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Full Length Research Paper

Mössbauer experiments in a rotating system on the time dilation effect

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In this contribution, we analyze both the old Mössbauer experiments in a rotating system and our new experiment on this subject, which unambiguously indicate the presence of an additional component in the relative energy shift $\Delta E/E$ between emission and absorption lines, as compared with the classic relativistic expression written to the accuracy c^{-2} (that is $\Delta E/E=-u^2/2c^2$, where u is the tangential velocity of absorber, and c the light velocity in vacuum). The additional dilation of time for the rotating absorber constitutes more than 20% from the relativistic value, and it many times exceeds the measuring uncertainty. We discuss a possible origin of this effect and the ways of its further experimental verification.

Key words: relativistic dilation of time, rotating systems, Mossbauer effect.

INTRODUCTION

Soon after the discovery of the Mössbauer effect, a series of experiments with resonant γ-quanta in rotating systems were carried out (Hay et al., 1960; Champeney and Moon, 1961; Hay, 1962; Kündig, 1963; Granshaw and Hay, 1963; Champeney et al., 1965). In these experiments, an absorber orbited around a source of resonant radiation (or vise versa). The goal was to verify the relativistic dilation of time for a moving resonant absorber (source), which induces a relative energy shift between emission and absorption lines at the value:

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

For sub-sound tangential velocity $u\approx 300$ m/s, the value of $\Delta E/E$ has the order of magnitude 10^{-12}, which can be reliably measured with the aid of Iron-57 Mössbauer spectroscopy, providing the relative energy resolution of resonant γ-quanta about 10^{-14} and higher. Correspondingly, all the authors of the mentioned papers reported a confirmation of relativistic expression (1) with the accuracy about 1%. Later the relativistic dilation of time had been confirmed with much better precision ($10^{-8}...10^{-9}$) in the experiments on ion beams (Bailey et al., 1977; McGowan et al., 1993), and this achievement deprives physicists of further interest in repetition of the Mössbauer experiments in rotating systems.

Nonetheless, at the modern time, we inspected closer at these experiments to verify the prediction by Yarman on the additional variation of time rate in bound systems (Yarman, 2006; Yarman, 2010). Not going in this paper into any details of Yarman's hypothesis, which was a stimulated factor for the present research, we refer to our paper (Kholmetskii et al., 2008), where we surprisingly revealed serious errors in the data processing and in the interpretation of Mössbauer experiments on the time dilation effect. After elimination of these errors, we generally concluded that there is an additional dilation of time for the rotating observer, which induces an excess of $\Delta E/E$ in comparison with Equation (1) to the value much larger (the order of magnitude and more) than the measuring uncertainty. This finding stimulated the performance of our own experiment on this subject, based on a novel method for measurement of small energy shifts of resonant lines, which completely

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confirmed the presence of the additional dilation of time as compared with the standard relativistic effect, for the rotating absorber. Further, we separately analyze various factors, which could distort the results of our measurements. Finally, we discuss a possible origin of the effect revealed and the ways for its further experimental verification.

Analysis of known Mössbauer experiments in a rotating system

Among the experiments (Hay et al., 1960; Champeney and Moon, 1961; Hay, 1962; Kündig, 1963; Granshaw and Hay, 1963; Champeney et al., 1965), a separate attention should be accorded to the experiment by Kündig (1963) since he was the only one who applied a first order Doppler modulation of energy of γ-quanta on a rotor at each fixed rotation frequency ν, implementing a motion of the source along the radius of the rotor. As such, he recorded the shape and the position of resonant line on the energy scale versus the rotation frequency and thus his results were insensitive to the presence of possible mechanical vibrations in the rotor system. In contrast, other authors (Hay et al., 1960; Champeney and Moon, 1961; Hay, 1962; Granshaw and Hay, 1963; Champeney et al., 1965) measured only the count-rate of detected γ-quanta at each fixed ν, and their results were not protected from the distortions induced by the vibrations. This explains why Kündig's experiment is much more informative and reliable than the others. In these conditions, it was regrettable to reveal a number of errors in the data processing implemented by Kündig, which have been displayed in Kholmetskii et al. (2008). The row data available in Kündig (1963) for three various rotation frequencies allowed deriving the correct experimental values of the relative energy shift between emission and absorption lines versus the rotational frequency, which yields:

$$\Delta E/E = -ku^2/c^2, \qquad (2)$$

with $k = 0.596 \pm 0.006$.

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 resonant line on the velocity (energy) scale, which is insensitive to vibrations of rotor, despite of line broadening caused by the vibrations. This methodological feature favorably distinguishes the framework of his experiment from other aforementioned experiments (Hay et al., 1960; Champeney and Moon, 1961; Hay, 1962; Granshaw and Hay, 1963; Champeney et al., 1965), where an influence of chaotic vibrations on the width of resonant line in fact was ignored. In particular, Kündig observed an approximately exponential increase of the line width up to 1.5 times under variation of the rotation frequency ν from 183 rev/s to 517 rev/s. It does not mean yet that the same appreciable increase of linewidth took place for the rotors applied in Hay et al. (1960), Champeney and Moon (1961), Hay (1962), Granshaw and Hay (1963) and Champeney et al. (1965). 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 (Hay et al., 1960; Champeney and Moon, 1961; Hay, 1962; Granshaw and Hay, 1963; Champeney et al., 1965). Amongst them, the experiment by Champeney et al. (1965) is distinguished by the numerous experimental data, obtained for different absorbers (5 pieces) and Mössbauer sources ^{57}Co in two different matrices. The reanalysis of this experiment we achieved in Kholmetskii et al. (2008), has shown that its results are well fitted into k>0.5, too. In particular, our estimation with regards to Champeney et al. (1965) unlike what they had originally reported, yields k=0.61±0.02.

In our own viewpoint, the observation k>0.5 does not create any doubts in the validity of the special relativity, which has numerous experimental confirmations. Rather, we conjecture that the energy shift of absorption resonant line is induced not only via the standard time dilation, but also via some additional effect, which requires an additional experimental research. We thus describe further our own Mössbauer experiment in a rotating system recently performed (Kholmetskii et al., 2009) and shedding light on the origin of this unknown effect.

Modern Mössbauer experiment in a rotating system

In planning a new Mössbauer experiment on the time dilation effect, we realized that a direct repetition of Kündig experiment anyway would leave some doubts on the presence of possibly missed technical factors, which distort the measured value of k in Equation (2)[1]. Hence, we decided to repeat neither the scheme of Kündig experiment, nor the schemes of other experiments (Hay et al., 1960; Champeney and Moon, 1961; Hay, 1962; Granshaw and Hay, 1963; Champeney et al., 1965), 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 did not measure the Mössbauer spectra on a rotor, and followed the scheme (Hay et al., 1960; Champeney and Moon, 1961; Hay, 1962; Granshaw and Hay, 1963; Champeney et al., 1965), where the number of counts N of detected γ-quanta at different rotation frequencies ν is

[1] One of such factors might be the finite length of piezotransducer applied by Kündig. Hence some 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 convinced proof.

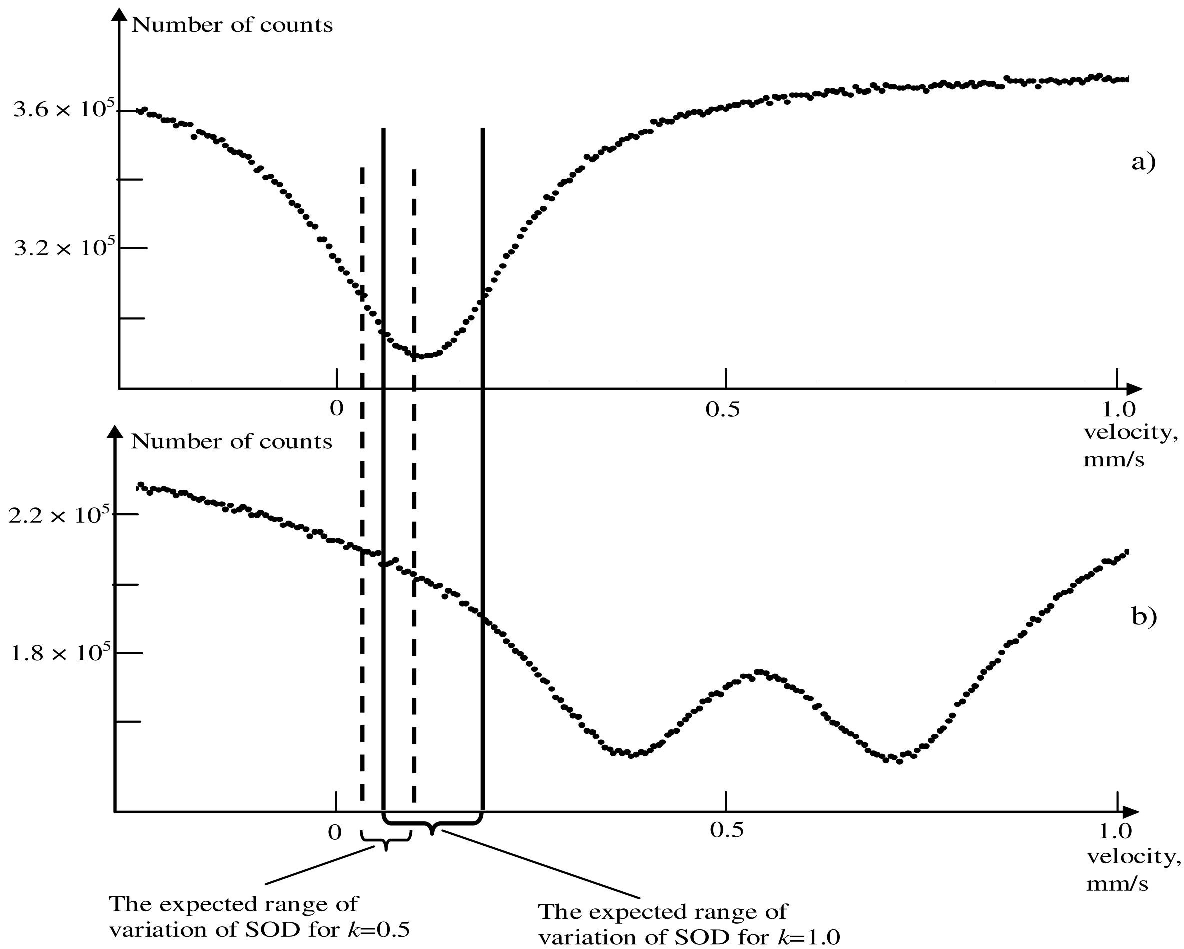

Figure 1. Reproduced from (Kholmetskii et al. (2009)): Mössbauer spectra of absorber 1 ($K_4{}^{57}Fe(CN)_6 \times 3H_2O$ (a) and absorber 2 ($Li_3{}^{57}Fe2(PO_4)_3$ (b), obtained with the source $^{57}Co(Cr)$ at the room temperature T_R=295±2 K, and the expected range of variation of SOD in our rotor experiment for two limited hypotheses on *k*.

recorded. This means that only several points $N(\nu_i)$ in the selected part of Mössbauer spectrum are measured, which correspond to the second order Doppler (SOD) shift at the given frequencies ν_i. However, in contrast with the experiments (Hay et al., 1960; Champeney and Moon, 1961; Hay, 1962; Granshaw and Hay, 1963; Champeney et al., 1965), we did 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. The idea of this method is based on the obvious fact that the vibrations, if available, spread the given resonant line, but do not influence the total area and position of this line on the energy scale. Hence, one can easily understand that for two resonant lines shifted on the energy scale, say, at their linewidth Γ, the equal broadening of these lines due to vibrations induces 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 the required information on the level of vibrations and separate from SOD its contribution into the $N(\nu)$ dependence. This allows obtaining an unbiased estimate of *k* even with the appreciable level of vibrations in the rotor system, although with a higher measuring uncertainty than in the direct measuring algorithm applied by Kündig.

In our experiment, we carried out measurements with two absorbers, whose resonant lines are shifted at (0.295 ± 0.001) mm/s with respect to each other (Figure 1). In this figure, we also show the expected range of variation of SOD in our experiment for k = 0.5 and k = 1.0. 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%. The other relevant parameters of both absorbers are listed in Table 1. The Mössbauer spectra of absorbers were measured by means of the Mössbauer instrument package MS-2000IP (Kholmetskii et al., 2004), using the Mössbauer source $^{57}Co(Cr)$ with the

Table 1. Parameters of resonant absorbers applied in our measurements.

Absorber	Surface density ρ_s, (mg/cm^2)	Debye-Waller factor *f'* at T = 293 K (Vagizov et al., 2009)	Debye temperature Θ_D (K)	Mass with the holder (g)
$K_4Fe(CN)_6 \times 3H_2O$	135	0.34 ± 0.01	194 ± 2	1.10 ± 0.01
$Li_3Fe_2(PO_4)_3$	135	0.61 ± 0.01	289 ± 2	1.10 ± 0.01

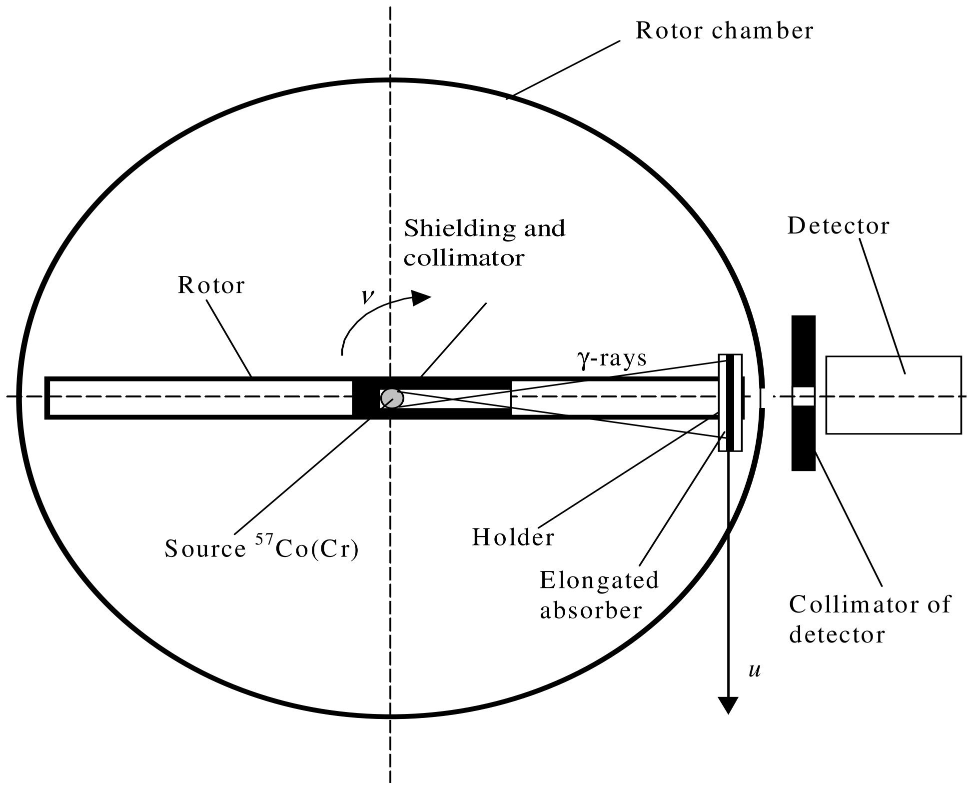

Figure 2. Schematic of the present experiment.

activity 20 mCi. The Debye temperature of the source Θ_D =380 K; the factor f = 0.75 ± 0.01 at the room temperature 293 K.

Another idea of our new Mössbauer experiment is to use a rotor with the substantially different radius than in the previous experiments. In particular, in the Kündig experiment, the radius of the rotor r was about 10 cm (Kündig (1963); in the Champeney et al. (1965) experiment, $r \approx 5$ cm; in our own measurements, we have chosen the rotor radius 30.5 cm (Kholmetskii et al., 2009). In such a case an equal tangential velocity in these experiments is reached at the substantially different values of centrifugal acceleration. One can see that in our experiment, the acceleration is about three times smaller than in the Kündig experiment and six times smaller than in the Champeney experiment. Hence, comparing the obtained values of k in all these experiments, we get information on possible dependence of this coefficient on the centrifugal acceleration.

The general scheme of our experiment is presented in Figure 2. The rotor we applied has the form of flat streamlined rod, and it was made from a special ultra-strong and light aluminum alloy doped by titanium and exposed to special thermal treatment. The 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 made of a special tempered aluminum alloy and fixed at the edge of the rotor. The rotor was put into the semi-hermetic chamber of the ultracentrifuge K-80 (Belmashpribor, Minsk) with the diameter 63.0 cm, which was continuously pumped out during measurements; a stationary pressure was about 100 mmHg. In these conditions, there was a heating of the rotor during its rotation, and the average equilibrium temperature inside the rotor chamber was equal to 335 K, with variation ±3 K at various measuring runs. After some test measurement runs, we measured the temperature difference between the source and absorber at their location on the rotor, and it never exceeded 2 K. Xe-filled proportional counter for detection of γ-quanta was located outside the rotor system. A measurement of SOD was carried out in the range of ν = 70 to 120 rev/s (u = 134 to 230 m/s). It corresponds to variation of linear velocity $u_1 = c\left(u^2/2c^2\right)$ = (0.030 to 0.088) mm/s (for k = 0.5).

Each measuring cycle started with the maximal frequency ν=120 rev/s with its further decrease to 70 rev/s with steps of 10 rev/s. The relative accuracy of setting of ν is 0.1%. The number of output pulses of the detector was measured during 100 s 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 $1.6{\cdot}10^4$.

For the convenience of a reader, we reproduce from (Kholmetskii et al., 2009)) the experimental results obtained with both absorbers, Figures 3a and b, correspondingly. In the processing of these data, we applied a few step algorithm, which allowed us to estimate the value of k in Equation (2):

1. First we consider the coefficient k as a free fitting parameter, and assume any of its particular value (for example, one can vary k between 0.5 and 1.0). At various k, we plot the expected theoretical curves $N_{id}(\nu)$ for the rotor experiment with a zero level of vibrations (the “idealized rotor experiment”). Since in a real experiment, the vibrations are always present, the theoretical curves we draw for each absorber deviate from corresponding experimental data, no matter what the assumption on k is.
2. 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 models the line broadening due to vibrations at various ν_i.
3. 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 corresponding theoretical curve $N_{id}(\nu)$, then we adopt that the hypothesis on a given value of k is false and should be rejected.
4. A new value of k is chosen, and the steps 2 and 3 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 Equation (2) and level of vibrations, manifesting as $\Gamma(\nu_i)$ set. We have found that the maximal line broadening in our rotor system is about the same, like in the Kündig experiment (≈1.30Γ), and the self-consistent results are obtained to be almost k = 0.7. In Figure 3a, we show the corrected data for k = 0.7 (hollow circles) via taking into account a broadening of resonant line due to vibrations. A least square fit specifies this observation to lead to k = (0.68±0.03).

We subsequently analyze various sources of possible systematic errors in the evaluation of SOD in our experiment as thus described.

Estimation of systematic errors in the evaluation of SOD

Time stability of operation of rotor system and detector of resonant gamma-quanta

In the ultracentrifuge K-80, the rotation frequency is set up and controlled automatically in a digital format. For the available accuracy of frequency setting 0.1%, a corresponding estimated uncertainty of k is about 0.0006, and can be well neglected.

We separately investigated a variation of count-rate of detector of resonant gamma-quanta with time, detecting resonant gamma-quanta in the fixed measuring conditions during the fixed time interval (one hour), and repeating this measurement for ten hours. In each of such measurement, we accumulated about 10^7 counts, providing a relative statistical error of about $3{\cdot}10^{-4}$. Within this error, we did not find a variation of detectors' parameter for the entire time interval of 10 h. Therefore, for a typical time of a single measuring run in the rotor experiment (about 1000 s), a possible variation of detector's count-rate represents a well negligible effect.

Estimation of the centrifugal pressure effect

In the rotor experiment, the centrifugal force creates the pressure on the absorber, which might change the electron density on the resonant nuclei and influences the isomer shift between emission and absorption lines. This could lead to the increase of measured k. The influence of centrifugal pressure on measured value of k was already estimated by us for the experiment by Kündig (Kholmetskii et al., 2008), and found to be negligible. Our choice of a larger rotor diameter in comparison with the Kündig experiment diminishes proportionally the centrifugal pressure. For the diameter of rotor d = 61.0 cm, the mass of absorbers 1.10 g (Table 1), their area 15 × 55 mm = 825 mm^2 (Kholmetskii et al., 2009), and typical rotation frequency ν = 100 rev/s, the pressure is

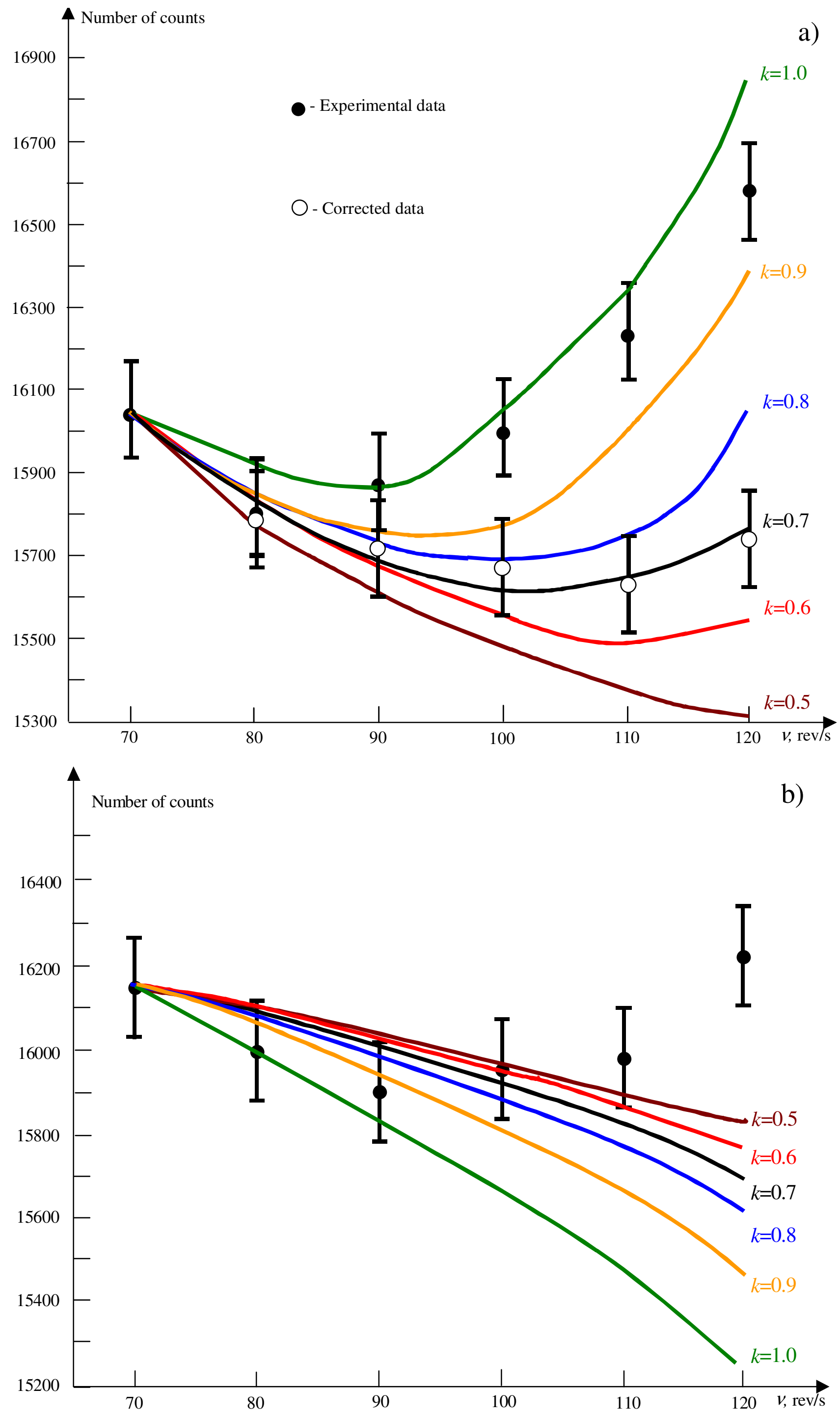

Figure 3. Reproduced from Kholmetskii et al. (2009): The experimental data (black circles) for absorber 1 (a), and absorber 2 (b) in comparison with the corresponding curves $N_{id}(\nu)$ (continuous lines) computed at different k for the idealized rotor experiment. Corrected data for the absorber 1 are re-computed at k=0.7 via taking into account the level of vibrations in the rotor system.

about 3.2 bar. At the same time, it is known that any changes in Mössbauer spectra due to the pressure become detectable with the pressure more than 1 kbar (Pasternak and Taylor, 1999).

Thus the effect of pressure is totally negligible in our measurements.

Estimation of the temperature effects

As mentioned, the rotor operation induced the increase of temperature inside the rotor chamber to the equilibrium value T_C = 335 K, with the temperature difference between the source and absorber up to 2 K. In our paper (Kholmetskii et al., 2009), we estimated the influence of temperature effect on the measured value of *k* to be negligible, assuming a Debye temperature of both absorbers about 300 K and more, which is the typical value for many iron compounds. However, after the publication of Kholmetskii et al. (2009), the work (Vagizov et al., 2009) has been published, where the Debye temperature Θ_{D1} for $K_4Fe(CN)_6 \times 3H_2O$ (absorber 1) was measured with a high enough precision, which occurred unexpectedly low (194 ± 2 K, Table 1). Thus, one needs to reanalyze again the influence of the temperature effects, where one can distinguish two additional components of systematic error in the measurement of *k* related to the temperature dependence of Mössbauer spectra:

1. The decrease of factor f (for the source) and f' (for the absorber) with temperature rise by $\Delta T = T_C - T_R$= 335 K–295 K= 40 K in comparison with the room temperature;
2. The relative change of line positions of the source and absorber at the temperature difference 2 K.

The decrease of probability of recoil-free interaction (the Debye-Waller factor) with the increase of *T* may distort the measured value of *k* due to corresponding change of the value of resonant effect ε in Mössbauer spectra. Thus, first one needs to estimate a variation of ε with *T*. It can be done through a known relationship between ε and the effective resonant thickness of absorber C_a (Kholmetskii and Missevitch, 1992):

$$\varepsilon = \chi f\left(1 - e^{-C_a/2} J_0\left(C_a/2\right)\right), \tag{3}$$

where J_0 is the Bessel function of first kind of zero order, *f* is the Debye-Waller factor for the source, and χ is the coefficient describing the influence of a background radiation, which for high-quality spectrometric system is close to unity. Using the data of Table 1 for the first absorber $K_4Fe(CN)_6 \times 3H_2O$ (ρ_{s1} = 135 mg/cm^2, f'_1 = 0.34±0.01), we find its effective resonant thickness at room temperature C_{a1} = 0.67 ± 0.01. Further, using ε_1 = (20.9 ± 0.1) % for the first absorber derived from the Mössbauer spectrum in Figure 1a, *f* = 0.75 ± 0.01 at the room temperature, we estimate χ = 0.960 ± 0.005. Now we are in the position to calculate the value of ε_1 at the equilibrium temperature T=335 K in the rotor chamber. For this purpose, we apply a known dependence of f' on *T* (Goldanskii and Herber, 1968):

$$f' = \exp\left\{-\frac{6E_R}{k_B\Theta_D}\left(\frac{T}{\Theta_D}\right)^2 \int_0^{\Theta_D/T}\left(\frac{1}{e^x - 1} + \frac{1}{2}\right) x\,dx\right\}, \tag{4}$$

where Θ_D is the Debye temperature of resonant absorber, $E_R = E_0^{\,2}/2Mc^2$ is the recoil energy imparted to an isolated nucleus of mass *M*; E_0 is the energy of resonant gamma-quanta, and k_B is the Bolzmann constant. For Θ_{D1} = 194 ± 2 K (Table 1), we determined from Equations (3) and (4) a relative decrease of ε_1 for the first absorber with the temperature rise of 40 K:

$$(\delta\varepsilon/\varepsilon)_1 = 0.077 \ . \tag{5}$$

Acting in a similar way and using the data of Table 1 for the second absorber $Li_3Fe_2(PO_4)_3$, we find the decrease of ε_2 with the same temperature rise by 40 K:

$$(\delta\varepsilon/\varepsilon)_2 = 0.065 \, . \tag{6}$$

Introducing corresponding corrections into the number of counts for both Mössbauer spectra in Figure 3, and applying again the algorithm for evaluation of *k* as described , we found that the temperature corrections to the value of resonant effect (Equations 5 and 6) lead to the systematic error -0.02 in the evaluation of *k*. Thus, the coefficient *k* corrected to the change of probability of recoil-free interaction with temperature becomes *k* = (0.66±0.03).

The temperature difference of 2 K between the source and absorber induces a thermal energy shift between their lines, which can be estimated from the known expression for the temperature shift of resonant lines (Goldanskii and Herber, 1968). For the values of f', C_a and Θ_D to be presented above for both absorbers, and ΔT = 2 K (at *T* = 335 K), the corresponding line shift is about 0.0007 mm/s. For such a tiny velocity shift, a distortion in the numbers of counts obtained in the rotor experiment practically can be ignored.

Thus, we conclude that the temperature difference between the source and absorber gives a negligible contribution into the measured value of *k*, whereas the excess of equilibrium temperature in the rotor chamber over the room temperature induces the decrease of estimated value of *k* by -0.02 in comparison with the initially obtained result.

Table 2. Comparison of the basic properties of Kündig (1963) experiment, Champeney et al. (1965) experiment and our own Mössbauer experiment in rotating system (Kholmetskii et al., 2009).

Parameter / Experiment	ν_{max} (rev/s)	R_A (cm)	u_{max} (m/s)	Centrifugal acceleration (*g*)	$\left(\frac{\Gamma(\nu_i)}{\Gamma(\nu=0)}\right)_{max}$	Signal/noise*
Kündig (1963)	586	9.3	340	1.3×10^5	1.45	≥200
Champeney et al. (1965)	1400	4.2	370	3.1×10^5	?	45
Present experiment	120	30.5	230	1.8×10^4	1.30	40

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

CONCLUSION

Thus, like in the processing of data of Kündig's experiment, we have corrected (Kholmetskii et al., 2008), we once again reveal an appreciable deviation of k in Equation (2) from the relativistic prediction k=0.5. Again, we trust in the validity of special relativity and the usual relativistic dilation of time due to the motion, which has numerous confirmations. Rather, we conjecture that with reference to the Mössbauer experiment on a rotor, the energy shift of resonant lines is induced not only via the standard time dilation, but also via some additional effect missed to the moment.

Thus, the implementation of new Mössbauer experiments in rotating systems seems to be an essential task, in order to collect new data on the energy shift between emission and absorption lines in various conditions. We suggest that such a new experiment should be 'direct', and the first order Doppler modulation of the energy of resonant radiation should be applied. In addition, in order to exclude any speculations on a possible change of characteristics of Doppler modulator in a rotating system, one needs to apply 'an independent method' for the measurement of relative velocity between the source and absorber based on optical interferometry (Yoshimura et al., 1977). We are convinced that such a new experiment will provide the most precise measurement of k. At the same time, we believe that our own Mössbauer experiments in rotating system, in spite of a lower accuracy of measurement in comparison with the Kündig experiment, has its own independent significance in a number of 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 measurements essentially differ from each other.
2. The corrected result we have provided about Kündig experiment (k = 0.596 ± 0.006), the corrected result we have drawn about Champeney et al. (1965) experiment (k = 0.61±0.02), and the result of the present experiment (k = 0.66±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 (Table 2: 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 from other Mössbauer experiments (Hay et al., 1960; Champeney and Moon, 1961; Hay (1962; Kündig, 1963; Granshaw and Hay, 1963; Champeney et al., 1965). 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 2), which allows the assumption that the unknown effect, inducing the increase of k, solely depends on u^2. If so, it becomes difficult to reject the assumption that the effect has fundamental roots.

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