Functional Materials 11, No.3 (2004)

Thermodynamical mechanisms of elastically anisotropy straining stresses in the changes of the phase transition and properties of magnetic dielectrics under *T*-*H*-*P* influence

P.I.Polyakov, S.S.Kucherenko

A.Galkin Donetsk Institute for Physics and Engineering,
National Academy of Sciences of Ukraine,
72 R.Luxembourg St., 83114 Donetsk, Ukraine

Basing on experimental investigations, the role of elastically anisotropic straining stresses in the formation and change of structural phase transitions and properties of magnetic dielectric have been proposed and explained. From experimental investigations of the resonance properties of $CuCl_2 \cdot 2H_2O$ single crystal, being a low-temperature magnetic dielectric, a correspondence between the T, H and P influence (1 K, 4 kOe, 3 kbar) on structural phase transition has been determined. The thermomagnetic and thermobaromagnetic effects have been revealed. Their peaks have the same temperature T_{PP} = 0 K coincident with the temperature T_{ST} of structural phase transition. Sign alternation in "cooling" and "heating" effects of $T_P(H)$ shifting are also found. The critical points P_X, T_X and P have the temperature parameter T_P = 9.2 K that differs significantly from the known T_N = 4.3 K in these materials. The magnetization, field-temperature, and field-frequency dependences have been considered, and a conformity in changes of the properties before and after the structural phase transition has been established. The effect of thermo-EAS striction is found, which is a regularity in the phase state changing under thermostriction influence in magnetic dielectric. The competitive mechanisms of thermo- and magnetostriction causing changes in the high-frequency properties give rise to two resonances before and after the structural phase transition.

На основе экспериментальных исследований предложен и пояснен механизм роли упругих анизотропных деформирующих напряжений в возникновении и изменениях фазовых переходов и свойств магнитных диэлектриков. Из экспериментальных данных по резонансным свойствам монокристалла $CuCl_2 \cdot 2H_2O$, являющегося низкотемпературным магнитным диэлектриком, определено соответствие между влиянием T, H и P (1 K, 4 kOe, 3 kbar) на структурный фазовый переход. Обнаружены термомагнитный и термобаромагнитный эффекты. Их максимумы имеют одинаковую температуру T_{PP} = 0 K, совпадающую с температурой T_{ST} структурного фазового перехода. Обнаружена также знакопеременность "охлаждающего" и "нагревающего" эффектов в сдвигах $T_P(H)$. Критические точки P_X, T_X и P имеют температурный параметр T_P = 9.2 K, значительно отличающийся от известного значения T_N = 4.3 K для этих материалов. Рассмотрены намагничивание, температурно-полевые и частотно-полевые зависимости и установлено соответствие в изменениях этих свойств до и после структурного фазового перехода. Обнаружен эффект термо-УДА стрикции, являющийся закономерностью изменения фазового состояния магнитного диэлектрика под влиянием магнитострикции. Конкурирующие механизмы термо- и магнитострикции, вызывающие изменения высокочастотных свойств, являются причиной двух резонансов до и после структурного фазового перехода.

Practically simultaneously, nontrivial phenomena were observed in the solid state physics. In experimental works [1, 2], a sudden correlation between electrical conductivity and ferromagnetic state in the initially dielectric manganese perovskite $LaMnO_3$ has been investigated and shown. In [3–5], unusual changes of magnetic, magneto-thermal, and resonance properties of low-temperature magnetic dielectric $CuCl_2 \cdot 2H_2O$ have been shown. The noted features and related phenomena were studied during last decade in detail. The results obtained have brought a significant contribution to fundamental physics of phase transitions. However, discovery of the so-called "super-effect", e.g. a colossal magnetoresistance of manganites in the Curie point vicinity and conductivity in HTSC, rise a question about the nature of the phenomena [6]. The understanding of the mechanisms of those effects and processes and also defining the causal base of phase transitions and properties would provide a considerable advance in application of the effects and would be an achievement of the physical science as a whole.

Now, there is a trend to investigate properties and phase transitions under temperature T, magnetic field H and a hydrostatic pressure P action. Significant results have been reached, and new effects and regularities have been revealed. We would pay attention to consequent and generalizing analysis of the data concerning changes in phase transitions (PT) and properties of magnetic semiconductors under T-P-H influence [7–11]. In these works, thermodynamic mechanisms of elastically anisotropic straining (EAS) stresses under temperature, magnetic field and pressure influence on the phase transitions and properties of manganites have been determined, and the sign alternation concept of T-H-P influence has been introduced. This makes possible to establish identical mechanisms of T-H-P influence on the structural phase transition and properties of other magnetic materials. The study of the low-temperature magnetic dielectric $CuCl_2 \cdot 2H_2O$ single crystal is the most representative in this case. From the first investigation data, the main concepts of models and theories of ferro- and antiferromagnetism were formulated [12–15].

The considerable attention to this magnetic dielectric and comprehensive investigation of its properties was reflected in numerous works [16–23]. One of the aims is the study of magnet-containing single crystal interaction with high-frequency electromagnetic field under applied magnetic field. It should be noted that the same fine resonance technique allows to solve a number of relevant thermodynamic problems concerning phase transitions and properties, and to determine a number of parameters, to test and evaluate the theoretical models, as well as to suggest the nature of explored physical processes. A comparative analysis of magnetization and high-frequency behaviors of $CuCl_2 \cdot 2H_2O$ single crystal [12, 14–18] depending on both temperature and magnetic field intensity has allowed to explain the properties and nature of antiferromagnetism (AFM). The fundamental theory of AFM and the basic states of its phase transition energy distribution are stated in [24, 25]. In monographs [26–28] and [29–32], the detailed theory considering the AFM features was described. In these works, the substantiation of fundamental phenomena and effects of antiferromagnetism in easy and hard planes was developed, the high-frequency properties of the meter and decimeter range in magnetic fields up to 15 kOe at temperatures $T < 4.2$ K were determined. This attracts attention to $CuCl_2 \cdot 2H_2O$ investigations, and the obtained results turned acceptable for a number of magnetic materials and they have much contributed to the fundamental bases of phase-transition physics.

One of the relevant directions in AFM experimental research is the study of resonance in $CuCl_2 \cdot 2H_2O$ single crystal under hydrostatic pressure [33–35]. In those works, extensive information on the phase equilibrium curves, the elastic and magnetoelastic parameters has been obtained, and the dependences of exchange and magnetic interactions on interatomic distances have been shown. Correlation between these results and research data for magnetic semiconductors [8–10], where elastically anisotropic straining nature and sign alternation of T-H-P influence has been established, allowed to define the main aim of this work: to establish an identical mechanism of temperature, magnetic field and pressure influence on properties and phase transitions in $CuCl_2 \cdot 2H_2O$ single crystal, and also to prove that these mechanisms are universal for both magnetic semiconductors and magnetic dielectrics.

Using the analytic methodology of the experiments with magnetic semiconductors [8–10], we try to consider the AFM resonance data in copper chloride dihydrate under T-H-P effect [34, 35]. The resonance has been observed at frequencies $\nu_1 = 0.7$ GHz, $\nu_2 = 2.85$–3.15 GHz and $\nu_3 = 4.5$–4.88 GHz in the temperature range $1.68 \leq T \leq 4.2$ K under hydrostatic pressures $P = 0$; 5.2; 9.2; 11.2 kbar by a specially developed method presented in [11]. The investigations have been carried out under thorough optical and X-ray orientation. In this case, of interest is the research of lattice features and anisotropy of elastic properties in $CuCl_2 \cdot 2H_2O$ along the marked directions at hydrostatic pressure [30].

Now let attention be paid to experimental technique. The external magnetic field in the range 0–12 kOe was oriented along the *ab* plane of the crystal. The resonance was observed at all the selected frequencies (except for $\nu_1 = 0.7$ GHz) in the pressure range 0–11.2 kbar at two values of magnetic field, if the angle ψ between the field direction H and the easy axis a did not exceed the AFMR failure angle ψ_f. At $\nu_1 = 0.7$ GHz, the resonance was observed only in magnetic field H_{2P} belonging to the phase transition field. The resonance disappeared at weak deviations of field H from axis a in the *ab*-plane. In the isochronous diagrams, the resonance absorption was observed reliably only at $T \leq 3.5$ K and $P = 0$ in the whole temperature range. As the pressure increases ($P > 9$ kbar), the temperature range of resonance is increased up to 4.2 K. We take the temperature-field dependences (Fig. 1a) of phase transition change $H_{st}(T) = H_P(T)$ under *T-H-P* effect from [34, 35]. It can be noted that $H_P(T)$ dependence at $H \| a$ has a peculiar character of linearity observed in [20, 36] in the temperature range up to 4.2 K at $P = 0$ (Fig. 1a, curve 1). Some discrepancy in numerical values is explained by high response of resonance parameters to the sample orientation with respect to magnetic field. However, the linearity on the dependences is maintained.

Form the linear regions of temperature-field dependences (Fig. 1a), we can estimate the conformity parameters of *T-H-P* influence on the phase transition shift. Using the approximation method, we can mark and numerically estimate the linear phase transition shifts at T and H variations (Fig. 1a) at fixed pressures $P_1 = 0$ kbar (curve 1), $P_2 = 5.2$ kbar (curve 2), $P_3 = 9.2$ kbar (curve 3) and $P_4 = 11.2$ kbar (curve 4). It is found that $\Delta P/\Delta T = 3$ kbar/K and $\Delta H/\Delta P = 1.3$ kOe/kbar. This means that temperature variation by $\Delta T = 1$ K and magnetic intensity variation by $\Delta H = 4$ kOe result in the same phase transition shift in $H_P(T)$ dependence as the pressure variation of $P = 3$ kbar. These results define numerical estimations for the *T-H-P* influence (1 K ~ 4 kOe ~ 3 kbar) proving a significant role of the EAS stress mechanism in the low-temperature range.

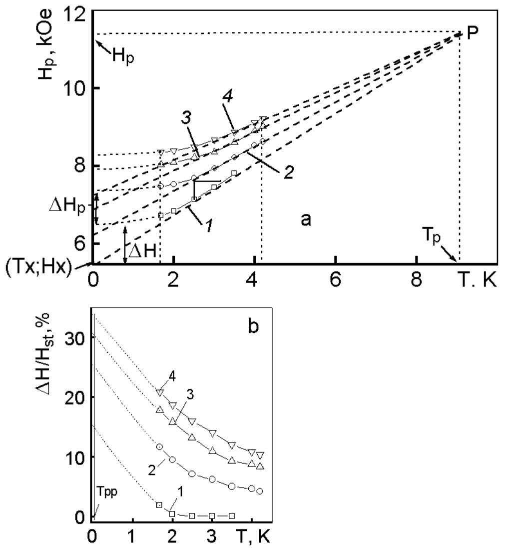

Fig. 1. Temperature-field dependence of the field of the phase transition at different pressures on a frequency $\nu = 0.73$ GHz: *1* — $P = 0$; *2* — $P = 5.25$ kbar; *3* — $P = 9.25$ kbar; *4* — $P = 11.2$ kbar. (b) Temperature dependence of thermomagnetic effect: *1* — $P = 0$ and thermobaromagnetic effect: 2 — $P = 5.25$ kbar; 3 — $P = 9.25$ kbar; 4 — $P = 11.2$ kbar.

The same T_{PP} temperature of magneto-, baro-, and baromagnetoresistive peaks has been established in magnetic semiconductors [8–10] coincident with T_{ms} temperature of metal-semiconductor phase transition that is the regularity of a structural phase transition. Using the same methods, we will show analogous regularities in magnetic dielectrics. We introduce the concept of thermomagnetic $(H_{st0} - H_{stH})/H_{st0}$ and thermobaromagnetic effects $(H_{st0} - H_{stHP})/H_{st0}$ (Fig. 1b) from temperature-field dependences (Fig. 1a). Here, H_{st0} is the basic parameter of intersection of linear approximation with field axis at the point $H_X = 5.5$ kOe at $P = 0$. H_{stH} is the regularity of structural phase transition shift under magnetic field; H_{stHP} is the variation of structural phase transition under magnetic field and pressure. These constructions and techniques grounding the final result are justified and do not contradict the physical sense as well. They show a possibility for subsequent analysis and conclusions that do not differ from the accepted ones.

The constancy and equality of maxima temperature for thermomagnetic and thermobaromagnetic effects are analogous to the same results in magnetic semiconductors. It follows (Fig. 1b) that the maxima of magneto-, baro- and baromagnetoresistive effects have the same temperature T_{PP} coincident with the temperature of structural metal-semiconductor phase transition. This made it possible to affirm that T_{PP} coincides with T_{ST} temperature of structural phase transition of the magnetic dielectrics. These results first published in [37] enable the following conclusions from the analysis of approximated dependence (Fig. 1a, curve 1). The numerical parameter $H_X \approx 5.5$ kOe is defined for detected critical point $T_X = 0$, showing that magnetoelastic anisotropy by "heating" effect [10] of the magnetic field realizes the structural phase transition at $H_X(T = 0) \approx 5.5$ kOe. The same regularities of the role of magnetoelastic anisotropy, but in stronger fields, has been marked by the critical line T_X with parameter $H_X(T = 0)$ [10]. This is seen in magnetostriction dependences of $LaMnO_3$ single crystal. These conclusions allow to define identical mechanisms of magnetoelastic anisotropy.

We would draw attention to correspondence estimations of P and H influences (3 kbar ~ 4 kOe) that shift the phase transition by the same magnitude as temperature elevation by 1 K. We will explain the importance of mechanisms of EAS stress of P and H influence, in regularities of "cooling" and "heating" effects in dynamics of $T_P(H)$ $T_P(H,P)$ dependences that was first revealed in [9, 10]. First, with magnetic field increasing at $P = 0$, the magnetoelastic striction mechanism in $T_P(H)$ dependence causes the "cooling" effect. For the phase transition realization in this case, an additional thermoelastic expansion is necessary and thus a temperature increase. T_{PP} remains constant. The inverse, "heating" effect is as follows: as the magnetic field strength drops, the magnetostriction influence weakens, and as temperature decreases, the thermo-EAS stress mechanism provides conditions necessary for the phase transition. In this case, T_{PP} remains constant again. Second, regularities of the effect of hydrostatic pressure and magnetic field simultaneous influence are the most interesting. Here, we mark a very important result: sign alternation of the effects. To overcome "supercooling" due to pressure rising up to 11.2 kbar, an additional change of the magnetic field strength close to H_X at $T = 0$ K plays a "heating" role down to critical point $T_{ST} = 0$ K where magnetoelastic anisotropy provides the phase transition. The further growth of magnetic field strength causes of "cooling" effect: this means that pressure and magnetic field shift the phase transition by the sign reversal mechanism of the effects. Conditions of phase transition realization remain constant, T_{PP} is a constant, too. Analogous "heating" effect of the magnetic field is realized in $LaMnO_3$ at the temperatures below the structural phase transition that is seen in $H_g(T)$ dependence [10].

This means that the "cooling" and the "heating" effects define the competition of baro- and magnetoelastic stresses on the one hand, and thermoelastic expansion on the other hand. The role of these mechanisms appears in sign reversal of properties and phase transitions that has been first established in [10]. Explicit correspondence of estimations of T-H-P influence on the phase transition shift allows to explain the linear and nonlinear regions of temperature-field dependences (Fig. 1a). As the temperature rises, the linear segment appears in the case of priority of the thermal expansion force over that of magnetoelastic compression. This is the explanation of $T_P(H)$, $T_P(H,P)$ behaviors. The role of both "cooling" and "heating" effects of P and H influence does not contradict the physical sense in this case.

It is to note that at different pressures, the temperature-field dependences of phase transitions (Fig. 1a) tend to approach to each other that allows to mark critical points P and T_X by approximation. The sense of such constructions is justified physically and is very significant. It is necessary to specify and generalize the regularities of the marked critical points. T_X is the original point of the approximated temperature-field dependence (Fig. 1a (curve 1)) with coordinates $H_0 = 5.5$ kOe and $T_0 = 0$ K. This result was already considered in [37], and the same coordinates have been obtained from the phase diagram. The same critical point is shown in Fig. 2c. Such construction means that the phase transition at $T = 0$ K and $H_X = 5.5$ kOe is realized by magnetoelastic anisotropy. The revealed critical point P is a result of the above considerations; it is fixed at the intersection of approximated temperature-field dependences under varying pressures (P_1, P_2, P_3, P_4) and has coordinates $T_P = 9.2$ K and $H_P = 11.5$ kOe (Fig. 1a). Note that the temperature parameter of critical point $T_P = 9.2$ K exceeds more than twice the critical tem-

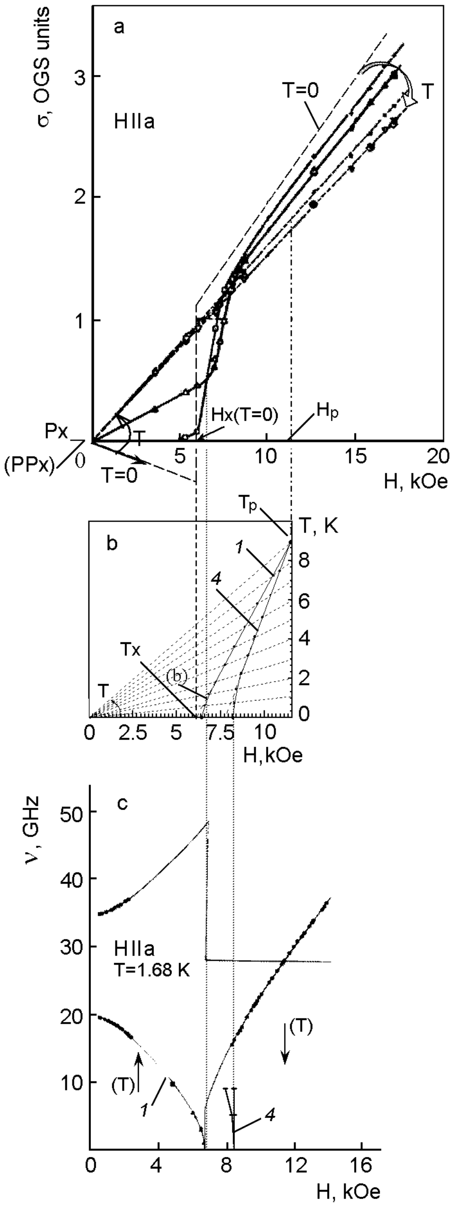

Fig. 2. Behavior of magnetization of $CuCl_2 \cdot 2H_2O$ monocrystal at external magnetic field directed along the easy axis: *1* — 1.59 K, *2* — 3.02 K, *3* — 4.1 K. (b) Temperature-field dependence of the field of the phase transition at pressures: *1* — $P = 0$; *2* — 11.2 kbar. (c) Frequency-field dependence of AFMR in $CuCl_2 \cdot 2H_2O$ at $H \| a$ and $T = 1.65$ K: *1* — $P = 0$, *2* — $P = 11.2$ kbar.

perature $T_N = 4.33$ K, known from numerous investigations [4, 5, 38]. As a consequence, the described reasoning and regularity of the obtained results has caused additional research of the true thermodynamic mechanism in the chosen magnetic dielectric.

To ascertain the features of these mechanisms, let the magnetic susceptibility in $CuCl_2 \cdot 2H_2O$ single crystal presented in [3] be considered (Fig. 2a). These results were among the main arguments for the formation of basic concepts of the antiferromagnetism model. The study of magnetization was done on single crystal samples in the form of disks (2.5×5 mm^3) oriented and fixed manually, without optical and the X-ray control, that gave a relevant error and affected further interpretation of the results. Fig. 2a illustrates the dynamics of magnetic susceptibility under H oriented along the easy axis at fixed temperatures T = 1.59; 3.02; 4.1 K. Here, some interesting features are to be noted:

(a) At $H < H_0$ (let $H_0 = H_{ST}$) and temperatures $T = 1.59$; 3.02; 4.1 K, the authors [3] observed slight changes in magnetic susceptibility vs. field rise dependence, while the temperature variation (thermoelastic striction) influences essentially the slope of magnetization. As the temperature rises, the dependence is deviated counter-clockwise. As a consequence, in the same figure it is possible to construct an approximation of the dependence (Fig. 2a, the dashed line) at $T = 0$ K, that does not contradict the logic of the experiment.

(b) At $H > H_0$ and for the same temperatures, a clockwise deviation of the dependence is observed with temperature rise. Behavior of the properties at $T = 0$ is marked by dashed line. The similar changes in the slopes of magnetostriction dependences at temperature rise are observed in a single crystal of the magnetic semiconductor $LaMnO_3$ [10]. This is explained by the changes due to the competitive effect of thermo- and magnetoelastic strictions.

To understand better the magnetization jump (Fig. 2a, dashed line), we superpose the behavior thereof with temperature-field dependences $T_P(H)$, $T_P(H,P)$ (Fig. 2b) using the method of common coordinates for both the magnetic field and temperature. Note that temperature axis is presented in angular coordinates. Such coordinates are more evident for explanation of the change in properties and phase transitions under thermo-, magneto- and baro-EAS stresses. But in these constructions and considerations, it is very difficult to to take into account the main error associated with the single crystal adjusting with respect to the magnetic field; however, the main tendencies are maintained.

The magnetization jump marked by dashed line is observed at the point with coordinates $T_X = 0$ K and $H_X = 5.5$ kOe (Fig. 2a), it defines the structural phase transition at temperature 0 K. Such methodology of the analysis is justified and agrees with analogous results in [10] but concerning $LaMnO_3$. The extrapolations of all the magnetization dependences intersect in one point P_X (PP_X). This is the regularity in changes of properties under the influence of magnetic field and temperature in magnetic dielectric. Such intersection is determined by symmetry and lattice features of $CuCl_2 \cdot 2H_2O$ structure before and after the phase transition (Fig. 2a). In contrast, the locations of critical points P_X and PP_X in magnetostriction dependence for $LaMnO_3$ are located at different sides of the phase transition. This is the regularity of magnetic semiconductors structural feature, because the position difference for these points is a result of structural variety of multicomponent magnetic systems.

The results presented and their substantiation are significant for the interpretation of regularities in changes, as well as in forming the properties and phase transitions in physics of low-temperature magnetic dielectrics and in other materials. This makes it possible, first, to define, basing on the described concepts and estimations of correspondences (Fig. 2a,b), the regularities of the phase transition change in the dynamics of magnetization and high-frequency properties under temperature effect and "cooling"/"heating" effect of magnetic field and pressure via the of EAS stress mechanism. Second, to demonstrate, taking the "cooling" effect of magnetic field influence on the phase transition $T_P(H)$ dependence as an example, a regularity of oppositely directed effect of thermostriction on changes in magnetization properties. This regularity is showned by the dashed line at $T = 0$ K. Such regularity establishes the presence of the elastically straining stress mechanism, that fixes the structural phase transition in a wide temperature range. Such redistribution of stresses under temperature influence can be treated as an effect of thermoelastic straining striction (Fig. 2a).

Now let the effect of thermoelastic straining striction be defined and explained. The changes in the structural phase transition taking into account the symmetry and lattice features at temperature variation via the EAS stress mechanism implement the conditions for jump-like changes in properties of the sample under study at the structural phase transition temperature $T_{ST} = 0$ K. In the dependence indicated in Fig. 1a by a dot-and-dash line, there is a jump and a maximum. This means that as the temperature rises, a sudden change in properties occurs in the region of phase transition due to the EAS compression mechanism, that has the form of a jump in the magnetization curve, and, as we think, a resistivity jump but already under the superconduction effect. Those are the regularities of lattice and symmetry features of the structure. In this case, the magnetic field causes the "cooling" and "heating" effects. Using these mechanisms and the effect of thermoelastic striction on the properties of other magnetic materials, we can trace the correlation with the obtained results. It was noted before that the understanding of regularities of structural phase transition in low-temperature magnetic dielectric $CuCl_2 \cdot 2H_2O$ is a key to superconducting effect insight and, as we think, to CMR effect in magnetic semiconductors as well as conductivity of HTSP materials.

The investigation of the role of the EAS stress mechanism in regularities of changes in phase transitions and properties defines the interest to determining the nature of high-frequency properties in $CuCl_2 \cdot 2H_2O$ under H and T influence. There are a lot of publications [12–18] devoted to resonance properties of copper chloride dihydrate in wide ranges of temperature and magnetic field. The most comprehensive explanation of models and theory using the molecular field approximation for the same sample is presented in [16, 17]. Changes in resonance properties in a rotating magnetic field has been theoretically explanined in [18, 23, 36]. However, the proposed models do not establish reliably the mechanisms, or define the constants, nor show the complete spectrum of the frequency-field dependences at fixed temperature $T = 0$ K. The extensive information on experimental investigations of low-temperature properties in a wide magnetic field range defines the direction of our analysis.

Let the low-frequency branch (Fig. 2c) of frequency-field dependence [36] be considered. It is consistent with the results described above (Fig. 2a,b,c). Here, it is easy to see the point b (Fig. 2c) that is located on the critical line $T_P(H)$. The point (b) with coordinates $H_{st} = 6.8$ kOe $T = 1.68$ K corresponds to the critical line $T_P(H)$ (Fig. 2c) that is a consequence of "cooling" effect of magnetic field on the phase transition change. In the initial segment of frequency dependence in weak fields and fixed thermoelastic expansion (T = 1.68 K), the non-linear dependence is a consequence of competitive influence of thermoelastic expansion and magnetostriction. Such non-linearity may be estimated using the correspondence described above. It is the pressure of 5 kbar that corresponds to the temperature 1.68 K. At temperatures exceeding the phase transition (Fig. 2c), with the same correspondence estimations, taking into account at fixed thermoelastic expansion (T = 1.68 K), the magnetoelastic compression became of priority. The field from 6.8 kOe and higher is adequate to pressure of 5 kbar and higher, respectively. It follows that the behavior of magnetization after the phase transition follows the behavior of magnetostriction in $LaMnO_3$ [10], where the temperature and magnetic field influences on properties are oppositely directed.

As a consequence, the low-frequency branch of the frequency-field dependence is nothing but plurality of different magnetic resonances in magnetic properties before and after the structural phase transition. All the above denotes the basic role of the established of EAS stress mechanisms of T and H influence, that is the reason for additional interpretation of resonance conditions differing from conventional ones. This will be discussed later on.

It should be noted that the revealed regularities prove that the EAS stress mechanisms of T-H-P influence are identical in low- as well as in high-temperature range. As a consequence, this allows to consider the phase diagram of $CuCl_2 \cdot 2H_2O$ [5, 18, 21], using namely the described mechanisms. The dependence shown in [5] allows to consider magnetic properties under account for the competitive mechanism of thermo-, magneto-EAS stresses, and "cooling" effect of the magnetic field. In its initial region, this dependence demonstrates a significant priority of thermoelastic expansion (close to 4.3 K). As the field increases, a slight change in properties results in the slope angle change before and after the phase transition. The phase transition dynamics in this case is a consequence of "cooling" effect of the magnetic field close to critical point P with coordinates (H_P,T_P). At further magnetic field increasing at fixed temperature, with correspondence estimations of T-H-P influences (1 K ~ 4 kOe ~ 3 kbar) taken into account, results in the priority change. This appears as non-linearity (sign reversal) of properties in high-intensity magnetic field. Such interpretation of the EAS stresses role forms a basis for explanation of the phase diagram regularities and of high-frequency properties [23] for the sample type considered. It is logically and physically justified by the described analysis.

The experimental detection of changes in properties can point to the presence of both critical points and lines. Establishing of their variety, conditions of existence, and attributes allow to judge the mechanism forming the behavior of magnetic susceptibility, heat capacity, resonance properties not only in the phenomenological models and theories, but it can also be a subject of independent investigations. Now, there is no consistent analysis of physical mechanism that is responsible for the variety of critical lines and points. No analytical methods have been developed to study thereof in both physically accessible and inaccessible regions, that is a missing link in a chain of scientific investigations. It is possible to fill the gap by analyzing the true thermodynamic mechanism of EAS stresses that realize physical regularities directly in described variety of critical lines and points and associate the symmetry and lattice structure features with phase transitions and properties.

To establish the role of the EAS stresses mechanism of T-H-P influence on magnetic susceptibility and high-frequency properties (Fig. 1a, Fig. 2a,b), we define regularities in the construction of both the critical lines and points in low-temperature magnetic dielectric. $T_P(H)$, $T_P(H,P)$ are the temperature field dependences of phase transitions shift under H and P influences; P_X, PP_X are intersection points of extrapolated linear dependences before and after the phase transitions (Fig. 2a). Those are due to structural features; T_X is the intersection point of the approximated temperature-field dependences. It has coordinates $T = 0$, $H_X(T = 0) =$ 5.5 kOe (Fig. 1a, Fig. 2a, b); P is the critical point with coordinates $T_P = 9.2$ K, $H_P =$ 11.5 kOe that is formed by intersection of approximated linear temperature-field dependences of the phase transition shift at fixed pressures (Fig. 1a, Fig. 2b). It is the point of correspondent equality of thermo- and magnetoelastic anisotropies; $T_P =$ 9.2 K is the temperature parameter of critical point; $T_X = T_{PP} = 0$ K is the intersection point of $T_P(H)$ dependence with H axis at $H_X = 5.5$ kOe. This point coincides with maxima of thermomagnetic and thermobaromagnetic effects and defines the position of the structural phase transition at $T = 0$ K. Such displacement of critical lines and points and their correspondence allow to establish and explain regularities of relations between structural, symmetry features and mechanisms of thermo-, baro-, magneto-EAS stresses in changes of properties and phase transitions in $CuCl_2 \cdot 2H_2O$.

To that end, using the construction results of the critical lines $T_P(H)$, $T_P(H,P)$ and points T_X, $H_X(T = 0)$, P_X, PP_X in magnetic dielectric, we define their values in the course of competitive influence of thermo- and magneto-EAS stresses and the role of elastic anisotropy in formation of the phase transitions and properties.

a) When comparing the magnetization (Fig. 2a), temperature-field (Fig. 2b) and frequency-field (Fig. 2c) dependences, it is to note that the temperature shift is connected with the thermo-EAS stress priority, where the elasticity anisotropy implements a jump of structural phase transition in critical point T_X as well as the effect of thermoelastic straining striction at temperature rise. In this case, $T_X = T_{PP} = T_{ST} = 0$ K at $H = 0$. The further increasing of magnetic field results in the appearance of effects, properties, and $T_P(H)$ changes.

b) By analogy with magnetic semiconductors [10], we show regularities of magneto-EAS stresses (Fig. 2a,b,c). The influence of "heating" effect of the magnetic field via the magnetoelastic anisotropy realizes the structural phase transition that is displayed as a magnetization jump in the critical point T_X at $H_X(T = 0) \approx 5.5$ kOe and $T = 0$ K. The further increase of magnetic field strength appears in "cooling" effect of $T_P(H)$ shift. In the critical point P, elastic and magnetoelastic anisotropies are equal to one another (Fig. 2a,b,c).

c) Let the simultaneous effect of H and T on the phase transition and properties be considered. The phase transition dynamics is explained by linear and nonlinear dependences of $T_P(H)$, $T_P(H,P)$ according to magnitude of T and H, using the described above estimations, mechanism of EAS influence and very significant sign reversal of T and H influences. The same regularities are displayed in frequency-field dependence (Fig. 2c), and in the phase diagram that defines the role of T and H influence via the EAS stress mechanisms in the low-temperature investigations.

It is to note that comparison of similar results for magnetic semiconductor $LaMnO_3$ [10] shows correspondence and differences (sign reversal) in displacement of critical points and lines, that define regularities in properties and phase transitions. In this case, the EAS stress mechanism remains constant.

To conclude, using the non-typical but substantiated analysis, it is possible to associate the entire lattice, electrical, magnetic and elastic properties of investigated materials. The role of T-H-P influence, its relative correspondence in properties and phase transitions via the EAS stresses mechanism, and relation to the structural binding energy through pressure parameter in both the high-temperature as well as low-temperature regions for different classes of substances allowed to colligate the results obtained. According to the analysis of experimental results for high-frequency properties and magnetic susceptibility of $CuCl_2 \cdot 2H_2O$ single crystal under high hydrostatic pressure, magnetic field and temperature, the following features have been established: (i) the linear regularity of phase transition shift $T_P(H)$, $T_P(H,P)$, estimations of correspondence of T-H-P influence (1 K ~ 4 kOe ~ 3 kbar); (ii) the role of thermomagnetic and thermobaromagnetic effects being maximum at the same temperature T_{PP} coincident with the structural phase transition temperature $T_{ST} = 0$ K; (iii) the role of "cooling" and "heating" effects. By analogy with magnetic semiconductors, sign reversal of effects have been revealed and explained through mechanism of EAS stresses at phase transition shifting; (iv) the critical point P with the temperature parameter $T_P = 9.2$ K is the result of regularity of coincident equality of elastic and magnetoelastic anisotropies; (v) the role of EAS stresses mechanism of T and H influences in changes of magnetization behavior and effect of thermoelastic straining striction; (vi) the role of regularities of T and H influences via the EAS stress mechanism in high-frequency properties, and existence of two resonances in properties before and after the structural phase transition; (vii) effect of competitive mechanism of thermo- and magneto-EAS stresses in phase diagrams; (viii) variety of critical lines $T_P(H)$, $T_P(H,P)$ and points T_X, P_X, PP_X, $H_X(T = 0)$ and P.

Considering revealed critical lines and points for the investigated material class, the correspondence and sign reversal of competitive T and H and the influence on properties and phase transitions shown in critical lines $T_P(H)$, $T_P(H,P)$ and points T_X, P_X, PP_X, $T_{PP} = T_{ST} = 0$ K, $P(T_P = 9.2$ K) via the of EAS stress mechanism have been established. The thermo- and magnetoelastic anisotropies have a significant role in these processes. Comparing critical lines and points P_X, PP_X, T_X with parameter $H_X(T = 0)$ in both investigated systems: magnetic semiconductor $LaMnO_3$ [10] and dielectric $CuCl_2 \cdot 2H_2O$, defining differences (sign reversal) of its displacement allow to determine of causal role of the mechanisms of EAS stresses that are forming and changing structural phase transitions and properties. In consequence, it may be stated that such explanation of experimental results evidencess that it is necessary and important to account for regularities of the thermo-, magneto-EAS stresses mechanism that form and change the properties and phase transitions. The presented and justified analysis of experimental data allows us to predict the involvement of the same mechanisms in realization of long-time studied effects of a colossal magnetoresistance (CMR) and conductance in HTSC structures. Drawing the analogy in the influence of EAS stress mechanism in manganites and magnetic dielectric $CuCl_2 \cdot 2H_2O$ on dynamics of structural phase transition, properties, effects with the revealed regularities of critical lines and points taken into account, it may be stated, according to authors of [6], that understanding of the described analysis would favor a faster and forecasted application of these results for making new models and theories and explanation the variety of remarkable phenomena and effects in solid state physics.

These results show that at investigation of a wide class of materials, the revealed regularities and mechanism of bulk elasticity may be used. Their application would promote establishing and understanding of true physical processes at investigations in solid-state physics, as well as the law of corresponding states could be interpreted as the law of elastically straining conformities, and established regularities of temperature, magnetic field and pressure influences could be treated as laws of elastically anisotropic straining stresses and sign reversal. Constancy of T_{PP} temperature could be interpreted as the law of elastic and magnetoelastic anisotropies.

References

1. G.H.Jonker, J.H.Van Santen, *Physica*, **16**, 337 (1950).
2. R.N.Van Santen, G.H.Jonker, *Physica*, **16**, 599 (1950).
3. J.Van Den Handel, H.M.Gijsman, N.J.Poulis, *Physica*, **18**, 862 (1952).
4. N.J.Poulis, G.E.Hardeman, B.Bolyer, N.Commun, *Physica*, **18**, 429 (1952).
5. G.J.Butterworth, V.S.Zidell, *J.Appl.Phys.*, **40**, 1033 (1969).
6. V.M.Loktev, Yu.G.Pogorelov, *Fiz.Nizk.Temp.*, **26**, 231 (2000).
7. S.S.Kucherenko, V.P.Pashchenko, P.I.Polyakov et al., *Fiz.Nizk.Temp.*, **27**, 761 (2001).
8. P.I.Polyakov, S.S.Kucherenko, *Pis'ma v Zh. Tekhn.Fiz.*, **28**, 8 (2002).
9. P.I.Polyakov, S.S.Kucherenko, *J.Magn. Magn.Mater.*, **248**, 396 (2002).
10. P.I.Polyakov, S.S.Kucherenko, *Fiz.Nizk. Temp.*, **28**, 1041 (2002).
11. P.I.Polyakov, V.P.Pashchenko, S.S.Kucherenko, *Defect and Diffusion Forum*, **208–209**, 307 (2002).
12. N.J.Poulis, J.Van der Handle, J.A.Poulis, C.J.Gorter, *Phys.Rev.*, **82**, 552 (1951).
13. J.Ubbink, J.A.Poulis, H.J.Gerritsen, C.J.Govter, *Physica*, **18**, 361 (1952).
14. J.N.Poulis, N.J.Gerritsen, C.J.Gorter, *Physica*, **19**, 928 (1953).
15. Cf., *J.Phys.Radium*, **12**, 149 (1951).
16. K.Vosida, *Program of Theor.Phys.*, **7**, 425 (1952).
17. T.Nagamija, *Program of Theor.Phys.*, **11**, 309 (1954).
18. H.J.Gerritsen, *Physica*, **21**, 639 (1955).
19. H.Jamazaki, M.Date, *J.Phys.Soc.Jap.*, **21**, 1615 (1966).
20. G.E.G.Hardeman, N.J.Poulis, *Physica*, **21**, 728 (1955).
21. V.G.Baryakhtar, A.A.Galkin, S.N.Kovner, V.A.Popov, *Zh.Eksp.Teor.Fiz.*, **58**, 494 (1970).
22. V.V.Eremenko, V.M.Naumenko, Yu.G.Pashkevich, V.V.Pshiko, *Pis'ma v Zh.Eksp.Teor. Fiz.*, **38**, 97 (1983).
23. V.G.Baryakhtar, V.V.Eremenko, V.M.Naumenko, *Zh.Eksp.Teor.Fiz.*, **88**, 1382 (1985).
24. T.Nagamiya, K.Yosida, R.Kubo, *Antiferromagnetism and Phys.*, **4**, 1 (1955).
25. E.V.Zarochencev, V.A.Popov, *Fiz.Tverd.Tela*, **6**, 1579 (1964).
26. A.C.Borovik-Romanov, Antiferromagnetism: Results of Science, Nauka, Moscow, (1972) [in Russian].
27. E.A.Turov, Physical Properties of Magnetically Ordered Crystals, USSR Acad. of Sci., Moscow (1963) [in Russian].

28. K.P.Belov, A.K.Zvezdin, A.M.Kadomtseva, R.Z.Letvin, Orientational Transitions in Rare-Earth Magnetics, Nauka, Moscow (1979) [in Russian].
29. P.I.Polyakov, Abstr. Dr. Sci. Thesis, Donetsk (1996).
30. V.G.Baryakhtar, A.A.Galkin, S.V.Ivanova et al., *Fiz. Tverd. Tela*, **21**, 1517 (1979).
31. A.V.Oleynik, P.I.Polyakov, *Fiz. Tverd. Tela*, **24**, 3190 (1982).
32. A.V.Oleynik, P.I.Polyakov, V.A.Popov, *Fiz. Tverd. Tela*, **28**, 2635 (1986); *Fiz. Nizk. Temp.*, **13**, 155 (1987); *Fiz. Tverd. Tela*, **30**, 183 (1988); *Fiz. Tverd. Tela*, **34**, 679 (1992).
33. A.A.Galkin, S.N.Kovner, P.I.Polyakov, *Dokl. AN SSSR*, **208**, 811 (1973).
34. A.A.Galkin, V.A.Popov, P.I.Polyakov, *Fiz. Nizk. Temp.*, **2**, 49 (1976).
35. A.A.Galkin, V.A.Popov, P.I.Polyakov, *Fiz. Tverd. Tela*, **17**, 2123 (1975).
36. A.A.Galkin, A.V.Votchinov, I.K.Danshin, V.A.Popov, *Fiz. Nizk. Temp.*, **7**, 1314 (1981).
37. P.I.Polyakov, S.S.Kucherenko, in: Proc. 18th Conf. on New Magnetic Materials in Microelectronics Moscow. State Univ., Moscow (2002), p.714.
38. S.A.Friedberg, N.Commun, *Physica*, **18**, 714 (1952).

Термодинамічні механізми пружно-анізотропних деформуючих напруг у змінах фазового переходу та властивостей магнітодіелектрика під впливом T-H-P

П.І.Поляков, С.С.Кучеренко

На основі експериментальних досліджень запропоновано та пояснено механізм ролі пружних анізотропних деформуючих напруг у виникненні та змінах фазових переходів та властивостей магнітних діелектриків. З експериментальних даних про резонансні властивості монокристалу $\mathrm{CuCl_2 \cdot 2H_2O}$, що є низькотемпературним магнітним діелектриком, визначено відповідність між впливом T, H і P (1 K, 4 kOe, 3 kbar) на структурний фазовий перехід. Виявлено термомагнітний та термобаромагнітний ефекти. Їх максимуми мають однакову температуру T_{PP} = 0 K, яка співпадає з температурою T_{ST} структурного фазового переходу. Виявлено також знакозмінність "охолоджувального" та "нагрівального" ефектів у зсувах $T_P(H)$. Критичні точки P_X, T_X та P мають температурний параметр T_P = 9.2 K, який значно відрізняється від відомого значення T_N = 4.3 K для цих матеріалів. Розглянуто намагнічування, температурно-польові та частотно-польові залежності та встановлено відповідність у змінах цих властивостей до та після структурного фазового переходу. Виявлено ефект термо-УДА стрикції, що є закономірністю зміни фазового стану магнітного діелектрика під впливом магнітострикції. Конкурентні механізми термо- та магнітострикції, які викликають зміни високочастотних властивостей, є причиною двох резонансів до та після структурного фазового переходу.