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INFLUENCE OF CONDUCTION ELECTRONS IN A HEAVILY-DOPED MAGNETIC SEMICONDUCTOR : A ^{151}Eu MÖSSBAUER STUDY OF EUROPIUM HEXABORIDE

J.M.D. Coey, O. Massenet, M. Kasaya^{*+} and J. Etourneau^{*}

Groupe des Transitions de Phases, C.N.R.S., B.P. 166, 38042 Grenoble Cedex, France

^{}Laboratoire de Chimie du Solide du C.N.R.S., Université de Bordeaux I, 33405 Talence, France*

Résumé.— Dans cinq échantillons différents d'hexaboride d'euporium, EuB_6 , on a observé que l'euporium était divalent et aucune évidence de valence intermédiaire n'a été observée. L'ordre magnétique évolue depuis l'ordre ferromagnétique dans le matériau presque stoechiométrique à l'ordre antiferromagnétique dans $\text{EuB}_{5.8}\text{C}_{0.2}$ passant par une région intermédiaire mictomagnétique avec un échange inhomogène autour de $\text{EuB}_{5.9}\text{C}_{0.1}$. On suggère que des amas ferromagnétiques d'euporium autour des atomes de carbone donneurs sont couplés antiferromagnétiquement à ceux entourant un carbone adjacent par échange direct électronique.

Abstract.— The europium is divalent and no evidence of mixed valence is found in any of five different samples of europium hexaboride. The magnetic order evolves from ferromagnetic in near-stoichiometric material to antiferromagnetic in $\text{EuB}_{5.8}\text{C}_{0.2}$ passing through a mictomagnetic region with inhomogeneous exchange around $\text{EuB}_{5.9}\text{C}_{0.1}$. There it is suggested that ferromagnetic europium clusters around the carbon donors are coupled antiferromagnetically by direct exchange of electrons from adjacent donors.

The magnetic properties of europium hexaboride are the subject of some controversy. In the original work, Geballe et al reported EuB_6 as a ferromagnetic semiconductor with $T_c = 8.5 \text{ K}$ [1]. Subsequent measurements on other polycrystalline samples yielded values in the range 8–15 K. The first single crystal [2] however did not order ferromagnetically despite a positive paramagnetic Curie temperature, $\theta_p = 9 \text{ K}$ [3]. Isikawa et al interpreted their data as showing that the crystal was antiferromagnetic and suggested that this is the intrinsic behaviour of the compound [2]. Very recently, Kasaya et al have studied crystals and powders of $\text{EuB}_{6-x}\text{C}_x$ with controlled carbon content, $0 < x < 0.21$ [4]. Carbon acts an electron donor in the B_6 framework, so x is approximately the conduction-electron content. θ_p was found to decrease regularly from +15 K to -7 K with increasing x , crossing zero at $x = 0.13$. It appears that conduction electrons contribute an antiferromagnetic exchange interaction. At the same time there is a small decrease in lattice parameter from 4.1855 for undoped samples to 4.1695 Å for $x = 0.21$.

In this paper, we report ^{151}Eu Mössbauer data on five samples of europium hexaboride produced in different ways, including two intentionally doped with carbon. We were particularly interested

to find out if samples with $\theta_p \sim 0$ were magnetically ordered, and whether the exchange interactions in doped samples were spatially homogeneous.

Details of the samples appear in the table. It will be convenient to take the lattice constant a_0 as the characteristic parameter of each sample as the work of Kasaya et al suggests that a_0 decreases uniformly with increasing conduction electron content, n . Although carbon was not determined in sample III, comparison with the data in reference 4 suggests $x \sim 0.05$.

Mössbauer spectra were obtained on absorbers with 25 mg/cm^2 of each sample at 296 K and at several temperatures in the range 1.6 – 20 K. At room-temperatures a single line with a typically divalent isomer shift, $-12.7(1) \text{ mm/s}$ relative to the source ^{151}Sm in SmF_3 , was observed in all five samples. No sign of a Eu^{3+} line was seen at any temperature, so a limit of 3 % is thereby set on any possible inhomogeneous valence mixture. Nor is there any significant variation of the isomer shift between 20 and 296 K ($< 0.2 \text{ mm/s}$), a result which places a limit of 2 % on any change in homogeneous valence admixture with temperature. These results were confirmed by measurements of the susceptibility which gave a temperature-independent Curie constant of $7.7(2)$ at temperatures up to 800 K, as expected for Eu^{2+} . It follows that the gap between the 4f level and the conduction band in EuB_6 is at

⁺Permanent address : Department of Physics, Tohoku University, Sendai 980, Japan.

Sample No	Description	Lattice Parameter a_0 (Å)	Carriers/Eu n	Ordering Temperature T_c (K)	H_{hf} (1.6) (kOe)	H_{hf} (4.2) (kOe)	ΔH_{hf} (4.2) (kOe)	Reference
I	Stoichiometric powder	4.1855 (3)	~ 0	12.5 (.5)	332	308	~ 0	4
II	I, heated in Eu vapour	4.1855 (3)	~ 0	10.7 (.5)	336	277	~ 0	-
III	Single crystal	4.1810 (3)	0.03	6.3 (.3)	316	262	40	2
IV	Carbon-doped powder $x = 0.14$	4.1733 (3)	0.14 ⁺	7 (1)	nd	270	25	4
V	Carbon-doped powder $x = 0.21$	4.1695 (3)	0.21 ⁺	5.5 (.5)	313	274	~ 0	-

⁺ Assumed equal to x in the formula $\text{EuB}_{6-x}\text{C}_x$

Table I : Details of the europium hexaboride samples.

least 0.2 eV, in accord with resistivity measurements at high temperatures which yielded an activation energy of 0.3 eV /5/.

The appearance of magnetic hyperfine splitting indicates that all our samples are magnetically ordered at 4.2 K, regardless of the value of θ_p . Three typical spectra are shown in figure 1.

Fig. 1 : Mössbauer spectra at 4.2 K of ferromagnetic (I), mictomagnetic (III) and antiferromagnetic (V) samples of europium hexaboride. Particulars of each sample are given in the table.

Both the nominally stoichiometric samples (I and II) and the most carbon rich one (V) show unbroadened lines in the magnetic spectra, but the lines of samples with intermediate lattice parameters (III

and IV) are greatly broadened. The corresponding spread in hyperfine field ΔH_{hf} is given in the table. Line broadening in sample III cannot be due to macroscopic inhomogeneity because identical spectra were obtained for samples from different parts of the crystal. Nor is it related to the proximity of the ordering temperature (by poor temperature control or homogeneity) because it is absent in V, whose ordering temperature is just as low as that of III or IV. The broadening disappears in spectra taken at 1.6 K, so it must be associated with inhomogeneity of the exchange interactions on a microscopic scale. The breadth of the exchange distribution can be estimated from local molecular field theory /6/ to be roughly as great as its average value. The absence of any significant broadening in samples I, II and V shows that the exchange interactions there are essentially homogeneous.

Magnetic ordering temperatures were derived for all five samples by extrapolating the hyperfine field to zero. For the ferromagnets, I and II, these temperatures agree fairly well with those obtained from Arrott plots /7/. For the other samples they correspond to a cusp in the susceptibility /7/. V appears to be antiferromagnetic, from the consistency between θ_p , T_c and $x(T_c)$. III and IV however may best be described as mictomagnets since they contain a spatially inhomogeneous distribution of exchange interactions of both signs. The susceptibility cusp in these two samples is eliminated in fields of 2-3 kOe whereas that of sample V persists in fields greater than 10 kOe. Figure 2 shows the magnetic phase diagram of the europium hexaboride system as a function of lattice parameter. The second scale relates a_0 to the

approximate conduction electron concentration using the results in reference /4/.

Fig. 2 : Magnetic phase diagram of europium hexaboride showing paramagnetic (P), ferromagnetic (F), mictomagnetic (M) and antiferromagnetic (AF) regions. The ordering temperatures • and + are derived respectively from Mössbauer and magnetic /7/ data. 0 indicates the paramagnetic Curie temperatures /4/.

The small difference (~ 20 kOe) between the hyperfine fields, extrapolated to $T = 0$, in ferromagnetic samples represents the sum of the contribution of the conduction electron spin polarisation to the latter and the supertransferred hyperfine interaction.

While the basic ferromagnetic exchange coupling in near-stoichiometric EuB_6 can be understood in terms of the mechanism proposed for EuO /8/, it is puzzling that the addition of conduction electrons can give an antiferromagnetic contribution. The RKKY interaction is positive at short distances and low conduction electron densities. The first negative region occurs between 4.5×10^{21} and 2.6×10^{22} per cc at the nearest neighbour distance of EuB_6 . It is impossible to obtain antiferromagnetic nearest-neighbour coupling at concentrations of order 0.05 electrons/Eu (6.8×10^{20} per cc) even taking account of the fact that the electron density is not uniformly distributed, but peaked near the donor sites. In the most favourable case, assuming hydrogenic wave functions and a dielectric constant $\epsilon \sim 4$, the electron density at europium sites adjacent to a carbon impurity is only 2.0×10^{21} .

The antiferromagnetic coupling must therefore take place at much longer distances. Figure 3 shows how it may come about. There is a high density of states in the impurity band close to a carbon donor and the added electron there couples ferromagnetically to the surrounding group of europium ions.

Fig 3 : Schematic representation of mictomagnetic EuB_6 . Ferromagnetic clusters formed around the donor centres are coupled antiferromagnetically by direct exchange between electrons from adjacent donors.

Mid-way between the donors however the electron density is much lower and direct overlap of their hydrogenic wave functions gives antiferromagnetic coupling between the electrons from adjacent donors. In this way, the inhomogeneous exchange in the mictomagnetic region of $\text{EuB}_{6-x}\text{C}_x$ finds a natural explanation. At higher electron concentrations the density in the impurity band becomes uniform and the exchange homogeneous.

Finally we note that there are some signs of competing exchange interactions in nominally stoichiometric, ferromagnetic EuB_6 . The rise in the magnetization and hyperfine field below the Curie point is much less abrupt than that given by the Brillouin function. Also the specific heat anomaly is broad and complex /1,9/. These effects probably stem from the presence of some 10^{19} carriers, even in the best materials prepared so far. If these carriers turn out to be extrinsic, due to defects or impurities such as trivalent rare earths, then EuB_6 , with its simple structure and almost rigid Boron lattice, should be an ideal compound for studying the influence of conduction electrons on the magnetism and transport properties for a magnetic semiconductor.

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