The presence of magnetic intensity well above T$_C$ (attributed to short-range order) has already been observed in the specific heat and susceptibility of HoCo$_2$B$_2$C [15]. Similar short-range features were observed in the neutron diffraction studies on the HoNi$_2$B$_2$C isomorph [2].

In stark contrast with the exotic features of the low-field region of the forced magnetization: while $M(T, H)$ of R = Dy, Ho is typical of a forced domain movement of an FM state, that of R = Er is characteristic of a field-induced spin-flop anomaly of an AFM structure. The upper inset gives the saturated magnetization when $H \rightarrow \infty$ ($\mu_H \rightarrow 0$); for R = Dy and Er, no saturation is attained even for a field of 15 T. Similar high-field magnetization features were observed in TbCo$_2$B$_2$C (see figure 2 of [12]) and TmCo$_2$B$_2$C (see figure 6 of [16]).

In an earlier work, we reported that HoCo$_2$B$_2$C undergoes a zero-field, order-to-order magnetic transition at $T_m$ = 1.5 K [15]. Unfortunately, during the present work, we were unable to collect diffractograms below 1.5 K. Nonetheless, considering the evidence collected on ErCo$_2$B$_2$C (see section 3.1) and TbCo$_2$B$_2$C [12], we are inclined to attribute such a transition at $T_m$ to a minor contaminating magnetic phase.

3.3. DyCo$_2$B$_2$C

Figure 8 shows the thermal evolution of the diffraction pattern of DyCo$_2$B$_2$C when cooled through the magnetic transition temperature ($T_C$ = 8.0(2) K). On subtracting the paramagnetic diffractogram at 10 K from the one at 1.4 K, we obtain the magnetic diffraction pattern shown in the upper panel of figure 8. This pattern can be indexed on the basis of an FM cell having the same dimensions as those of the crystalline one. Assuming such a ferromagnetic unit cell and the orientation of the moments to be along the (110) axis, we carried out a Rietveld refinement on the diffractograms of figure 8. The refined patterns are shown in figure 9 and the obtained zero-field magnetic moment of Dy at 1.3 K is 5.2(2) $\mu_B$. Based on the analysis of powder, isothermal magnetization measurements at 1.35(5) K (see figure 3), this moment value is similar to the spontaneous moment ($\mu_{(H\rightarrow0)}$ = 5.3 ± 0.2 $\mu_B$) but lower than the saturation moment ($\mu_{(\uparrow\rightarrow\downarrow)\rightarrow0}$ = 6.2±0.1 $\mu_B$).

It is noted that all these moment values are lower that the one reported for the DyNi$_2$B$_2$C isomorph (see table 1).

**Figure 3.** Magnetization isotherms of RCo$_2$B$_2$C (R = Dy, Ho, Er) measured at the indicated temperatures. The lower inset shows an expansion of the low-field region of the forced magnetization: while $M(T, H)$ of R = Dy, Ho is typical of a forced domain movement of an FM state, that of R = Er is characteristic of a field-induced spin-flop anomaly of an AFM structure. The upper inset gives the saturated magnetization when $H \rightarrow \infty$ ($\mu_H \rightarrow 0$); for R = Dy and Er, no saturation is attained even for a field of 15 T. Similar high-field magnetization features were observed in TbCo$_2$B$_2$C (see figure 2 of [12]) and TmCo$_2$B$_2$C (see figure 6 of [16]).

**Figure 4.** Low-temperature magnetic diffractogram of ErCo$_2$B$_2$C obtained after subtracting the nuclear contributions (diffractogram at 8 K) from the one at 50 mK; the solid vertical bars index the magnetic pattern. The inset shows the difference pattern obtained after subtracting the diffractogram at 700 mK from that of 50 mK: evidently there is no change in the magnetic structure (see the text). The indicated uncertainties are statistical in nature and represent one standard deviation.
Table 1. Some structural and magnetic parameters of the isomorphous RNi$_2$B$_2$C and RCo$_2$B$_2$C series (R = Tm, Er, Ho, Dy, Tb). The room-temperature cell dimensions of RNi$_2$B$_2$C (RCo$_2$B$_2$C) are determined from neutron [24] (x-ray [15, 16]) diffraction. The magnetic properties of RNi$_2$B$_2$C are taken from [24, 25] while those of TbCo$_2$B$_2$C and TmCo$_2$B$_2$C are taken, respectively, from [12] and [16]. The symbols have their usual meanings. $|\vec{\mu}|$ refers to the value obtained from the neutron diffraction analysis.

| R    | M   | a (Å) | c (Å) | $T_{\text{crit}}$ (K) | Mode | $\vec{k}$ | Easy axis |
|------|-----|-------|-------|------------------------|------|----------|-----------|
|      | Co  |       |       |                        |      |          | (0, 0, 1) |
| Tm   | Ni  | 3.473 | 10.647| 0.8                    | FM   | (0, 0, 0) | (0, 0, 1) |
| Er   | Co  | 3.4844| 10.607| 1.53                   | TSW  | (0.093, 0.093, 0) | (0, 1, 0) |
| Ho   | Ni  | 3.5019| 10.5902| 4.0                    | AF   | (0.553, 0, 0) | (1, 1, 0) |
| Dy   | Co  | 3.5177| 10.5580| 6.8                    | AF   | (0, 0, 0) | (1, 0, 0) |
| Tb   | Ni  | 3.5536| 10.4352| 8.0                    | FM   | (0, 0, 0) | (1, 0, 0) |

Figure 5. Lower panel: three-dimensional plot of representative powder diffractograms of HoCo$_2$B$_2$C. The intensities are measured over a wide range of scattering angle (here, for clarity, they are shown only up to 55°) and at various temperatures. The enhancement of the intensities at the positions of the nuclear Bragg peaks is clearly manifested below $T_C$. The fact that there are no additional magnetic peaks and that the Ho site is at the 4a site indicates that the magnetic arrangement must be due to an onset of ferromagnetism (see text). This is confirmed in the upper panel, which shows the difference plot of $I(1.5\,K) - I(10\,K)$ together with the Bragg peak identifications.

Figure 6. Rietveld refinement of representative powder diffractograms of HoCo$_2$B$_2$C. Symbols, solid line, and short vertical bars represent, respectively, observed intensities, model calculation, and positions of the Bragg reflections. The difference plots are shown in the lower part of each panel. For the reliability factors of the refinements see section 2. The vertical arrows indicate the positions of the strongest contaminating peaks.

4. Discussion and conclusion

As mentioned above, the crystalline electric field environment around the $R^{3+}$ site in the RCo$_2$B$_2$C series is expected to be the same as the one observed in the isomorphous RNi$_2$B$_2$C series. Consequently, the single-ion properties of $R^{3+}$ should be similar: specifically, the ordered moment direction in the sequence of pairs DyT$_2$B$_2$C, HoT$_2$B$_2$C, and ErT$_2$B$_2$C ($T =$ Co, Ni) should be similar (see table 1). This working assumption is particularly helpful since the zero-field powder neutron diffraction technique is only able to identify the deviation of the moment with respect to the unique (tetragonal) axis. In the present case, it can identify that the moments are within the $ab$-plane, but not the easy axis within the plane. Then, based on this similarity of the CEF properties, the easy axis of both R = Dy, Ho is taken to be (1, 1, 0) while that of R = Er is taken to be along the (0, 1, 0) direction. It is reassuring that these arguments have been experimentally verified for the case of the TbCo$_2$B$_2$C single crystal [12].

A comparison of the magnetic phase diagrams of the RCo$_2$B$_2$C and RNi$_2$B$_2$C series shows that there are four distinct differences among these isomorphs.
Figure 7. Thermal evolution of the ordered magnetic moment for HoCo$_2$B$_2$C as obtained from the neutron diffraction refinements of figure 6. $T_c$ is indicated by the vertical arrow.

Figure 8. Lower panel: representative diffractograms of DyCo$_2$B$_2$C measured at 1.4, 4, 7, and 10 K. The upper panel shows the difference plot (after subtracting the pattern at 10 K from the one at 1.4 K): the pattern is indexed based on a ferromagnetic structure.

First, the magnetic transition temperatures of RCo$_2$B$_2$C are lower and do not follow a de Gennes scaling. In an earlier report [15], we illustrated the decisive influence of the CEF effect on the variation of the transition points, $T_{\text{crit}}$, by quoting the work of Noakes and Shenoy [26], which showed that $T_{\text{crit}}$ can be enhanced much more than predicted by the de Gennes analysis if the second-order crystal-field parameter $B_{0}^2$ is large and positive:

$$T_{\text{crit}} \propto \xi \left( \sum_{J_z} J_z^2 \exp\left( -3 B_{0}^2 J_z^2 / T_{\text{crit}} \right) \right)^{-1} \left( J (J+1) \sum_{J_z} \exp\left( -3 B_{0}^2 J_z^2 / T_{\text{crit}} \right) \right).$$

This relation shows that the de Gennes scaling is not expected to be obeyed since $B_{0}^2$ is not a smooth function of $\xi$ and that, moreover, $T_{\text{crit}}$ of the individual RT$_2$B$_2$C isomorphs would be different if the $B_{0}^2$ were not the same: this case is evident in, say, TbCo$_2$B$_2$C ($T_c = 6.3$ K, $B_{0}^2 = 0.8$ K) and TbNi$_2$B$_2$C ($T_N = 15$ K, $B_{0}^2 = 1.2$ K).

Second, the values of the ordered magnetic moments of RCo$_2$B$_2$C are smaller than those of RNi$_2$B$_2$C isomorphs and both are lower than the corresponding free ion value. This reduction is also attributed to crystalline electric field effects: the variation of $B_{0}^2$ between the TbCo$_2$B$_2$C and TbNi$_2$B$_2$C isomorphs supports this viewpoint.

Third, the observation that the studied RCo$_2$B$_2$C compounds do not exhibit any type of incommensurate...
modulated states is an indication that those nesting features that are responsible for the modulated mode in the RNi$_2$B$_2$C isomorphs [8] must have been quenched in the Co-based compounds. Indeed, the details of the electronic structure of YCo$_2$B$_2$C and YNi$_2$B$_2$C are quite different [13, 14].

Fourth, there is no evidence of any metamagnetic field-induced transitions (except for the spin-flip transition of R = Er) in the magnetization isotherms shown in figure 3 for R = Dy, Ho, Er (for TbCo$_2$B$_2$C see figure 2 of [12], while for TmCo$_2$B$_2$C see figure 6 of [16]). No field-induced metamagnetic transitions are expected in commensurate FM structures.

The four above-mentioned observations highlight the delicate balance between the exchange, crystalline, and dipolar interactions in establishing the exotic magnetic phase diagrams of these borocarbides. It is worth mentioning that the incommensurate modulation (third property) and the field-induced metamagnetic transitions are expected in commensurate FM structures.

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