ANISOTROPIC EXCHANGE INTERACTION BETWEEN THE MAGNETIC IONS IN TERBIUM.

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The ionic moments in the rare earth metals, which are due to the unfilled 4f-shell, are coupled together indirectly through the conduction electrons. In the RKKY-model the interaction between the localized spin and the spins of the conduction electrons is assumed to be a delta function in space. This model for the s-f exchange interaction has been extended in order to take into account the distribution in space of the localized 4f-electrons, and the orbital momentum of the conduction electrons with respect to the ions. A detailed discussion can be found in the review articles [1,2].

In most experiments and theoretical calculations on the heavy rare earth metals the exchange interaction is described by an isotropic Heisenberg interaction, proportional to the susceptibility of the conduction electrons and modified by a form factor because of the finite range in space of the s-f interaction. The presence of magnetic anisotropy is then related to single ion anisotropy only. However, in a study of the spin waves in the conical magnetic phase of Er, Nicklow et al. [3] found that their results could be explained only if the Heisenberg Hamiltonian was augmented by a large anisotropic two-ion coupling. In Tb, because of the ferromagnetic ordering of the moments, explicit information about the anisotropy of the exchange interaction cannot be obtained from the spin wave dispersion relation as in Er. However, the change of the spin wave energies, when applying an external field, permits a distinction between the isotropic and anisotropic part. This technique has been used for determining the magnetic anisotropy of Tb-10%Ho [4] and of pure Tb [5], by studying the behaviour of the spin wave energy gap at zero wave vector.

The spin wave Hamiltonian is composed of two different kinds of terms, single ion and two-ion contributions ($\mathcal{H}_I$ and $\mathcal{H}_{II}$), where the single ion term comprises the Zeeman energy and crystal field effects, $\mathcal{H}_{CF}$ (including those of magnetoelastic origin)

$$\mathcal{H}_I = \mathcal{H}_{CF} - g\mu_B \sum_i \vec{J}_i \cdot \vec{H} \quad (1)$$

where J_i is the total angular moment on site i and H is the internal magnetic field. The exchange coupling between the moments, which we allow to be anisotropic, can be written

$$\mathcal{H}_{II} = - \sum_{i>j} \sum_\alpha K^{\alpha\alpha}(ij)\, J_i^\alpha J_j^\alpha \quad (2)$$

where J_i^α is the α-Cartesian component of J_i.

For a ferromagnet with the magnetization and field along a b-axis (perpendicular to the a- and c-axis) we have the following expression for the energy of the spin waves

$$\varepsilon(q) = \{[A(q) + B(q)][A(q) - B(q)]\}^{\frac{1}{2}} \quad (3)$$

where

$$A(q) + B(q) = J[K^{cc}(0) - K^{cc}(q)] + J[K^{bb}(0) - K^{cc}(0)] + A_{CF} + B_{CF} + g\mu_B H \quad (4)$$

and

$$A(q) - B(q) = J[K^{aa}(0) - K^{aa}(q)] + J[K^{bb}(0) - K^{aa}(0)] + A_{CF} - B_{CF} + g\mu_B H \quad (5)$$

All the parameters in eqs. (4) and (5) depend implicitly on the magnitude and the direction of the magnetization. The relative magnetization, σ, is a function of temperature and field. The field dependence of σ can be obtained from molecular-field theory as

$$d\sigma/dH = g\mu_B J(1 - \sigma)/k_B T_N \quad (6)$$

which is zero at low temperatures.

The field dependence of the square of the magnon energies is then

$$d\varepsilon^2(q)/dH = 2g\mu_B A(q) + (\partial\varepsilon^2(q)/\partial\sigma)(d\sigma/dH) \quad (7)$$

Thus, by measuring the field dependence of the magnon energies at zero and finite wave vector, it is possible to determine the q-dependence of the aa- and cc-components of the exchange interaction.

The energy of spin waves propagating in the c-direction of Tb has been studied by inelastic neutron scattering. The energies have been measured as function of field applied along both the easy and hard directions in the basal plane at three different temperatures (4.2, 53, and 134 K). An external field of up to 100 kG could be applied.

The observed coupling between the magnons and the transverse phonons propagating along the c-axis perturbs strongly the field dependence of the magnon energies. In a previous analysis of the experimental results [5,6] the influence of this interaction was neglected, which together with the ambiguity in sign of B(q) (when B(q) becomes close to zero) led to exchange parameters which differed rather much from those deduced in the present analysis. In this analysis corrections have been made for the magnon-phonon interaction (more details are going to be published elsewhere [7]).

In order to bring the exchange parameters in an appropriate form, which allows a least squares analysis of all the experimental results, we define

$$J[K^{cc}(0) - K^{cc}(q)] = \mathcal{J}(q)\sigma^{j(q)} + \mathcal{K}(q)\sigma^{k(q)} + \mathcal{C}(q)\sigma^{k(q)}\cos 6\phi \quad (8)$$

and

$$J[K^{aa}(0) - K^{aa}(q)] = \mathcal{J}(q)\sigma^{j(q)} - \mathcal{K}(q)\sigma^{k(q)} + \mathcal{D}(q)\sigma^{k(q)}\cos 6\phi \quad (9)$$

where ϕ is the angle between the direction of magnetization and the easy axis (b-axis). There was no experimental evidence for distinguishing between the temperature dependence of the three anisotropy parameters $\mathcal{K}(q)$, $\mathcal{C}(q)$ and $\mathcal{D}(q)$.

These four exchange parameters in connection with the two corresponding magnetization exponents, which are shown in fig. 1-3, reproduce satisfactorily the field and temperature dependence of the magnon energies. Furthermore, the integrated intensities of the neutron groups behave qualitatively in accordance with the anisotropy deduced. An extrapolation of the exchange parameters up to 200 K (σ = 0.6) produces a dispersion relation in the easy direction, which agrees very well with the measured magnon energies. A more complete and detailed description is going to be published [7].

C o n c l u s i o n

The anisotropy of the exchange interaction between the hexagonal axis and the basal plane in Tb, which at 4.2 K amounts to about 30%, is much smaller than the anisotropy observed in Er. The relatively large difference between the cc-components of the exchange interaction in the easy and in the hard directions may be connected with the corresponding anisotropy parameter deduced at zero wave vector [5,7] ($\Delta M = -1.41\ \sigma^{15.5}$). The rapid decrease of the anisotropy parameters with relative magnetization, σ^{12}, implies that the exchange interaction is effectively isotropic above 150 K. Such a high exponent does indicate that the anisotropy depends on the distortion of the lattice from hexagonal symmetry [6].

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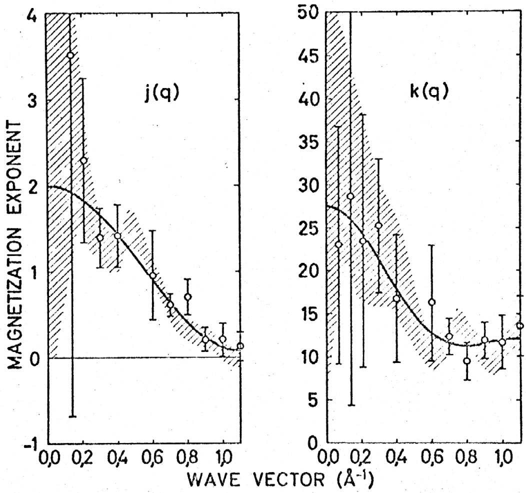

Fig. 1. The relative magnetization exponents j(q) and k(q).

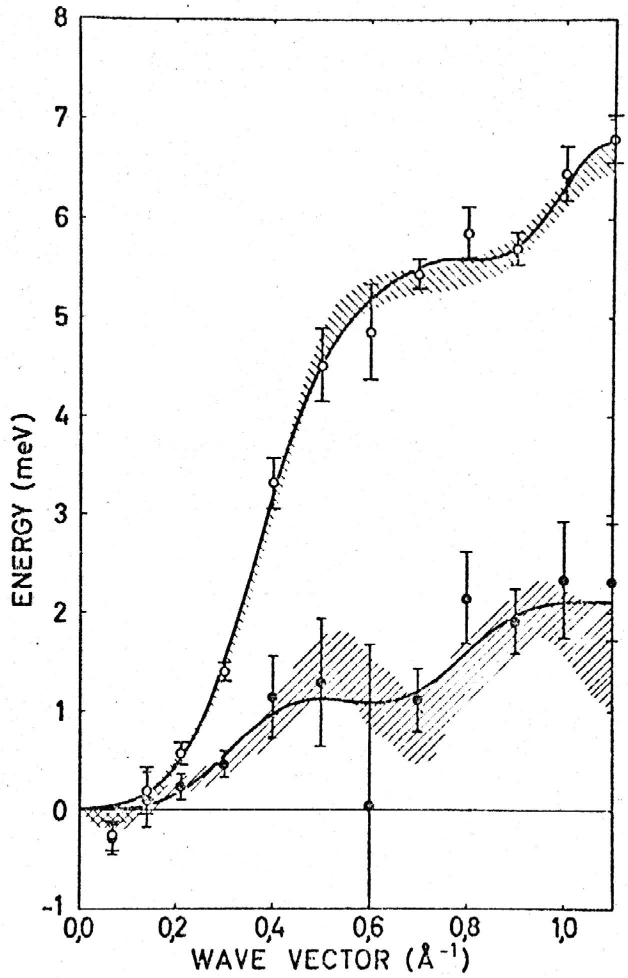

Fig. 2

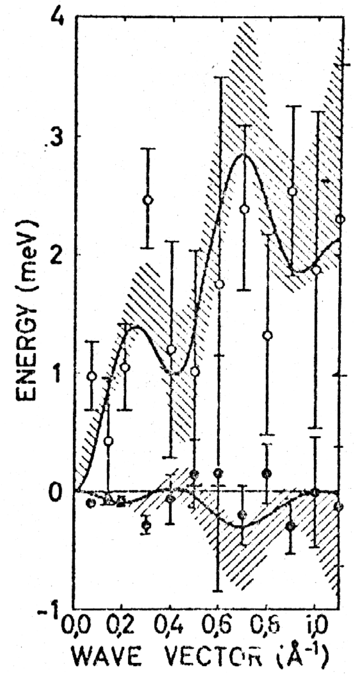

Fig. 3

Fig. 2. The isotropic part, $\mathcal{J}(q)$, and the anisotropic part, $\mathcal{K}(q)$, of the exchange interaction (represented by open and closed symbols respectively).

Fig. 3. The basal plane anisotropy parameters $\mathcal{E}(q)$ (open symbols) and $\mathcal{D}(q)$ (closed symbols).
The solid lines on all the figures are the results of the least squares fitting to the experimental points. The cross hatched regions show the standard deviations of the fits.