# Effect of commensurability on the temperature dependence of the angle of rotation of the magnetic helix in a single-crystalline dysprosium

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The temperature dependence of the angle of rotation $\varphi$ of the magnetic moments in a helicoidal antiferromagnetic phase has been studied in a single-crystalline dysprosium. An abrupt change in $\varphi$ has been detected at the points of commensurability of the periods of the crystal and magnetic structures.

Heavy rare-earth metals, terbium, dysprosium, and holmium, are now being studied extensively in order to detect anomalous behavior of various physical quantities at the commensurability points.[1–3] Between the Curie and Néel temperatures these rare-earth metals form a modulated (helicoidal) antiferromagnetic structure, whose period changes monotonically with temperature.[4,5] The long-wave modulation of the magnetic structure may be caused either by the anisotropy of the basal plane or by the interaction of the spins of a relativistic nature, which leads to linear derivatives in the order parameter in the expression for the free energy. [6,7] The temperature dependence of the wave vector describing this structure is generally different in these cases, especially near the commensurability points. Anomalies in the temperature dependence of the wave vector near the commensurability points have recently been observed in holmium and erbium in experiments on the scattering of synchrotron radiation. The commensurability effects are largely determined by the purity of the samples and are strongly suppressed in imperfect crystals. On the other hand, impurities and crystal defects facilitate the retention of the helicoidal state in the paramagnetic region and lead to a reduction of the angle of the helicoid and to its "freezing" near the Néel temperature.[10] In pure single-crystal samples, however, there are no helicoidal spin correlations in the paramagnetic region and the helicoidal structure vanishes at the phase-transition point $T_N$ (upon heating).[11]

In this letter we report the results of a neutron-diffraction study of single-crystalline dysprosium with an electrical resistivity ratio 17 at 300 K and 4.2 K. We measured the angular position of the magnetic satellite relative to the nuclear (002) reflection at various temperatures[12]:

$$\varphi = \pi\left(\frac{2c\sin\theta}{\lambda} - l\right) ,$$

where $c$ is the lattice constant in the direction of the $c$ axis, $\lambda$ is the wavelength of the monochromatic neutrons, $\theta$ is the angle at which the magnetic satellite is visible, and $l$ is the Miller index ($l = 2$).

Figure 1 shows the temperature dependence of the helicoid angle. A linear approximation for all experimental points was carried out by the method of least squares (curve 1). We see that the experimental points do not conform well to a straight line. On the other hand, abrupt changes in the helicoid angle are found to occur at certain temperatures near their commensurable values $\varphi_{ci}$.

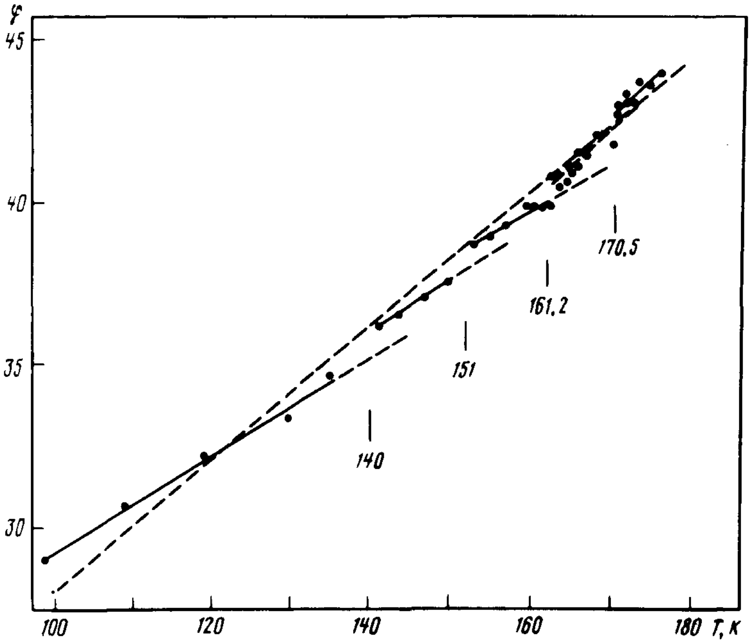


FIG. 1. Temperature dependence of the helicoid angle obtained upon heating the sample. The dashed line is drawn through all experimental points by the method of least squares and the straight-line segments are drawn through the set of points by the method of least squares. The vertical bars denote the commensurability temperatures.

Theoretically, such a temperature dependence of the wave vector is seen when the expression for the free energy contains terms which are linear in the gradients of the order parameter—the Lifshitz invariants, along with the terms which describe the crystalline anisotropy.[7] A minimization of the free-energy functional in this case leads to a nonlinear sine-Gordon equation for the order-parameter phase, which describes the "simple spiral" magnetic structure, $\eta = \rho e^{i\varphi}$ (where the amplitude $\rho = \text{const.}$) The problem involving the transition to the helicoidal state was first analyzed in this form by Dzyaloshinskii.[6] This problem was solved in terms of the amplitude elliptic function[7]

$$\varphi(z) = Am(qz, \kappa),$$

where $A$ and $\kappa$ are the numerical coefficients ($0 < \kappa < 1$), $q = \sqrt{v}/\kappa, v$ is the anisotropy parameter, and $z$ is a coordinate in the direction perpendicular to the basal plane. For finite $\kappa$ this solution describes a step function with a constant phase, where the width of the steps increases with increasing $\kappa$. Physically, this situation implies the appearance of a commensurate periodic structure which is divided by a soliton grating where the wave vector varies very rapidly. Such an abrupt variation of the wave vector can also be effected near the commensurability points by changing the temperature due to the change in the order-parameter amplitude.[6,7]

The experimental data which were obtained can be approximated by a linear dependence by dividing the entire temperature interval into regions separated by commensurability temperatures $T_{ci}$ after excluding their neighborhoods. Approximation of these regions by a linear function showed that the total mean square deviation, $(\Delta\varphi)^2 = 0.08$, in this case is an order of magnitude smaller than that of a linear approximation of all experimental points, $(\Delta\varphi)^2 = 9.45$.

On the basis of our experimental results we thus conclude that an unstable helical structure causes the angle of rotation of the helix to change abruptly in the neighborhood of the angles $\varphi_{ci}$. This abrupt change, which occurs in a narrow temperature interval ($< 0.5$ K), apparently can be described in terms of the theory advanced by Dzyaloshinskii[6] and Izyumov and Syromyatnikov.[7]


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