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Rare-Earth Metals

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Magnon Interactions in Terbium

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Magnon energies and lifetimes have been studied in Tb and Tb–10% Ho single crystals by inelastic neutron scattering. The lifetimes of magnons propagating in the c-direction have been measured in the ferromagnetic phase of Tb, and are found to decrease with increasing temperature and wavevector, probably principally due to magnon–magnon interactions. The interaction of magnons with phonons has also been observed and the effect of Ho impurities on this interaction studied. In addition, excitations which are ascribed to local modes associated with the Ho ions have been observed. The dependence of the indirect exchange interaction on temperature in the alloy gives information on the mechanisms responsible for the transition from the helical to ferromagnetic structures. The dependence of the magnon energies on magnetic field at low temperatures gives detailed information on the role of magnetoelastic effects in the magnetic anisotropy. It is found that the cylindrically symmetric magnetoelastic effect gives a large contribution to the $q=0$ magnon energy, in accordance with the "frozen lattice" model, and that the hexagonal anisotropy is probably principally due to crystal field effects.

In previous publications,[1,2] we have presented data on the magnon dispersion relations in rare-earth metals and deduced from them the form of the indirect exchange interaction between the magnetic moments. We have also made preliminary measurements of the lifetimes of the magnons, and studied their interactions with phonons and impurities. In this paper, we will present further results on the magnon interactions and also briefly mention some new measurements of magnon energies as a function of temperature and magnetic field which elucidate further the mechanisms determining the magnetic interactions in the rare earths.

The measurements were made by the inelastic scattering of neutrons from single crystals of Tb and Tb–10% Ho, and the magnons manifest themselves as peaks in experimental scans in which, for instance, the momentum transfer from the neutrons is fixed while the energy transfer varies. In such constant q scans, the width of the neutron group, when corrected for the experimental resolution, gives the energy broadening or lifetime of the magnon state. The results of such lifetime measurements for magnons propagating in the c-direction of Tb are shown for different temperatures in Fig. 1. The experiments were performed in such a way that the magnon width was always greater than the experimental resolution, which was corrected for by the method described by Nielsen and Møller.[3] As may be seen from Fig. 1, the magnon widths increase rapidly with both temperature and wavevector, and we ascribe the temperature-dependent part of this broadening to magnon–magnon scattering. There is a small residual magnon width at 4.2°K at large wavevectors, which is probably due to the absorption of magnons by the conduction electrons.

The energies of the excitations propagating in the c-direction of Tb at 4.2°K are shown in Fig. 2. Where the magnon dispersion relation crosses that of the transverse optical phonons, an interaction occurs between them, which results in excitations of mixed magnon and phonon character and splits the dispersion relation by about 1.7 meV. The addition of 10% Ho modifies this

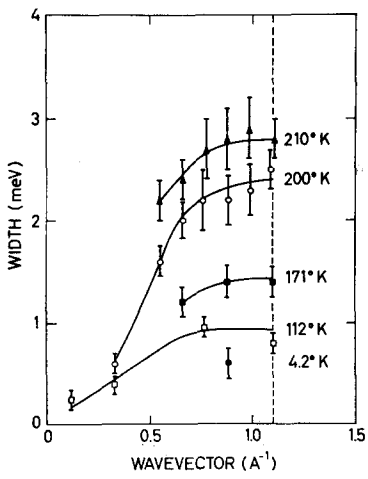

FIG. 1. Magnon widths as a function of wavevector and temperature in the c-direction of Tb, in the double zone representation.

behavior substantially, as may be seen in Fig. 2. The magnon–phonon interaction is substantially enhanced so that the splitting of the dispersion curve is increased to approximately 3 meV, and furthermore, additional splittings appear away from the crossing point with the transverse optical phonons. In addition, a small branch of excitations is observed in the gap produced by the magnon–phonon splitting, and this is ascribed to the local modes associated with the Ho impurities, which were observed earlier as a resonance in the dispersion relation in the a-direction at 110°K. In the earlier measurements, the resonance was observed at about 4 meV, with a width of about 1 meV, comparing well with the values 4.25 meV and 0.88 meV recently calculated by Blackman.[4] At 4.2°K, the local mode energy has increased to between 5 and 6 meV, because of the increase in the anisotropy and exchange parameters, and appears as a localized mode in the gap produced by the magnon–phonon interaction, with some dispersion due to the finite concentration.

In order to study the mechanisms of exchange and anisotropy in more detail, we have made further measurements of the magnon dispersion relations in this alloy as a function of temperature and magnetic field. The results for the c-direction at two different temperatures in the helical phase and at a temperature just below T_c are shown in Fig. 3, together with the values of the Fourier transformed exchange parameters $J(q)$ deduced from them. As the temperature is reduced, the maximum in $J(q)$ which stabilizes the helical structure decreases in magnitude and changes its position, due to the perturbation in the electronic structure, which is a consequence of the additional periodic potential associated with the helical ordering. At the Curie temperature T_c, this maximum becomes too small to prevent the anisotropy forces, which increase with decreasing temperature, from causing a transition to a ferromagnetic structure. The exchange interaction changes abruptly with the electronic structure at T_c.

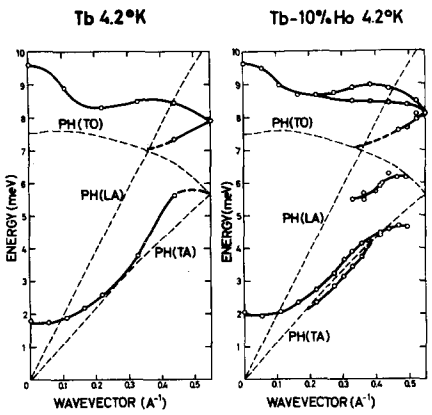

FIG. 2. The dispersion relations for excitations at 4.2°K propagating in the c-direction for Tb and Tb–10% Ho. The dashed curves are the phonon dispersion relations.

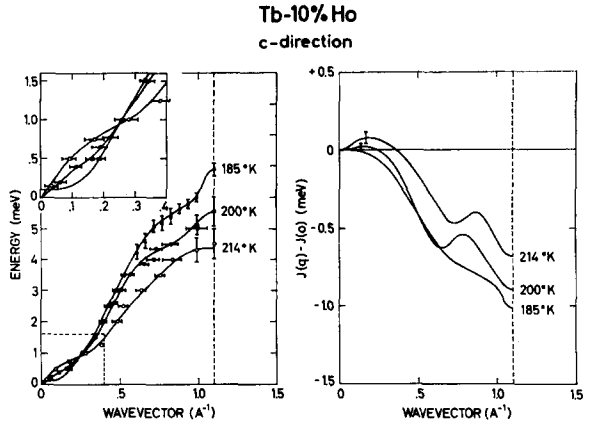

FIG. 3. Magnon dispersion relations in the c-direction for Tb–10% Ho in the helical and ferromagnetic (185°K) phases, in the double zone representation. The temperature dependence of $J(q)$ deduced from these results is also shown.

The origin of the anisotropy forces which give rise to the energy gap at $q=0$ in Fig. 2 has been extensively discussed by Cooper.[5] We have observed that the application of a magnetic field large enough to turn the moments into the hard direction in the basal plane does not reduce this gap to zero, which verifies the applicability of the Turov–Shavrov[6] "frozen-lattice" model, according to which a large contribution to the gap is made by the magnetoelastic effect with cylindrical symmetry about the c-axis. In addition, the temperature dependence of this term and the axial and hexagonal anisotropies have been measured and agree quite well with the calculations of Cooper.[5] The temperature dependence of the latter indicates that the hexagonal anisotropy is primarly due to the crystal field, rather than to the hexagonally symmetric magnetoelastic term. The details of these measurements will be published elsewhere.

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