*International Tables for Crystallography* (2006). Vol. D, Figure 1.5.7.1, p. 135.



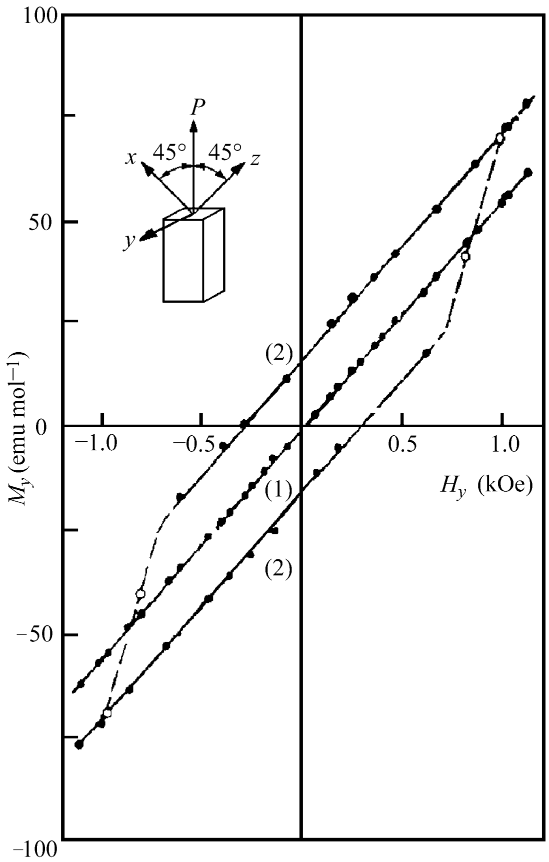


Fig. 1.5.7.1. The dependence of the magnetic moment of $CoF_2$ on the magnetic field. (1) Without stress; (2) under the stress $T_{xz} = 33.3$ MPa (Borovik-Romanov, 1960).

$$\begin{aligned}\tilde{\Phi} = \tilde{\Phi}_0 &+ (A/2)\mathbf{L}^2 + (a/2)(L_x^2 + L_y^2)\\ &+ (B/2)\mathbf{M}^2 + (b/2)(M_x^2 + M_y^2)\\ &+ d(L_xM_y + L_yM_x)\\ &+ 2\lambda_1(M_xT_{yz} + M_yT_{xz})L_z\\ &+ 2\eta_1(L_yT_{yz} + L_xT_{xz})L_z\\ &+ 2\lambda_2M_zL_zT_{xy} + 2\eta_2L_xL_yT_{xy} - \mathbf{MH}. \qquad (1.5.7.5)\end{aligned}$$

In this expression, the sums $(T_{ij} + T_{ji})$ that appear in the magnetoelastic terms have been replaced by $2T_{ij}$, as $T_{ij} \equiv T_{ji}$.

The analysis of expression (1.5.7.5) in the absence of stresses proves that fluorides may possess weak ferromagnetism provided that $a < 0$ ($L_z = 0$) (see Section 1.5.5.1). Here we shall discuss the easy-axis structure of the fluorides $MnF_2$, $CoF_2$, $FeF_2$ (see Fig. 1.5.5.3*b*). In the absence of magnetic fields and stresses only $L_z \neq 0$ for this structure. All other components of the vector **L** and the magnetization vector **M** are equal to zero. The magnetic point group is $\boldsymbol{D}_{4h}(\boldsymbol{D}_{2h}) = 4'/mmm'$.

To transform the potential $\tilde{\Phi}(L_i, M_j, T_{k\ell})$ [(1.5.7.5)] into the form $\Phi(T, \mathbf{T}, \mathbf{H})$ [(1.5.7.1)], one has to insert into the magnetoelastic terms the dependence of the components of **L** and **M** on the magnetic field. The corresponding relations, obtained by minimization of (1.5.7.5) without the magnetoelastic terms, are

$$\begin{aligned} M_x &= \frac{a}{a(B+b)-d^2}H_x; \quad & L_x &= -\frac{d}{a(B+b)-d^2}H_y;\\ M_y &= \frac{a}{a(B+b)-d^2}H_y; \quad & L_y &= -\frac{d}{a(B+b)-d^2}H_x; \qquad (1.5.7.6)\\ M_z &= \frac{1}{B}H_z; & L_z &\simeq \text{constant}.\end{aligned}$$

To a first approximation, the component $L_z$ does not depend on the magnetic field.

Inserting the relations (1.5.7.6) for $M_i$ and $L_i$ into the magnetoelastic terms of (1.5.7.5), one gets the following expression for the corresponding terms in $\Phi(T, H_i, T_{jk})$:

$$\begin{aligned}\Phi(T, H_i, T_{jk}) = \Phi_0(T, H_i) &+ 2L_z\frac{a\lambda_1 - d\eta_1}{a(B+b)-d^2}T_{yz}H_x\\ &+ 2L_z\frac{a\lambda_1 - d\eta_1}{a(B+b)-d^2}T_{xz}H_y + 2L_z\frac{\lambda_2}{B}T_{xy}H_z. \qquad (1.5.7.7)\end{aligned}$$

In this case, the expression for the magnetoelastic energy contains only three components of the stress tensor: $T_{yz}$, $T_{xz}$ and $T_{xy}$. Using (1.5.7.2), we get formulas for the three main components of the piezomagnetic effect:

$$M_x = 2L_z\frac{d\eta_1 - a\lambda_1}{a(B+b)-d^2}T_{yz} = 2\Lambda_{xyz}T_{yz} = \Lambda_{14}T_4, \qquad (1.5.7.8)$$

$$M_y = 2L_z\frac{d\eta_1 - a\lambda_1}{a(B+b)-d^2}T_{xz} = 2\Lambda_{yxz}T_{xz} = \Lambda_{25}T_5, \qquad (1.5.7.9)$$

$$M_z = -2L_z\frac{\lambda_2}{B}T_{xy} = 2\Lambda_{zxy}T_{xy} = \Lambda_{36}T_6. \qquad (1.5.7.10)$$

In all three cases, the piezomagnetic moment is produced in the direction perpendicular to the shear plane. Comparing (1.5.7.8) and (1.5.7.9), we see that $\Lambda_{25} = \Lambda_{14}$. This is in agreement with the equivalence of the axes *x* and *y* in the tetragonal crystals. If the stress is applied in the plane *xz* (or *yz*), the vector **L** turns in the shear plane and a component $L_x$ (or $L_y$) is produced:

$$L_x = 2L_z\frac{\eta_1(B+b) - d\lambda_1}{a(B+b)-d^2}T_{xz}. \qquad (1.5.7.11)$$

For $T_{xy}$ stress, no rotation of the vector **L** occurs.

Formulas (1.5.7.8)–(1.5.7.10) show that in accordance with Table 1.5.7.1 the form of the matrix $\Lambda_{i\alpha}$ for the magnetic point group $\boldsymbol{D}_{4h}(\boldsymbol{D}_{2h}) = 4'/mmm'$ is

$$\boldsymbol{\Lambda}_{i\alpha} = \begin{bmatrix} 0 & 0 & 0 & \Lambda_{14} & 0 & 0\\ 0 & 0 & 0 & 0 & \Lambda_{14} & 0\\ 0 & 0 & 0 & 0 & 0 & \Lambda_{36}\end{bmatrix}. \qquad (1.5.7.12)$$

The relations (1.5.7.8)–(1.5.7.10) show that the components of the piezomagnetic tensor $\Lambda_{ijk}$ are proportional to the components of the antiferromagnetic vector **L**. Thus the sign of the piezomagnetic moment depends on the sign of the vector **L** and the value of the piezomagnetic effect depends on the domain structure of the sample (we are referring to S-domains). The piezomagnetic moment may become equal to zero in a polydomain sample. On the other hand, piezomagnetism may be used to obtain single-domain antiferromagnetic samples by cooling them from the paramagnetic state in a magnetic field under suitably oriented external pressure.

There are relatively few publications devoted to experimental investigations of the piezomagnetic effect. As mentioned above, the first measurements of the values of the components of the tensor $\Lambda_{ijk}$ were performed on crystals of $MnF_2$ and $CoF_2$ (Borovik-Romanov, 1960). In agreement with theoretical prediction, three components were observed: $\Lambda_{xyz} = \Lambda_{yxz}$ and $\Lambda_{zxy}$. The largest value obtained for these components was $\Lambda_{14} = 21 \times 10^{-10}$ Oe$^{-1}$. The piezomagnetic effect was also observed for two modifications of $\alpha$-$Fe_2O_3$ (Andratskii & Borovik-Romanov, 1966). The magnetic point group of the low-temperature modification of this compound is $\boldsymbol{D}_{3d} = \bar{3}m$. In accordance with form (7) given above, the following nonzero components $\Lambda_{ijk}$ were found for the low-temperature state:

$$\Lambda_{xyz} = -\Lambda_{yxz}, \qquad (1.5.7.13)$$

$$\Lambda_{yyy} = -\Lambda_{yxx} = -\Lambda_{xxy}. \qquad (1.5.7.14)$$

  references