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Mössbauer spectroscopy under acoustical excitation: thick target effects

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Abstract A new model of Mössbauer absorption (transmission) spectra with an adequate analysis of the possible effects of acoustic excitation in the thick targets is proposed. In particular, the dependence of the line width of acoustical satellites on the degree of phase correlation of the sound oscillations of resonant nuclei in the target is established by calculations and confirmed in experiment. Such a model is stimulated by an increase in the informativeness of the Mössbauer experiments, using thick samples in ultrasound (US) field, and by possible applications of this research technique. The test measurements of Mössbauer absorption spectra on stainless steel are carried out. The fitting of these spectra confirms the relevance of modifications of the model base of Mössbauer processes in US field.

Keywords Mössbauer absorption · Acoustical modulation · Raman scattering · Thickness effect

1 Introduction

Acoustic modulation of Mössbauer spectra (MS) was discovered already in the period of formation of gamma resonance spectroscopy [1]. The mechanism of realization of this phenomenon is closely related to the Mössbauer effect, and after the first experiments, it was

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recognized as an effective tool of gamma-optics. These expectations were justified later, in particular, in the Mössbauer experiments on acoustic excitation of the target, performed in the forward scattering (FS) scheme. First, it is a cycle of known works (see [2] and references therein) on the observation of forward scattering spectra on the stainless steel, where ultrasound (US) satellites with a new peculiarities of their formation were revealed. New possibilities of the FS detection scheme were also demonstrated in Mössbauer measurements [3], performed by the delayed coincidence method, using an external parameter (the phase value of sound at the instant of appearance of the signal photon). The time domain MS, which are formed under these conditions, also acquire a structure (set of maxima over a decaying exponential curve), determined by the value of the external parameter. In general, the works [2, 3] allowed to expand our views of the mechanisms (and possibilities) of US control of the MS structure. It was found that the structure of both the frequency and time domain spectra in FS scheme, unlike to the US structure of the traditional absorption spectra [1], appears only at the significant phase correlation of the acoustic vibrations of the resonant nuclei in the target. In addition, both these structures under discussion can be observed only for sufficiently thick targets. This similarity is explained by the fact [4, 5] that both ultrasonic effects [2, 3] are a consequence of the same phenomenon - coherent amplification of Raman scattering of gamma photons in the forward direction. The purpose of this report is to revise the Mössbauer absorption (transmission) model for a thick sample in the US excitation regime, taking into account the possibility of coherent amplification of Raman scattering of gamma photons. The revision is in demand primarily to achieve the internal consistency of the models of Mössbauer processes used in various schemes of the Mössbauer experiment. The need for such a revision is caused, in particular, by an anomalous broadening of the absorption lines, which was observed experimentally in [2]. The same was confirmed by model calculations in [5]. A return to this problem involves a correct analysis of Mössbauer processes occurring in the US field and the development of the model base for experiments on acoustic modulation. The demand for the proposed model is demonstrated by the results of fitting (processing) the spectra of test experiments performed in the absorption scheme in stainless steel.

2 Acoustic modulation of the Mössbauer absorption spectra of thick targets

The acoustical modulation of the Mössbauer absorption spectrum can be demonstrated by the example of a separate Mössbauer nucleus bounded in a crystal. The classical model of this phenomenon is most convincing [1, 6]: a spectrum having a single absorption line under the action of a nucleus oscillation with frequency Ω and amplitude x (in the direction of the gamma radiation wave vector k_γ) acquires additional absorption lines (satellites) spaced by $n \cdot \hbar\Omega$, $n = \pm1, \pm2, ..$ from the initial (main) line ($n = 0$). The absorption line intensities of this spectrum A_n are determined by Bessel functions $A_n = J_n^2(b), \quad n = 0, \pm1, \pm2, ..$with a modulation index $b = k_\gamma \cdot x$. It should be noted that at US satellites formation, the probability of the Mössbauer (phononless with respect to lattice vibrations) transition is conserved, i. e.$\sum_{n=-\infty}^{\infty} J_n^2(b) = 1$. A quantum description of the phenomenon under consideration was proposed by Abragam [7]. Now the spectrum is calculated using the sound mode oscillator and the intensities of the spectral lines are obtained in the form $A_n^q = \exp\left(-m^2\right) I_n\left(m^2\right)$, $(n = 0, \pm1, \pm2, ..)$, where $I_n\left(m^2\right)$ is the modified Bessel function and

$m^2 = \left\langle \left(k_\gamma \cdot x\right)^2 \right\rangle$ (here the averaging over the mixed state of the oscillator is assumed). Soon the relationship of this result with classical line intensities ($J_n^2(b)$) was established [8]:

$$A_n^q = \exp\left(-m^2\right) I_n\left(m^2\right) = \int db J_n^2(b)\, P_{Rayl}(b, m),$$
$$P_{Rayl}(b, \sigma) = \left(b/\sigma^2\right) \exp\left(-b^2/2\sigma^2\right), \quad (1)$$

where the Rayleigh function $P_{Rayl}(b, \sigma)$ describes the distribution of modulation index values, specific for the equilibrium (mixed) state of the quantum oscillator. Obviously, another quantum state of the oscillator must be matched by another distribution of the modulation index values. In particular, for the Glauber state (a quantum analog of the classical oscillation of a nucleus with a constant amplitude [9]) of a sound oscillator, one should expect a delta-like distribution of the modulation index b, i.e. the result close to [1]. At the same time, the stationary mixed state for a sound oscillator controlled by an external converter must correspond now to the Rice distribution function $P_{Rice}(b, m)$ [10, 11] (instead of the Rayleigh function). The realization of one or another distribution function under the influence of an external US transducer, obviously, depends on the oscillatory system properties of the used sample. Thus, according to [12], rapid relaxation in the oscillatory system leads to the formation of a sound oscillator's mixed state and to the Rayleigh distribution for the modulation index. Slow relaxation, on the other hand, will preserve the coherence transferred to the nucleus by an external source. The behavior of real samples can deviate from that described in [12] and, as shown in [13], depend additionally on the intensity of the external US excitation. Thus, the distribution of the modulation indices, obtained by fitting the experimental MS, is a source of information on the processes describing the transfer of the vibrational energy from external source to the nuclei. An adequate model for the distribution function for a target under specific vibration conditions is necessary for receiving the reliable information from experiments. At the same time, we have to achieve the same adequacy in the modeling of interaction of gamma ray with oscillating target's nuclei. Here we have to use the main ideas of the dynamical Mössbauer absorption theory [14–16] and the new possibilities of Mössbauer study of thick targets [2, 3, 5]. These features demand to take into account the possibility of constructive interference of the Raman FS amplitudes, if the oscillations of the nuclei are in phase. The result of this interference behavior is also known as formation of superpositional states of gamma radiation [2, 16] within the target. So, under the conditions described, the source radiation can cause the formation of a coherent superposition of the Raman FS amplitudes, differing in the energies of both the primary and the scattered photons. One results in the formation of an US structure of the Mössbauer radiation behind the target and in coherent enhancement of the radiation intensity transmitted through the target. These effects were explicitly studied in [2]. In addition, superpositional states of gamma radiation in the target lead to essential changes in the parameters of the Mössbauer spectra, which are measured in usual absorption scheme [2, 5]. The spectrum of this type differs substantially from the spectrum of a target with nuclei oscillating in the absence of any phase correlation. We shall see below that the absorption spectra corresponding to the two limiting modes of correlation of the nuclear vibrations in the absorber can differ greatly in their parameters (integral absorption and the line width of the US satellites). This means that only an adequate simulation of the Mössbauer processes in the ultrasonic field can ensure the reliability of the information obtained as a result

of fitting the experimental spectra. In addition, the modified model, of course, is of interest as a tool for obtaining additional (non-local) information. In essence, the change in the Mössbauer transmission under discussion should be considered as a thickness effect [17–19], the realization of which now depends on the degree of phase correlation of the nucleus sound oscillations [5].

As the starting point of the model, it is suggested to use the transmission integral $T(\omega_s, \omega_a, t_e, b)$ [5], directly expressed through the FS spectrum $F(\omega, \omega_s, \omega_a, t_e, b)$. In the case of a target with nuclei, oscillating in-phase and with an equal amplitudes, this integral is expressed in terms of the FS spectrum $F_2(\omega, \omega_s, \omega_a, t_e, b)$calculated precisely for these conditions [2, 5]:

$$T_2(\omega_s, \omega_a, t_e, b) = \int d\omega F_2(\omega, \omega_s, \omega_a, t_e, b) = \int d\omega' F_2'\left(\omega', \omega_s, \omega_a, t_e, b\right), \quad (2)$$

$$F_2(\omega, \omega_s, \omega_a, t_e, b) = \sum_k \frac{\Gamma_s/2\pi}{(\omega_s + k\Omega - \omega)^2 + (\Gamma_s/2)^2} \times \left| \sum_q J_q(b) J_{k+q}(b) \exp\left[\frac{-it_e\Gamma_a/4}{\omega - (k+q)\Omega - \omega_a + i\Gamma_a/2} \right] \right|^2, \quad (3)$$

$$F_2'\left(\omega', \omega_s, \omega_a, t_e, b\right) = \frac{\Gamma_s/2\pi}{(\omega_s - \omega')^2 + (\Gamma_s/2)^2} \sum_k \left| \sum_q J_q(b) J_{k+q}(b) \exp\left[\frac{-it_e\Gamma_a/4}{\omega' - q\Omega - \omega_a + i\Gamma_a/2} \right] \right|^2. \quad (3')$$

Here ω_s (ω_a) and Γ_s (Γ_a) are the frequency and the width of the Mössbauer source (absorber) resonance, $t_e = \sigma_0 f_a n d$ is the effective thickness of the absorber, and k, q are the integer summation indices. In (2) an alternative expression for the absorption spectrum is also presented, which is now the result of averaging (integration over ω') of the absorption spectrum for monochromatic radiation by the target in in-phase oscillations mode (see F_2' (3')), taking into account the source radiation line form. Formally, such a transformation is achieved by introducing a new variable of integration $\omega' = \omega - k\Omega$ in (2). Of course, it seems more appropriate to calculate F_2' using the explicit expression for the gamma wave behind the target with in-phase oscillating nuclei, - the target's response to the monochromatic radiation of the source [14, 15]. A rigorous derivation of F_2' was performed in [16], in the framework of the quantum-electrodynamic model.

The originality of the model based on the expressions (2) and (3) becomes more convincing when compared with the traditional approach to acoustic modulation of the absorption spectra, represented by the transmission integral.

$$T_3(\omega_s, \omega_a, t_e, b) = \int d\omega F_3(\omega, \omega_s, \omega_a, t_e, b), \quad (4)$$

$$F_3(\omega, \omega_s, \omega_a, t_e, b) = \frac{\Gamma_s/2\pi}{(\omega_s - \omega)^2 + (\Gamma_s/2)^2} \exp\left[\sum_q J_q^2(b) \frac{-t_e(\Gamma_a/2)^2}{(\omega - q\Omega - \omega_a)^2 + (\Gamma_a/2)^2} \right]. \quad (5)$$

Here $F_3(\omega, \omega_s, \omega_a, t_e, b)$ is the FS frequency spectrum, calculated on the assumption that there is no phase correlation of the nuclei oscillations in the target [5]. In thin absorber

approximation, expression (4) transforms to the sum of Lorentzians with intensities $J_q^2(b)$, i.e. to the result that is well-known in traditional models [1, 6–8, 12]:

$$T_3 = 1 - \sum_q \frac{J_q^2(b)\, t_e \Gamma_a \Gamma_{as}/4}{(\omega_s - q\Omega - \omega_a)^2 + (\Gamma_{as}/2)^2}, \qquad \Gamma_{as} = \Gamma_a + \Gamma_s. \tag{6}$$

On the other hand, the expression T_2, also in thin absorber approximation, differs qualitatively from expression (6):

$$\begin{aligned} T_2 \;=\; & 1 - \sum_q \frac{J_q^2(b)\, t_e \Gamma_a \Gamma_{as}/4}{(\omega_s - q\Omega - \omega_a)^2 + (\Gamma_{as}/2)^2} + \sum_q \frac{J_q^2(b)\, t_e^2 \Gamma_a \Gamma_{as}/16}{(\omega_s - q\Omega - \omega_a)^2 + (\Gamma_{as}/2)^2} \\ & + \int \sum\nolimits_k d\omega \frac{\Gamma_s/2\pi}{(\omega_s + k\Omega - \omega)^2 + (\Gamma_s/2)^2}\, t_e^2\, (\Gamma_a/4)^2 \\ & \times \sum_{q,m\neq 0} \frac{\left(J_q(b)\, J_{q+k}(b)\right)\left(J_{q+m}(b)\, J_{q+m+k}(b)\right) R(k,q,m,\omega_a,\Gamma_a,\Omega)}{\left[(\omega - (k+q)\,\Omega - \omega_a)^2 + (\Gamma_a/2)^2\right]\left[(\omega - (k+q+m)\,\Omega - \omega_a)^2 + (\Gamma_a/2)^2\right]}, \end{aligned} \tag{7}$$

$$R(k,q,m,\omega_a,\Gamma_a,\Omega) = \left\{\left[(\omega - (k+q)\,\Omega - \omega_a)^2 + (\Gamma_a/2)^2\right] - m\Omega\,(\omega - (k+q)\,\Omega - \omega_a)\right\}. \tag{8}$$

Indeed, the second sum in expression (7), a positive definite quantity, can be regarded as an decrease in the intensity of the absorption line (relative to the case T_3 (6) or to the first sum in (7)). In the experiment this corresponds to an increase in the radiation intensity behind the absorber. This can also be represented as the dependence of the integral absorption, $S = \int T d\omega_s$, on the degree of phase correlation of the oscillations of the target's nuclei (in particular, $S_2 < S_3$ [5]). However, within the framework of this paper, the characteristic behavior of the satellite linewidths in the spectrum T_2 is of more interest. This effect is also related to the already mentioned second sum in (7). Essentially, this sum is responsible for Raman forward scattered gamma radiation (with line width Γ_{as}), which in the case of a thick target gradually replaces the radiation from the source (with a width Γ_s) and contributes to the appearance of the secondary Raman radiation (but already with a width $\Gamma_{as} + \Gamma_a$). In view of the foregoing, it is easy to verify that the spectra T_2 and T_3 differ substantially in the line widths of their satellites. Figure 1a, b and c shows the model absorption spectra, differing from each other only in the phase correlation degree of the nuclei oscillations in target, calculated for different values of the target thickness, t_e. We see, how the spectra of T_2 and T_3, practically coinciding at the target thickness $t_e = 0.2$ (Fig. 1a), begin to differ greatly in the line widths of the satellites with increasing of the target thickness (Fig. 1b, c). On Fig. 2 the dependence of the satellite linewidths on the target thickness for these two cases is presented. It is obvious, that the primary reason for this difference is the coherent enhancement of Raman forward scattering in case T_2. This difference can also be interpreted as the result of an increase of the gamma-photon's effective mean free path for case of T_2, due to the return of Raman photons to the direction of the initial photon motion.

The transmission integrals T_2 and T_3 (for in-phase and chaotic oscillations of the target's nuclei, respectively) admit an analytic representation. In the case, when the degree of phase correlation of nuclei oscillations (expressed, say, by a symbol β) serves as fitting parameter, we can introduce the transmission integral, $T_2(\beta) \equiv T_2(\omega_s, \omega_a, t_e, b, \beta) = \int d\omega F_\beta(\omega, \omega_s, \omega_a, t_e, b)$, also represented by the forward scattering spectrum (F_β). The spectrum F_β for such a regime with partial phase correlation, as rule, cannot be represented analytically, but there are examples of the effective use of numerical calculations within the

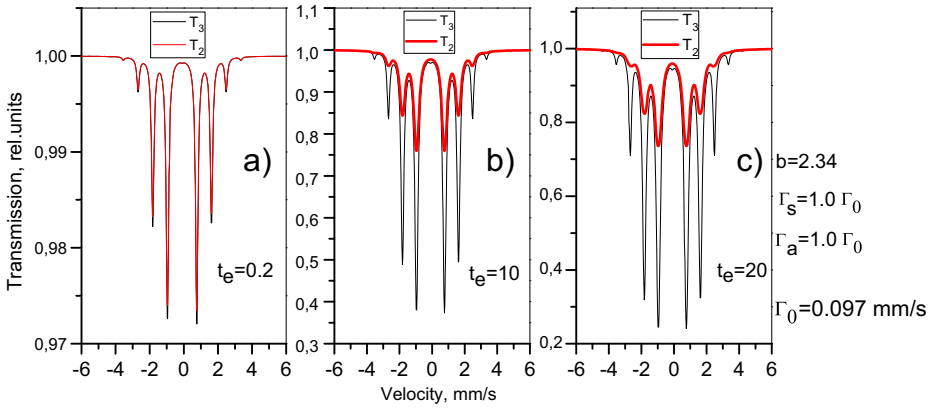

Fig. 1 The model transmission spectra T_2 and T_3, calculated using (2,3) and (4,5), respectively, for different target's thickness: **a** $t_e = 0.2$; **b** $t_e = 10$; **c** $t_e = 20$

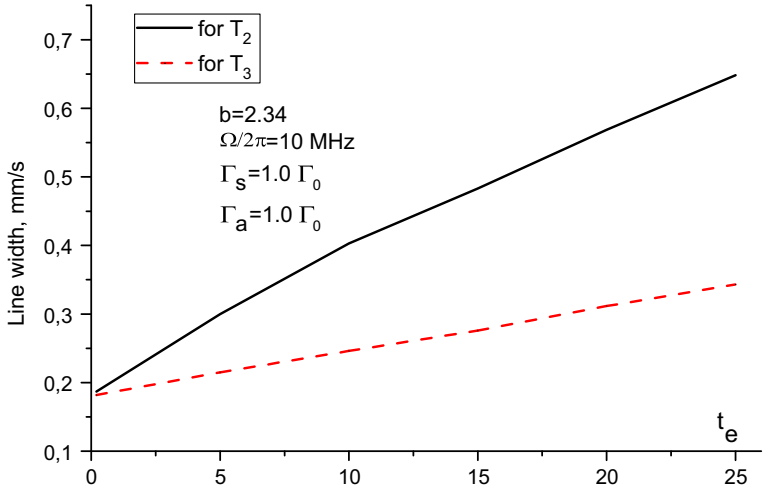

Fig. 2 The satellite's line widths for T_2 and T_3 versus target's thickness

framework of such a partial random model [4, 20]. Note that in a real experiment with a thick target, there are many reasons that contribute to the violation of the expected mode of in-phase oscillations (hence, to the deviation of the Mössbauer response from the F_2 function). On the other hand, an even greater simplification would be the description of the sound wave, initiated in the crystal by an external converter, within the framework of the model F_3, completely disregarding the Bloch theorem. Thus, a model that allows an arbitrary level of correlation of nuclei vibrations (F_β, T_β), looks as the most adequate tool for fitting the Mössbauer processes in a sound field.

Summarizing the foregoing, we note that in the proposed model, transmission integrals (T_2, T_3, T_β) corresponding to the sound vibrations of the resonant nuclei in target with different degrees of phase correlation are initially allowed . Within the framework of such a model, the choice in favor of a specific transmission integral (the level of phase correlation

of nuclei oscillations) is solved by the fitting of the experimental spectrum. The fitting is carried out on the basis of model expressions obtained by averaging T_2, T_3, T_β on the modulation index, as was done in the case of the traditional model [8, 12] (see (1). In particular, for T_2 the model expression looks as:

$$\langle T_2(\omega_s, \omega_a, t_e, b)\rangle_b = \int dbP(b)T_2(\omega_s, \omega_a, t_e, b) = \int d\omega \langle F_2(\omega_s, \omega_a, t_e, b)\rangle_b. \quad (9)$$

Simulation of the distribution function $P(b)$ in the case of thick targets remains a very important element of the fitting procedure for experimental spectra. In case (9), for example, one should remember the condition for the formation of a Mössbauer response T_2 (in-phase sound oscillations of nuclei in a target with constant amplitude). This is necessary in order to avoid possible contradictions, when considering the physical models of the formation of the desired distribution $P(b)$associated with the spatial distribution of the oscillation amplitudes. In this connection, we note that the averaging of type (9) was used in the case of fitting the forward scattering spectra [2], with a discussion of the conditions for its correctness. In addition, the formation of a sound field in a thick target is a process that depends mostly on its structural features. This leads to the necessity of modifying the known averaging schemes in (9), using new distribution functions and justifying them at the level of physical modeling.

The Rayleigh distribution, which is sufficiently substantiated at the physical level [8, 12], was successfully used at the initial stage of studies on US modulation of MS [12], but not all experiments could be explained on its basis [13, 21]. The reason for these failures is that the quantum averaging using the equilibrium state of the sound mode oscillator [7], which in this case leads to a function $P_{Rayl}(b, \sigma)$ in expression (1), is not completely correct. In this case, it seems more natural to average over the modulation index in (9) using the Rice distribution function $P_{Rice}(b, \sigma, \nu)$. Such averaging corresponds to quantum averaging on the stationary (but non-equilibrium) state of the oscillator controlled by an external converter [10, 11]. In favor of this two-parameter function is also the effective use of it in problems associated with activation of the system by an external coherent signal [22].

$$P_{Rice}(b, \sigma, \nu) = \left(b/\sigma^2\right) \exp\left(-\left(b^2 + \nu^2\right)/2\sigma^2\right) I_0\left(b\nu/\sigma^2\right). \quad (10)$$

3 Fitting of experimental Mössbauer spectra on stainless steel using the modified model

Further, the model, proposed above (2), (3) and (9), is used to describe the acoustically modulated Mössbauer transmission spectra, measured on a stainless steel (SS). A piston-like acoustic transducer - a polarized film of polyvinylidene fluoride (PVDF) with 28 μm thickness was used, which showed high efficiency in creating mechanical harmonic oscillations with homogeneous amplitude, both in KHz [23] and MHz frequencies [3]. The transducer (model LDT0-28K, Measurement Specialties Inc., USA) was glued to a 2 mm thick plexiglass plate and excited by a radio frequency generator (HP, model 8116A). A 25 μm thick SS foil (Alfa Aesar, type 304) with an effective thickness of 5.18 served as a target, which was glued to the piezoelectric transducer with epoxy glue.

The measurements were carried out at the 6.2 V, 12.2 V and 15.4 V for voltage values on the converter. The value 12.2 V, in particular, was chosen with intent to make modulation index close to 2.4, so the main line of the spectrum ($J_0(2.4) = 0$) with delta-like distribution function $P(b)$ will be excluded. Using for the fitting two functions, $P_{Rayl}(b, \sigma)$ and

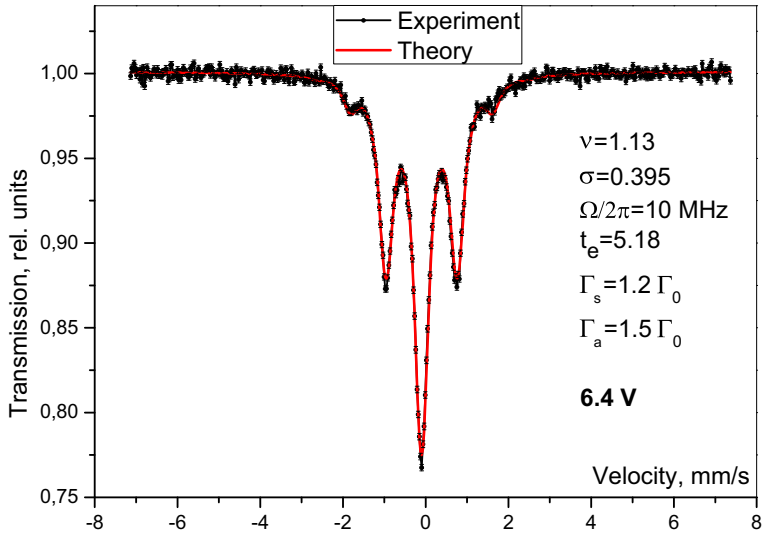

Fig. 3 The results of fitting of transmission spectra on SS using (9) and $P\,(b) = P_{Rice}\,(b, \nu, \sigma)$ at U= 6.4 V on the converter

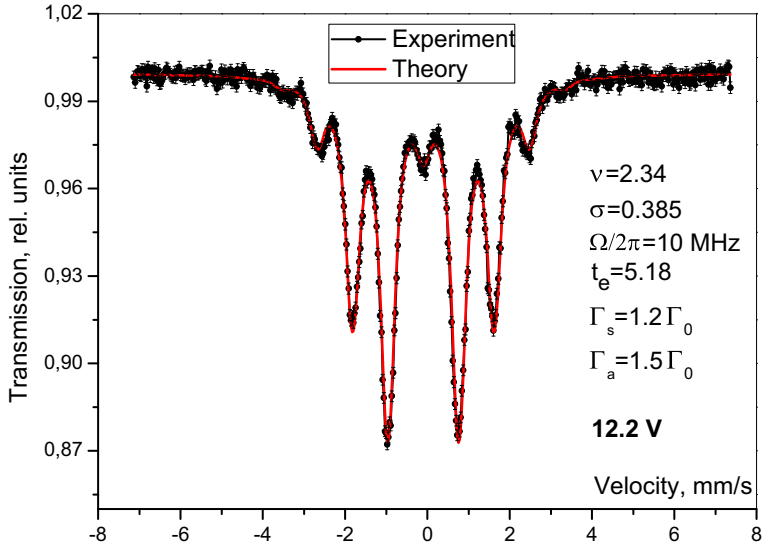

Fig. 4 The results of fitting of transmission spectra on SS using (9) and $P\,(b) = P_{Rice}\,(b, \nu, \sigma)$ at U= 12.2 V on the converter

$P_{Rice}\,(b, \nu, \sigma)$, the suitability of the Rice function for this purpose was uniquely established. By fitting the experimental spectra (see Fig. 3, 4 and 5), the parameters of the Rice function were determined: for 6.2 V - $\nu = 1.13,\ \sigma = 0.395$; for 12.2 V - $\nu = 2.34,\ \sigma = 0.385$; for the 15.4V - $\nu = 2.93,\ \sigma = 0.42$. Here we are convinced that for a 12.2 V voltage on the converter the parameter $\sigma = 0.385$ ensures the correct behavior of the spectrum (only

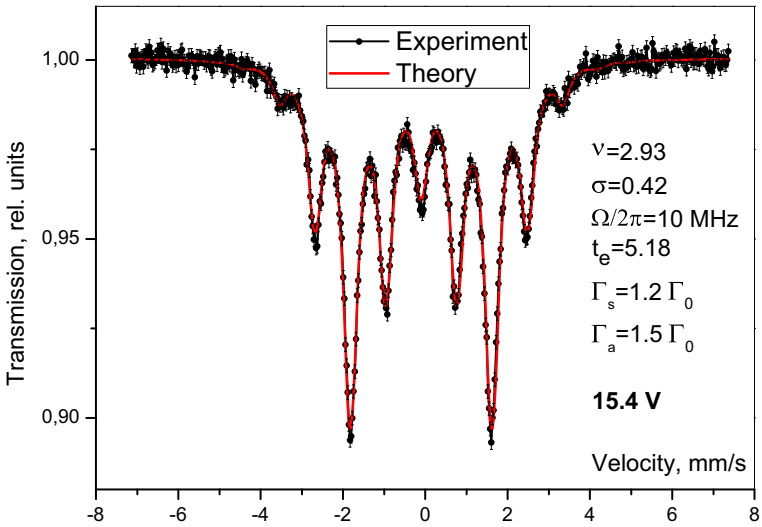

Fig. 5 The results of fitting of transmission spectra on SS using (9) and $P(b) = P_{Rice}(b, \nu, \sigma)$ at c) U= 15.4 V on the converter

in this case the central part of the spectrum is reproduced). The main result of the fitting is the confirmation of the proposed model for acoustic modulation, the pronounced satellites broadening effect due to coherent Raman FS, associated with $F_2(\omega, \omega_s, \omega_a, t_e, b)$. At the same time, the experimental spectra cannot be described by the traditional scheme (using $F_3(\omega, \omega_s, \omega_a, t_e, b)$ instead of $F_2(\omega, \omega_s, \omega_a, t_e, b)$). The attempt to fit the spectra on the basis of $F_3(\omega, \omega_s, \omega_a, t_e, b)$ leads to greatly overstated values of the parameters Γ_s and Γ_a. The result of spectrum fitting for the sample in the absence of US excitation can serve as an additional argument in favor of the proposed model (F_2, T_2). Such a procedure, which is based on a standard expressions [5]:

$$T_1(\omega_s, \omega_a, t_e, b) = \int F_1(\omega, \omega_s, \omega_a, t_e, b) d\omega, \tag{11}$$

$$F_1(\omega, \omega_s, \omega_a, t_e, b) = \frac{\Gamma_s}{2\pi} \frac{1}{(\omega - \omega_s)^2 + (\Gamma_s/2)^2} \exp\left[\frac{-t_e(\Gamma_a/2)^2}{(\omega - \omega_a)^2 + (\Gamma_a/2)^2}\right], \tag{12}$$

leads to the values $\Gamma_s = 1.2$ and $\Gamma_a = 1.5$ (Fig. 6), confirming the result of the fitting of the acoustically modulated spectrum on the F_2 basis. It should also be noted that under the conditions of this experiment a sound field, described by the Rice function [10, 11], is realized. For values of the parameters describing the measured spectrum, this function can be represented by a normal distribution $P_{Rice}(b, \nu, \sigma) \simeq P_{norm}(b, \nu, \sigma)$ with a good accuracy.

In this experiment, the broadening effect of the satellites due to the in-phase oscillations is obvious, since the width of each of the satellites is more than the width of the absorption line for the sample in the absence of sound: 0.47 mm/s > 0.44 mm/s.

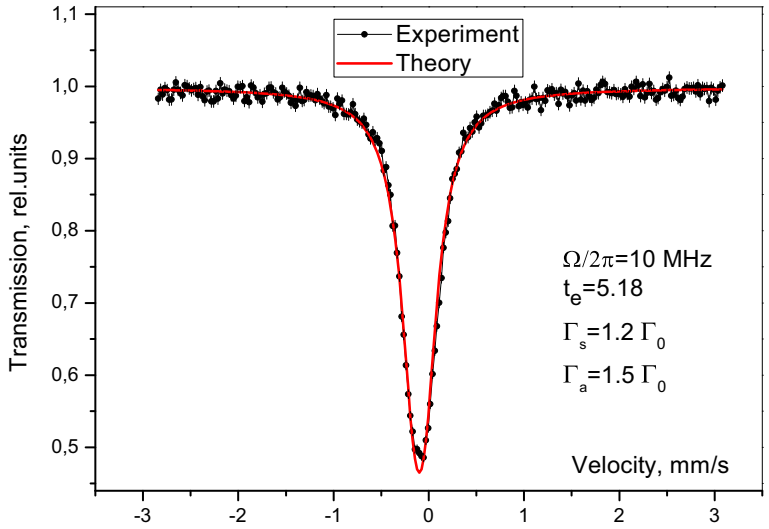

Fig. 6 The result of fitting for transmission spectrum on SS in absence of US excitation

4 Conclusion

The new model of acoustic modulation of the Mössbauer transmission spectra is proposed. The return to this topic is largely stimulated by interesting results of Mössbauer studies in the FS scheme. The peculiarity of effects, found in FS experiments [2, 3, 20, 24, 25] with thick targets excited by US or RF magnetic fields, is based on the constructive interference of forward Raman scattering amplitudes. This (interference) mechanism, represented by the FS spectrum, F_2, was also used by us as an essential element of the acoustic modulation model proposed for Mössbauer absorption spectra of thick targets. In this model the interaction of a gamma photon (emitted by a source) with an ensemble of nuclei in the target is considered initially, instead of the interaction with a separate target's nucleus. Thus, the internal consistency of the models concerning the US and RF assisted spectra, registered in various schemes of the Mössbauer experiment, has been achieved.

The proposed model allows describing the spectra for a traditional sample for Mössbauer measurements, stainless steel (SS), in the regime of acoustical excitation. The fitting of the spectra unambiguously confirms the assumption of in phase oscillations of the nuclei in the conditions of this experiment. The information (about the degree of the phase correlation of the nuclei vibrations) obtained in this case serves as an example of additional (nonlocal) information, extracted from Mössbauer measurements. The Rice distribution function proved to be the most suitable for fitting the experimental spectra on SS for all voltage values of US transducer used in this experiment.

The proposed model may be considered as an attempt to develop a dynamical model of Mössbauer processes. There is the possibility of generalizing this approach: by including the US models of oscillations in the regime of limited phase correlation and, on the other hand, by performing experimental measurements on systems of a more complex structure.

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