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CRITICAL EXONENTS OF ERBIUM

P. de V. du Plessis (1), G. H. F. Brits (1, 2)* and G. A. Eloff (2)*

(1) Department of Physics, Rand Afrikaans University, Johannesburg, 2000, South Africa
(2) Atomic Energy Corporation of S.A. (Ltd), Pretoria, South Africa

Abstract. – The exponent \( \beta \) that describes the sinusoidally modulate \( d \leftrightarrow \) paramagnetic phase transition crosses over from a value of 0.39 near \( T_N \) to a mean field value away from \( T_N \). Electrical resistivity measurements near \( T_N \) are given for the \( c \) axis and the critical behaviour is discussed.

Erbiun orders below its Néel temperature \( T_N = 85 \) K with its spins directed along the \( c \) axis of the hcp crystal and with the amplitude of spins in successive basal plane layers sinusoidally modulated \([1]\). Unlike the theoretically well studied spiral magnets Dy, Ho and Tb, which are characterized by a \( n = 4 \) component order parameter \([2]\), theoretical predictions about the nature of the phase transition in erbium, which is characterized by a \( n = 2 \) order parameter, are largely lacking \([3]\). Our recent neutron scattering and ultrasonic measurements indicate that the sinusoidal \( \leftrightarrow \) paramagnetic phase transition in erbium is of a continuous nature and occurs without any evidence of hysteresis in \( T_N \) as observed in heating and cooling runs \([4]\). Simultaneous measurement on an as received erbium crystal of the magnetic order parameter, using neutron scattering, and of the ultrasonic attenuation and velocity anomalies, indicate that the Néel temperature as observed with neutrons is 0.25 K lower than that indicated by ultrasonics. This difference, however, disappeared after annealing the crystal in vacuum at 950 °C \([4]\).

The critical exponent \( \beta \) that characterizes the sublattice magnetization was studied through neutron scattering on single crystal erbium. A study of the critical behaviour of the electrical resistivity was also conducted. Single crystals were obtained from Goodfellow (Cambridge, England) and have a purity of 99.99 %. Temperatures were controlled, using an Air Products refrigerator, to within ± 0.03 K for the neutron measurements and ± 0.01 K for the resistivity measurements. A temperature stabilization time of 15 min was allowed between successive temperature points in order to ensure thermal equilibrium conditions during measurements. The neutron measurements were performed in transmission mode on a thin disc shaped crystal. A \( \kappa\phi \)-diffractometer, employing 1.4 Å neutrons selected with a Ge (3 1 1) monochromator crystal, was used. The resistivity was determined by a standard four-point measurement on a \( c \) axis bar shaped crystal using a 7 decade potentiometer.

It is known that the magnetic order of Er is characterized by the occurrence of higher harmonics at lower temperatures \([1]\). Our measurements indicate that the third harmonic (e.g. \( 1 0 1 - 3 \delta \)) vanishes above 75 K and consequently the order parameter was studied by measurement of the intensity of the first order harmonic above this temperature. Integrated \( \omega - 2 \theta \) intensity scans through the \( 1 0 \delta \) magnetic satellite were performed as a function of temperature. The results, after subtraction of the background contribution, are depicted in figure 1. The observed intensity \( I \) is given by

\[
I = A t^{2 \beta} + C_- t^{-\gamma} + C_+ t^{-\gamma}. \tag{1}
\]

The reduced temperature is denoted by \( t = |(T - T_N)/T_N| \). The first term describes the spontaneous sublattice magnetization \( M \propto t^\beta \), while the following two terms, with amplitudes \( C_- \) and \( C_+ \), refer to the critical scattering below and above \( T_N \) respectively. From an analysis of the paramagnetic data it follows that \( \gamma = 1.45 \pm 0.2 \) and \( C_+ = 0.35 \pm 0.05 \) (broken line in Fig. 1). A correction for the critical scattering below \( T_N \) was made using Schofield's parametric representation of the equation of state \([5]\)

\[
C_- = \frac{\beta}{C_+} \left[ \frac{2 \beta (\gamma - 1)}{(1 - 2 \beta) \gamma} \right]^{(\tau - 1)}. \tag{2}
\]

The exponent \( \gamma \) is taken the same above and below \( T_N \), according to the scaling hypothesis. A least-squares fit of all measured data points (73 K to \( T_N \)) yields \( \beta = 0.48 \) and \( T_N = 80.5 \) K. Using these parameters, the first term in equation (1) is plotted by a broken line in figure 1 (fit B). A satisfactory fit to the experimental points is achieved. The effect of systematically deleting the lower temperature points from the \( \beta \)-analysis was investigated. It was found that the calculated value of

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\[ R(T) = \frac{A}{\alpha} \left[ |t|^{1-\alpha} / (1 - \alpha) - |t| \right] + B |t| + C \]

where \( \alpha \) is the specific heat critical exponent, \( A \) is the critical amplitude of the resistivity and \( B \) and \( C \) are constants. This equation was successfully used to describe the critical resistivity of Dy.

The temperature dependence of the resistance of the c axis bar shaped Er crystal is depicted in figure 2. Fitting of the experimental data against equation (3) using the Marquardt maximum-neighborhood method yield five constants above \( T_N \) and five below \( T_N \), the later which are denoted by primes. These are tabulated in figure 2. Values of \( C \) and \( T_N \) pertaining to the

\[ \beta \text{ decreases in a continuous manner. The solid line, fit A, in figure 1 shows the fit obtained if only measurements between 80.5 K and } T_N \text{ are considered and this yields a value of } \beta = 0.45. \text{ Two further fits for which the lowest temperatures were restricted to 84.08 K and 84.44 K are shown in the inset to figure 1 and yield values of } \beta = 0.41 \text{ and } \beta = 0.39 \text{ respectively. It is concluded that for sinusoidally ordered erbium the critical exponent } \beta \text{ assumes a value of } \beta = 0.39 \text{ near } T_N, \text{ and crosses over to a mean field value of } \beta = 0.5 \text{ at lower temperatures.} \]

For ferromagnets it is generally accepted that the specific heat and temperature derivative of the resistivity both have the same \( t^{-\alpha} \) dependence. The situation for antiferromagnets is more controversial, since superzone boundaries come into play. Balberg and Maman [6] as well as Malmström and Geldart [7] argued that "close enough" to \( T_N \) the effect of superzone boundaries leading to a dependence on the magnetization, can be neglected. Hence, for the critical region close to \( T_N \) the resistance is given by [6]

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