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МЁССБАУЭРОВСКИЕ ЭКСПЕРИМЕНТЫ ВО ВРАЩАЮЩЕЙСЯ СИСТЕМЕ И ФИЗИЧЕСКАЯ ИНТЕРПРЕТАЦИЯ ИХ РЕЗУЛЬТАТОВ

А. Л. ХОЛМЕЦКИЙ¹⁾, Т. ЯРМАН²⁾, О. ЯРМАН³⁾, М. АРИК⁴⁾

¹⁾Белорусский государственный университет, пр. Независимости, 4, 220030, г. Минск, Беларусь

²⁾Стамбульский университет Окана, Акфират, 34959, г. Стамбул, Турция

³⁾Стамбульский университет, Беязит, 34452, г. Стамбул, Турция

⁴⁾Босфорский университет, Бебек, 34342, г. Стамбул, Турция

Обсуждаются результаты современных мёссбауэровских экспериментов во вращающейся системе, которые показывают наличие дополнительного энергетического сдвига между испускаемым и поглощенным резонансным излучением в дополнение к релятивистскому сдвигу резонансных линий из-за эффекта замедления времени для источника и поглотителя с разными радиальными координатами. Анализируются имеющиеся попытки объяснить происхождение дополнительного энергетического сдвига. Они включают в себя обобщения специальной теории относительности на основе гипотезы о существовании предельного ускорения в природе, гипотезу о зависящем от времени эффекте Доплера, а также общую теорию относительности с учетом метрических эффектов во вращающейся системе при синхронизации часов этой системы с лабораторными часами. В ходе исследования устанавливается, что все эти попытки остаются безуспешными до настоящего времени. Таким образом, предлагаются возможные пути решения этой проблемы, основанные на сочетании метрических эффектов во вращающихся системах с квантово-механическим описанием резонансных ядер в кристаллических ячейках.

Ключевые слова: эффект Мёссбауэра; вращающаяся система; теория относительности.

MÖSSBAUER EXPERIMENTS IN A ROTATING SYSTEM AND PHYSICAL INTERPRETATION OF THEIR RESULTS

A. L. KHOLMETSII^a, T. YARMAN^b, O. YARMAN^c, M. ARIK^d

^aBelarusian State University, 4 Niezaliežnasci Avenue, Minsk 220030, Belarus

^bIstanbul Okan University, Akfirat, Istanbul 34959, Turkey

^cIstanbul University, Beyazit, Istanbul 34452, Turkey

^dBogazici University, Bebek, Istanbul 34342, Turkey

Corresponding author: A. L. Kholmetskii (kholm@bsu.by)

We discuss the results of modern Mössbauer experiments in a rotating system, which show the presence of an extra energy shift between the emitted and absorbed resonant radiation in addition to the relativistic energy shift of the resonant lines due to the time dilation effect in the co-rotating source and absorber with different radial coordinates. We analyse the available attempts to explain the origin of the extra energy shift, which include some extensions of special theory

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Авторы:

Александр Леонидович Холмецкий – главный научный сотрудник кафедры ядерной физики физического факультета.
Толга Ярман – профессор.
Озан Ярман – доцент.
Метин Арик – профессор.

Authors:

Alexander L. Kholmetskii, chief researcher at the department of nuclear physics, faculty of physics.
kholm@bsu.by
Tolga Yarman, professor.
Ozan Yarman, associate professor.
Metin Arik, professor.





of relativity with hypothesis about the existence of limited acceleration in nature, with hypothesis about a so-called «time-dependent Doppler effect», as well as in the framework of the general theory of relativity under re-analysis of the metric effects in the rotating system, which is focused to the problem of correct synchronisation of clocks in a rotating system with a laboratory clock. We show that all such attempts remain unsuccessful until the moment, and we indicate possible ways of solving this problem, which should combine metric effects in rotating systems with quantum mechanical description of resonant nuclei confined in crystal cells.

Keywords: Mössbauer effect; rotating system; theory of relativity.

Introduction

As is known, the first series of Mössbauer experiments in a rotating system has been carried out in the early 1960s soon after the discovery of the Mössbauer effect (see, e. g., [1–6]). Their common goal was to verify the relativistic dilation of time in the laboratory conditions, which manifests itself via the relative energy shift between the resonant lines of a resonant source and a resonant absorber, fixed on the rotor at different distances from the rotational axis.

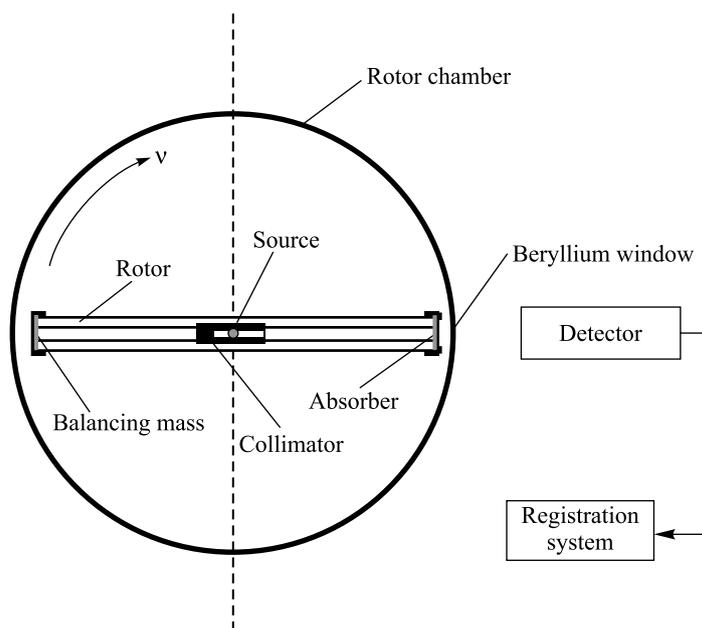
A relative energy resolution of resonant γ -quanta for iron-57 Mössbauer spectroscopy has a typical value 10^{-13} – 10^{-14} (see, e. g., [7]), which ensures a reliable measurement of the time dilation effect for sub-sound tangential velocities.

For a typical configuration, where the source is located at the origin of the rotating system and the absorber on the rotor rim (see figure), such a relative energy shift between the emission and absorption resonant lines is given by the equation

$$\frac{E_s - E_a}{E_s} \equiv \frac{\Delta E}{E} = -k \frac{u^2}{c^2}, \quad (1)$$

where E_s is the energy of resonant radiation for the source; E_a is the energy of resonant radiation for the absorber; u stands for the tangential velocity of absorber; c is the light velocity in vacuum, and k is some coefficient, which is determined experimentally; according to special relativity (SR), it should be equal to $\frac{1}{2}$ (the second order Doppler shift).

We point out that the sign «minus» on the right site of equation (1) corresponds to the blue shift of the energy of resonant radiation, where $E_a > E_s$.



A typical scheme of the Mössbauer rotor experiment.

The intensity of the resonant radiation passing resonant absorber is measured by the detector at the time moments,

when the source, the absorber and the detector are aligned into a straight line.

The thin iron-containing film of the resonant absorber is located inside beryllium shell of thickness of about 1 mm to prevent the absorber deformation due to centrifugal force



It is worth noticing that all Mössbauer rotor experiments performed in the 20th century [1–6] actually reported the value $k = \frac{1}{2}$, and at the indicated energy resolution about 10^{-13} – 10^{-14} , the relative measurement uncertainty of this coefficient was about 1 %.

By such a way, the results of the experiments [1–6] had been recognised as one more successful and precise test of SR under laboratory conditions.

Later the relativistic dilation of time had been confirmed with much better precision (10^{-8} – 10^{-9}) in the experiments on ion beams [8; 9]. This result seems deprived physicists on interest to further repetition of the Mössbauer experiments in the rotating systems and until the end of 20th century, no experiments on this subject had been carried out.

At the first decade of 21st century, being motivated by the conjecture of Yarman that the coefficient k in equation (1) can be substantially larger than $\frac{1}{2}$, we decided to reanalyse the available results of the Mössbauer rotor experiments, where special attention has been given to the experiment by Kündig [5] with its ingenious implementation, involving a linear Doppler modulation to the energy of emitted resonant radiation in the rotating system. For this purpose, Kündig applied a piezo-oscillation of the source in the radial direction of the spinning rotor, which allowed to him to measure the shape and the position of resonant line at different angular velocities of the rotor. Therefore, the random mechanical vibrations in the spinning rotor (which are always present), only broadened the resonant line, but did not influence the position of this line on the energy scale. By such a way, Kündig directly measured the shift of resonant line upon the energy scale as the function of rotating frequency regardless of the level of vibrations in the rotor system.

In all other experiments [1–4; 6], only the count-rate of resonant gamma-quanta passing through the resonant absorber versus the rotational frequency was measured, which varied not only due to a variation of the relative energy shift between the emission and absorption lines, but also due to the broadening of the resonant lines caused by rotor vibrations. Unfortunately, the authors of the mentioned experiments [1–4; 6] completely ignored vibrations in the rotor system, which made their results inconclusive.

Thus, in our reanalysis of the Mössbauer experiments in a rotating system, we focused on the Kündig's experiment [5], and surprisingly disclosed computational errors in his data processing. After their elimination, we found that the experiment [5] in fact yields k near 0.6 [10], and the deviation from the relativistic prediction $k = 0.5$ many time exceeded the measurement uncertainty.

Later (see, e. g., [11]), we have found some non-accounting factors (such as the dependence of piezoelectric constant on the centrifugal acceleration in the rotor system), which indicated that the value of k should be even larger, than 0.6, i. e.

$$k \geq 0.6. \quad (2)$$

Thus, the obtained inequality (2) should be recognised as the actual result of the experiment by Kündig.

Our reanalysis of the experiment by Kündig motivated us to carry out our own experiment on this subject [12], where we proposed a new methodological approach, which, being much simpler from a technical viewpoint compared to the linear Doppler modulation of resonant radiation used by Kündig, also allowed us to eliminate the influence of vibrations in the rotor system on the measured energy shift of the resonant lines.

For this purpose we measured the absorption curves (the dependence of the detector's countrate as the function of rotational frequency) for two resonant absorbers, whose resonant lines are shifted with respect to each other approximately by their linewidth [12].

Thus, having obtained the absorption curves for each resonant absorber, we compose the system of two equations with two unknown variables, which could affect the intensity of resonant radiation passing through the resonant absorber: the resonant absorption of γ -radiation, and the broadening of resonant lines due to vibrations in the rotor system. Hence, having solved the system of these equations, we separate both effects from each other, and finally obtain the dependence of the relative energy shift $\frac{\Delta E}{E}$ of the resonant radiation of the source and the absorber as a function of the tangential velocity u of the resonant absorber. As an outcome, we obtain the correct value of the coefficient k regardless of the level of vibrations in the rotor system, though with a larger measurement uncertainty in comparison with the experiment by Kündig [5].

The first our experiment has been conducted in Minsk, in 2008, under the contract between Istanbul Okan University, Savronik company (Istanbul) and Belarusian State University. The result of this experiment [12]

$$k = 0.66 \pm 0.03 \quad (3)$$

is in a strong contradiction with the relativistic prediction $k = 0.5$, though in full conformity with our reestimation of the Kündig experiment (2).



Furthermore, in 2014, in Istanbul University we carried out one more experiment on this subject in the framework of the contract between Istanbul University and Belarusian State University. In this new experiment, the mechanical characteristics of rotor system had been substantially improved in comparison with our first experimental setup. The result of this experiment [13]

$$k = 0.68 \pm 0.02, \quad (4)$$

in fact, confirmed the correctness of our re-estimation of the experiment by Kündig (2), as well as our first experimental result (3).

Thus, equations (2)–(4) definitely indicate the presence of an extra energy shift between the emitted and the absorbed resonant radiation in the rotating system, which emerges in addition to the usual second order Doppler shift due to dilation of time for an orbiting resonant absorber.

Discussions about the origin of such extra energy shift (EES), which we have abbreviated as EES, continue up to the present day, though no consensus has yet been achieved.

We have to emphasise that the disclosure of the origin of EES obviously goes beyond the scope of SR, so that we have to apply either the formalism of general relativity (GR), or some reasonable generalisations of SR, in order to understand the EES.

Here, it is worth to mention the successful explanation of EES in the framework of the novel YARK theory of gravity, which naturally combines gravity and quantum mechanics [11]. At the same time, it is clear that the search for an explanation of EES within the framework of standard relativistic presentations remains the most topical problem.

From this point of view, in section «Proposed explanations of the origin of the EES in Mössbauer rotor experiments», we analyse in chronological order the available attempts to explain the origin of EES either via some extensions of SR [14–16], or in the framework of GR, and show that so far all such attempts remain unsuccessful.

In section «Conclusion», we discuss new approaches for full understanding of the results of Mössbauer rotor experiments and draw our conclusions.

Proposed explanations of the origin of the EES in Mössbauer rotor experiments

In this section we review, in chronological order, various ideas to explain the experimental results (3), (4), which include:

- generalisation of SR by Caianiello [14] and its application to the analysis of Mössbauer rotor experiments by Friedman et al. [15]; performance of new experiments on this topic at the European Synchrotron Radiation Facilities (ESRF, Grenoble) and their analysis [17–19];
- the idea of the so-called «time-dependent» Doppler effect [16];
- re-analysis of metric effects in rotating systems [20–24].

We will show below that none of the available explanations of the origin of EES, existing at the moment, can be recognised satisfactory from the physical and mathematical viewpoints, and new ways for a solution of this problem are required.

Generalisation of special relativity by Friedman et al. One of the first attempts to explain the origin of EES, expressed via the inequality (2), was done by Friedman et al. on the basis of their generalisation of SR (see [15]) with the negation of the clock hypothesis by Einstein. This way Friedman et al. followed to Caianiello [14] and assumed the presence of a limited acceleration in nature a_m . Further on, they suggested to modify space-time transformation between uniformly accelerated frames in their own way, which is reduced to the usual relativistic transformation in the limit $a_m \rightarrow \infty$.

Then, reanalysing the second order Doppler effect in a rotating system in the framework of their approach, they arrived at the following expression for the relative energy shift between the resonant source (located on the rotational axis) and the resonant absorber on the rotor rim [15]:

$$E = \left(1 + \frac{R\omega^2}{a_m}\right) \left(1 - \frac{R^2\omega^2}{c^2}\right)^{-1/2} E_0,$$

where E_0 , E stand for the energies of emitted and absorbed radiation, correspondingly; R is the radial coordinate of the absorber, and ω is the angular velocity. Based on this equation, these authors derived the relative energy shift between the emission and absorption resonant lines in the following form:

$$\frac{\Delta E}{E} = \frac{E_0 - E}{E_0} \approx -\frac{R\omega^2}{a_m} - \frac{R^2\omega^2}{2c^2} = -\frac{u^2}{c^2} \left(\frac{1}{2} + \frac{c^2}{Ra_m}\right). \quad (5)$$



Thus, comparing equations (1) and (5), we find that in the extended relativity of Friedman et al., the coefficient

$$k = \frac{1}{2} + \frac{c^2}{Ra_m}. \quad (6)$$

Addressing now to the original work by Caianiello [14], we point out his own estimation of the limited acceleration via the light velocity c and the Planck length l_p as

$$a_m = \frac{c^2}{l_p} \approx 5.5 \cdot 10^{51} \text{ m/s}^2. \quad (7)$$

Thus, substituting equation (7) into equation (6), we obtain

$$k = \frac{1}{2} + \frac{l_p}{R}.$$

At $l_p \approx 1.616 \cdot 10^{-35}$ m and $R \approx 0.1$ m, the difference of the coefficient k from $\frac{1}{2}$ is near 10^{-34} , which represents quite a negligible value.

However, in this situation Friedman et al. assumed [15] that the actual value of the limited acceleration a_m could be much smaller and be accessible for measurements in the Mössbauer rotor experiments. In particular, Friedman et al. pointed out that the rectified result (2) of the experiment by Kündig can be explained by equation (6) in the case, where the limited acceleration in nature

$$a_m \approx 10^{19} \text{ m/s}^2. \quad (8)$$

This is indeed a huge acceleration from a practical point of view, which exceeds by many orders of magnitude the typical acceleration of particles in accelerators, though it is still accessible for measurements in the Mössbauer rotor experiments via equation (6).

Concurrently equation (6) indicates that under adoption of the hypothesis by Friedman (8), the coefficient k must depend on the rotor radius R . Therefore, according to Friedman, the value of k should be different in the experiment by Kündig [5] (where $R = 9.3$ cm), and in our experiments [12] ($R = 30.5$ cm) and [13] ($R = 16.1$ cm). However, all of these experiments yield the comparable values of k near $\frac{2}{3}$.

These results are obviously at odds with equation (6), which predicts a strong dependence of the coefficient k on the rotor radius R under the hypothesis of Friedman (8).

In this situation, Friedman et al. claimed [17] that the result of the experiment by Kündig as we reanalysed (2) is correct, whereas our experimental results (3) and (4) are, in their opinion, wrong, because the assumption about a random character of rotor vibrations, which was used under the data processing of the experiments [12; 13] is incorrect.

In order to demonstrate the validity of their claim, Friedman et al. mounted their own experimental setup on ESRF [17] for the measurement of the Mössbauer effect in a rotating resonant absorber with the synchrotron source of resonant radiation, where they measured the level of vibrations in the rotor with respect to a *laboratory observer*, using a suitable vibration probe. Friedman et al. actually detected some non-random vibration component, which allegedly was ignored in our measurements [12; 13].

However, in our paper [25] we emphasised the principal difference between the Mössbauer rotor experiments with the synchrotron radiation and with a point-like resonant source. In the first case, where the source of resonant radiation is located in a laboratory frame, while the resonant absorber is fixed on the rotor, its mechanical vibrations *as the whole* affect the shape of measured resonant line. In the second case, where both the source and the absorber are fixed on the rotor, only *relative vibrations* between source and absorber affect the shape of the resonant line. As we have shown [25], for modern rotor systems, the relative rotor vibrations are about two orders of magnitude smaller than the absolute rotor vibrations, measured by a laboratory observer. Under this circumstance, the non-random component of absolute rotor vibration estimated by Friedman et al. [17], becomes about two orders of magnitude smaller for the relative vibrations between co-rotating source and absorber, which thus can be well neglected in all experiments with usual point-like resonant source fixed on the rotor [1–6; 12; 13].

This conclusion once again validates the rectified result of the Kündig experiment (2) as well as our results (3) and (4).

Further on, Friedman et al. carried out their own experiment in Grenoble for the measurement of the Mössbauer effect in rotating resonant absorber, using the synchrotron source of resonant radiation, resting in a laboratory [18]. As the result, they obtained the new estimation for the limited acceleration

$$a_m \approx 10^{17} \text{ m/s}^2, \quad (9)$$



which is two orders of magnitude larger than their previous estimation (8) made on the basis of equation (2), which we obtained in the reanalysis of the experiment by Kündig.

However, we have indicated in [25] a number of non-accounted systematic errors in their experiment, which totally invalidate the result (9).

Later, Friedman et al. agreed that their result (9) is indeed incorrect, and suggested the improved technical realisation of their new experiment on ESRF [19].

In this respect, in our recent paper [26] we have shown that the entire approach by Friedman et al. based on the application of the synchrotron source of resonant radiation to the measurement of the Mössbauer in a rotating absorber has a number of principal shortcomings in comparison with the standard approach, where both a point-like source and compact resonant absorber are fixed on the rotor.

What is more, we have mentioned the recent estimation of the lowest limit of the maximal acceleration [27]

$$a_m \geq 5 \cdot 10^{21} \text{ m/s}^2 \quad (10)$$

obtained via the analysis of the temperature dependence of the Mössbauer effect in ^{67}Zn , which is about two orders of magnitude more sensitive to the relative energy shifts of resonant lines in comparison with the ^{57}Fe Mössbauer spectroscopy [7].

Substituting the value (10) into equation (6), we obtain that the extra energy shift, expressed by the term $\frac{c^2}{Ra_m}$, has the order of magnitude 10^{-4} (at $R \approx 0.1$ m), which is many times less than the measurement uncertainty of the coefficient k , and can be totally ignored.

Hence, we conclude that the hypothesis by Friedman et al. about a possible influence of the maximal acceleration in nature on the measured energy shift between emission and absorption lines in a rotating system, is totally invalidated by equation (10), as well as by our argumentation presented in references [25; 26].

«**Time-dependent» Doppler effect.** This idea has been advanced reference [16], and it is based on the assumption that the interaction of resonant γ -quanta with resonant nucleus happens during a finite time interval τ , when the velocity of orbiting absorber has time to rotate at a finite angle and, as the result, its resonant nuclei can acquire a non-zero velocity component on the direction of propagation of γ -radiation. If so, then some contribution of the linear Doppler effect to the measured shift between emission and absorption lines can emerge, and this effect, according to Benedetto and Feoli [16], is capable to explain the origin of the extra energy shift between emission and absorption lines.

Indeed, according to this idea, the extra energy shift should be defined by the equation

$$\omega\tau \left(\frac{u}{c} \right) = \text{EES},$$

where τ is the typical interaction time of resonant nucleus with resonant γ -quantum.

According to these authors, the interactional time τ should be comparable with the lifetime of the excited resonant nucleus. This assumption, however, already contradicts the common approach, where the interaction of resonant nucleus with a resonant γ -quantum is divided into three different and independent from each other stages: the absorption of resonant γ -quantum, the formation of excited nucleus, and the emission of resonant γ -quantum, where the lifetime of excited nucleus many orders of magnitude exceeds practically instantaneous moments of the absorption and emission of resonant γ -quanta.

In contrast to this commonly adopted representation, the authors of [16] assumed that the interactional time τ is comparable with the lifetime of excited nucleus, and they estimated it via the equation $\tau = \frac{h}{\Gamma}$ (h being the Planck constant), where, however, instead of using the natural width of resonant line Γ , they have used the width of resonant lines measured by Friedman et al., in their experiment [18], which was more than 10 times larger than the natural linewidth due to the influence of various experimental factors, such as rotor vibrations and others [18]. As the result, instead of the well-known lifetime of resonant line $\tau = 98$ ns (see, e. g., [7]), Benedetto and Feoli obtained $\tau = 5.19$ ns [19], which has no actual physical meaning.

Therefore, the entire idea by Benedetto and Feoli about the «time-dependent» Doppler effect not only contradicts the standard representation about the process of interaction of resonant nucleus with resonant γ -quantum, but it anyway does not provide the correct numerical value for the EES. Thus it should be recognised incorrect. For more detailed criticism of their idea, see reference [28].

Reanalysis of metric effects in a rotating system. The first attempt to explain the origin of EES in the framework of GR has been done in reference [20], where the author claimed that, before measuring the intensity of resonant radiation, passing across a resonant absorber, the clock in the origin of the rotating system and the laboratory clock (attached to the detector of γ -quanta) must be synchronised. In order to derive his «synchronisation effect», Corda used the known expression for the Langevin metric of a rotating frame (see, e. g., [29])



$$ds^2 = \left(1 - \frac{r'^2 \omega^2}{c^2}\right) c^2 dt'^2 - 2\omega r'^2 d\varphi' dt' - dr'^2 - r'^2 d\varphi'^2 - dz'^2 \quad (11)$$

resulting from the transformation of the cylindrical space-time coordinates between the laboratory frame (t, r, φ, z) and the rotating frame (t', r', φ', z')

$$t = t', \quad (12)$$

$$r = r', \quad (12a)$$

$$\varphi = \varphi' + \omega t', \quad (12b)$$

$$z = z'. \quad (12c)$$

Further on, considering the expression for the proper time interval $d\tau$ in a rotating system, resulting from equation (11),

$$d\tau^2 = dt'^2 \left[1 - \frac{2\omega r'^2 d\varphi'}{c^2 dt'} - \left(\frac{\omega r'}{c}\right)^2 - \left(\frac{d\sigma'}{cdt'}\right)^2 \right], \quad (13)$$

where $d\sigma'^2 = dr'^2 + (r'd\varphi')^2 + dz'^2$, Corda claimed that the last two terms on the right site of equation (13) can be neglected in the case, where the tangential velocity of the detector u is much smaller than the light velocity c . Hence, using the relationship

$$d\varphi' = \omega dt'. \quad (14)$$

Corda simplified equation (13) to the form

$$d\tau = dt' \left(1 - \frac{r'^2 \omega^2}{c^2} \right). \quad (15)$$

Then, integrative equation (15) along the path of resonant γ -quantum propagating from the origin of coordinates $r = 0$ to the rotor rim $r = R$, Corda obtained [20; 21]

$$d\tau = dt' \left(1 - \frac{u^2}{6c^2} \right). \quad (16)$$

According to this author, the relationship (16) additionally contributes the measured energy shift between resonant lines in the Mössbauer rotor experiments at the value

$$\left(\frac{\Delta E}{E}\right)_{\text{synch}} = -\frac{1}{6} \frac{u^2}{c^2},$$

which, being added to the usual second order Doppler shift,

$$\left(\frac{\Delta E}{E}\right)_{\text{Doppler}} = -\frac{1}{2} \frac{u^2}{c^2},$$

yields the total shift

$$\left(\frac{\Delta E}{E}\right)_{\text{total}} = -\frac{2}{3} \frac{u^2}{c^2},$$

seemingly in a perfect agreement with our experimental results (3) and (4).

However, in our subsequent responses [30; 31] we argued that this «synchronisation effect», even it would exist, is totally immeasurable in the Mössbauer rotor experiments and thus, it anyway cannot contribute the measured value of the coefficient k in equation (1).

Further persistence by Corda in advocating his «synchronisation effect» [22] motivates us to look closer at the procedure of its derivation, and to find two errors in this procedure.

The first error is the use of approximate expression for the proper time (15), with the omission of the terms of the second order in $\frac{u}{c}$. However, this is inadmissible, since the measured energy shift between emission

and absorption lines has the order of magnitude $\left(\frac{u}{c}\right)^2$. Therefore, instead of the approximate equation for the proper time (15) used by Corda, one has to use the exact expression (13).



The second error is committed by Corda in equation (14), where the sign «minus» is missed. Thus, the correct equation is

$$d\varphi' = -\omega dt' \quad (17)$$

(see equation (12b) at $\varphi = 0$). Substituting equation (17) into the correct equation for the proper time interval (13), we arrive at the trivial equality

$$d\tau = dt'. \quad (18)$$

Thus, in contrast to the claim by Corda, equation (18) shows that the rate of a clock in the origin of a rotating system and the rate of a laboratory clock attached to the detector are identical to each other at any value of the angular velocity of a rotor. This result is well understandable from a physical viewpoint, because the point center of the rotor has a zero tangential velocity at any value of the angular velocity. Therefore, both clocks – on the rotational axis and in the laboratory – remain synchronised at any rotational frequency, so that the alleged «synchronisation effect» by Corda disappears, and the equality $k = \frac{2}{3}$ revealed in our experiments [12; 13] (see equations (3) and (4)) remains unexplained.

Finally, we consider the remaining attempts to explain the origin of the EES in GTR: the «modified synchronisation effect» by Corda [22], «desynchronisation effect» by Iovane and Benedetto [23] and «geometric approach» by Podosenov et al. [24], which have the common feature:

- 1) the use of the Langevin metric (11);
- 2) the use of the constraint

$$\varphi' = \text{const} \quad (19)$$

for propagating resonant γ -quanta.

Then, combining equations (11), (12) and (19), the authors of [22–24] obtained the expression for the proper time of propagation of γ -quanta from the source in the origin and the absorber on the rotor edge, which can be presented in the general form as

$$\tau = \frac{R}{c} + \delta\tau. \quad (20)$$

Here, the value $\delta\tau$ is responsible either for the «synchronisation effect» (according to Corda [22]), or «desynchronisation effect» [23], or for the frequency change of resonant radiation for resonant absorber [24].

At the same time, the physical meaning of the proper time interval $\delta\tau$ in equation (20) is well understandable, when we realise that the applied constraint (19) means that resonant γ -quanta propagate from the source to absorber along the radial direction of the rotating frame and thus, a laboratory observer sees some curved path of such γ -quanta. Hence, it becomes obvious that in the laboratory frame the propagation time of γ -quanta from point $r = 0$ to point $r = R$ becomes larger than $\frac{R}{c}$ at the value $d\tau$ on the right site in equation (20).

However, such a curved path for resonant γ -quanta is impossible in empty space and thus, we have to realise that the constraint (19) implies the presence of a very thin optic guide of resonant γ -quanta, connecting the source and the absorber fixed on the rotor.

Now it is worth to emphasise than none of the known Mössbauer rotor experiments used such guides for resonant γ -quanta and, moreover, such guides are not invented yet!

In the absence of such guides, we have to abandon the constraint (19) in the favour of the equality

$$\varphi = \text{const}, \quad (21)$$

corresponding to propagation of γ -radiation along a straight line in empty space.

The equality (21) directly yields equation (17), and we have shown above that with this equation any «synchronisation effect» disappears (see also references [32–34]).

Thus, at the moment, the origin of the EES in the framework of GR remains unexplained.

Conclusion

Since the discovery of the EES between emission and absorption resonant lines in the Mössbauer rotor experiments [12; 13], a possible origin of this effect, emerging in addition to the energy shift due to relativistic dilation of time, became a subject of intensive discussions; where the explanation of EES either with some reasonable extension of SR, or within the framework of GR remains the most topical problem up to now.

We have shown that the generalisation of SR by Friedman et al. via introducing a maximal acceleration in nature with an assumed value measurable via the Mössbauer effect [15] is not supported by modern measurements; in particular, by using ^{67}Zn resonance [27]. The latter yielded the lowest limit (10), which anyway cannot explain the observed value of the EES.



We have further shown that the recent attempt [16] to understand the origin of the EES under the framework of usual relativistic concepts, or in the framework of GR with some allegedly missed effects [20–24] are all mistakable and should be denied.

Thus, further search regarding the possible explanation of the origin of the EES under GR remains to be a very topical problem. To this end, our idea [11] to involve the quantum mechanical properties of resonant nuclei confined in crystal cells – which has already been successfully applied to the explanation of the EES under the framework of YARK gravitation theory – could perhaps be extended to a general relativistic treatment as well. This might engender a promising way, insofar as the principal feature of our idea – viz., the constancy of the energy of the crystals for both resonant source and resonant absorber under the recoil-free interaction of the resonant nuclei with Mössbauer radiation – should also be exercised within the framework of GR. However, a detailed analysis of this problem, as well as our proposal for indirect verification of this idea [35] lies outside the scope of the present contribution.

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