On the low-temperature behavior of the longitudinal magnetic susceptibility of chromium oxide

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Abstract

It is shown on the basis of phenomenological approach, that antiferromagnetic vector $\mathbf{L}$ in the AFM phase of chromium oxide may be collinearly canted from the 3-fold axis even in the case of weak external magnetic field $\mathbf{H}$; the finite (non-zero) magnitude of the longitudinal magnetic susceptibility in the low temperature region is also explained.

Key words: collinear cant; Cr_2O_3; longitudinal magnetic susceptibility

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1. Introduction

Antiferromagnetic Cr_2O_3 ($T_N = 310K$) corresponds to the magnetic point symmetry group $\bar{3}'m'$ [1], where the prime denotes the time reversal transformation. According to experimental data [2], the longitudinal magnetic susceptibility $\chi_{||}$ in Cr_2O_3 does not tend to zero at low temperature, but reaches some finite value. Our aim was to give a phenomenological explanation of temperature dependence of $\chi_{||}$ using the non-equilibrium thermodynamic potential [3], which is introduced with regard to symmetry limitations.

2. Phenomenological approach

In the antiferromagnetic (AFM) phase the phenomenological description of Cr_2O_3 is based on the thermodynamic potential, which is the polinomial expansion in magnetization vector $\mathbf{M}$ and the antiferromagnetic vector $\mathbf{L}$ and its components, invariant under transformations of the paramagnetic symmetry group [4] of Cr_2O_3 for the star $\{\mathbf{k} = 0\}$, that is $R(-3)c1'$ ($\bar{3}m1'$). We expand the Gibbs potential G to the second order in $\mathbf{M}$, and to the sixth order in $\mathbf{L}$ and its components [5]:

$$\begin{aligned} G = G_0 &+ \frac{1}{2}A\mathbf{L}^2 + \frac{1}{2}B\mathbf{M}^2 + \frac{1}{2}D(\mathbf{LM})^2 + \frac{1}{2}D'\mathbf{L}^2\mathbf{M}^2 \\ &+ \frac{1}{4}CL^4 + \frac{1}{6}IL^6 + \frac{1}{2}A'({L_x}^2 + {L_y}^2) \\ &+ \frac{1}{4}C'({L_x}^2 + {L_y}^2)^2 + \frac{1}{6}I'({L_x}^2 + {L_y}^2)^3 \\ &+ \frac{1}{4}KL_z(3{L_x}^2L_y - {L_y}^3) \\ &+ \frac{1}{6}K'L^2L_z(3{L_x}^2L_y - {L_y}^3) \\ &+ \frac{1}{6}R_1({L_x}^3 - 3L_x{L_y}^2)^2 \\ &+ \frac{1}{6}R_2(3{L_x}^2L_y - {L_y}^3)^2 - (\mathbf{MH}), \qquad (1) \end{aligned}$$

here z-axis is parallel to the 3-fold axis, and x-axis coincides with one of the two-fold axes.

We will further show that potential (1) allows the existence of phases with collinearly canted $\mathbf{L} = L\{\cos\phi\sin\theta, \sin\phi\sin\theta, \cos\theta\}$ ($\theta \neq 0$). Let's consider the angle ϕ values when $\mathbf{H} \parallel Oz$. As the consequence of collinear cant of spins from the 3-fold axis the magnetic symmetry group of the chromium oxide in AFM

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phase is either $2/m'$ ($\sin 3\phi \neq 0$) or $2'/m$ ($\sin 3\phi = 0$). On the other hand, it is known that in the spin-flop (SF) phase spins in the elementary cell of Cr_2O_3 lie along the two-fold axis [6,7], and the magnetic group corresponding to the spin-flop phase is $2'/m$. This means that the inequality

$$R_1 < \frac{-|K|}{L^2} + R_2 \tag{2}$$

is satisfied. Then it is reasonable to assume that in the AFM phase, of the minima of potential G corresponding to different values of ϕ, those are present in which $\sin 3\phi = 0$. Allowing for the equation $\sin 3\phi = 0$ in (1) we denote the part of G which depends on θ as G_θ. Constant K is renormalized to include K', and we introduce, as usual [3],

$$\chi_\perp = \{B + D'L^2\}^{-1} \tag{3}$$

$$\chi_{||} = \{B + (D + D')L^2\}^{-1}. \tag{4}$$

Then

$$\begin{aligned} G_\theta = \frac{1}{2}(\chi_\perp - \chi_{||})H^2 \cos^2\theta + \frac{A'}{2}L^2 \sin^2\theta \\ + \frac{C'}{4}L^4 \sin^4\theta + \frac{I'}{6}L^6 \sin^6\theta + \frac{R_1}{6}L^6 \sin^6\theta \end{aligned} \tag{5}$$

Minimising (5) with respect to θ we find that there may exist several phases corresponding to local minima of G_θ. Among them, for instance, are phases

$$\begin{aligned} G_\theta^1 &= \frac{1}{2}(\chi_\perp - \chi_{||})H^2, \quad \theta = 0; \\ G_\theta^2 &= \frac{A'}{2}L^2 + \frac{C'}{4}L^4 + \frac{I' + R_1}{6}L^6, \ \theta = \pi/2 \ (SF); \\ G_\theta^{3'''} &= \frac{1}{2}(\chi_\perp - \chi_{||})H^2 \cos^2\theta + \frac{A'}{2}L^2 \sin^2\theta \\ &\quad - |\frac{C'}{4}|L^4 \sin^4\theta - \frac{1}{6}|I' + R_1|L^6 \sin^6\theta. \end{aligned} \tag{6}$$

In the phase $G_\theta^{3'''}$ the value of $(\sin^2\theta)$ is defined as

$$\begin{aligned} \sin^2\theta_{1,2} = \left\{-C' \pm \sqrt{C'^2 - 4(I' + R_1)(A' - \chi h^2)}\right\} \\ \times \left\{2(I' + R_1)L^2\right\}^{-1}. \end{aligned} \tag{7}$$

Here $h = H/L$, $\chi = (\chi_\perp - \chi_{||})$. Phase $G_\theta^{3'''}$ can be present under following conditions on constants of (1):

$$\begin{aligned} 2|I' + R_1|L^2 > |C'| + \sqrt{C'^2 + 4|I' + R_1|(A' - \chi h^2)}, \\ C' < 0, \quad I' + R_1 < 0. \end{aligned} \tag{8}$$

As to which phase is realized depends on the magnitudes and signs of constants of the expression (1) for G. It is generally presumed that the terms of the expansion (1) decrease rapidly with the order of $\mathbf{L}$ and that the inequalities

$$A'L^2 >> C'L^4 >> (I' + R_1)L^6 \tag{9}$$

are satisfied. But these conditions must be broken to make the realization of "canting mechanism" which is considered in this paper possible. Then phase $G_\theta^{3'''}$ may become more energetically advantageous thanG_θ^1, which leads to collinear cant of spins.

3. Conclusion

As we can see, in certain temperature and external magnetic field region the angle θ may not be equal to zero, and that is why the observed longitudinal magnetic susceptibility χ_z ($\mathbf{H} \ || \ Oz$) differs from the true longitudinal magnetic susceptibility $\chi_{||}$, namely:

$$\chi_z = \chi_{||}\chi_\perp \left(B + [D' + D\sin^2\theta]L^2\right). \tag{10}$$

This analysis shows that when one describes low-temperature effects in chromium oxide, the "standard" expansion to the second order in $\mathbf{M}$ and $\mathbf{L}$ vectors is not sufficient. From the microscopic point of view this means that one should take into account the anisotripy energy — $\mathbf{S_R}\Phi_{\mathbf{RR'}}\mathbf{S_{R'}}$ [4], where $\Phi_{\mathbf{RR'}}$ is proportional to the square of the spin-orbit coupling constant.

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