# Influence of magnetic ordering on the phonon spectra of compounds with giant magnetostriction

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The nuclear gamma resonance method was used to study the influence of magnetic ordering on changes in the overall characteristics of the phonon spectrum of $U(Fe_{0.9}Mn_{0.1})_2$. An increase in the probability of resonant absorption was observed below the Curie point ($T_C = 123$ K), which agrees with the results of T. K. McGuire and R. H. Herber [Solid State Commun. **48**, 393 (1983)] for pure $UFe_2$ ($T_C = 160$ K), in contrast to softening of the phonon spectrum of some rare-earth compounds with the same structure below $T_C$ [H. Shechter, D. Bukshpan-Ash, and I. Nowik, Phys. Rev. B **14**, 3087 (1976); D. Bukshpan, H. Shechter, and I. Nowik, J. Magn. Magn. Mater. **7**, 212 (1978)]. The possible mechanisms giving rise to the observed effects are considered. It is suggested that the main reason for renormalization of the phonon spectra as a result of a magnetic phase transition in compounds $RFe_2$ and $AFe_2$ (where R and A are, respectively, the rare-earth and actinide ions) with a giant magnetostriction is the magnon–phonon interaction.

## I. INTRODUCTION

Intermetallic compounds of the $RFe_2$ and $AFe_2$ type (where R and A are, respectively, rare-earth and actinide ions) with the cubic crystal structure (cubic Laves phases) exhibit a giant magnetostriction.[1] The spontaneous magnetostriction of these compounds distorts the cubic structure and such distortion can be orthorhombic or tetragonal, depending on the direction of the easy magnetization axis.

An investigation of the magnetostriction-induced distortions of the crystal structure of $UFe_2$ was reported in Ref. 2. The large value of the magnetostriction constant reaching $\lambda_{111} = 3\times10^{-3}$ at $T = 4.2$ K indicated a strong magnetoelastic coupling. The weakness of the experimentally determined magnetic anisotropy was explained by random cancellation of two large contributions with opposite signs: the anisotropy of the undeformed lattice and the anisotropy associated with the magnetoelastic interaction.

The probability of the Mössbauer effect $f$ and the thermal shift of the spectrum (i.e., the second-order Doppler shift) are related to the lattice dynamics and reflect the global characteristics of the phonon spectrum. In the absence of the magnetoelastic interaction these parameters are monotonically decreasing functions of temperature. When this interaction is present, considerable anomalies can be expected near the Curie point $T_C$. Such anomalies were reported in Refs. 3–5. It was found that in some $RFe_2$ compounds (where R = Tb, Dy, Ho) the process of magnetic ordering is accompanied by softening of the phonon spectrum at temperatures $0.7\,T_C < T < T_C$ (Refs. 3 and 4). In the case of pure $UFe_2$ the opposite effect of an increase in the probability of $f$ below the Curie point was observed.[5] It is of fundamental interest to identify the reasons for the different reactions of the phonon spectrum to the appearance of a magnetic order in $RFe_2$ and $UFe_2$. It is important to determine whether this difference reflects basically different magnetoelastic interaction mechanisms in rare-earth and actinide Laves phases with a giant magnetostriction.

We investigated in detail the temperature dependences of $f$, $\delta_T$, and other Mössbauer parameters of the compound $U(Fe_{0.9}Mn_{0.1})_2$ characterized by $T_C = 123$ K. It should be pointed out immediately that the anomaly of $\delta_T$ which we observed below $T_C$ was not correlated with the probability $f$ and, therefore, did not provide useful information on the lattice dynamics in its pure form. This effect was of intrinsic interest and it is outside the scope of the present paper. We describe the details of our experiments in Sec. II and in Sec. III we give a brief account of the methods used in the analysis of the results. The main results and discussion are presented in Sec. IV. We consider three possible mechanisms of changes in the probability as a result of magnetic ordering: the magnetostrictive deformation, the exchange interaction between magnetic ions, and the magnon–phonon interaction. We assume that the main contribution to the renormalization of the phonon spectrum by a magnetic phase transition in the compounds $RFe_2$ and $AFe_2$ is made by the last mechanism (magnon–phonon interaction) which provides a consistent explanation of the available experimental results.

## II. EXPERIMENTS

The methods used in the preparation of the samples and in analyzing their composition and structure were described in Ref. 6. The nuclear gamma resonance (NGR) measurements were made on a polycrystalline sample with an effective thickness of about 0.3 mg/cm$^2$ in terms of $^{57}$Fe. These measurements were made using a constant-acceleration spectrometer and an AI-1024-4 pulse analyzer. The source of gamma photons was $^{57}$Co(Pd) of 20 mCi activity. The temperature dependences were recorded using a cryostat in which the cooling agent was a vapor–gas mixture circulated through heat exchangers. Temperature was kept constant with a two-stage controller by simultaneous continuous regulation of the flow of the cooling agent and of the voltage applied to a heater inside the cryostat. This system made it

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possible to keep the temperature of a sample constant to within 0.01 K. Temperature measurements were accurate to within 0.1 K. We measured only the relative change in the probability on the assumption that in the case of a sufficiently thin absorber the area under the spectrum was approximately proportional to the probability $f$. The precision of determination of the change in the area under the spectrum was improved and the influence of the instrumental drift was avoided using a control absorber. Since the effective magnetic field at the $^{57}$Fe nuclei in $UFe_2$ was anomalously low ($H_i < 40$ kOe at 0 K), it was possible to select a suitable absorber with a single absorption line and a large positive isomeric shift, thus obtaining a standard line which did not overlap the investigated spectrum throughout the investigated temperature range. With this in mind we used a thin $RbFeF_3$ absorber (with its effective thickness less than 0.1 mg/cm$^2$ in terms of $^{57}$Fe), for which the isomeric shift relative to Fe(Pd) was $\delta_0 = 1.166$ mm/s. This control or standard absorber was placed in front of the cryostat and was kept at the same (room) temperature as the source. The presence of the control absorber made it possible to normalize the area under the spectrum of the sample determined at each temperature and also to correct the calibration of the spectrometer against the absorption line of the control. This was particularly important in the determination of small changes in $\delta_T$. At temperatures in the range 14–300 K a total of 43 spectra was determined. At temperatures 125–105 K ($T_C = 123$ K) the measurements were made in steps of 1 K.

## III. ANALYSIS OF EXPERIMENTAL RESULTS

The compound $UFe_2$ has the cubic structure of the $MgCu_2$ type with 8 uranium atoms and 16 iron atoms forming four tetrahedral groups inside a unit cell, and the threefold axes of these groups are directed along the body diagonals of a cube. Since above the Curie point $T_C$ all the iron atoms are structurally equivalent, the NGR spectrum of $UFe_2$ recorded in the paramagnetic range is a doublet associated with the presence of an electric field gradient (EFG) with the principal axis $V_{zz} \| \langle 111 \rangle$ at the iron nuclei. Therefore the spectra obtained above $T_C$ were analyzed in the usual way by the least-squares method.

Below the Curie point the standard description of the NGR spectra of $UFe_2$ by a set of Lorentzian curves is invalid, since even at $T = 0$ the energies of the magnetic and quadrupole interactions are of the same order of magnitude. A model description of such a spectrum becomes possible only by numerical solution of the Hamiltonian of the combined hyperfine interaction.[7] Since the easy axis is [111], magnetic ordering gives rise to magnetic inequivalence of the iron atoms and to a strong asymmetry of the spectrum (Fig. 1). The spectrum splits into two subspectra with the intensity ratio 3:1, in accordance with the populations of the iron positions characterized by different angles $\theta$ between the direction of the effective magnetic field $\mathbf{H}_i$ and the EFG. The magnetoelastic distortions give rise to a further inequivalence and the angles $\theta$ differ from the values typical of an undistorted structure.[7-9] In the code we ignored the inequivalence because of the magnetostrictive deformation, but this inequivalence was manifested by a gradual increase of the line widths in the subspectra during cooling. The number of variable parameters in the least-squares method included not only the parameters associated with the local fields at the nuclei and the usual characteristics of the absorption spectrum of a sample, but also the parameters associated with the control (standard) absorber.

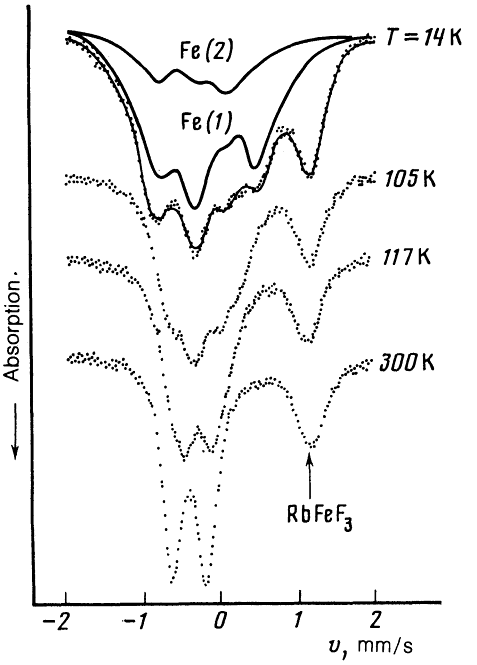

FIG. 1. Nuclear gamma resonance spectra of $U(Fe_{0.9}Mn_{0.1})_2$ obtained at different temperatures. The continuous curves in the upper part of the figure are the results of a numerical analysis: Fe(1) and Fe(2) correspond to the positions of Fe with different populations (see text).

We used a data analysis procedure[7] which made it possible to deal with the NGR spectra even when the energies of the magnetic and quadrupole interactions with the EFG tensor of the general type were comparable. An interpretation of the NGR spectrum of $UFe_2$ below $T_C$ was also given in Ref. 7 and adopted without changes in the present study.

## IV. RESULTS AND DISCUSSION

Figure 1 shows, by way of illustration, typical NGR spectra of $U(Fe_{0.9}Mn_{0.1})_2$ recorded at different temperatures. The uppermost spectrum obtained at $T = 14$ K was analyzed into the component subspectra labeled Fe(1) and Fe(2). In the figures and in the text the index (1) will be used for the positions with the higher population and the index (2) for the positions with the lower population. Figure 2 shows the dependences of the effective magnetic fields $H_i$ for two types of magnetically inequivalent iron atoms. At $T = 0.5T_C$ the field $H_i$ was approximately 10% less than in pure $UFe_2$ under the same conditions.[7-9] This reduction in $H_i$ and lowering of $T_C$, due to replacement of some of the Fe atoms with Mn, was in agreement with the results of magnetic measurements[10] on samples of similar composition. The difference between the values of $H_i$ for Fe(1) and Fe(2) was related to the different magnitudes of the dipole contributions to the local fields. The difference $\Delta H = H_i(1) - H_i(2)$ was similar to the value of $\Delta$H for pure $UFe_2$ and when the temperature increased it decreased from 4.7 kOe at 14 K to zero at $T \approx 0.9T_C$.

The temperature dependence of the amplitude of the mean-square displacements $\langle x_{jk}{}^2 \rangle_T$ is plotted in Fig. 3. We

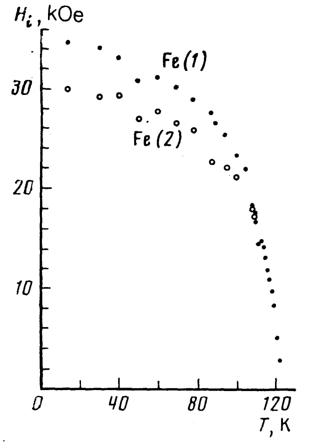

FIG. 2. Temperature dependences of the effective magnetic fields at the iron nuclei for two types of iron atoms.

determined experimentally the natural logarithm of the normalized total area under the spectrum proportional to $\langle x_{jk}^2\rangle_T$. Then, Eqs. (3) and (4) given below were used to find the Debye temperature for $^{57}$Fe. At two points in the high-temperature range, where the approximation given by Eq. (3) was valid, we found the value of $\langle x_{jk}^2\rangle_T$ corresponding to a given temperature and, consequently, the scale in Fig. 3. Since the absolute measurements of the probability $f$ were not made, the values of $\langle x_{jk}^2\rangle_T$ were not exact, but the relative changes in the amplitude of the mean-square displacements were given correctly by the results plotted in Fig. 3. Clearly, cooling from room temperature to $T_C = 123$ K reduced $\langle x_{jk}^2\rangle_T$ slowly, but in the range $0.8T_c < T < T_c$ the value of $\langle x_{jk}^2\rangle_T$ fell rapidly by a factor of about 3.5. This fall could be somewhat overestimated because the sample was not very thin in terms of $^{57}$Fe. Further cooling had practically no effect on the amplitude of the mean-square displacements. The observed anomaly was evidence of renormalization of the phonon spectrum induced by magnetic ordering.

In the case of a weak or zero anisotropy of the mean-square displacements of atoms and for harmonic interatomic forces the average probability of the Mössbauer effect can be written as follows:

$$f=\exp\left(-\langle x_{jk}^2\rangle_T/\lambda\!\!\!^{-2}\right), \tag{1}$$

where $\lambda\!\!\!^{-2}$ is the reduced wavelength of the gamma photons and $\langle x_{jk}^2\rangle_T$ is the mean-square displacement of an atom $k$ in a direction $j$. The absence of an anisotropy of the mean-square displacements in UFe$_2$, at least in the paramagnetic region, follows from the equality of the intensities of the components of the doublet (see the spectrum in Fig. 1 at $T = 300$ K).

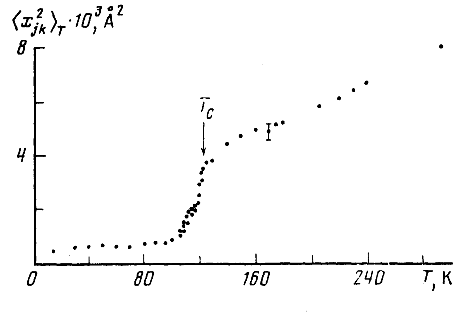

FIG. 3. Temperature dependence of the amplitude of mean-square displacements of $\langle x_{jk}^2\rangle_T$ of $^{57}$Fe in $(\mathrm{U(Fe_{0.9}Mn_{0.1})_2}$.

When the phonon spectrum is approximated by the Debye model, the temperature dependence of the mean-square displacements is described by the expression

$$\langle x_{jk}^2\rangle_T=\frac{3\hbar^2}{M_k k_B\Theta_f}\left[\frac{1}{4}+\frac{T}{\Theta_f}\varphi_1\left(\frac{\Theta_f}{T}\right)\right], \tag{2}$$

where $M_k$ is the mass of a resonating atom, $\Theta_f$ is the "Mössbauer" Debye temperature deduced from the measurements of the probability $f$, $k_B$ is the Boltzmann constant, and $\varphi_1(x)$ is the integral Debye function given by

$$\varphi_1(x)=\frac{1}{x}\int_0^x\frac{t}{e^t-1}\,dt.$$

In the range of validity of the high-temperature approximation ($T\gtrsim\Theta_f/3$), we have

$$\langle x_{jk}^2\rangle_T=3\hbar^2T/M_k k_B\Theta_f^2. \tag{3}$$

If the absorber is sufficiently thin, the area $S$ under the spectrum is approximately proportional to the probability $f$. We then have

$$\ln S\sim\ln f=-\langle x_{jk}^2\rangle/\lambda\!\!\!^{-2}. \tag{4}$$

The relationship

$$-\partial\ln S/\partial T=3\hbar^2/M_k k_B\Theta_f^2$$

gives the value $\Theta_f = 310 \pm 25$ K, which is in good agreement with the result reported in Ref. 5 for pure UFe$_2$. The anomaly of $\langle x_{jk}^2\rangle_T$ observed below $T_C$ can be explained on the assumption that, because of the strong magnetoelastic coupling, the value of $\Theta_f$ in the region of a magnetic phase transition is a function of the magnetization. Then the observed relative change in $\langle x_{jk}^2\rangle_T$ reflects the increase in $\Theta_f$ in Eq. (2) by a factor of about 1.8 at temperatures 123–100 K or an increase in the probability by about 15%.

We shall consider three mechanisms which, in our opinion, can be responsible for the observed anomaly: the bulk compression due to the magnetostrictive deformation, the exchange interaction between magnetic atoms, and the perturbation of the phonon spectrum by the magnon–phonon interaction.

*1. Magnetostrictive compression.* An experimental investigation of the influence of pressure on the probability $f$ in the case of $^{57}$Fe and different metal matrices has yielded the following relationship between the increase in the probability $\Delta f/f$ and in the volume $\Delta V/V$ (Ref. 10):

$$\Delta f/f=-\mathrm{const}\,\Delta V/V,$$

where the constant varies from one material to another, but its value is close to unity. According to the results of thermal measurements the change in the volume of a unit cell of UFe$_2$ due to magnetic ordering is $\Delta V/V = -1.5\times10^{-3}$ (Ref. 11). Consequently, an increase in the probability due to this mechanism should not exceed a fraction of a percent.

*2. Exchange interaction.* The influence of magnetic ordering on the Mössbauer effect probability was considered theoretically in Ref. 12. The perturbation of the phonon spectrum of a crystal due to the exchange interaction of magnetic ions was determined. It was found that the dependence of the exchange interaction energy on the degree of ordering of the spin system and on the distance between the interacting atoms should renormalize the phonon spectrum correlated with the magnetization of a crystal. The final expression for $\langle x_{jk}^2 \rangle_T$ obtained allowing for the exchange interaction in a cubic crystal considered in the Debye approximation is

$$\langle x_{jk}^2 \rangle_T = \frac{3\hbar^2}{M_k k_B} \frac{1}{\Theta_f (1+B)^{1/2}} \times \left[ \frac{1}{4} + \frac{1}{(1+B)^{1/2}} \frac{T}{\Theta_f} \varphi_1 \left( \frac{\Theta_f}{T} (1+B)^{1/2} \right) \right]. \quad (5)$$

The influence of the exchange interaction is allowed for by a parameter $B$, defined by

$$B = -(8\pi^2 \langle \hat{S}_i \hat{S}_k \rangle a^2 / v^2 M_k) I''(a), \quad (6)$$

where $a$ is the distance between neighboring atoms; $v$ is the velocity of sound; $I''(a)$ is the second spatial derivative of the exchange integral; $\langle \hat{S}_i \hat{S}_k \rangle$ is the spin correlation function; the indices $i$ and $k$ label the neighboring magnetic atoms. According to Ref. 12, magnetic ordering of this type should be accompanied by an increase in the probability, which is in qualitative agreement with our results and with Ref. 5, but it is in conflict with the results of Refs. 3 and 4. We shall estimate this contribution to the increase in $f$ in the case of $UFe_2$ below $T_C$.

We shall find the exchange integral from the Curie temperature. If $T_C = 120–160$ K, $s = 1/2$, and $z = 6$ (in the case of $UFe_2$ each iron atom has six equidistant nearest Fe neighbors), we obtain $I \approx (5–7) \times 10^{-15}$ erg. The functional dependence of the exchange integral on the distance between the neighboring interacting atoms can be represented by[13]

$$I(\mathbf{x}_{ik}) = \text{const} \exp(-\lambda |\mathbf{x}_{ik}|), \quad (7)$$

where $\mathbf{x}_{ik}$ is the interatomic vector. The order of magnitude of $\lambda$ for the pair exchange coupling due to an overlap of the wave functions of the neighboring atoms has been estimated as $\lambda \approx 2 \times 10^8$ cm$^{-1}$ (Ref. 13). When the Fe–6Fe distance between the nearest neighbors is $a = |\mathbf{x}_{ik}| \approx 2.5$ Å, we obtain $I''(a) \approx (1.3–2)$ erg/cm. The velocity of sound in $UFe_2$ can be estimated by two methods. Knowing the elastic constant $C_{44} = 2.02 \times 10^{11}$ dyn/cm$^2$ (Ref. 2) and the density $\rho = 13.2$ g/cm$^3$, we can find the transverse wave velocity $v_s = (C_{44}/\rho)^{1/2} \approx 1.2 \cdot 10^5$ cm/s. Using the experimental value of the Young modulus $E \approx 5 \times 10^{10}$ erg/cm$^3$ at $T = 250$ K (Ref. 2), we can find the longitudinal velocity of sound $v_l$ (or the highest value of $v_s$ on the assumption that the medium is isotropic):

$$v_l = [E(1-\sigma)/(\rho(1+\sigma)(1-2\sigma))]^{1/2},$$

where $\sigma$ is the Poisson ratio. If $\sigma = 1/4$, we find that $v_l \approx 2 \cdot 10^5$ cm/s. The maximum value of the parameter is then $B \approx (1.2–1.6) \times 10^{-2}$. Substitution in Eq. (5) readily demonstrates that the maximum possible increase in the probability for $\Theta_f = 310$ K and $T \approx 120–160$ K is at most 1–1.5%, which is an order of magnitude less than the actual value.

*3. Magnon–phonon interaction.* In the majority of cases the waves traveling in magnetically ordered materials can be regarded as noninteracting pure spin and pure elastic waves, because of the smallness of the magnetoelastic coupling constants. An allowance for the interaction is necessary only near a resonance when the frequencies are equal, as are the vectors of the elastic and spin waves. However, the situation may change considerably in substances with a giant magnetostriction and, consequently, with a strong magnetoelastic interaction. Therefore, in cubic Laves phases $RFe_2$ and $AFe_2$ with large values of the magnetoelastic coupling constants the interaction between the branches may be significant not only near a resonance, but also in the range of frequencies and wave numbers far from the resonance values, which is reflected in the overall properties of the phonon spectrum. In view of the absence of a theoretical analysis of the influence of the magnon–phonon interaction on the Mössbauer effect probability, we shall try to obtain very rough estimates on the basis of the results of Refs. 14 and 15 where the dispersion relationships were derived for coupled magnetoelastic waves in the case when the coupling is weak.

We shall use the dispersion equation[14] for transverse magnetoelastic waves traveling along the anisotropy axis and for an acoustic wave with the "left-handed" circular polarization:

$$(\omega^2 - \omega_m(\mathbf{k}))(\omega - \omega_s(\mathbf{k})) - \eta\gamma M_0 \omega_s^2(\mathbf{k}) = 0, \quad (8)$$

where $\omega_m$ is the spin wave frequency; $\omega_s$ is the acoustic wave frequency; $M_0$ is the saturation magnetization; $\eta$ is the dimensionless magnetoelastic constant given by $\eta = B_2^2/\rho v_2^2 M_0^2$, where $B_2$ is the magnetoelastic constant. In the case of cubic crystals the magnetoelastic constant is related to the magnetostriction constant[16]: $\lambda_{111} = -B_2/3C_{44}$, which in the case of $UFe_2$ gives $B_2 \approx -1.8 \times 10^9$ erg/cm$^3$ and this value is two orders of magnitude greater than for ordinary ferromagnets. The dimensionless constant $\eta$ in Eq. (8) then exceeds the usual values by at least four orders of magnitude.

Bearing in mind the smallness of the gap in the spin wave spectrum of $UFe_2$, which is due to the smallness of the anisotropy field $H_A = 4 \times 10^3$ Oe (Ref. 17), we can expect the presence of two points of intersection of the dispersion characteristics of noninteracting elastic and spin waves[15]:

$$\omega_{01} = \gamma H_A, \quad \omega_{02} = v_s^2/C - \gamma H_A \approx v_s^2/C, \quad (9)$$

where the constant $C$ given in Ref. 18 can be represented in the form

$$C = 2\gamma A/M_0, \quad (10)$$

where $A = 2Is^2/a_0$; $I$ is the exchange integral; $a_0$ is the lattice constant. Using the values $I = (5–7) \times 10^{-15}$ erg, $s = \frac{1}{2}$, $a_0 \approx 7$ Å, and $M_0 = 230$ G, we obtain $C \approx (5–9) \times 10^{-3}$ cm$^2$/s and the following points of intersection:

$$\omega_{01} \approx 8 \cdot 10^{10}\ \text{s}^{-1} \text{ and } \omega_{02} \approx (2–8) \cdot 10^{12}\ \text{s}^{-1}.$$

Bearing in mind that at temperatures $T < \Theta_D$ the density maximum of thermally populated phonon states occurs in the frequency range close to $\omega \approx kT/\hbar$, we can expect that the main contribution to the change in the characteristics of the phonon spectrum at $T \sim T_C$ to be due to the interaction in the high-frequency part of the spectrum. Figure 4a shows the spectrum of coupled magnetoelastic waves in $UFe_2$ calculated using Eq. (8) on the assumption that the dispersion relationships for phonons and magnons are $\omega_s = v_s k$ and $\omega_m = \omega_0 + Ck^2$. We can see that the dispersion curves of elastic and spin waves, which cross in the absence of the

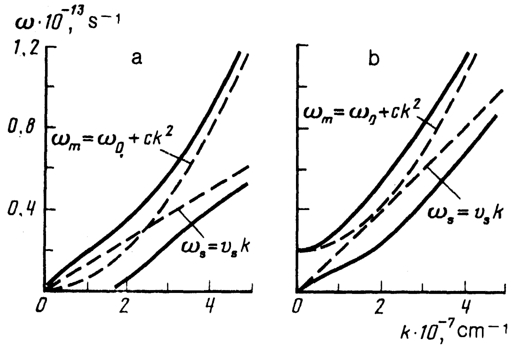

FIG. 4. Spectra of coupled magnetoelastic waves: a) $UFe_2$, calculated for the following values of the parameters in Eq. (8): $v_s = 1.2\times 10^5$ cm/s, $H_A = 4\times 10^3$ G, $C = 5\times 10^{-3}$ cm²/s, $M_0 = 230$ G, $\omega_0 = 8\times 10^{10}$ s$^{-1}$; b) $RFe_2$ and $AFe_2$ calculated assuming the following parameters: $v_s = 2\times 10^5$ cm/s, $H_A = 10^5$ G, $C = 5\times 10^{-3}$ cm²/s, $M_0 = 10^3$ G, $\omega_0 = 2\times 10^{12}$ s$^{-1}$. The dashed lines are the dispersion curves for unperturbed elastic ($\omega_s$) and spin ($\omega_m$) waves.

interaction (dashed curves), are repelled by an amount $\Delta\omega \approx 3\cdot 10^{12}$ s$^{-1}$ in the vicinity of $\omega_{02}$. We can also see that this repulsion remains large in a wide range of values of the wave vector. Since in the range of $k$ between the points of intersection the unperturbed phonon branch lies above the magnon branch, the repulsion shifts the phonon vibrations toward higher frequencies. Since the resonating nuclei vibrate mainly in such branches, we can expect an increase in the probability of the Mössbauer effects (i.e., an increase in the effective Debye temperature). This increase in $\Theta_f$ as a result of the interaction considered here can be estimated approximately from the ratio of the phonon frequencies in the presence and absence of repulsion. Since this ratio is a function of the wave vector, we shall assume that the average value of the frequency ratio near the crossing of noninteracting branches is approximately equal to 1.5 (see Fig. 4a), bearing in mind that the main contribution to the renormalization of the phonon spectrum near $T_C$ is due to the high-frequency phonons. This estimate is in satisfactory agreement with the experimentally observed increase in $\Theta_f$ by a factor of 1.8, which—as mentioned above—may be slightly overestimated.

The softening of the phonon spectrum as a result of magnetic ordering of $RFe_2$ (R = Dy, Tb, Ho) reported in Refs. 3 and 4 is not in conflict with this mechanism if we allow for the characteristic feature of the compounds $RFe_2$ and $AFe_2$, the high anisotropy fields $H_A \sim 10^5$ G (in this respect the compound $UFe_2$ is an exception). This creates a large gap in the spin wave spectrum and is responsible for the qualitative difference between the spectrum of coupled oscillations (Fig. 4b) and the spectrum observed in the case of $UFe_2$ (Fig. 4a). We can see from Fig. 4b that the repulsion due to the interaction results in softening of the phonon spectrum. The consequence of such softening should be a reduction in the probability reported in Refs. 3 and 4. The degree of softening should be of the same order of magnitude as the values given in Refs. 3 and 4.

It therefore follows that our allowance for the magnon–phonon interaction makes it possible to explain consistently the known Mössbauer $f$ experiments on rare-earth and actinide compounds with the cubic Laves phase structure, which exhibit a giant magnetostriction. It therefore follows that softening of the phonon spectrum is not a necessary consequence of magnetic ordering in compounds with a large value of the magnetostriction, contrary to the conclusion reached in Ref. 3. On the other hand, hardening of the phonon spectrum below $T_C$ is not a special feature of the actinide Laves phases, as suggested in Ref. 5. In our opinion the nature and degree of renormalization of the phonon spectrum as a result of magnetic ordering is governed by the magnetoelastic coupling constant, by the nature of the unperturbed dispersion curves of magnons and phonons, and by the gap in the spin wave spectrum. The actual temperature dependence of $\langle x_{jk}^2 \rangle_T$ should depend on many factors, including the values of the Curie and Debye temperatures and particularly on the temperature dependence of the magnetostriction constants.

We conclude by noting that in these experiments, as in Refs. 3 and 4, the process of magnetic ordering is accompanied by an anomalous shift of the center of the spectrum which is not correlated with the sign of the change in the probability. This is clearly typical of metallic ferromagnets and is not related to the second-order Doppler shift, but is due to changes in the electron states as a result of a magnetic phase transition.

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