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Magnetic structures of rare earth intermetallics

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Résumé. — Les expériences de diffraction neutronique ont été de première importance pour mettre en évidence la grande variété de propriétés magnétiques des composés intermétalliques de terre rare.

Abstract. — Neutron diffraction experiments, have been of first importance to evidence the large variety of magnetic behaviours of rare earth intermetallics.

Introduction. — The aim of this paper is to give a general view of the magnetic structure work done so far concerning rare earth intermetallic compounds $R_x M_y$, where the rare earth element is combined with a well defined stoichiometry to another metal or to a pnictide or chalcogenide element.

We shall first establish what kind of information we can obtain from a neutron diffraction experiment and give a few comments on how to characterize a magnetic structure and what are the components of the order parameter. After a brief survey of simple magnetic ordering observed in various series we shall analyse the reasons why rare earth intermetallics give rise to such a large variety of magnetic structures as non-collinear structures, incommensurate ordering.

1. Neutron scattering and magnetic structure. — We must keep in mind that a neutron experiment allows to determine only the value and the direction of the *Fourier components* $\mathbf{m}_k^i$ and not the moment distribution $\mathbf{m}_n^i$ which indeed must be deduced from the following relation :

$$\mathbf{m}_n^i = \sum_k \mathbf{m}_k^i e^{-2\pi i \mathbf{k} \cdot \mathbf{R}_n} \quad (1)$$

where $\mathbf{R}_n$ is a lattice translation and $i = 1, \dots, n_b$ label the Bravais lattices. In practice, a determination of a magnetic structure needs first the identification of the wave vector of each Fourier component by interpreting the Bragg angle of the magnetic peaks and in a second step the magnetic coupling of the Bravais lattices is obtained from Bragg peak intensities. It is an easy task when there is only one Bravais lattice, but it becomes more tedious with several ones, so considerations on phase transitions and group theory must be taken into account.

According to Landau a transition is characterized by a breaking of the symmetry and the order parameter associated with a second order phase transition transforms as an irreducible representation of the symmetry group G_0 of the paramagnetic phase. For a

space group G_0 , each irreducible representation is classified according to a wave vector $\mathbf{k}$ of the Brillouin zone of the Bravais lattice and to an index ν . This index labels the irreducible representation Γ_k^ν of the group G_k which leaves invariant the wave vector $\mathbf{k}$. Indeed the representation $\Gamma_{\{\mathbf{k}\}}^\nu$ must be considered which is the direct sum of the representations Γ_k^ν over the q -members of the star of $\mathbf{k}$. Then the order parameter has $d_\nu \cdot q$ components, where d_ν is the dimension of Γ_k^ν and each components is a linear combination of $\mathbf{m}_k^i$; for one Bravais lattice it reduces to $\mathbf{m}_k$. Therefore at the ordering temperature T_0 only one $\Gamma_{\{\mathbf{k}\}}^\nu$ becomes critical, the magnetic structure will be characterized by the parameters $(\mathbf{k}, \nu)$ and will be defined by the d_ν components of the order parameter $\Psi(\mathbf{k}, \nu)$. If this is not the case there exist fourth order terms which induce a first order transition. So the magnetic coupling of the Fourier components $\mathbf{m}_k^i$ is obtained, according to Landau theory, in such a way that all components $\Psi_i(\mathbf{k}, \nu')$ are equal to zero except those transforming as the critical representation Γ_k^ν . The only problem which remains is the determination of the components $\Psi_i(\mathbf{k}, \nu)$. This can be solved by using a method developed by Bertaut [1] based on group theory. It consists to induce a representation Γ of G_k by the $3 n_b$ Fourier components $m_{k,\alpha}^i$, to reduce it on the irreducible representations Γ_k^ν and to determine the basis vectors of these representations using the projection operator method.

2. Collinear magnetic structures. — Simple collinear magnetic structures are characterized by a wave vector $\mathbf{k}$ which corresponds to a *symmetry point* of the Brillouin zone, i.e. $\mathbf{k} = \mathbf{H}/2$ where $\mathbf{H}$ is a reciprocal lattice vector, and a magnetic site of high symmetry. However the long range nature of the RKKY interactions can lead to more complex ordering as we shall see in section 4. In figure 1 are reported the Brillouin zones of lattices which occur the most frequently in rare earth intermetallics.

Fig. 1. — Brillouin zones.

2.1 CUBIC LATTICES. — In a face centred cubic lattice there are three symmetry points corresponding to wave vectors $\mathbf{k} = [001]$ (type I), $\mathbf{k} = \left[\frac{1}{2}\frac{1}{2}\frac{1}{2}\right]$ (type II) and $\mathbf{k} = \left[\frac{1}{2}10\right]$ (type III). Two large series crystallise with a f.c.c. lattice : the Laves-phase compounds RM_2 ($M = \text{Al, Fe, Co, Ni, Os, Ir, Pt, Ru, Rh}$) and the monpnictides and monochalcogenides RX ($X = \text{N, P, As, Sb, Bi, S, Se, Te}$). The compounds of the first group are ferromagnets [2, 3] except CeAl_2 [4] which exhibits an incommensurate structure (see section 4). The compounds of the second group order mainly with a type II structure [5] except cerium and neodymium monpnictides which have a type I structure [6]. In both cases the two irreducible representations of the group $G_k(D_{3d}$ or D_{4h}) define two sets of order parameters. For $\mathbf{k} = \left[\frac{1}{2}\frac{1}{2}\frac{1}{2}\right]$, as an example, they are either $m_k^{\parallel}$, i.e. a moment direction along $\langle 111 \rangle$ (TbX) or $m_k^{\perp}$, i.e. a moment direction perpendicular to $\langle 111 \rangle$ (ErX). But a collinear structure with a moment direction along $\langle 100 \rangle$ (HoX, DyX) implies that a 4th order term exists in the energy.

In primitive cubic lattice the Brillouin zone has also three symmetry points :

$$\mathbf{k}_1 = [00\frac{1}{2}], \mathbf{k}_2 = \left[\frac{1}{2}\frac{1}{2}0\right] \text{ and } \mathbf{k}_3 = \left[\frac{1}{2}\frac{1}{2}\frac{1}{2}\right].$$

The last one has a cubic symmetry whilst for the first two points the symmetry is quadratic (D_{4h}). This implies that there are also two kinds of order parameters : $m_k^{\parallel}$ and $m_k^{\perp}$ (with respect to the tetragonal axis). Two large series belong to this system : the

equiatomic rare earth intermetallic compounds RM ($M = \text{Cu, Ag, Au, Zn, Al, Rh, etc.}$) with the CsCl structure and the compounds RM_3 ($M = \text{In, Pb, Sn, Pd, Tl}$) with the CaCu_3 structure [3]. In the RM group, RZn compounds are ferromagnets whereas RCu and RAg compounds [7, 8] order antiferromagnetically with $\mathbf{k} = \left[\frac{1}{2}\frac{1}{2}0\right]$ and $\mathbf{m}_k$ parallel to the tetragonal axis. However in HoCu [9] $\mathbf{m}_k$ is along $\langle 111 \rangle$. RRh [10] and RMg [11] compounds order with $\mathbf{k} = [00\frac{1}{2}]$ and $\mathbf{m}_k$ is parallel to $\mathbf{k}$, but in RMg complex magnetic structures have been observed involving two Fourier components ($\mathbf{k} = [00\frac{1}{2}]$ and $\mathbf{k} = 0$). The different values of the wave vector can be explain qualitatively by a RKKY model which leads to the sequence

$$\mathbf{k} = [00\frac{1}{2}], \quad \mathbf{k} = \left[\frac{1}{2}\frac{1}{2}0\right] \text{ and } \mathbf{k} = 0$$

when the number of conduction electrons increases. However some exceptions exist : Ce, Pr, NdZn are antiferromagnets ($\mathbf{k} = [00\frac{1}{2}]$) [12], Gd, Tb, DyRh are ferromagnets [13] and RMg compounds have a peculiar behaviour.

2.2 HEXAGONAL LATTICE. — In the hexagonal symmetry there exist five symmetry points defining three kinds of magnetic structures : hexagonal ($\mathbf{k} = 0$, $\mathbf{k} = [00\frac{1}{2}]$) orthohexagonal ($\mathbf{k} = \left[\frac{1}{3}00\right]$, $\mathbf{k} = \left[\frac{1}{3}0\frac{1}{2}\right]$) or triangular ($\mathbf{k} = \left[\frac{1}{3}\frac{1}{3}0\right]$, $\mathbf{k} = \left[\frac{1}{3}\frac{1}{3}\frac{1}{2}\right]$). The last two types have been observed within the rare earth intermetallic serie RGa_2 [14] and RAlGa [15] DyGa_2 , HoGa_2 and ErGa_2 order with an orthohexagonal cell whereas TbGa_2 and TbAlGa , HoAlGa have a triangular structure which is incommensurate along the c -axis for TbGa_2 . A large number of rare earth intermetallic compounds with cobalt and iron have an hexagonal structure, but they order usually in a ferro or ferrimagnetic structure [2, 3].

2.3 BODY CENTRED TETRAGONAL LATTICE. — This lattice has four symmetry points

$$\mathbf{k}_1 = [001] \text{ or } [100], \quad \mathbf{k}_2 = \left[\frac{1}{2}\frac{1}{2}0\right], \quad \mathbf{k}_3 = \left[\frac{1}{2}\frac{1}{2}\frac{1}{2}\right] \text{ and}$$

$$\mathbf{k}_4 = \left[\frac{1}{2}0\frac{1}{2}\right].$$

The rare earth intermetallics series RM_2 ($M = \text{C, Ag, Au}$) [16] with the CaC_2 -type structure and RCu_4Al_8 [17] with the ThMn_{12} -type structure are good examples. The compounds of the first group order at low temperature with a wave vector $\mathbf{k} = \left[\frac{1}{2}\frac{1}{2}0\right]$, but with increasing temperature a first order transition occurs towards a transverse sine wave modulation with $\mathbf{k} = [0.42, 0.42, 0]$. The compounds RCu_4Al_8 exhibit an antiferromagnetic order with $\mathbf{k} = [100]$ except TbCu_4Al_8 which has an incommensurate structure along the c -axis with $\mathbf{k} = [1, 0, 0.16]$.

2.4 FACE CENTRED ORTHORHOMBIC LATTICE. — A large number of equiatomic compounds crystallise

with an orthorhombic structure (RGa, RSi, RGe, RNi and with light elements RCu, RRh) which can be of CrB-type (Cmcm) or of FeB-type (Pnma). However, collinear magnetic structures occur only in the CrB-type structure because rare earth ions are located in a site of C_{2v} symmetry which has two Bravais lattices related by the inversion symmetry element. In RSi compounds [18], TmSi and DySi order with a wave vector $\mathbf{k} = [00\frac{1}{2}]$ whereas TbSi, HoSi and ErSi exhibit a structure with $\mathbf{k} = [\frac{1}{2}0\frac{1}{2}]$; thus there is no continuity across the serie which is quite difficult to understand in the frame of RKKY interactions.

3. Non-collinear magnetic structures. — In rare earth compounds the crystal field anisotropy takes a fundamental part in determining the moment direction, therefore the symmetry of rare earth sites will be an important parameter in the understanding of magnetic structures of rare earth intermetallics.

We may have a non-collinear magnetic structure if the unit cell contains several rare earth sites. This situation occurs in rare earth nickel intermetallics, for example RNi₃ compounds (R = Nd, Tb, Dy, Er) [19] are non collinear ferromagnets because the two rare earth sites have orthogonal easy axes. However in RCo₃ [9] the rare earth-cobalt interactions are large enough to align all the magnetism moments along the easy axis of the rare earth site which has the largest anisotropy.

Even if the unit cell contains only one rare earth site a non collinear structure is possible when the site symmetry is low enough. A good example is given by rare earth intermetallics which have the FeB-type structure as RNi [20], RNi_{1-x}Cu_x [21] and PrSi [22] compounds. In this structure there are four Bravais lattices and the site symmetry is a mirror parallel to the (010) plane (figure 2a). Thus the magnetic moment must lie perpendicular or within the mirror plane

because they have an Ising like behaviour. The moment direction within the plane is determined by the ratio of second order crystal field parameters such as $\tan 2\theta = V_2^{-2}/V_2^2$ [23] and will lie along the X or Y-direction (figure 2b) according to the nature of the rare earth ion. Moreover as the Bravais lattice (1) and (3) are related by a two-fold axis along x this leads to non-collinear magnetic structures of DyNi-type (Tb, Dy, Ho) or ErNi-type (Er, Tm) (figures 2c and 2d).

Non-collinear structures can occur also in highly symmetric lattices because fourth or higher order terms in the Hamiltonian can induce a coupling between the components of the order parameter. In section 1 we have seen that the moment distribution is in fact determined by the relation :

$$\mathbf{m}_n = \sum_{\mathbf{k} \in \mathbf{k}^*} \mathbf{m}_{\mathbf{k}} e^{-2\pi i \mathbf{k} \cdot \mathbf{R}_n}$$

Thus the problem is how to perform the sum : over one or several members of the star of $\mathbf{k}$? This gives rise to an ambiguity about the exact nature of the magnetic order which can be removed only by applying a pertinent perturbation to the crystal (a magnetic field or an uniaxial stress) or if there exists a crystallographic distortion at the magnetic ordering which lowers the symmetry. Then to each collinear structure described in section 2 we must associate multiaxis structures. Their number will depend on the number of members in the star and on the direction of $\mathbf{m}_{\mathbf{k}}$ with respect to $\mathbf{k}$. The number may be limited by the additional condition $\mathbf{m}_n = \mathbf{m}_0^2$. For a f.c.c. lattice and $\mathbf{k} = [\frac{1}{2}\frac{1}{2}\frac{1}{2}]$ the analysis of multiaxis structures has been given in [34] and we report in figure 3a the most symmetrical structures associated to one, two, three or four $\mathbf{k}$ -vectors. For $\mathbf{k} = [001]$ it exists three kinds of multiaxis structures, those corresponding to $\mathbf{m}_{\mathbf{k}}$ parallel to $\mathbf{k}$ are given in figure 3b. For example, the 3 $\mathbf{k}$ -vector structure has a cubic symmetry and the moment direction is $\langle 111 \rangle$ whereas in the collinear structure the moment lies along $\langle 001 \rangle$. Thus additional informations concerning the crystal field is needed. Such a situation occurs in CeP and CeAs and the 3 $\mathbf{k}$ -vector structure may correspond to the actual order because $\langle 111 \rangle$ is the easy axis and no tetragonal distortion has been found [25].

For the primitive cubic lattice multiaxis structures have an indetermination not only on the moment direction but also on the size of the magnetic cell [26]. For $\mathbf{k} = [00\frac{1}{2}]$ and $\mathbf{k} = [\frac{1}{2}\frac{1}{2}0]$ there are three members in the star giving rise to one, two or three $\mathbf{k}$ -vector structures. For example for $\mathbf{k} = [00\frac{1}{2}]$ the size of the magnetic cell will be $(a, a, 2a)$, $(2a, 2a, a)$ and $(2a, 2a, 2a)$ respectively. In figure 4 are reported those corresponding to $\mathbf{m}_{\mathbf{k}}^{\parallel}$. The 3 $\mathbf{k}$ -vector structure has been effectively evidenced in DyCu [8] and HoRh [13] in agreement with neutron spectroscopy experiments [27, 28] which indicate a $\langle 111 \rangle$ easy

Fig. 2. — Non-collinear magnetic structures in FeB-type compounds RNi. (a) and (b) local symmetry of the four Bravais lattices. (c) and (d) magnetic structures.

Fig. 3. — Typical examples of the most symmetrical multiaxial structures for a face-centred cubic lattice and a wave vector $\mathbf{k} = [\frac{1}{2}\frac{1}{2}\frac{1}{2}]$ (a) or $\mathbf{k} = [001]$ (b). The ions (1), (2), (3) and (4) are located respectively at (000), $(0\frac{1}{2}\frac{1}{2})$, $(\frac{1}{2}0\frac{1}{2})$ and $(\frac{1}{2}\frac{1}{2}0)$.

axis. Thus taking into account bilinear interactions and crystal field anisotropy the magnetic structure will be collinear with $\mathbf{m}$ along $\langle 100 \rangle$ or multiaxial with $\mathbf{m}$ along $\langle 111 \rangle$. However there are exceptions like HoCu which exhibits a collinear structure along $\langle 111 \rangle$. This situation implies a coupling of two distinct irreducible representations by a fourth order term. Thus the transition must be first order and will be driven not only by exchange interactions but also by a large strain coupling and (or) quadrupolar interactions. A similar situation occurs in rare earth mononictides when the easy axis is along $\langle 100 \rangle$ like in DySb. Non collinear structures can be induced also by a fourth order term which couples Fourier components with two distinct wave vectors. The *flip-flop* structure of HoP [7] is a good example, it is described by a Fourier component $\mathbf{m}_k^\perp$ (for $\mathbf{k} = [\frac{1}{2}\frac{1}{2}\frac{1}{2}]$ $\mathbf{m}_k$ is along $[10\bar{1}]$) and a ferromagnetic component $\mathbf{m}_0$ along $[101]$. Thus the magnetic moments in successive (111) ferromagnetic planes are aligned alternatively along $[001]$ or $[100]$. This kind of ordering results in strong quadrupolar interactions. Such stacking of ferromagnetic planes with orthogonal moment directions has been evidenced also in RMg compounds [11]. For example in TbMg a ferromagnetic component exists together with an antiferromagnetic component $\mathbf{m}_k$ where $\mathbf{k} = [00\frac{1}{2}]$ giving rise to (001) ferromagnetic planes with orthogonal moment directions. However in RMg compounds it is unlikely that this behaviour has its origin in quadrupolar interactions because such a canted structure has also been observed in GdMg [11] and in $\text{TbCu}_{1-x}\text{Zn}_x$ alloys [29]. Thus non collinear magnetic structures result not only from the 4f-electrons : one-ion anisotropy, coupling to strain, quadrupolar interactions, but also from conduction electrons because of their hybridised character.

4. Incommensurate magnetic structures. — The long-range and oscillatory variation of exchange interactions leads to magnetic structures which can be incommensurate with the lattice. These structures are characterized by wave vectors which are represented by a point on a symmetry line of the Brillouin zone.

Fig. 4. — Typical examples of the most symmetrical multiaxial structures for a primitive cubic lattice and a wave vector $\mathbf{k} = [00\frac{1}{2}]$ (a) or $\mathbf{k} = [\frac{1}{2}\frac{1}{2}0]$ (b).

To define the structure, the symmetry of G_k is of first importance. If $\mathbf{m}_k$ belongs to a two-dimensional representation we can write :

$$\mathbf{m}_k = \frac{m_0}{2} (\mathbf{u} - i\mathbf{v}) e^{i\varphi_k} \quad (10)$$

(10) describes a helical order (if the representation is one-dimensional it must exist almost two independent basis vectors). This situation occurs usually in uniaxial compounds having an easy plane and $\mathbf{k}$ along the c -axis as in heavy rare earth metals [30] or in R_2F_{17} with $\text{R} = \text{Ce}, \text{Tm}, \text{Lu}$ [31].

Otherwise $\mathbf{m}_k$ is one-dimensional and can be written as :

$$\mathbf{m}_k = \frac{A_k}{2} e^{i\varphi_k} \mathbf{u} \quad (11)$$

(11) leads to a sine wave modulation of amplitude A_k propagating along the $\mathbf{k}$ -direction with a polarization along $\mathbf{u}$. This situation occurs when G_k is C_{2v} because in this group the three components $m_k^\parallel$, $m_{k,\alpha}^\perp$, $m_{k,\beta}^\perp$ transform respectively in the three one-dimensional representations Γ_3 , Γ_2 and Γ_4 ; then only a sine wave modulation is possible with either a transverse polarisation as in TbAu_2 [16] or TbZn_2 [32] or a longitudinal polarisation as in Nd [30, 30a]. However in PrGa_2 and NdGa_2 [14] a helical structure with $\mathbf{k} = [\mathbf{k}00]$ has been proposed, thus either the transition is first order or the ordering corresponds to a transverse sine wave modulation. A sine wave modulation can be induced also by a large crystal field anisotropy which quenches the moments along well defined directions as in $\text{RNi}_{1-x}\text{Cu}_x$ compounds [21].

The large entropy associated to a sine wave modulation makes it unstable at zero temperature. Therefore when decreasing the temperature a squaring up of the modulation must occur. This is demonstrated by the progressive appearance of third or higher order harmonics as in Tm, Er [30] or in $\text{ErNi}_{0.6}\text{Cu}_{0.4}$ [21]. The entropy argument fails if the ground state is a singlet which has only an induced moment. This situation can occur for non-Kramers

ions as Tb, Ho, Tm; a good example is given by the two singlet system $\text{TbNi}_{0.6}\text{Cu}_{0.4}$ [21] which exhibits a sine wave modulation at all temperatures. The same behaviour has been found in CeAl_2 [4] although the ground state of Ce^{3+} ions is a well isolated Γ_7 doublet. Below $T_N = 3.8$ K CeAl_2 exhibits an incommensurate ordering with a wave vector $\mathbf{k} = [\frac{1}{2} + \tau, \frac{1}{2} - \tau, \frac{1}{2}]$ which corresponds to the point Q on the surface of the Brillouin zone (figure 1). The only element of the space group $\text{Fd}3m$ which leaves $\mathbf{k}$ invariant is the two-fold axis parallel to τ , i.e. $[\bar{1}\bar{1}0]$. Thus the order parameter will transform according to one of the two one-dimensional irreducible representation of the group G_k ($\{E, 000\}$ and $\{C_{2b}, \frac{1}{4}\frac{1}{4}\frac{1}{4}\}$). Then it has 24 components which is the largest observed number. In fact the moments lie along the $[111]$ direction (i.e. perpendicular to τ) and the coupling of the two Bravais lattices is antiparallel in agreement with group theory. Thus the magnetic structure consists of antiferromagnetic $(1\bar{1}0)$ planes in which the magnetic moments, lying along $[111]$, are modulated according to a sine wave propagating along $[\bar{1}\bar{1}0]$ (figure 5). This transverse sine wave modulation remains stable down to 0.4 K without any change of the τ -value ($\tau = 0.110 \pm 0.002$); within the experimental accuracy, this value is equal to $1/9$ and gives a wave length of $9a/\sqrt{2} = 51$ Å. This unusual result can be understood only if the ground state without magnetic interactions is a singlet may be of Kondo-type.

Fig. 5. — Transverse sine-wave magnetic structure of CeAl_2 .

In some compounds in spite of observing a squaring up of the modulation there is a phase transition towards a commensurate phase. This incommensurate-commensurate transition is observed to be either first order as in TbAu_2 [16] or TbZn_2 [32] or second order as in TbSi [33]. The order may be related to the symmetry of the wave vector of the commensurate phase. Such a transition is expected in ErZn_{12} [17] which has also a low temperature commensurate phase ($\mathbf{k} = [\frac{1}{2}\frac{1}{2}\frac{1}{2}]$).

Finally we want to emphasize the unusual magnetic properties of cerium monopnictides [34]. Among them CeSb has the most complex behaviour. In zero field CeSb exhibits six different magnetic structures [35] and we have shown [36] that they are indeed commensurate square wave structures with a wave vector $\mathbf{k} = [00k]$ such as $k = n/2$ $n = 1$ (figure 6) and that new phases exist when a magnetic field is applied (figure 7). All the structures can be generated by a periodic stacking of zero magnetized planes P and ferromagnetic planes with a magnetization parallel $M \uparrow$ or antiparallel $M \downarrow$ to the applied field. Three types of structures can be distinguished: (a) At low temperature only $M \uparrow$ and $M \downarrow$ planes exist, the structures

$$k = 4/7(+ + - - + + -), \quad k = 2/3(+ + -),$$

and $k = 0$ are successively observed when the field is increased. (b) At high temperature and low field $M \uparrow$, $M \downarrow$ and P -planes coexist leading to an *antiparamagnetic* order, the P -planes disappear at about $T_N/2$. (c) At high temperature and high field only $M \uparrow$ and P planes exist defining a *ferroparamagnetic* order.

Fig. 6. — Square wave magnetic structures associated to a wave vector $\mathbf{k} = (00k)$ with $k = n/2$ $n = 1$ as observed in CeSb . An arrow represents the direction of moments in a (001) plane. A special choice of the phase of the square wave gives rise to non-magnetic (001) planes (b).

Fig. 7. — Magnetic phase diagram of CeSb for a magnetic field applied along a $[001]$ direction. Dashed lines correspond to a change of the domain distribution. An arrow represents the directions of moments in a (001) plane.

This unusual result which leads to a magnetic order composed of sandwiches of magnetized and non magnetized (001) planes has been confirmed by specific heat experiments with an applied field [37] and by neutron experiments performed by Fisher *et al.* [38]. Moreover it is rather surprising that a small change of cerium ions by La or Y [39] or Sb atoms by As [40] suppress these unusual magnetic structures containing non-magnetized planes. While CeBi presents a complex magnetic behaviour it has a quite different phase diagram [41].

5. Conclusion. — In conclusion we want to emphasize, that because of space limitation, it was not possible to give a complete survey of the important work concerning the determination of rare earth intermetallic magnetic structures. For the future, the availability of single crystals will permit the development of *second generation* experiments in order to perform the determination of phase diagrams *versus* magnetic field or pressure, and also more detailed studies related to phase transition problems.

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