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Spin waves in the ferromagnetic phase of thulium

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Abstract

We have measured the spin wave dispersion in Tm along the c-axis in the ferromagnetic phase, following our earlier study in the ferrimagnetic phase. We find a shift in the crystal field splitting and a considerable difference in the exchange interaction between the two phases, attributed to the large increase of the c/a ratio which occurs at the transition to the ferromagnetic phase.

1. Introduction

Below $T_N = 56$ K, the moments in the rare-earth metal Tm are sinusoidally modulated along the c-axis. At 32 K there is a first-order lock-in transition to a ferr*i*magnetic phase with a 7-layer periodicity. Tm becomes ferr*o*magnetic when the internal field along the c-axis exceeds 2.8 T. We have earlier made an extensive study [1] of the magnetic excitations in Tm in the ferrimagnetic phase, from which we deduced the exchange interaction $\mathcal{J}(\boldsymbol{q})$ along the c-axis. Subsequently, we measured the dispersion in the ferromagnetic phase [2], but only in the basal plane, due to the magnet geometry. We found that the dispersion in the ferromagnetic phase was apparently much larger than predicted. In this paper, we report new measurements of the spin wave dispersion along the c-axis, in the ferromagnetic phase, allowing a more direct comparison with the results for the ferrimagnetic phase [1].

2. Experimental details

The measurements were made on the same Tm crystal as was used in our previous experiments, and were carried out using the triple-axis spectrometer E1 at the Berlin neutron scattering centre. The crystal was mounted, with its a-axis vertical, in a horizontal field cryomagnet, allowing the magnetic field to be applied along the c-axis. Because of the geometrical constraints arising from the magnet construction and the availability of only fixed values of $2\theta_m$, we operated the spectrometer with a constant incident neutron energy of $E_i = 25.2$ meV using a PG(004) monochromator, and collimations 40′/40′/40′. The calculated instrumental resolution was 1.8 and 1.2 meV at zero and 11 meV energy transfer, respectively. All measurements were made at $T = 1.7$ K.

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3. Experimental results

Under the geometrical and kinematic constraints, it was possible to make inelastic scans over energy transfers of 3–11 meV only between $\boldsymbol{Q} = (1, 0, 3)$ and (1, 0, 2.5). Measurements were first made in zero field. As the field was applied the intensity of the satellite peak at (1, 0, 2.72) was monitored to ensure that all of the sample had transformed into the ferromagnetic phase. The phase transition was completed in an applied field of 3.6 T, the field was increased further to 4.2 T for the measurements. Fig. 1 shows the results at $\boldsymbol{Q} = (1, 0, 3)$ and (1, 0, 2.5). We note that long counting times (2.5 h/point) were needed to obtain sufficiently accurate data.

4. Discussion

The results of the scan at $\boldsymbol{Q} = (1, 0, 3)$ in a field of 4.2 T agree very well with the previous observation at 4.5 T [2] of an acoustic peak at 6.7 meV and an optical one at 9.2 meV. The other scan at $\boldsymbol{Q} = (1, 0, 2.5)$ in 4.2 T indicates peaks at 5.1 and 8.5 meV. Only a single spin wave excitation is expected at this wave vector and the lower peak is interpreted as arising from the transverse phonons. However, the low energy peak lies nearly 1 meV below that expected for the pure transverse phonon mode. Both the reduction in energy and the relatively large intensity of this peak may be explained by a value of about

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-0.04 for the magnetostrictive ε-strain coupling H_ε. This value is slightly smaller than the average coupling $H_\varepsilon \approx -0.053$ derived in Ref. [1] for the ferrimagnetic case. The strong hybridization of the spin wave and the transverse phonon means that the unperturbed spin wave energy at A is between 0.7 and 0.8 meV smaller than the energy of the upper mode at $\boldsymbol{Q} = (1, 0, 2.5)$ i.e. about 7.75 meV.

Neglecting the coupling to the phonons, the spin wave energies are $E(\boldsymbol{q}) = \Delta + J[\mathcal{J}(0) - \mathcal{J}(\boldsymbol{q})]$, and from the three different modes obtained in the present scans we may derive $\Delta = 6.7$ meV and the value of $\mathcal{J}(0) - \mathcal{J}(\boldsymbol{q})$ at $\boldsymbol{q} = 0.5\boldsymbol{c}^*$ and $\boldsymbol{q} = \boldsymbol{c}^*$. As shown in Fig. 2, the two results derived for the two-ion coupling, when $\boldsymbol{q}$ is along the c-axis, differ significantly from the results obtained in the ferrimagnetic phase. The overall dispersion is increased by 50% and the strong minimum of $\mathcal{J}(0) - \mathcal{J}(\boldsymbol{q})$ in the ferrimagnetic phase is more or less suppressed. In addition to this change, $\Delta = 6.7$ meV is reduced substantially compared with the 8.8 meV predicted by the ferrimagnetic model developed in Ref. [1].

As also discussed in Ref. [2] these changes must be related to the drastic elongation of the lattice parameter c in Tm by about 0.7% occurring at the transition from the ferrimagnetic to the ferromagnetic phases at 4.2 K [3]. If the volume change at the transition is assumed to be of less importance, the increase of c by 0.7% indicates a change of the c/a ratio by 1%, from about 1.570 to 1.586. A simple scaling of the crystal field parameter B_2^0 with the deviation of the c/a ratio from its ideal value predicts a reduction of the crystal field splitting by nearly 1 meV, which compares in order of magnitude with the observed difference of 2.1 meV.

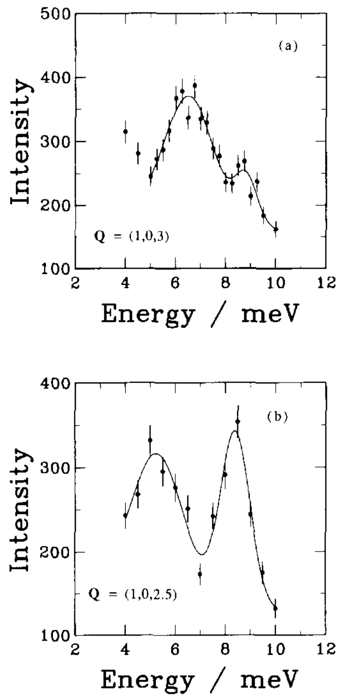

Fig. 1. Inelastic scattering from ferromagnetic Tm at (a) $\boldsymbol{Q} = (1, 0, 3)$ and (b) $\boldsymbol{Q} = (1, 0, 2.5)$.

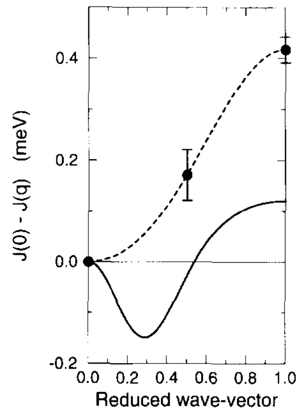

Fig. 2. Comparison of the exchange coupling along the c-axis in Tm in the ferrimagnetic (solid line) and ferromagnetic (dashed line) phases.

Andrianov [4] has discovered a universal relation between the turn angles in the periodically ordered heavy rare-earth metals and their c/a ratios. According to this relation $c/a = 1.570$ should correspond to a turn angle of about 50°, and systems with c/a larger than the critical value $(c/a)_{cr} \approx 1.582$ should be ferromagnetic. This means that not only the 2/7-ferrimagnetic structure but also the field-induced ferromagnetic phase of Tm fit into this scheme. It is known that the magnetic ordering of a rare-earth metal affects the Fermi surface which in turn modifies the RKKY coupling. However, that this mechanism may produce effects as large as deduced here in the case of Tm is a genuine surprise.

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