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Mössbauer experiment in a rotating system: The change of time rate for resonant nuclei due to the motion and interaction energy

A. L. Kholmetskii(1)(*), T. Yarman(2) and O. V. Missevitch(3)

(1) *Department of Physics, Belarus State University - 220030 Minsk, Belarus*
(2) *Okan University - Akfirat, Istanbul, Turkey & Savronik, Eskisehir, Turkey*
(3) *Institute for Nuclear Problems - 220050 Minsk, Belarus*

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Summary. — We verify a hypothesis suggested by the second co-author: the universality for all kinds of interactions change of time rate for any particles/objects as a function of their binding energy, which occurs in addition to relativistic dilation of time. In laboratory scale experiments, this effect can be checked by means of the Mössbauer effect with a resting resonant source and rotating resonant absorber (or vice versa). For the resonant nuclei bound in the solid-state absorber, coupled to a rotor, the additional change of time rate is expected. Correspondingly, an excess of relative energy shift $\Delta E/E$ between emission and absorption lines over the relativistic value $\Delta E/E \approx -u^2/2c^2$ for freely moving objects is expected. We thus reanalyze the known Mössbauer experiments in rotating systems and show that their results are well fitted into the expression $\Delta E/E = -k(u^2/c^2)$, with however the coefficient $k > 0.5$. We describe our own experiment on the subject, where we have measured $k = 0.68 \pm 0.03$. The result obtained is discussed.

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1. – Introduction

The present research was stimulated by a hypothesis proposed by the second co-author: the change of time rate for any interacting particle/object, no matter what kind of interaction it is a question of (refs. [1-3]). A change of time rate is the well-known effect for gravitation fields, where the general relativity and Yarman's approach (establishing proportionality between the variation of time rate and interaction energy) furnish astonishingly coincidental results, up to a third-order Taylor expansion [1]. At the same time, for electromagnetic and nuclear interactions, such a change of time rate (if measured in experiment) would be certainly a novel phenomenon. One should emphasize that for the moving interacting particle/object, the change of its time rate due to the

(*) E-mail: kholm@bsu.by

interaction and the conventional relativistic dilation of time are added to each other to the accuracy of calculations c^{-2}. For the freely moving particles, the relativistic dilation of time is observed alone, which has been confirmed in numerous experiments [4, 5].

On an experimental level, a measurement of the time rate for interacting objects is the most convenient, when they are in a bound state due to this interaction. Looking for the experiments on this subject, performed to the moment, we have found only a series of Mössbauer experiments in rotating systems [6-11], aimed to measure the Second Order Doppler (SOD) shift of resonant radiation between a rotating source and resting absorber (or vice versa). A relative energy resolution of resonant γ-quanta has a typical value of 10^{-13} to 10^{-15}, which allows a reliable measurement of the time dilation effect for sub-sound tangential velocities. In addition, atoms in the rotating absorber in these experiments undergo a centrifugal force, and their motion on a circular orbit is provided by a binding in the solid-state absorber. This implies the presence of a local electric field on the resonant nuclei, which counteracts the centrifugal force. Hence one is to expect an additional change of time rate for the nuclei of absorber due to their interaction electric energy, which is added to the conventional relativistic dilation of time due to its tangential velocity u (the latter is $\Delta E/E = -u^2/2c^2$ to the accuracy c^{-2}, where E is the resonant energy). For the configuration mentioned above (rotating absorber and resting source) both effects have a negative sign, and hence this expression is modified as

$$\Delta E/E = -k(u^2/c^2), \quad (1)$$

where, however, the value of k is expected to be larger than 0.5, if the hypothesis by Yarman is correct. Nonetheless, as known, the authors of [6-11] reported a confirmation of the relativistic expression for the time dilation effect: $k = 0.5$ with the accuracy of few percents. In the light of Yarman's hypothesis we decided to re-analyze carefully these experiments. We have revealed that the estimation $k > 0.5$ is indeed much better fitted into the results of the experiments (sect. **2**). This finding stimulated us to carry out our own Mössbauer experiment in a rotating system, which is described in sect. **3**. The results obtained by us confirm that the coefficient k in eq. (1) substantially exceeds 0.5. Finally, sect. **4** contains a discussion.

2. – Mössbauer experiments in a rotating system: re-analysis of known results

Among the papers mentioned above [6-11], we started our analysis with the experiment by Kündig [6], because he was the only one who successfully applied a first-order Doppler modulation of energy of γ-quanta on a rotor at each fixed rotation frequency, implementing an oscillating motion of the source along the radius of the rotor. By such a way he recorded the shape of the resonant line and determined its position on the energy scale *versus* the rotation frequency. In contrast, all other authors [7-11] measured only the count-rate of detected γ-quanta as a function of rotation frequency. Thus, it is needless to say that Kündig's experiment is much more informative and reliable than other experiments on the subject. In particular, he observed an essential (up to 1.5 times) broadening of the resonance line with increase of rotation frequency, caused by mechanical vibrations in the rotor. In Kündig's experiment this line broadening does not lead to additional systematic errors, but such a privilege did not hold in other experiments [7-11].

Nonetheless, the authors of [7-11], like Kündig, reported the confirmation of the standard relativistic time dilation effect with the measuring precision of about 1% (as they have claimed).

However, we revealed [12] that data processing in Kündig's experiment was erroneous. An intriguing fact is that after correction of the errors by Kündig, his data give the value $k = 0.596 \pm 0.006$ [12]. One sees that the deviation of this value from the relativistic expression $k = 0.5$ exceeds almost 20 times the measuring error.

We would like to emphasize again that due to applied modulation of energy of emitting resonant radiation, Kündig was successful to measure the *position* of the resonant line on the velocity (energy) scale, which is insensitive to vibrations of rotor, despite of line broadening. This methodological feature favorably distinguishes his experiment from others mentioned above [7-11], where the influence of chaotic vibrations on the width of the resonant line in fact was ignored. For high-quality rotor systems, the dependence of vibration level on rotation frequency usually has two minima: the lower one, at self-stabilization frequency, and the higher local minimum, when the centrifugal force acting on a rotor approaches the strength limit. Normally the rotor experiments are carried out within the range of rotation frequencies between these two minima, where in the absence of parasitic mechanical resonances (provided by a proper mechanical design), the level of vibrations gradually increases and finally goes down approaching the second minimum. In particular, Kündig observed an approximately exponential increase of the linewidth up to 1.5 times in a full range of variation of the rotation frequency. It does not mean yet that the same appreciable increase of linewidth took place for the rotors applied in [7-11]. At the same time, it is rather difficult to believe that a line broadening was totally absent, as was tacitly assumed by the authors of the mentioned papers [7-11]. Amongst them the experiment by Champeney *et al.* [11] is distinguished by the numerous experimental data, obtained for different absorbers (5 pieces) and Mössbauer sources ^{57}Co in two different matrices. The analysis of this experiment, implemented by us in ref. [12], has shown that its results are also well fitted into $k > 0.5$ ($k = 0.61 \pm 0.02$).

Thus, it seemed topical to repeat right away the Mössbauer experiments in rotating systems to measure the coefficient k in eq. (1). Such an experiment performed by us is described in the next section.

3. – Mössbauer experiment in a rotating system: our measurements with two resonant absorbers

Planning such an experiment, we realized that direct repetition of Kündig experiment anyway would leave some doubts on the presence of possibly missed technical factors, which distort the measured k(1). Hence we decided to carry out a new Mössbauer experiment on a rotor, which depicts neither the scheme of Kündig experiment, nor the schemes of other experiments [7-11], in order to get independent information on k. In particular, we did not apply the first-order Doppler modulation of the energy of gamma-quanta, in order to avoid the uncertainties mentioned in the footnote (1). Thus we followed the scheme [7-11], where the count-rate of detected γ-quanta N as a function of rotation frequency ν is measured. However, in contrast with the experiments [7-11], we do evaluate the influence of vibrations on the measured value of k. For this purpose we applied a method, which involves the joint processing of data collected for two selected resonant absorbers with the specified energy shift of resonant lines (subsect. **3**˙1). In

(1) One of such factors might be the finite length of the piezotransducer applied by Kündig. Hence some of its parts inevitably experience the centrifugal force, which could change the piezoelectric constant with variation of the rotation frequency. Although Kündig estimated this factor to be negligible, he did not present a convincing proof.

subsect. **3**˙2 we describe our experimental set-up. In subsect. **3**˙3 we present the data obtained and results of their processing, which are discussed in sect. **4**.

3˙1. *Methodology*. – In what follows, we consider k in eq. (1) as a parameter to be determined experimentally. In an idealized case, when the vibrations are absent in a rotating system, this coefficient is easily computed through the expression $k = cu_1/u^2$, u being the tangential velocity of absorber, and u_1 the relative velocity between the source and absorber, which corresponds to first-order Doppler shift to be equal to SOD shift at the given u. The former is measured for the same pair of "source plus absorber" with a standard Mössbauer spectrometer outside the rotor system.

Further on we proceed based on the fact that the non-vanished vibrations should always be present in the rotating system. Such vibrations are known to broaden the resonant line, but do not influence the total area and position of this resonant line on the energy scale. In a general case we have to adopt that the vibrations are not only present in the system, but also the vibration level depends on the rotation frequency. As we mentioned above, such a behavior of vibrations has been confirmed by Kündig (a broadening of the resonant line up to 1.5 times with increase of rotation frequency in a full range of its variation [6]). In this case the count-rate of the detector $N(\nu)$ as a function of the rotation frequency ν can essentially deviate from the corresponding dependence $N_{id}(\nu)$ in the idealized case (no vibrations), and accordingly, one may end up with distorted information on the value of k in eq. (1).

Our idea is to eliminate such distortion of k due to vibrations, applying two various resonant absorbers with the specified difference of line positions in Mössbauer spectra. For an optimal pair of such absorbers, the equal broadening of resonant lines due to vibrations induces the essentially different variations of detector's count-rate for each absorber. Comparing the data of the rotor experiment obtained with each absorber, we can get required information on the level of vibrations and separate its contribution into the $N(\nu)$ dependence on SOD.

Thus, we deal with two resonant lines: one of them has a minimum within a full range of variation of energy (absorber 1, fig. 1, a), and the second line has an appropriately larger isomer shift than for the first absorber, so that a full range of variation of energy of γ-quanta due to SOD lies on a slope of the line (absorber 2, fig. 1, b). Now let us show that a conjoined processing of data obtained in a rotor experiment with the absorbers 1 and 2 allows us actually to eliminate the influence of vibrations on the estimation of k. For this purpose we realize an algorithm as follows.

1) The Mössbauer spectra of both absorbers are measured with a high enough statistic quality.

2) The data of rotor experiment are collected for absorbers 1 and 2 in the same range of variation of rotation frequency.

3) Having assumed any particular value of k in eq. (1) (for example, one can vary k between 0.5 and 1.0), the expected theoretical curves $N_{id}(\nu)$ for the rotor experiment with a zero level of vibrations (hereinafter the "idealized rotor experiment") are plotted for both absorbers. Since in a real experiment the vibrations are always present, the theoretical curves we draw for each absorber, deviate from the corresponding experimental data, no matter what the assumption on k is.

4) For the chosen value of k, a variation of the width Γ for the resonant line of absorber 2 is implemented at each rotation frequency ν_i, so that the corrected data pass through the theoretical curve $N_{id}(\nu)$. As an outcome of this procedure we obtain the values of $\Gamma(\nu_i)$, which model the line broadening due to vibrations at various ν_i.

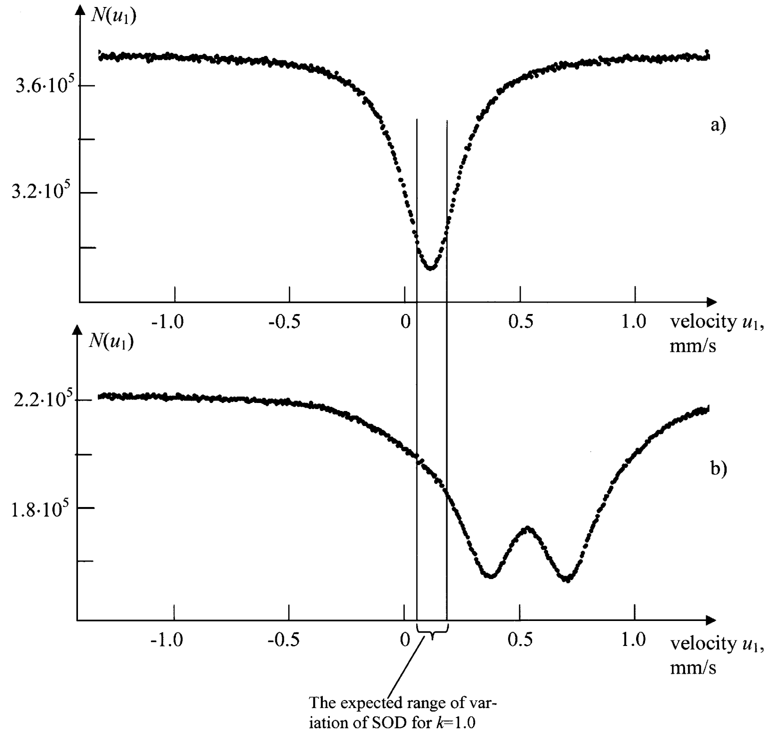

Fig. 1. – Mössbauer spectra of absorber 1 ($K_4{}^{57}Fe(CN)_6 \times 3H_2O$, a) and absorber 2 ($Li_3{}^{57}Fe_2(PO_4)_3$, b), obtained with the source $^{57}Co(Cr)$ at the room temperature. The range of variation of energy due to second-order Doppler shift at $k = 1.0$ is restricted by the vertical lines.

5) The values $\Gamma(\nu_i)$ obtained at the given k are applied to correct the experimental data for the absorber 1, obtained for the same k. As a result we get a new set of points, describing the expected data for the idealized rotor experiment. If these corrected data continue to deviate from the corresponding theoretical curve $N_{id}(\nu)$, then we adopt that the hypothesis on a given value of k is false and should be rejected.

6) A new value of k is chosen, and the steps 3-5 are repeated, while we obtain a self-consistent result for the absorber 1 with the minimal statistical test criterion χ^2 with respect to a set of corrected experimental data and theoretical curve $N_{id}(\nu)$. A corresponding magnitude of k is then adopted.

As a result we get the best fitting of experimental data with two sets of free parameters: the coefficient k in eq. (1) and level of vibrations, manifesting as $\Gamma(\nu_i)$ set. In subsect. **3**˙3 we use this algorithm to processing of data obtained, applying the MathCad Professional software.

We would like to add that a modern extended database on various Mössbauer compounds created by the Mössbauer Effect Data Center [13] allows us choosing the most optimal absorbers for realization of the algorithm just described. The absorber 1 represents a thin layer of the compound $K_4Fe(CN)_6 \times 3H_2O$ enriched by ^{57}Fe to 90%. The absorber 2 is a thin layer of the compound $Li_3Fe_2(PO_4)_3$ enriched by ^{57}Fe to 90%. Each absorber was packed between two beryllium plates transparent for resonant γ-quanta 14.4 keV. The Mössbauer spectra of absorbers were measured by means of the Mössbauer instrument package MS-2000IP [14].

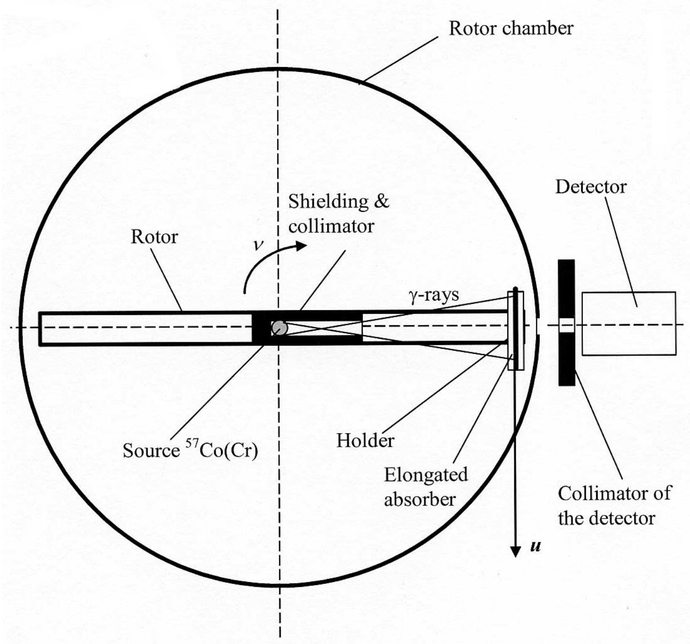

Fig. 2. – Schematic of the present experiment.

3˙2. *Experimental set-up.* – A rotor system applied by ourselves (see fig. 2) is based on the ultracentrifuge K-80 (Belmashpribor, Minsk) with the diameter of the working chamber 63.0 cm. The rotor has a length 61.0 cm. A Mössbauer source ^{57}Co(Cr) with the activity 20 mCi was put into a Cu-Pb shielding and collimating system and mounted on the rotation axis. A sample holder was fixed at the edge of the rotor. For the reasons explained below (see sect. **4**), we have chosen the distance between the source and the absorber ($R_A = 30.5$ cm) few times larger than picked for the Kündig experiment (where $R_A = 9.3$ cm). The difference of temperatures of the source and the absorber during rotation never exceeded 2 °C. For such a difference of temperatures, we can neglect the variation of the resonant line position due to thermal shift.

Xe-filled proportional counter for detection of γ-quanta was located outside the rotor system. The absorbers used have a rectangular form with the size 15×55 mm. In these conditions the average count-rate of the detector was about 3 pulses/s in the working energy window, selecting resonant γ-quanta of ^{57}Fe 14.4 keV. The background count-rate was less than 0.2 pulses/s. This allowed us to omit the time selection of output pulses of the detector, applied in earlier experiments [6-11].

A measurement of SOD was carried out in the range of rotation frequencies $\nu = 70$ to 120 rev/s. It corresponds to the change of tangential velocities of absorber $u = 134$ to 230 m/s. In terms of the first-order Doppler shift, it corresponds to a variation of the linear velocity $u_1 = c(u^2/2c^2) = (0.030$ to $0.088)$ mm/s (for $k = 0.5$).

Each measuring cycle started with the maximal frequency $\nu = 120$ rev/s with its further decrease to 70 rev/s with steps of 10 rev/s. The accuracy of setting of ν is ± 0.5 rev/s. The number of output pulses of the detector was measured during 100 seconds at each rotational frequency. Then a new measurement cycle was installed, and so on. A total number of counts at each ν has been obtained by summation over 50 cycles, and was about $1.6 \cdot 10^4$.

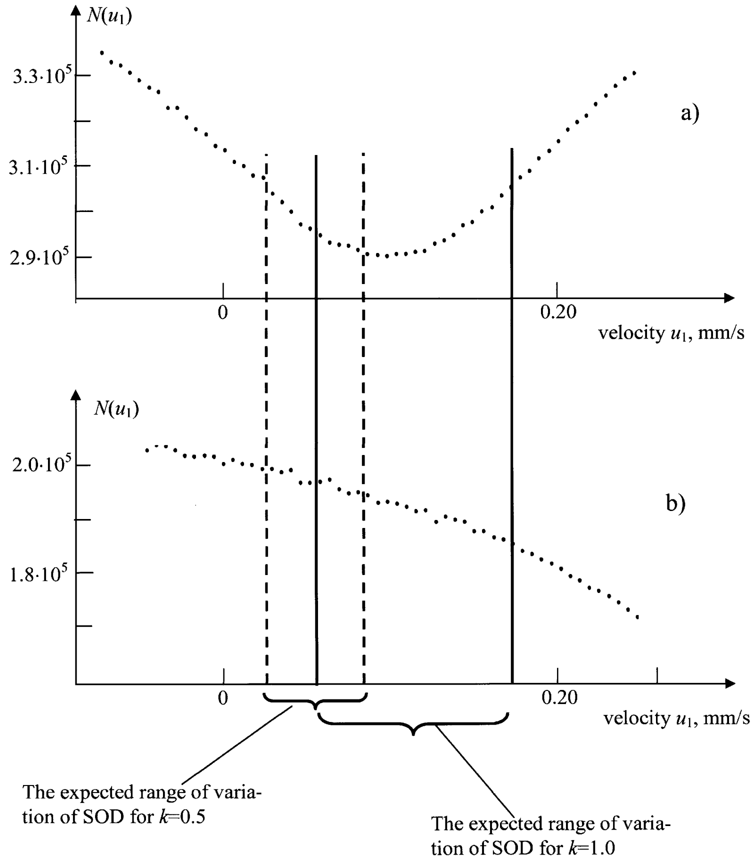

Fig. 3. – Expanded relevant fragments of Mössbauer spectra of $K_4{}^{57}Fe(CN)_6 \times 3H_2O$ (a), $Li_3{}^{57}Fe_2(PO_4)_3$ (b) and the expected range of variation of SOD in our rotor experiment for two limited hypotheses on k.

3˙3. *Results*. – In fig. 1, we have shown already the Mössbauer spectra of the absorbers 1 (a) and 2 (b). The spectrum of the first absorber represents a single line shifted at $+(0.095 \pm 0.001)$ mm/s with respect to the emission line of ^{57}Co(Cr) source. The value of the resonant effect is $(20.9 \pm 0.1)\%$. The spectrum of the second absorber represents a partially resolved doublet with the left line shifted at $+(0.390 \pm 0.001)$ mm/s with respect to ^{57}Co(Cr). The resonant effect is $(30.5 \pm 0.1)\%$. The expanded relevant fragments of both spectra are depicted in fig. 3, where the dashed vertical lines restrict a range of variation of SOD for $\nu = 70$ to 120 rev/s and $k = 0.5$, whereas the continuous vertical lines show the same range for $k = 1.0$.

One can see that the parameters of the Mössbauer spectrum of absorber 1 make it especially sensitive to the choice of two limited cases $k = 0.5$ and $k = 1.0$, if one considers the idealized rotor experiment (exempt of vibrations). If $k = 0.5$, then a count-rate of the detector should continuously decrease in a full range of variation of rotation frequency ν, and at $\nu = 120$ rev/s we only approach to the maximum of resonant absorption. If $k = 1.0$, then the count-rate of the detector reaches a minimal value already at $\nu \approx 90$ rev/s with further increase at higher ν.

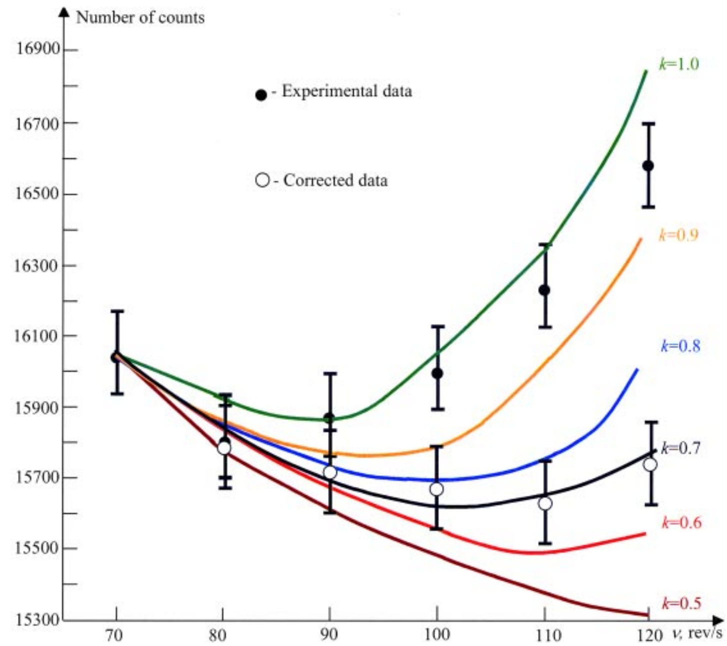

Fig. 4. – The experimental data for absorber 1 (black circles), and corrected data (hollow circles) re-computed at $k = 0.7$ via taking into account the level of vibrations in the rotor system. Continuous lines show the curves $N_{id}(\nu)$ expected at different k for the idealized (no vibrations) rotor experiment.

A similar analysis of the idealized rotor experiment with absorber 2 indicates that a count-rate of the detector decreases for both limited cases ($k = 0.5$; $k = 1.0$), but a slope of the falling curve is few times larger at $k = 1.0$.

In figs. 4, 5 we present the data of our rotor experiment (black circles), obtained with both absorbers. In these figures we also plotted the corresponding curves $N_{id}(\nu)$, expected in the idealized rotor experiment at various k. According to our approach to the data processing described above (subsect. **3**˙1), we use the data of fig. 5 (absorber 2) to evaluate the level of vibrations in the rotor system and estimate the line broadening $\frac{\Gamma(\nu_i)}{\Gamma(\nu=0)}$ at different v. Then we correct the experimental data for the absorber 1 at various k with account of vibrations in the system and compare them with the corresponding theoretical curves $N_{id}(\nu)$.

The analysis of fig. 5 (absorber 2) indicates that vibrations are present in the system (like they were in the Kündig experiment) and do influence the count-rate of the detector. On this stage we applied the step 4 of the algorithm described in subsect. **3**˙1, and extracted the values $\Gamma(\nu_i)$, describing a broadening of the resonant line with rotation frequency. Then, involving the set of the obtained values $\Gamma(\nu_i)$, we applied the steps 5-6 of the algorithm described above and did correct the experimental data for the absorber 1 at various hypotheses on k. We have found that self-consistent results are obtained nearly $k = 0.7$. In fig. 4 we show the corrected data for $k = 0.7$ (hollow circles) via taking into account a broadening of the resonant line due to vibrations (table I). A least-square fit specifies this observation to lead to $k = (0.68 \pm 0.03)$.

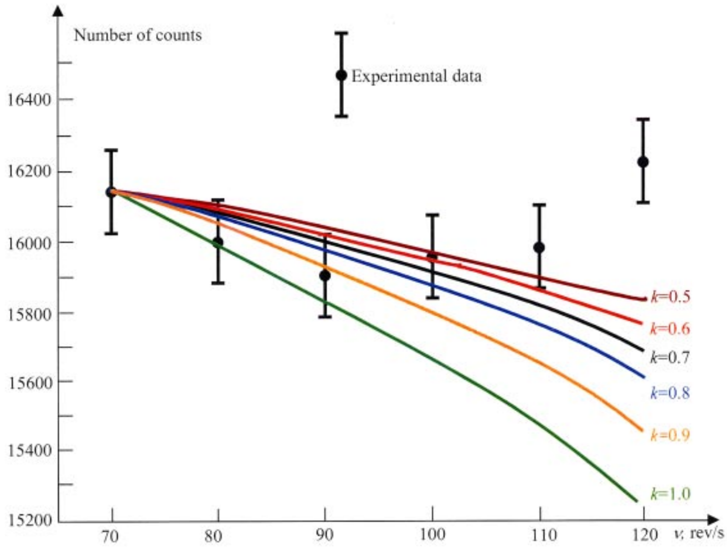

Fig. 5. – Experimental data for the absorber 2 in comparison with the curves $N_{id}(\nu)$ computed at different k for the idealized (no vibrations) rotor experiment.

4. – Discussion

The driving force of the present work was the experimental verification of an essential prediction by Yarman: the change of time rate for any interacting particles/objects as a function of their interaction energy, within both micro- and macro-scale domain, no matter what kind of interaction it is a question of [1-3].

We suggested carrying out a test of this prediction in a laboratory scale experiment, using the Mössbauer effect in a rotating system. We divided this test into two stages:

- the analysis of known Mössbauer experiments on the time dilation effect;
- the performance of our own experiment on this subject.

Table I. – *Relative broadening of the resonant line at various rotation frequencies* ν*. The linewidths at* $\nu = 100,\ 110,\ 120\,\text{rev/s}$ *are directly computed through the difference between the experimental data obtained with the absorber* 2 *and idealized curve* $N_{id}(\nu)$ *(fig.* 5*) at* $k = 0.7$*. The linewidths at* $\nu = 70,\ 80$ *and* $90\,\text{rev/s}$ *have been obtained by extrapolating the revealed exponential law (to be found also in the Kündig experiment* [6]*) of the line broadening as a function of* ν *(at the range* 100–$120\,\text{rev/s}$*), to the range of* $\nu = 70$–$90\,\text{rev/s}$*. Such an extrapolation has been applied, since a deviation of* $N_{id}(\nu)$ *curve from the experimental data at these lower frequencies is less than the statistic error of the data.*

Rotational frequency (rev/s)	70	80	90	100	110	120
Linewidth (in relative units)	1.01 ± 0.01	1.02 ± 0.01	1.04 ± 0.01	1.08 ± 0.01	1.15 ± 0.02	1.30 ± 0.03

Extrapolated (70–90) — Computed from data (100–120)

At the first stage we focused our attention to the experiment by Kündig [6], as the most reliable among the others [7-11]. We have revealed serious errors in the data processing implemented by Kündig, and after elimination of these errors, the coefficient $k = (0.503 \pm 0.006)$ in eq. (1) reported by Kündig has been transformed into $k = (0.596 \pm 0.006)$ [12]. In addition, we have found that the experiment [11], containing much more data than [7-10], is also well fitted into the supposition $k > 0.5$ ($k = 0.61 \pm 0.02$).

At the second stage we carried out our own Mössbauer experiment in a rotating system, applying a new method for correction of the experimental data obtained to a level of possible chaotic vibrations in the rotor. In addition, we had chosen the rotor diameter r substantially larger than in the known experiments [6-11] (see table II). It allows diminishing proportionally the centrifugal pressure on the absorber, which might change the electron density on the resonant nucleus and, by such a way, vary the isomer shift between emission and absorption lines, distorting the value of k in eq. (1). Although the significance of this effect was not supported by numerical estimations of [12], we decided to eliminate any speculations on the influence of pressure, choosing the rotor diameter more than 3 times larger than in Kündig's and other Mössbauer experiments in rotating systems. Nonetheless, we observe even a higher value of $k = (0.68 \pm 0.03)$ than drawn by the Kündig experiment.

Thus the present work allows clarifying a number of important points as follows.

1) The confirmation of the corrected result of Kündig's experiment $k > 0.5$ practically omits any suspicions on the influence of any experimental aspect, since the technique and methodology of Kündig's and our experiments essentially differ from each other.

2) The corrected result we have provided about Kündig experiment ($k = 0.596 \pm 0.006$), the corrected result we have drawn about Champeney *et al.* experiment ($k = 0.61 \pm 0.02$), and the result of the present experiment ($k = 0.68 \pm 0.03$) do not essentially deviate from each other, in spite of quite different (more than ten times) typical magnitudes of rotation frequencies and centrifugal accelerations in these experiment (see table II, 2nd and 5th columns). Hence one may assume that the effect causing the exceeding of k over the value 0.5 is insensitive to the centrifugal acceleration itself. Just the verification of this result led us to choose the rotor diameter essentially different than in other Mössbauer experiments [6-11]. The result seems actually important, insofar as it makes irrelevant any effects (even unknown) of solid-state physics, for example, a variation of factor f with the centrifugal pressure, etc.

3) The experiments in question are characterized by the comparable values of orbital velocity of absorber u (4th column of table II), which allows assuming that the effect, inducing the increase of k, solely depends on u^2.

Now let us show that the hypothesis by Yarman allows indeed obtaining such a dependence on u^2 with the qualitative agreement between calculated and measured values of k.

As a starting point, we observe that for a laboratory observer the resonant nuclei in the rotating absorber experience a centrifugal force. Thus, as we mentioned above, the requirement of equilibrium of the crystal implies the appearance of a local electric field E_r on resonant nuclei, lying in the radial direction so that to implement the equality

$$ZeE_r = -m_N \omega^2 r. \tag{2}$$

Herein Z is the atomic number of the resonant atom, ω is the rotation frequency, and m_N is the mass of the nucleus. Introducing the effective electric potential φ at the location

TABLE II. – *Comparison of the basic properties of Kündig experiment* [6]*, Champeney et al. experiment* [11]*, and our own Mössbauer experiment in a rotating system.*

Experiment	Parameter					
	$\nu_{\max}$ (rev/s)	R_A (cm)	$u_{\max}$ (m/s)	Centrifugal acceleration in "g"	$\left(\frac{\Gamma(\nu_i)}{\Gamma(\nu=0)}\right)_{\max}$	Signal/noise(*)
Kündig	586	9.3	340	$1.3 \cdot 10^5 g$	1.45	≥ 200
Champeney *et al.*	1400	4.2	370	$3.1 \cdot 10^5 g$	?	45
Present experiment	120	30.5	230	$1.8 \cdot 10^4 g$	1.30	40

* This is taken as the ratio of the relative height of the resonant line to the relative statistic error in the rotor experiment.

of the nucleus by the equality

$$E_r = -\partial\varphi/\partial r, \tag{3}$$

and combining eqs. (2) and (3), we obtain

$$\varphi = \frac{m_N \omega^2 r^2}{2Ze}\,. \tag{4}$$

According to the hypothesis by Yarman, the change of time rate of charged particle e with the binding energy $U = e\varphi$ in the electric field (where $\varphi = 0$ at the infinity, or in our case, on the rotational axis) is determined by the expression

$$\frac{\delta t}{t} = -\frac{U}{mc^2} = -\frac{e\varphi}{mc^2}\,. \tag{5}$$

The insertion of the potential (4) into eq. (5) gives the expression for a relative change of time rate in the local electric field as follows:

$$\frac{\delta t}{t} = -\frac{\omega^2 r^2}{2c^2} = -\frac{u^2}{2c^2}\,. \tag{6}$$

Thus, the hypothesis by Yarman already gives a correct dependence on u^2 of the additional dilation of time. Going to the numerical evaluation of the coefficient k in eq. (1) on the basis of this hypothesis, we first observe that, in general, eq. (6) cannot determine the change of time rate for the overall nucleus in the electric field. It is more precise to say that the electric field changes the time rate for protons, but does not affect the time rate for neutrons. Such an effect certainly influences the structure of energy levels of nucleus, but it would be, in general, incorrect to state that the energy of each level varies proportionally to the obtained value $\delta t/t$. Since the energy levels of nuclei cannot be computed up to date, it is also impossible to determine a variation of these levels due to a change of time rate for protons in the electric field. Thus at the qualitative level we may only assume that the variation of energy levels of nuclei should be sensitive not only to the value $\delta t/t$ in eq. (6), but also to a fraction of the protons in the nuclei (Z/A), *i.e.*

$$\left(\frac{\delta E}{E}\right)_{\delta t} = F\left(\frac{Z}{A}\right)\frac{\delta t}{t} = -F\left(\frac{Z}{A}\right)\frac{u^2}{2c^2}, \tag{7}$$

where the function F can be determined experimentally, at least in principle.

In the weak relativistic limit, which is perfectly fulfilled in our case, the effect (7) is added to the relativistic dilation of time $(\delta E/E)_{\mathrm{rel}} = -u^2/2c^2$, so that the total relative shift of the energy of nuclear level reads

$$\left(\frac{\delta E}{E}\right)_{\mathrm{total}} = \left(\frac{\delta E}{E}\right)_{\delta t} + \left(\frac{\delta E}{E}\right)_{\mathrm{rel}} = -k\frac{u^2}{c^2}, \tag{8}$$

where we have introduced the coefficient

$$k = \frac{1}{2}(1 + F(Z/A)). \tag{9}$$

In a rough approximation we can put $F(Z/A) = Z/A$. Hence for the resonant nucleus of iron ($Z = 26$, $A = 57$), we obtain $k = 0.728$, which is already in a good agreement with our result $k = 0.68 \pm 0.03$.

At this stage, we do not wish to insist that the prediction by Yarman *et al.* on the change of time rate for interacting particles/objects indicates a single possible way to explain the deviation of the coefficient k from 0.5. In any case, the implementation of new Mössbauer experiments in rotating systems seems to be an essential task, in order to collect new data on the relative energy shift between emission and absorption lines in various conditions. Planning such new experiments, one should recognize that the approach by Kündig (the first-order Doppler modulation of resonant radiation on a rotor) remains the best; in particular, one sees that the measuring error of k in his experiment is few times lower than in the reported experiment. This is not only due to a better statistic quality of Kündig's data obtained for the higher count-rate of detector, but also due to elimination of any correction of these data to a level of vibrations in a rotor system.

In addition, it seems interesting to carry out a Mössbauer rotor experiment with ^{181}Ta resonance, which has a more narrow resonance line than ^{57}Fe. It is even more important that the ratio (Z/A) for this element is lower than for ^{57}Fe (0.403 *versus* 0.456) and thus, if eq. (9) is valid at least at the qualitative level, the measured value of k for ^{181}Ta is expected to be lower than for ^{57}Fe resonance by $\sim 5\%$. This should be detectable in the Kündig-type experiment with application of the first-order Doppler modulation of resonant radiation.

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