Elastic and photoelastic properties of gadolinium molybdate crystals near a phase transition

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We measure the temperature dependences of the damping and velocity of longitudinal elastic waves with frequencies between 500 and 1000 MHz in gadolinium molybdate crystals near the phase transition. The temperature dependences of some photoelastic constants are also measured. Calculations of the elastic, velocity, and photoelastic parameters are carried out with account taken of a two-component order parameter. The theory is shown to describe the experimental results satisfactorily. Some coefficients in the free energy expansion are determined by comparing the experimental data with theoretical calculations.

Gadolinium molybdate ($Gd_2(MoO_4)_3$ is a ferroelectric crystal (Curie temperature 159°C), for which the spontaneous polarization is not a transition parameter.[1] The elastic and photoelastic properties of such crystals in the region of a phase transition should differ from the properties of ordinary ferroelectrics. The elastic properties (attenuation and velocity) of crystals of gadolinium molybdate were studied in[2,3]; however, these studies were carried out at low frequencies and were not exhaustive. In the present work, the problem has been set up of carrying out a measurement of the temperature dependence of the attenuation and velocity of high-frequency elastic waves and the temperature dependence of photoelastic constants in the region of a phase transition, and of comparing the experimental results with the theory for a ferroelectric with a two-component order parameter.

1. EXPERIMENTAL METHOD AND EXPERIMENTAL RESULTS

For measurement of the elastic and photoelastic constants of crystals, a method of Bragg scattering of light by elastic waves was used (λ_0 = 6328 Å). Longitudinal elastic waves with a frequency of 500-1000 MHz were excited by means of a lithium niobate piezoelectric transducer. The samples had average linear dimensions of about 1 cm. To make the temperature measurements, we used an optical thermostat, the temperature in which was changed from 20 to 200°C and stabilized to within 0.02°C. The attenuation coefficient of elastic waves Γ (in decibels per unit length) was calculated from the formula

$$\Gamma = \frac{10}{x_2 - x_1} \lg \frac{I(x_1)}{I(x_2)},$$

where $I(x_1)$ and $I(x_2)$ are the intensity of the scattered light at the points x_1 and x_2 along the direction of propagation of the elastic wave.

The possibility of carrying out measurements for $x_2 - x_1 \approx 1$ mm allowed us, first, to determine the high value of the attenuation and, second, practically to eliminate the effect on the results of the measurements of temperature gradients which in our experiments amounted to about 0.03 deg/mm. The velocity of the elastic waves was calculated from the scattering formula

$$v = \lambda_0 \nu / 2 \sin \theta_B,$$

where ν is the frequency of the elastic waves, θ_B the external Bragg angle. The scattering angles were measured by means of a GS-5 goniometer, on the stage of which attached the thermostat with the sample. The temperature dependences of the photoelastic constants were determined from the temperature dependences of the scattering intensity, attenuation and velocity of elastic waves.

All the measurements were carried out on single-domain samples. A small mechanical pressure was applied to the samples during the process of measurement to maintain the single-domain character. In certain samples, transparent electrodes were attached on the faces perpendicular to the Z axis. Through these electrodes, a constant electric field could be applied to the sample or it could be short-circuited. The accuracy of the measurements of the attenuation and the velocity amounted to about 10 and 1%, respectively. Inasmuch as the measurements of the photoelastic constants were carried out without a standard, the accuracy of these measurements did not exceed 30%.

The results of certain measurements are given in Figs. 1–4. As the transition temperature is approached from the ferroelectric phase, the damping of the elastic waves for propagation along the $\tilde{X}$ and X axes increases, while their velocity decreases, even in the temperature range far from the transition point (here and below, the notation XYZ applies to the axes of the ferroelectric phase and $\tilde{X}\tilde{Y}Z$ to the axes of the paraphase). Near the transition point, the damping increases by almost an order of magnitude while the velocity

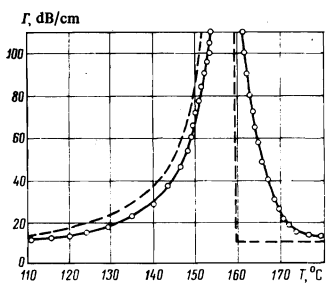

FIG. 1

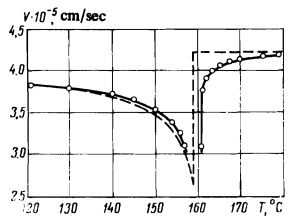

FIG. 2

FIG. 1. Temperature dependence of the attenuation of longitudinal elastic waves propagating along the $\tilde{X}$ axis. The frequency of the elastic waves here and in the subsequent drawings is 550 MHz. The dashed line is that calculated from Eq. (11).

FIG. 2. Temperature dependence of the velocity of longitudinal waves for propagation along the $\tilde{X}$ axis. The dashed line is that calculated from Eq. (11).

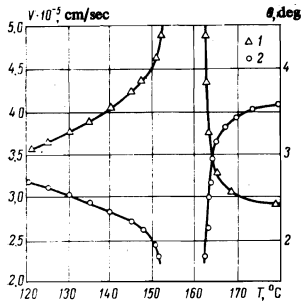

FIG. 3

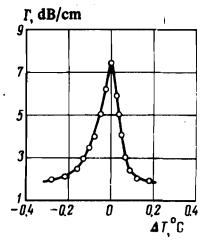

FIG. 4

FIG. 3. Temperature dependence of the Bragg angle (1) and velocity (2) for longitudinal waves along the X axis.

FIG. 4. Temperature dependence of the attenuation of longitudinal waves propagating along the Z axis.

fall off by a factor of 1.5 (the temperature dependence of the Bragg angle is also shown in Fig. 3. (The temperature dependence of the velocity can be calculated from it.) In the paraphase, the attenuation and velocity of the elastic waves change more rapidly with temperature than in the ferroelectric phase. In the range of temperatures adjacent to the transition point, the damping turned out to be so large that it was not possible to measure it. From an investigation of this temperature region, it follows, however, that no significant decrease in the attentuation is observed at the transition point. This decrease had been discovered at very low frequencies in [2].

Measurements of the frequency dependence of the damping of elastic waves of the types considered have shown that this dependence is close to quadratic. The imposition of an electric field of 5 kV/cm along the Z axis of the crystal led to a shift in the temperature dependence of the velocity and attenuation by ~2°C in the direction of higher temperatures, while the forms of the dependences themselves did not change.

For longitudinal waves propagating along the Z axis (Fig. 4), an anomalous change in the attenuation takes place in a narrow temperature range near the transition point, and the temperature dependence of the attenuation is almost symmetric relative to the transition point. The velocity of these elastic waves does not depend on the temperature within the limits of accuracy of the measurements. The photoelastic constants, as measurements have shown, do not change with changing temperature over the range of temperatures studied, again within the limits of accuracy of the measurements.

2. CALCULATION OF THE ELASTIC AND PHOTOELASTIC CONSTANTS

For comparison of the experimental results with theory, a calculation was made of the attenuation and velocity of the elastic waves. These calculations are carried out in principle in exactly the same way as in the well-known work of Landau and Khalatnikov.[5] The complications of the calculation are connected only with the fact that the order parameter in gadolinium molybdate is a two-component parameter.

We write down the equations of motion for the components of the order parameter and calculate their increase under the action of the prescribed elastic wave. The inertial effects will not be taken into account, so that only the expressions for the free energy and the dissipation function will be necessary for writing down the equations of motion. The part of the free energy dependent on the order parameters takes the form[6] (for the sake of compactness of writing, the notation is changed somewhat here)

$$F=\tfrac{1}{2}\alpha r^2+\tfrac{1}{4}\beta_1 r^4+\tfrac{1}{4}\beta_2 r^4\sin 4(\varphi-\varphi_0)+\tfrac{1}{6}\xi r^6+\delta_1 u_{zz}r^2 +\delta_2(u_{\tilde{x}\tilde{x}}+u_{\tilde{y}\tilde{y}})r^2+\delta_3 u_{\tilde{x}\tilde{y}}r^2\sin 2(\varphi-\varphi_0), \quad (1)$$

r, φ are the polar coordinares in the plane of the order parameters[6]. $u_{\tilde{i}\tilde{k}}$ are the components of the deformation tensor on the axes of the paraphase. The coupling between the order parameters and the polarizations is small[1] and is not taken into account here. The coefficient α depends linearly on the temperature:

$$\alpha=\alpha_c+a(T-T_c), \quad \alpha_c=3(\beta_2-\beta_1)^2/16\xi,$$

while the other coefficients are constant, and $\beta_2 \geq 0$, $\xi > 0$ and, inasmuch as the transition is a first order transition, $\beta_2 > \beta_1$. There is at most one quadratic invariant of the order parameter; therefore the dissipative function

$$\psi=\tfrac{1}{2}\mu(\dot{r}^2+r^2\dot{\varphi}^2)$$

depends only on one constant coefficient μ.

The coupling between the order parameter and the elastic deformations is assumed to be small, so that the effect of spontaneous deformation on the order parameter can be neglected when not too close to the transition point. Then, for $T < T_C$, the free energy reaches a minimum for[7]

$$r^2=r_0^2\equiv\frac{1}{2\xi}[\beta_2-\beta_1+\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}],$$

$$\varphi=\varphi_0\equiv\varphi_\beta-\frac{\pi}{8}+n\frac{\pi}{2},$$

where n is an integer. The values of φ_0, which differ by $\pi/2$, correspond to a domain with a different direction of polarization, and those which differ by π, to one and the same macroscopic state.[8]

In the presence of the elastic wave, characterized by the tensor u_{ik}, r and φ take on the increments Δr and $\Delta\varphi$, which satisfy the equations

$$\mu\Delta\dot{r}+2r_0^2\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}\,\Delta r=-(\partial^2F/\partial r\partial u_{ik})_0 u_{ik}, \quad (2)$$

$$\mu r_0^2\Delta\dot{\varphi}+4\beta_2 r_0^4\Delta\varphi=-(\partial^2F/\partial\varphi\partial u_{ik})_0 u_{ik}, \quad (3)$$

where the zero subscript on the derivatives indicates that they refer to the state of equilibrium. It must be noted here that the terms of the free energy which guarantee the coupling between the order parameter and the deformations are proportional to r^2. By virtue of this, the right-hand sides of Eqs. (2) and (3) are equal to zero above the transition point when r = 0, so that the propagation of the elastic wave in the linear approximation does not produce a change in the order parameter. In this connection, the gadolinium molybdate behaves in a manner similar to the usual ferroelectric that does not have a piezoeffect in the paraphase.

Setting $u_{ik} \sim \exp(-i\omega t)$, we obtain

$$\Delta r=-\frac{1}{1-i\omega\tau_r}\frac{1}{2r_0^2\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}}\left(\frac{\partial^2F}{\partial r\,\partial u_{ik}}\right)_0 u_{ik},$$

$$\Delta\varphi=-\frac{1}{1-i\omega\tau_\varphi}\frac{1}{4\beta_2 r_0^4}\left(\frac{\partial^2F}{\partial\varphi\partial u_{ik}}\right)_0 u_{ik}.$$

It turns out that, in spite of the fact that the dissipative function is characterized by a single coefficient, the

modulus r and the phase φ of the order parameter have different relaxation times:

$$\tau_r=\frac{\mu}{2r_0^2\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}},\quad \tau_\varphi=\frac{\mu}{4\beta_2 r_0^2}.$$

The existence of Δr and $\Delta\varphi$ leads to a contribution to the elastic stress tensor

$$\Delta\sigma_{ik}=\left(\frac{\partial^2 F}{\partial u_{ik}\partial r}\right)_0\Delta r+\left(\frac{\partial^2 F}{\partial u_{ik}\partial\varphi}\right)_0\Delta\varphi=\Delta c_{iklm}u_{lm},$$

where

$$\Delta c_{iklm}=-\frac{1}{1-i\omega\tau_r}\frac{1}{2r_0^2\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}}\left(\frac{\partial^2 F}{\partial r\,\partial u_{ik}}\right)_0\left(\frac{\partial^2 F}{\partial r\,\partial u_{lm}}\right)_0 -\frac{1}{1-i\omega\tau_\varphi}\frac{1}{4\beta_2 r_0^4}\left(\frac{\partial^2 F}{\partial\varphi\,\partial u_{ik}}\right)_0\left(\frac{\partial^2 F}{\partial\varphi\,\partial u_{lm}}\right)_0 \tag{4}$$

is the contribution to the elastic modulus tensor c_{iklm}. The change in the polarization in the elastic wave, connected with the piezoeffect, leads to a similar contribution. However, in contrast with the usual ferroelectrics, this contribution in the case of gadolinium molybdate does not depend on the temperature and therefore it is convenient to include it in the bare tensor c_{iklm}, i.e., taken for an order parameter equal to zero.

The complex contribution to the elastic modulus tensor leads to damping and to renormalization of the velocity of the elastic wave:

$$\Gamma=-\frac{\operatorname{Im}\Delta c_{uqqu}}{c_{uqqu}}\frac{\omega}{v},\quad \frac{\Delta v}{v}=\frac{1}{2}\frac{\operatorname{Re}\Delta c_{uqqu}}{c_{uqqu}}. \tag{5}$$

Here the indices u and q denote the directions of polarization and the wave vector of the elastic wave.

Using formulas (4), (5), we write out the damping coefficient and the contribution to the sound velocity for several cases. In propagation of an elastic wave along the $\tilde{X}$ axis, we have

$$\Gamma=\frac{2\delta_2^2}{\tilde{c}_{11}v}\frac{1}{\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}}\frac{\omega^2\tau_r}{1+\omega^2\tau_r^2},$$
$$\frac{\Delta v}{v}=-\frac{\delta_2^2}{\tilde{c}_{11}}\frac{1}{\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}}\frac{1}{1+\omega^2\tau_r^2}, \tag{6}$$

and for the case of propagation along the X axis,

$$\Gamma=\frac{2[\delta_2-\delta_3\sin 2(\varphi_0-\varphi_\delta)]^2}{c_{11}v\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}}\frac{\omega^2\tau_r}{1+\omega^2\tau_r^2}+\frac{\delta_3^2\cos^2 2(\varphi_0-\varphi_\delta)}{c_{11}v\beta_2}\frac{\omega^2\tau_\varphi}{1+\omega^2\tau_\varphi^2}$$
$$\frac{\Delta v}{v}=-\frac{[\delta_2-\delta_3\sin 2(\varphi_0-\varphi_\delta)]^2}{c_{11}\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}}\frac{1}{1+\omega^2\tau_r^2}-\frac{\delta_3^2\cos^2 2(\varphi_0-\varphi_\delta)}{2c_{11}\beta_2}\frac{1}{1+\omega^2\tau_\varphi^2} \tag{7}$$

In the case of propagation along the Y axis, the corresponding formulas differ from (7) by the replacement of δ_3 by $-\delta_3$, and along the Z axis, we have

$$\Gamma=\frac{2\delta_1^2}{c_{33}v}\frac{1}{\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}}\frac{\omega^2\tau_r}{1+\omega^2\tau_r^2}$$
$$\frac{\Delta v}{v}=-\frac{\delta_1^2}{c_{33}}\frac{1}{\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}}\frac{1}{1+\omega^2\tau_r^2}. \tag{8}$$

For a transverse elastic wave, polarized along $\tilde{Y}$ and propagating along $\tilde{X}$,

$$\Gamma=\frac{\delta_3^2}{2\tilde{c}_{66}v}\omega^2\left[\frac{\sin^2 2(\varphi_0-\varphi_\delta)}{\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}}\frac{\tau_r}{1+\omega^2\tau_r^2}+\frac{\cos^2 2(\varphi_0-\varphi_\delta)}{2\beta_2}\frac{\tau_\varphi}{1+\omega^2\tau_\varphi^2}\right],$$
$$\frac{\Delta v}{v}=-\frac{\delta_3^2}{4\tilde{c}_{66}}\left[\frac{\sin^2 2(\varphi_0-\varphi_\delta)}{\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}}\frac{1}{1+\omega^2\tau_r^2}+\frac{\cos^2 2(\varphi_0-\varphi_\delta)}{2\beta_2}\frac{1}{1+\omega^2\tau_\varphi^2}\right] \tag{9}$$

and for a wave polarized along Y and propagating along X, the coupling constant vanishes and, consequently, the correction to the velocity of the elastic wave and also to the damping coefficient vanish.

All the temperature dependences are determined by the temperature dependence of the expression

$$\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}=(\beta_2-\beta_1)\left[\frac{1}{4}+\frac{4a\xi}{(\beta_2-\beta_1)^2}(T_c-T)\right]^{1/2}.$$

The coefficients for $(T_C - T)$ can be determined from the measurements of the jump in the specific heat at constant electric field and pressure $\Delta C = 6\times10^{-3}$ cal/g-deg[9] and the entropy jump $\Delta S = 0.7$ cal/mole-deg.[9,10] Using the expressions

$$\Delta S=\frac{3}{8}\frac{\beta_2-\beta_1}{\xi}a,\quad \Delta C=\frac{T_c a^2}{\beta_2-\beta_1},$$

we get $4a\xi/(\beta_2-\beta_1)^2\cong 10^{-1}$ deg^{-1}. This numerical value gives excellent agreement between the theoretical temperature dependence of the polarization and the experimental results,[11] with the exception of the vicinity of the transition point of the order of 5°.

We consider further the photoelastic properties of the crystals. They are determined by the dependence of the reciprocal dielectric permittivity tensor ϵ^{-1}_{ik} on the deformations. In order to take account of the contribution to ϵ^{-1}_{ik} from the order parameter, we must make use of the fact that the tensor properties of ϵ^{-1}_{ik} are identical with the properties of the stress tensor ϵ_{ik}, the form of which is determined by the free energy (1). We have

$$\tilde{\varepsilon}^{-1}_{11}=(\tilde{\varepsilon}^{-1}_{11})_{\substack{u_{ik}=0\\ r=0}}+\tilde{p}^0_{11}u_{\tilde{x}\tilde{x}}+\tilde{p}^0_{12}u_{\tilde{y}\tilde{y}}+\tilde{p}^0_{13}u_{zz}+g_1r^2,$$
$$\tilde{\varepsilon}^{-1}_{33}=(\tilde{\varepsilon}^{-1}_{33})_{\substack{u_{ik}=0\\ r=0}}+\tilde{p}^0_{31}u_{\tilde{x}\tilde{x}}+\tilde{p}^0_{31}u_{\tilde{y}\tilde{y}}+\tilde{p}^0_{33}u_{zz}+g_3r^2,$$

where $\tilde{p}^0_{ik}$ are the photoelastic coefficients which are not connected with the order parameter. For the condition $\omega\tau_r \ll 1$, we get

$$\Delta\tilde{\varepsilon}^{-1}_{11}=\left[\tilde{p}^0_{11}-\frac{2g_2\delta_2}{\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}}\right]u_{\tilde{x}\tilde{x}},$$
$$\Delta\tilde{\varepsilon}^{-1}_{33}=\left[\tilde{p}^0_{33}-\frac{2g_3\delta_1}{\sqrt{(\beta_2-\beta_1)^2-4\alpha\xi}}\right]u_{zz}. \tag{10}$$

3. DISCUSSION OF THE RESULTS

The nearly quadratic frequency dependence of the damping, and also the absence of velocity dispersion, allow us to conclude that, at the frequencies used in the research, and for temperatures that are not too close to the transition point, the relation $\omega\tau \ll 1$ is satisfied. In this case, the formulas (6)–(8) for the attenuation and velocity of these types of waves, which have been studied experimentally, can be put in much simpler form.

Longitudinal waves along $\tilde{X}$:

$$\Gamma=\frac{2\delta_2^2\mu\xi}{\rho v^3(\beta_2-\beta_1)^3}\frac{\omega^2}{(1+\sqrt{t})t}$$
$$\frac{\Delta v}{v}=-\frac{\delta_2^2}{\rho v^2(\beta_2-\beta_1)}\frac{1}{\sqrt{t}}\quad t\equiv\frac{1}{4}+\frac{T_c-T}{10}. \tag{11}$$

longitudinal waves along X:

$$\Gamma=\frac{2[\delta_2-\delta_3\sin 2(\varphi_0-\varphi_\delta)]^2\mu\xi}{\rho v^3(\beta_2-\beta_1)^3}\frac{\omega^2}{t(1+\sqrt{t})}+\frac{\delta_3^2\mu\xi\omega^2\cos^2 2(\varphi_0-\varphi_\delta)}{2\rho v^3\beta_2^2(\beta_2-\beta_1)(1+\sqrt{t})},$$
$$\frac{\Delta v}{v}=-\frac{[\delta_2-\delta_3\sin 2(\varphi_0-\varphi_\delta)]^2}{\rho v^2(\beta_2-\beta_1)}\frac{1}{\sqrt{t}}-\frac{1}{2\rho v^2\beta_2^2}\delta_3^2\cos^2 2(\varphi_0-\varphi_\delta) \tag{12}$$

and longitudinal waves along Z:

$$\Gamma = \frac{2\delta_1^2\mu\xi}{\rho v^3(\beta_2-\beta_1)^3}\frac{\omega^2}{t+(1+\sqrt{t})}$$
$$\frac{\Delta v}{v} = -\frac{\delta_1^2}{\rho v^2(\beta_2-\beta_1)}\frac{1}{\sqrt{t}}. \quad (13)$$

It follows from a comparison of the experimental results shown in Figs. 1 and 2 for the wave $u_{\tilde{x}\tilde{x}}$ with Eq. (11) that in this case the tensor well describes the temperature dependences of the attenuation and velocity. The best correspondence between experiment and calculation is given for

$$\frac{\delta_2^2}{\beta_2-\beta_1} = 1.5\cdot 10^{11}\ \text{erg/cm}^3 \qquad \frac{\mu\xi}{(\beta_2-\beta_1)^2} = 4\cdot 10^{-12}\ \text{sec}.$$

It then follows that the expression for the temperature dependence of the relaxation time of the order parameter modulus is given by

$$\tau_r = \frac{4\cdot 10^{-12}}{\sqrt{t}(1+\sqrt{t})}\ [\text{sec}].$$

The agreement between theory and experiment should be expected only for temperatures that are not too close to the transition point, inasmuch as the coupling of the order parameter with the elastic wave cannot be regarded as weak close to this point; moreover, a large contribution to the attenuation and velocity can be made by the fluctuation mechanism, which is not taken into account in the theory. According to the theory, the attenuation and change in the velocity in the paraphase should be absent; therefore the experimentally observed dependences should as a whole be due to the fluctuation mechanism. The contribution of such a mechanism, as follows from the experimental results, turns out to be very important. This fact also explains the asymmetry of the temperature dependences of the attenuation and velocity; in the paraphase, these dependences are determined only by the fluctuations, and in the ferroelectric phase, both by the fluctuations and by the coupling with the order parameter.

The experimental results for longitudinal waves along the X axis can be explained qualitatively in the same fashion; however, a quantitative comparison is difficult to make, since Eqs. (12) contain two components and there exists considerable arbitrariness in the choice of the unknown parameters. The comparison of the results of the experiment for longitudinal waves along the Z axis with Eq. (13) shows that $\delta_1 \leq 10^{-1}\delta_2$.

Starting out from the symmetric form of the temperature dependence of the attenuation and a narrow range of temperatures, in which such a dependence exists, the conclusion can be made that the attenuation of this type of wave, both in the para- and in the ferroelectric phase, is determined by the fluctuation mechanism.[12] The small width of the temperature peak of the attenuation shows that for a longitudinal wave along the Z axis, the coupling with the fluctuations is significantly weaker than for longitudinal waves along and X and $\tilde{X}$ axes.

An interesting feature of the temperature dependence of the attenuation, due to coupling with the order parameter, is the relatively slow change in the attenuation upon departure from the transition point. For large coupling constants, such as is the case for longitudinal waves along the X and $\tilde{X}$ axes, this attenuation should be considerable even at room temperature (we note that the expansion (1) is still valid at room temperature, as follows from the data on the temperature dependence of the polarization). In the case of a small or zero coupling constant, the attenuation at room temperature should be determined only by the lattice mechanism, i.e., it should be less than in the first case. As shown in this research, the coupling constant is small for the wave u_{zz} and is equal to zero for the waves u_{xy} and $u_{\tilde{x}\tilde{z}}$. It follows from the experiment of[4] that the attenuation of these types of waves at room temperature is smaller by a factor of several fold than the attenuation of the waves u_{xx}, u_{yy} and $u_{\tilde{x}\tilde{x}}$, i.e., in actuality, the coupling with the order parameter can make a considerable contribution to the attenuation in temperature ranges that are far from the transition point. The large attenuation at room temperature is observed also for a wave of the type $u_{\tilde{x}\tilde{y}}$, i.e., the coupling constants in Eq. (9) are sufficiently large for this wave.

In conclusion, we consider the question of the temperature dependence of the photoelastic constants. In correspondence with the expressions obtained in Sec. 2, this dependence is determined by the contribution of mechanisms not connected with the phase transition, and the contribution from the order parameter. The first mechanism is practically independent of the temperature, and the temperature dependence of the contribution from the order parameter is determined, according to (10), by the expression $(1/4 + (T - T_c)/10)^{-1/2}$ with a coupling constant which includes the coefficients g, δ and $\beta_2 - \beta_1$. From the experimentally discovered lack of temperature dependence of the photoelastic constants, it follows that $g\delta/(\beta_2 - \beta_1) \lesssim 10^{-2}$.

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