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► **To cite this version:**

A. Woods, T. Holden, B. Powell, M. Stringfellow. TEMPERATURE DEPENDENCE OF SPIN WAVE ENERGIES IN ERBIUM. Journal de Physique Colloques, 1971, 32 (C1), pp.C1-1179-C1-1181. 10.1051/jphyscol:19711422 . jpa-00214465

HAL Id: jpa-00214465

<https://hal.science/jpa-00214465v1>

Submitted on 4 Feb 2008

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TEMPERATURE DEPENDENCE OF SPIN WAVE ENERGIES IN ERBIUM

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Résumé. — Les modes de propagation des ondes de spin le long de l'axe C sont étudiés dans la phase magnétique conique de l'Erbium en fonction de la température, par diffusion inélastique de neutrons. Le mode de vecteur d'onde de transfert $cQ/2\pi = (0, 0, 2)$ a une énergie de $2,02 \pm 0,08$ meV à 5,0 °K et $1,63 \pm 0,08$ meV à 18,5 °K ce qui représente une décroissance de 19 %. Le mode dont $cQ/2\pi = (0, 0, 1)$ a une énergie $3,76 \pm 0,08$ meV à 5,0 °K et $3,59 \pm 0,08$ meV à 18,5 °K, soit une décroissance de moins de 5 %. L'analyse des énergies d'ondes de spin suggère que l'anisotropie effective varie rapidement avec une température. Dans la phase magnétique plus complexe — pour des températures supérieures à celles de la phase conique — la distribution de l'énergie des neutrons diffractés est large et contient plusieurs structures, bien qu'on observe aucun pic de neutrons correspondant à un mode bien défini.

Abstract. — Spin wave modes propagating along the c-axis in erbium have been studied as a function of temperature in the conical magnetic phase with the technique of inelastic neutron scattering. The mode at wavevector transfer $cQ/2\pi = (0, 0, 2)$ has an energy of 2.02 ± 0.08 meV at 5.0 °K and 1.63 ± 0.08 meV at 18.5 °K which is a decrease of 19 %. The mode at $cQ/2\pi = (0, 0, 1)$ has an energy of 3.76 ± 0.08 meV at 5.0 °K and 3.59 ± 0.08 meV at 18.5 °K which is a decrease of less than 5 %. Analysis of the spin wave energies suggests that the effective anisotropy varies rapidly with temperature. In the more complex magnetic phase in the temperature range above the conical phase the energy distributions of scattered neutrons were broad and contained some structure although no sharp neutron groups corresponding to well-defined spin wave modes were observed.

Neutron inelastic scattering measurements of spin wave energies in the conical magnetic phase of Er are reported in this paper. In addition to measurements at 5.0 °K, measurements were also made at 15.0 and 18.5 °K, below the high temperature limit of the cone phase (19.0 °K in our specimen) and at 19.2 °K. As the temperature is raised the spin wave energies decrease but the decrease is more marked at low magnon wavevectors than at high magnon wavevectors.

The spin wave energy versus wavevector dispersion relation for the conical magnetic structure has been given by Cooper et al. [1]

$$\frac{\hbar\omega}{S} = \cos \theta \{ J(\mathbf{k}_0 + \mathbf{q}) - J(\mathbf{k}_0 - \mathbf{q}) \} + \sqrt{F_1 F_2} \quad (1)$$

$$F_1 = 2 J(\mathbf{k}_0) - J(\mathbf{k}_0 + \mathbf{q}) - J(\mathbf{k}_0 - \mathbf{q})$$

$$F_2 = \cos^2 \theta F_1 + 2[L-K(\mathbf{q}) + J(\mathbf{k}_0) - J(\mathbf{q})] \sin^2 \theta.$$

Here θ is the semi apex angle of the cone, S is the total angular momentum, $L-K(\mathbf{q})$ is the effective anisotropy including anisotropic exchange, \mathbf{k}_0 is the spiral wavevector, and $J(\mathbf{q})$ is the Fourier transformed exchange. If we assume, as is often done [2] that the anisotropic exchange can be neglected, the effective anisotropy becomes $L-K(0)$. Examination of the magnon structure factors [3] for the four domains present shows that, at each value of wavevector transfer \mathbf{Q} , two modes dominate the scattering with magnon wavevectors $\mathbf{q} = (\mathbf{Q} - 2\pi\tau + \mathbf{k}_0)$ and

$\mathbf{q} = -(\mathbf{Q} - 2\pi\tau - \mathbf{k}_0)$. At $cQ/2\pi = (0, 0, 1)$ and $(0, 0, 2)$ these modes are degenerate.

The measurements were made on a crystal of Er with a triple axis crystal spectrometer controlled in the constant momentum transfer (constant $-\mathbf{Q}$) mode [4]. The spin wave dispersion curve for propagation along the c-axis is shown in figure 1 for 5.0 and

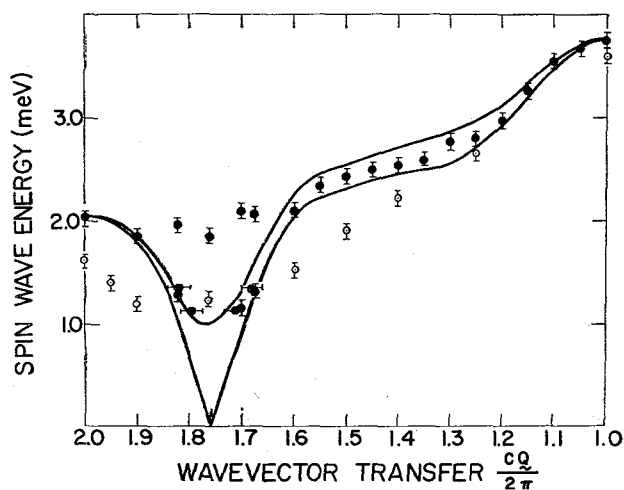


FIG. 1. — Spin wave energy versus wavevector dispersion curves for Er in the c-direction at 5.0 °K (●) and 18.5 °K (○). The solid curves represent the fit to equation (1) of the 5.0 °K data with $L-K(0) = 0.78$ meV ignoring the data in the neighbourhood of $cQ/2\pi = 1.76$. The arrow is the position of the satellite wavevector.

(*) Visitor from A. E. R. E. Harwell now returned.

18.5 °K. No double groups which might correspond to both dominant modes were observed except near $c\mathbf{Q}/2\pi = (0, 0, 1.76)$, the satellite position, and it was concluded that both modes contribute to each observed peak. By fitting the average value of eq. (1) for the two domains at each wavevector to the observed results the exchange and anisotropy may be found. If all the data at 5.0 °K is analysed, the value of $L-K(\mathbf{0})$ obtained (which is sensitive to the data near $c\mathbf{Q}/2\pi = (0, 0, 1.76)$ because of the cancellation of terms in eq. (1)) is 3.5 meV. This value is thought to be too large because (i) the magnon structure factors are incompatible with observation at $c\mathbf{Q}/2\pi = (0, 0, 1)$ and (ii) $J(\mathbf{k}_0) - J(\mathbf{0})$ is much smaller than the value of 0.075 meV deduced from the paramagnetic Curie temperature and the Néel temperature.

To avoid this difficulty we have analysed the data except near $c\mathbf{Q}/2\pi = (0, 0, 1.76)$. Without this data it is only possible to set approximate limits on the possible range of values of $L-K(\mathbf{0})$ of 0.1 and 1.0 meV. The solid line shows the dispersion curves for the two dominant modes calculated from the best fit of eq. (1), averaged over both domains, to the 5 °K data when $L-K(\mathbf{0})$ is fixed at 0.78 meV which is a theoretical estimate due to Kasuya [5]. This value yields $J(\mathbf{k}_0) - J(\mathbf{0}) = 0.077$ meV which is consistent with the molecular field estimate given above.

The energy distribution of scattered intensity in Er at $c\mathbf{Q}/2\pi = (0, 0, 1.0)$ and $(0, 0, 2.0)$ for temperatures of 5.0, 15.0, 18.5 and 19.2 °K is shown in figure 2.

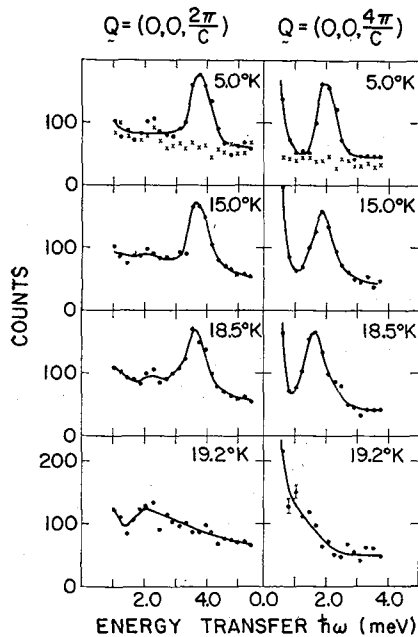


FIG. 2. — Temperature dependence of spin wave energies at $c\mathbf{Q}/2\pi = (0, 0, 1)$ and $(0, 0, 2)$. The crosses represent the fast neutron contribution to the background as measured with cadmium covering the beam aperture. The peaks are normalised to the same number of neutrons falling on the sample.

Examination reveals a difference in the temperature dependence of the spin wave energy at the two wave-

vectors which is also evident in figure 1. If the value of $L-K(\mathbf{0})$ were as large as 3.5 meV the anisotropy would dominate F_2 in eq. (1) at all wavevectors and would give a percentage decrease in spin wave energy which is the same at all wavevectors for a given temperature interval. This is also not in accord with experiment. At 19.2 °K there are no well-defined neutron groups although there is considerable inelastic scattering intensity. At this temperature, where the magnetic structure is possibly a tilted elliptical spiral [6], Cooper et al. [1] have shown that only a broad distribution of magnetic inelastic scattering will be observed corresponding to the excitation of many coupled spin waves.

The simplest interpretation of the temperature dependence of the spin wave energies is that the anisotropy $L-K(\mathbf{0})$ alone varies with temperature through the dependence of the anisotropy on the total ordered moment in Er [7]. The exchange is assumed to be temperature independent in this temperature range. This interpretation of the temperature dependence of spin wave energies appears to work reasonably well for Ho ([8] and [9]). Qualitatively the magnitude of the exchange contribution at $c\mathbf{Q}/2\pi = (0, 0, 1)$ is greater than that at $(0, 0, 2)$ and this is capable of explaining part of the difference between the results at the two wavevectors. We may use the values of $J(\mathbf{q}) - J(\mathbf{0})$ deduced from the 5.0 °K data analysed with $L-K(\mathbf{0}) = 0.78$ meV to estimate the values of $L-K(\mathbf{0})$ relevant to the elevated temperature from the data in figure 2. The spin wave energies at $c\mathbf{Q}/2\pi = (0, 0, 1)$ and $(0, 0, 2)$ at 18.5 °K give $L-K(\mathbf{0}) = 0.68 \pm 0.06$ and 0.42 ± 0.06 meV respectively. From the estimated variation of ordered moment in Er [6] and Kasuya's estimates of the anisotropy the value of $L-K(\mathbf{0})$ at this temperature is approximately 0.5 meV which is in qualitative agreement with the figures deduced from experiment. However, from the disagreement of the two experimental values above it is concluded that the spin wave renormalization is more complicated than we have envisaged.

Two difficulties have thus appeared in understanding the spin wave energies in Er which are at present unresolved. The first is the scattering near $c\mathbf{Q}/2\pi = (0, 0, 1.76)$ which requires large values of $L-K(\mathbf{0})$ which are in turn inconsistent with observations at other wavevectors and temperatures. The second is the difference in the temperature dependence of spin wave energies at different wavevectors. In connection with the first difficulty it is possible, though we believe unlikely, that unrecognized processes may be contributing to the scattering. On the other hand it may indicate that a sizeable anisotropic exchange is operating and that the effective anisotropy depends on magnon wavevector. It is also possible that the Hamiltonian is incomplete either because of terms omitted or because the conical structure of Er is distorted in some way.

Acknowledgements. — We wish to thank E. A. Glaser, R. Campbell and H. Nieman for invaluable experimental assistance and R. J. Elliott and our colleagues at Chalk River for useful discussions.

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