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MAGNETIC ORDERING IN DILUTE YTb AND YEr ALLOYS

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Abstract. - Dilute YEr alloys show the existence of sinusoidally modulated antiferromagnetism down to the lowest impurity concentrations studied. Extrapolation of the Néel temperatures for both YEr and YTb suggests a critical concentration is \( \approx 0.8 \) % Tb, Er. Ordering in such dilute alloys may result from exchange enhancement in the yttrium host.

Following our earlier study of YTb alloys [1], we have investigated the magnetic phase diagram of YEr alloys with Er concentrations between 3 % and 10 %, using a combination of heat capacity measurements and neutron diffraction. Heat capacity measurements were made on arc-melted polycrystalline samples, using a modified adiabatic heating technique, described elsewhere [2]. Figure 1 shows the magnetic contribution to the specific heat of four alloys, obtained by subtracting the specific heat of pure Y. The data show clearly a cooperative anomaly due to a magnetic phase processing. The samples were mounted in a variable temperature cryostat which allowed measurements in the range 1.7 K to 150 K. For the Y(6 %)Er crystal scans were made at a fine mesh of points along the (001) and (101) lines in reciprocal space at a temperature of 4.3 K. There was no indication of magnetic diffuse or Bragg scattering along the (001) direction, but intense Bragg peaks were found at the (10Q) and (1,0,2-Q) positions, with \( Q = 0.28(2\pi/c) \). This value of Q is identical to that found in YTb alloys [1], which display helical antiferromagnetism with a 50° interlayer turn angle. In the present case however, the absence of bragg peaks at the (00Q) positions shows that the magnetic moments in the YEr alloys are aligned along the c-axis direction and are longitudinally modulated with wavevector Q. This corresponds to a modulation wavelength of 20 Å, or 7 atomic layers. This magnetic structure is consistent with the known single ion anisotropy for Er in Y: susceptibility measurements on very dilute YEr alloys [3] show large anisotropy with \( \chi_1 \) very much greater than \( \chi_2 \). Each of the four YEr crystals studied, containing 3, 4, 6 and 8 % Er, were found to display Bragg scattering at the (10Q) position at low temperatures. The widths of the Bragg peaks were resolution limited, showing that the modulated order is established over very large distances. The temperature variation of the integrated intensities under the Bragg peaks is shown in figure 2. The Néel temperatures deduced from these data and the heat capacity anomalies vary linearly with Er concentration. Extrapolation would suggest that the critical concentration for long range order is \( \leq 0.8 \) % Er. This

Fig. 1. - Magnetic component of specific heat for YEr alloys with 3, 5, 7 and 10 % Er versus temperature obtained by subtracting the specific heat of a pure Y sample.
value agrees well with that deduced from our earlier measurements on YTb alloys.

Discussion and conclusion

The persistence of long range magnetic order to such low concentrations of rare earth impurities in yttrium is strong evidence for the indirect exchange between rare earth impurities in yttrium. Independent support for this conclusion is provided by the spin wave measurements of Wakabayashi and Nicklow [4] on alloys of Y(10% Tb) and Y(10% Ho). They found that the Fourier transform of the interplanar exchange couplings $J(q)$ displays a very large peak at the modulation wavevector $(0,0,Q)$. There is a large curvature in $J(q)$ in the vicinity of the maximum, which can be related to the range of the exchange couplings in a simple way: expansion of $J(q)$ of $q$ near $(0,0,Q)$ gives

$$J(q) = J(Q) \left\{ 1 - \frac{1}{2} \rho^2 (Q-q)^2 \right\}$$

(1)

where

$$\rho^2 = \sum_r \Sigma^2 J(r) / \sum_r J(r)$$

and $J(r)$ are the interplanar exchange constants. With the data for $J(q)$ presented in [4] we find $\rho^2$ for the YTb and YHo alloys to be 133 Å$^2$. This gives as a measure of the range of the exchange $\rho = 11.5$ Å, which is 4 times the interplanar spacing along the $c$ axis.

In the RKKY model the indirect exchange $J(q)$ is governed by the exchange $j(q)$ between the localised 4f moment and the conduction electrons and the susceptibility $\chi(q)$ of the conduction electrons:

$$J(q) = j(q)^2 \chi(q).$$

(2)

For these dilute alloys one would expect $\chi(q)$ to be close to that for pure yttrium. Theoretical calculations of $\chi(q)$ for yttrium have been carried out by Liu et al. [5]. These do indeed show a substantial peak in $\chi(q)$ along the $\Gamma\Lambda\Gamma$ direction, but the maximum occurs at $q_z = 0.375(2\pi/c)$, rather than $0.28(2\pi/c)$, the observed modulation wavevector. This discrepancy probably arises from the neglect of the $q$ dependence of the matrix elements in the calculation, and from the $q$ dependence of $j(q)$. The calculated $\chi(q)$ would predict a value of $J(Q) - J(0)$ for yttrium alloys which is three or four times larger than that for the heavy rare earth metals. The spin wave measurements indicate an even bigger ratio, of order ten. This suggests that there might be a degree of exchange enhancement of $\chi(q)$ in yttrium. In this case the susceptibility would be

$$\chi(q) = \frac{\chi_0(q)}{1 - U(q)\chi_0(q)}$$

(3)

where $U(q)$ arises from the Coulomb interaction between the conduction electrons. Clearly if the bare susceptibility $\chi_0(q)$ is sharply peaked at $q = Q$, the greatest enhancement will occur in the vicinity of the peak: $\chi(Q) = S\chi_0(Q)$, where $S = (1 - U(Q)\chi_0(Q))^{-1}$ is the enhancement factor. The curvature of $\chi(q)$ in the vicinity of $Q$ is increased by a factor $S^2$. By combining (1) and (2) it can be seen that the range of the exchange interactions in real space is enhanced by a factor $S$. Comparing the calculated $\chi_0(q)$ [5] and the experimental $J(q)$ [4] suggests a value of $S$ in the range 3-5. This is not as large as in Pd, for example. However it would be of interest to reexamine the bulk properties of yttrium to see if there is independent evidence of exchange enhancement. We searched for evidence of spin fluctuations in the total scattering from a single crystal of pure yttrium at 1.7 K in the vicinity of both the $(0,0,2,Q)$ and $(1,0,Q)$ positions. However two hour scans with the D16 multidetector showed no extra scattering. This is perhaps not surprising since the low energy of the incident neutrons and the low temperature of the sample would allow an integration over only a small fraction of the spin fluctuation spectrum.

Recently Sherrington and Wiethege [6] have demonstrated that exchange enhancement tends to stabilise long range periodic order at the expense of spin-glass order, thereby lowering the critical concentration separating these phases. The persistence of antiferromagnetic order to remarkably low concentrations of rare earth impurities in yttrium is strong evidence for the existence of exchange enhancement in the host metal.