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Comparison of traditional and synchrotron beam methodologies in Mössbauer experiments in a rotating system

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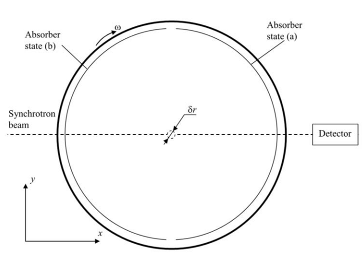
Recent Mössbauer experiments in a rotating system reported by others in the literature have involved the application of synchrotron radiation onto a spinning semi-circular resonant absorber. Here, the physical interpretation of these methodologies, and their alleged performance improvement, is analyzed in the light of our own team's past experience based instead on the traditional laboratory setup. It is shown that a number of fundamental shortcomings in the approach reported in the literature deprives it of any practical significance with respect to the improvement of the technique of Mössbauer rotor experiments with a synchrotron source. It is concluded that, at present, only Mössbauer experiments relying on an ordinary compact source of resonant radiation and a resonant absorber both fixed on the rotor promise to provide crucial information with respect to the physical origin of the observed energy shift between emitted and absorbed resonant radiation in a rotating system.



1. Introduction

During the past decade, Mössbauer experiments in rotating systems and various attempts to physically interpret their results have attracted considerable attention (see, for example, Kholmetskii *et al.*, 2008, 2009, 2011, 2015, 2016, 2018*a*,*b*, 2019*a*,*b*,*c*; Friedman & Gofman, 2010; Friedman *et al.*, 2016, 2017; Corda, 2015, 2016, 2018, 2019; Yarman *et al.*, 2015, 2016; Benedetto & Feoli, 2018; Iovane & Benedetto, 2019). We point out two recent papers on this subject by Friedman *et al.* (2016, 2017) and outline their experiments where a synchrotron source of resonant radiation was applied to measure the Mössbauer effect for an orbiting resonant absorber. The specific goal of these experiments was to verify the influence of the acceleration of the absorber on the measured energy shift between emission and absorption resonant lines – which can, in effect, be considered as a test of the hypothesis about the existence of a maximal acceleration in nature (*e.g.* Caianiello, 1981). Friedman *et al.* (2016, 2017) actually claimed to have gathered statistically significant measurement results indicative of the influence of the acceleration of the resonant absorber on the energy shift of its resonant line. However, the most recent paper by Friedman *et al.* (2019) recognized the failure of their previous experimental attempts (Friedman *et al.*, 2016, 2017) to achieve any definitive conclusion and, based on the accumulated experience, the authors suggest in their latter paper an 'indispensible' (in their opinion) plan for the realization of a decisive Mössbauer rotor experiment using synchrotron radiation.

One would ordinarily welcome such an endeavour by Friedman *et al.* (2019), as they recognize their previous mistakes (Friedman *et al.*, 2016, 2017) and further aspire to achieve progress towards improving the performance of informative Mössbauer rotor experiments with a synchrotron beam; but, it seems evident that actual progress in this field must be based, foremost of all, on the presentation of an objective state-of-the-art with respect to measuring the Mössbauer effect in a rotating system and its physical interpretation – which, unfortunately, was not the case in the paper by Friedman *et al.* (2019) as will be shown below in Section 2.

Further on, in Section 3, we complement the analysis of Friedman *et al.* (2019) regarding their setup (Friedman *et al.*, 2016, 2017) with some crucial points missed in their paper, and show that, given the present stage of development in experimental technique, Mössbauer experiments in a rotating system based on a usual point-like source of resonant radiation attached to a rotor along with a resonant absorber undoubtedly have advantages in comparison with Mössbauer rotor experiments contingent upon synchrotron radiation due to two principal reasons: (i) the absence of the linear Doppler effect between the source and the absorber of resonant radiation when both are attached to the rotor, and (ii) the drastic decrease of relative vibrations between the source of resonant radiation and resonant absorber when both are rigidly fixed on the rotor in comparison with the case where a source of resonant radiation (*i.e.* the synchrotron beam in the experiments by Friedman *et al.*) is located in the laboratory frame. These two factors taken together allow Mössbauer rotor experiments with point-like resonant sources to be much simpler to manage and much more sensitive to the energy shifts between the lines of emission and absorption compared with synchrotron Mössbauer experiments targetting a semicircular rotating absorber as attempted by Friedman *et al.* (2016, 2017).

Moreover, we highlight the fact that a recent reasonable estimation of the lowest limit of the assumed maximal acceleration in nature at the value 5×10^{21} m s^{-2} – obtained via the analysis of the temperature dependence of the Mössbauer effect in ^{67}Zn (Potzel, 2016) – makes any would-be influence of such an acceleration on the energy shift between emitted and absorbed resonant lines in a rotating system practically immeasurable. This condition deprives of all practical significance the 'indispensable plan' by Friedman *et al.* (2019) to measure the Mössbauer effect of a rotating absorber by means of resonant synchrotron radiation. Finally, our conclusions are given in Section 4.

2. Historical background

The first series of Mössbauer experiments in a rotating system were carried out in the early 1960s soon after the discovery of the Mössbauer effect (*e.g.* Hay *et al.*, 1960; Champeney & Moon, 1961; Hay, 1962; Granshaw & Hay, 1963; Champeney *et al.*, 1965). In a typical configuration thereby, a point-like source of resonant radiation is fixed on the rotor axis, while a resonant absorber is located at the rotor's edge. The goal of these experiments was to verify the classical relativistic dilation of time for the orbiting resonant absorber undergoing uniform circular motion, which entails the relative energy shift between the resonant lines of the source and the absorber by the value

$$\frac{\Delta E}{E} = -k\frac{u^2}{2c^2}, \tag{1}$$

where the coefficient k should be equal to 0.5 according to relativity theory (here u stands for the tangential velocity of the absorber, and c is the speed of light in vacuum). It is important to emphasize that at sub-sound velocities u, the ratio $\Delta E/E$ is comparable with the relative width of the resonant line. This happenstance opens a realistic way to evaluate the effect (1) under laboratory conditions via the measurement of the intensity I of resonant radiation emitted by the source and passing across the absorber at different but constant tangential velocities u. Then, having measured independently the shape of the resonant line of the absorber outside the rotor system, one can calculate the relative energy shift $\Delta E/E$ between emission and absorption lines using the measured dependence $I(u)$ to finally obtain the value of the parameter k in equation (1).

This procedure had been implemented in the majority of Mössbauer rotor experiments of the 20th century (*e.g.* Hay *et al.*, 1960; Champeney & Moon, 1961; Hay, 1962; Granshaw & Hay, 1963; Champeney *et al.*, 1965), where all the authors reported the confirmation of the relativistic dilation of time (1) with the k = 0.5 value that had been evaluated with a relative uncertainty near 1%.

Here, one should emphasize that the applied procedure for the determination of the ratio $\Delta E/E$ from the measured dependence I on u essentially implies the independence of the shape of the resonant lines from the rotational frequency. However, this is generally not the case due to the unavoidable presence of mechanical vibrations in the rotor system that broaden the resonant lines and proportionally decrease their height.

The essential influence of vibrations on the shape of the resonant line had been explicitly demonstrated in an ingenious experiment by Kündig (1963), where the author realized a linear Doppler modulation of the energy of the resonant radiation of the source located on the rotor axis. For this purpose, Kündig used a special piezotransducer to realize a reciprocating motion of the resonant source towards or backward from the absorber, and measured the shape and position of the resonant line of the absorber at different rotational velocities. Thanks to such a unique setup, Kündig actually observed the broadening of the resonant line due to rotor vibrations with a relative value of more than 50% at the maximal tangential velocity of the resonant absorber $u \simeq 300$ m s^{-1}.

As a matter of fact, this outcome invalidated the results of other experiments (*e.g.* Hay *et al.*, 1960; Champeney & Moon, 1961; Hay, 1962; Granshaw & Hay, 1963; Champeney *et al.*, 1965) that were implemented with total ignorance of the broadening of the resonant lines due to rotor vibrations, which could essentially affect the measured intensity of the resonant radiation passing across the absorber.

Next, it is worth emphasizing one more disclosure by Kündig (1963): that the broadening of the resonant lines due to vibrations kept the symmetry of the lines' shape. Hence, Kündig concluded that rotor vibrations have a chaotic character and do not affect the *position* of the resonant line upon the energy scale. Based on such a realization, the Kündig experiment allowed to directly measure the position of the resonant line on the energy scale as a function of the tangential velocity u of the resonant absorber. After processing his data, Kündig (1963) reported a perfect confirmation of the classical relativistic time dilation effect (1) with the coefficient $k = 0.5$ that he evaluated with a relative uncertainty of less than 1%.

Later on, a new wave of interest towards Mössbauer experiments in a rotating system emerged in the 21st century after the publication of our paper (Kholmetskii *et al.*, 2008) featuring a critical re-analysis of the experiment by Kündig. It was motivated by the prediction of Yarman (2004, 2006) stating that, in a rotating system, the coefficient k in equation (1) should be considerably larger than 0.5. As a result of our re-analysis, we found computational errors committed by Kündig in his data processing, whereby, after their elimination, we re-estimated the coefficient k in (1) to be

$$k = 0.596 \pm 0.006, \tag{2}$$

which substantially deviates from the classical relativistic prediction $k = 0.5$ and exceeds by many times (one order of magnitude or more) the measurement uncertainty (Kholmetskii *et. al.*, 2008). Moreover, as we have shown in our subsequent publications, the presence of unaccounted-for systematic errors in the Kündig experiment [in particular, a possible variation of the parameters of the piezotransducer with the increase of rotational frequency (Yarman *et al.*, 2015)] transforms the equality (2) into the inequality

$$k \geq 0.6. \tag{3}$$

These findings motivated us to carry out our own Mössbauer rotor experiments in 2008 (in Minsk) and in 2014 (in Istanbul), which yielded practically identical and profound results:

$$k = 0.66 \pm 0.03 \tag{4}$$

(Kholmetskii *et al.* 2009, 2011) and

$$k = 0.69 \pm 0.02 \tag{5}$$

(Kholmetskii *et al.* 2015; Yarman *et al.* 2016).

In our experiments, we used an original measurement methodology which allowed us to eliminate the influence of rotor vibrations on the measured energy shift between emission and absorption lines without applying Kündig's complicated linear Doppler modulation of the energy of resonant γ-quanta (Kündig, 1963). The details of our measurement algorithm and data processing can be found in Kholmetskii *et al.* (2009) and Yarman *et al.* (2016).

The obtained results (3)–(5) indicate that, in a rotating system, the energy shift between emitted and absorbed resonant radiation is not only due to the classical relativistic dilation of time for the orbiting absorber but also includes an additional component – which we named 'the extra energy shift' (EES) – whose physical meaning requires clarification.

Up to this moment, there were several competing attempts to disclose the physical meaning of the EES, the first among which had been made by Friedman & Gofman (2010) on the basis of the hypothesis about the existence of a maximal acceleration a_m in nature.

At this point, one should notice that, in Friedman *et al.*'s most recent paper (Friedman *et al.*, 2019), this hypothesis is presented in a totally misleading way to the common reader. Indeed, as their motivation for the hypothesis, Friedman *et al.* (2019) refer to the historical experiment by Kündig (1963) who, as we have mentioned above, mistakenly claimed a perfect confirmation of the standard expression for the relativistic dilation of time with the coefficient $k = 0.5$ in equation (1). Even so, Friedman *et al.* (2019) avoided referring to our critical re-estimation of Kündig′s result (Kholmetskii *et al.*, 2008) that started the whole debate, as well as to our experiments (Kholmetskii *et al.*, 2009, 2011, 2015; Yarman *et al.*, 2016) which, in fact, gave rise to the entire series of 21st century works about the Mössbauer effect in a rotating system – whereby, among various attempts to provide a physical answer, the hypothesis by Friedman & Gofman (2010) mentioned above constitutes only one such attempt.

In general, the assumption about the existence of a maximal acceleration in nature is not a novel one (see, for example, Caianiello, 1981), and the crucial issue is the estimation of the numerical value of a_m, which was suggested by Caianiello (1981) to be

$$a_m = c^2/l_P \simeq 5.5 \times 10^{51}\ \mathrm{m\,s^{-2}}, \tag{6}$$

where $l_P \simeq 1.616 \times 10^{-35}$ m is the Planck length.

It is needless to say that the maximal acceleration (6), even if it existed, is impossible to detect in any laboratory-scale experiment. However, in contrast to the fundamental estimation (6), Friedman & Gofman (2010) assumed *ad hoc* that the actual value of a_m could be much smaller than the value (6), and might be possible to measure through a Mössbauer rotor setup – insofar as providing (according to them) the explanation of the observed EES.

Indeed, if their maximal acceleration a_m actually exists, then the energy shift between emission and absorption lines in a rotating system should be given by the relationship (Friedman & Gofman, 2010)

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

(where R is the rotor radius), which yields the following expression for the coefficient k in equation (1) (Friedman & Gofman, 2010):

$$k = 1/2 + c^2/Ra_m. \tag{7}$$

Thus, comparing equation (7) with the result of the experiment by Kündig (2) the way we had rectified in our paper (Kholmetskii *et al.*, 2008), Friedman & Gofman (2010) obtained their own estimation of the maximal acceleration,

$$a_{\rm m} \simeq 10^{19}\,{\rm m\,s^{-2}}, \tag{8}$$

which, though, is more than 30 orders of magnitude smaller than the fundamental value (6).

Omitting at this stage any particulars with respect to the result (8), we point out that, in the case of the validity of equation (8), the coefficient k in equation (7) should depend on the rotor radius and, therefore, Mössbauer experiments with different rotor radii should yield different values of k in equation (1). However, this presumption by Friedman & Gofman (2010) has not been confirmed in the experiments carried out by our team in 2008 (Kholmetskii *et al.*, 2008) and in 2014 (Yarman *et al.*, 2016), where we had used rotors with essentially different radii (30.5 cm and 16.1 cm, respectively) but came out with practically the same values of k [see equations (4) and (5)].

Thus, the application of equation (7) to our experiments (Kholmetskii *et al.*, 2008; Yarman *et al.*, 2016) already *invalidates* the assumed limit (8) for Friedman *et al.*'s maximal acceleration, indicating that the actual value of $a_{\rm m}$, if real, should be much higher.

Under these circumstances, Friedman *et al.* (2016) baselessly claimed that our experiments (Kholmetskii *et al.*, 2008; Yarman *et al.*, 2016) are both incorrect, inasmuch as going on to suggest we allegedly did not take into account the (for us inconsequential) non-random character of rotor vibrations that they had disclosed in their own configuration (Friedman *et al.*, 2016).

However, as we will show in Section 3, this result by Friedman *et al.* (2016) is relevant only with regard to Mössbauer rotor experiments using synchrotron radiation, and is not applicable to Mössbauer rotor experiments that rely on ordinary sources – where the level of relative vibrations between the source and the absorber (with both of them rigidly fastened onto the rotor) is a few orders of magnitude smaller than the level of vibrations in Mössbauer rotor experiments utilizing a synchrotron source. In such a situation, a non-random component of rotor vibrations which bothered Friedman *et al.* (2016, 2017, 2019) is totally negligible in our experiments (Kholmetskii *et al.*, 2008; Yarman *et al.*, 2016), and thus does not affect the validity of the measurement outcomes (4) and (5).

It is worth emphasizing that equations (4) and (5) allow one to assume that the actual coefficient k in equation (1) is equal to 2/3 and does not depend on the rotor radius R.

Nowadays, the value k = 2/3, which has not even been mentioned by Friedman *et al.* (2016, 2017, 2019), is anyway considered by the majority of the authors as the most adequate match to the available experimental data (*e.g.* Yarman *et al.*, 2015; Corda, 2015, 2016, 2018, 2019; Iovane & Benedetto, 2019).

At present, the successful explanation of the equality k = 2/3 in equation (1) is given by Yarman *et al.* (2015), where the resonant nucleus in a crystal cell is considered as a quantum particle inside a three-dimensional potential hole after explicitly taking into account the geometry of a rotating disk. At the same time, it is also anticipated by Yarman *et al.* (2015) that the geometry of the rotating disc differs from the standard relativistic prediction.

The latter circumstance motivated researchers to seek the explanation for the equality k = 2/3 entirely under the framework of the general theory of relativity (GTR) (*e.g.* Corda, 2015, 2016, 2018, 2019; Benedetto & Feoli, 2018; Iovane & Benedetto, 2019). However, the approach by Corda (2015, 2016, 2018, 2019) to derive k = 2/3 contains mathematical errors, which we explicitly disclosed (see Kholmetskii *et al.*, 2019*a*,*b*), whereas the explanations of Benedetto & Feoli (2018) and Iovane & Benedetto (2019) are not acceptable from a physical viewpoint (see Kholmetskii *et al.*, 2018*a*,*b*, 2019*a*,*b*,*c*). Thus, the experimental result k = 2/3 still awaits its consistent explanation within the framework of the GTR.

Therefore, further performance and finer interpretation of Mössbauer experiments in a rotating system necessitates state-of-the-art research, whereby the hypothesis by Friedman & Gofman (2010), leading to equations (7) and (8), represents only one of many assumptions – which, moreover, already contradicts the experimental results (4), (5).

Nevertheless, even in this situation, the hypothesis about a maximal acceleration having the value (8) has been presented by Friedman *et al.* (2016, 2017, 2019) as the prime candidate for explaining our novel disclosures in Mössbauer experiments in a rotating system. As we have stated before, this is definitely not the case.

What is more, we will show in the next section that, even after the implementation of Friedman *et al.*'s (2019) 'indispensable plan' for the improved performance of Mössbauer rotor experiments with a synchrotron source, their sensitivity as regards the relative shift of the resonant lines shall anyway remain much lower in comparison with the sensitivity of ordinary Mössbauer experiments in a rotating system. This renders further application of a synchrotron source to Mössbauer rotor experiments highly impractical; especially considering a more befitting estimation of the maximal acceleration upper limit,

$$a_{\rm m} \leq 5 \times 10^{21}\,{\rm m\,s^{-2}} \tag{9}$$

(Potzel, 2016), as mentioned in the *Introduction*. In that case, the acceleration-dependent term in equation (7) for the coefficient k should be less than 10^{-3} for typical experimental conditions, which is already a few times smaller than the measurement uncertainty of even the most sensitive experiment by Kündig (1963), and therefore lies outside the range of any realistic evaluation.

3. Synchrotron source and point-like sources in Mössbauer rotor experiments

In their most recent paper, Friedman *et al.* (2019) compared Mössbauer rotor experiments that employ a synchrotron beam with those reliant on point-like sources to argue that, in the latter case, '... *For technical reasons, it is very complicated to keep the balance of a fast rotating disc with a Mössbauer source on a transducer on it. Therefore, in order to detect the influence of time dilation of a rotating disc, the source has to be* *installed outside the rotating disc*'. Friedman *et al.* (2019) thus contend that the advantages of a synchrotron source over reliance on typical Mössbauer sources are evident.

However, while proclaiming the alleged advantages of their new technique, Friedman *et al.* avoided answering the principal question as to why their experiments with a synchrotron beam (Friedman *et al.*, 2016, 2017) completely failed to retrieve any information about the coefficient k in equation (1) – whereas known experiments with point-like sources of resonant radiation (Kündig, 1963; Kholmetskii *et al.*, 2009; Yarman *et al.*, 2016) already provided a successful evaluation of the coefficient k with a relative uncertainty of only a few percent.

A detailed answer to this question is given in our preceding paper (Kholmetskii *et al.*, 2018*a*), which was published at the time of the submission of the most recent paper by Friedman *et al.* (2019), but nonetheless before its acceptance for publication. For the convenience of the reader, we now summarize the main points of our argumentation.

First of all, we would like to highlight the fact that, in all previous Mössbauer rotor experiments with ordinary point-like sources of resonant radiation, nobody tried to put these sources outside the rotor system unlike what Friedman *et al.* imply in their comparison of traditional practice with their synchrotron beam setup; on the contrary, a resonant source and a resonant absorber were always fixed on the rotor. In that case, we immediately gain two principal advantages over a synchrotron source:

(i) Virtual disappearance of the linear Doppler effect between the source and the absorber [for corresponding calculations, see, for example, Yarman *et al.* (2015); Kholmetskii *et al.* (2018*a*)];

(ii) A drastic decrease (up to a few orders of magnitude) in the influence of mechanical vibrations the rotor undergoes on the shape of the measured resonant line in comparison with the synchrotron experiments by Friedman *et al.* (2016, 2017).

We once again want to accentuate the fact that the pronounced advantages (i) and (ii) in Mössbauer rotor experiments reliant on ordinary sources directly stem from the rigid attachment of both the source and the absorber to the rotor.

In contrast, in the synchrotron rotor experiments by Friedman *et al.* (2016, 2017, 2019), where the source of resonant radiation is disattached from the rotor, the linear Doppler effect between the synchrotron source and the rotating absorber strongly dominates over the second-order Doppler effect for even a very thin beam spot focused on the rotor axis. In that respect Friedman *et al.* (2019) write: '*. . . it was . . . confirmed experimentally (Friedman et al., 2016) that the absorption line of a rotating Mössbauer absorber is broadened during the rotation and that this broadening is linearly proportional to the rotation frequency and also to the size of the beam at the centre of rotation of the disk*'.

In order to evaluate the influence of the linear Doppler effect on the measurement sensitivity in relation to the relative energy shift between emission and absorption lines, one has to estimate its numerical value. As we have shown (Kholmetskii *et al.*, 2018a), at the maximal tangential velocity of the absorber u = 300 m s^{-1} and at the width of the synchrotron beam of 5 µm achieved by Friedman *et al.* (2016), the measured width of the resonant line becomes 50 times (!) larger than the natural linewidth [which, for the isotope ^{57}Fe, is equal to 0.19 mm s^{-1} (Goldanskii & Herber, 1968)]. It is obvious that this effect, which is totally avoided in experiments based on the traditional methodology, drastically reduces the measurement sensitivity in the energy shifts between emitted and absorbed resonant radiation.

Contradistinctively, in traditional Mössbauer rotor experiments with an ordinary resonant source fixed on the rotor, the measured width of the resonant line of the absorber is comparable with its natural width due to the absence of the linear Doppler effect between the source and the absorber [see the advantage (i)].

One more principal factor to consider in Mössbauer rotor experiments, which essentially affects the measurement precision, is the presence of rotor vibrations that not only enlarge the width of the measured resonant line (in the case of chaotic vibrations) but also can displace its maximum due to a non-random vibration component. In the analysis of these factors, the advantage (ii) in usual Mössbauer rotor experiments with point-like sources in comparison with those utilizing a synchrotron source becomes crucial, because the *relative vibrations* between the source and the absorber – when they are both fixed on the rotor – are always much smaller than the *absolute vibrations* of the rotor as measured in the laboratory frame.

The corresponding numerical estimations by Kholmetskii *et al.* (2018*a*) show that, at the maximal tangential velocity u = 100 m s^{-1} used by Friedman *et al.* (2016), and for a rotor made from aluminium alloy (which is the case for the experiments conducted by Friedman *et al.*), the random components of vibrations in the rotor system broaden the resonant line by approximately 60 times (!) in comparison with the case where a point-like resonant source and an absorber are both fixed on the rotor.

Therefore, due to the combined action of the linear Doppler effect and rotor vibrations, the measured width of the resonant line in the synchrotron experiments by Friedman *et al.* (2016, 2017) turns out to be two orders of magnitude (!) larger than its natural linewidth. Needless to say, for such a wide line, it is practically impossible to garner any reliable information about its energy shifts at a few parts of the natural linewidth, as is required for the precise estimation of the coefficient k in equation (1).

Thus failing to measure the coefficient k in equation (1) and being incapable of directly extracting a_m from their equation (7), Friedman *et al.* (2016, 2017) suggested another way to verify their hypothesis about the existence of a maximal acceleration in nature; they compared the intensities of the resonant radiation passing across the rotating absorber at its two different angular positions – characterized by the opposite directions of centripetal accelerations upon the axis of the synchrotron beam [named as states (*a*) and (*b*) by Friedman *et al.* (2016, 2017, 2019)]. In these states, the sign of the maximal acceleration a_m in equation (7) is different, which leads to the corresponding difference of the coefficient k and the corresponding difference of the intensities of the resonant radiation passing across the resonant absorber in the states (a) and (b). Accordingly, having measured these intensities, one can right away determine the value of a_m in equation (7) despite the failure in measuring directly the coefficient k in equation (1).

An important advantage of their approach, in the opinion of Friedman *et al.* (2016, 2017), is the conjoint measurement of Mössbauer spectra and rotor vibrations, including its non-random component. Unlike the random vibration component (which does broaden the resonant line, but does not affect its position on the energy scale), the non-random vibration component makes the shape of the resonant line asymmetrical and displaces its measured position on the energy scale. According to the estimation by Friedman *et al.* (2016), the corresponding shift of the measured absorption line in their experiment yielded a value near 0.60 mm s^{-1} in velocity units, which thus exceeds by approximately three times the proper width of the resonant line at 0.19 mm s^{-1}. Therefore, in the opinion of Friedman *et al.* (2016), all previous Mössbauer experiments in a rotating system – including the experiment by Kündig (1963) and the experiments by our team (Kholmetskii *et al.*, 2009; Yarman *et al.*, 2016) – are erroneous due to the ignorance of the non-random components of rotor vibrations. This circumstance, in the opinion of Friedman *et al.* (2016), allows ignoring, in particular, the results of our team (4) and (5), which yielded practically identical values for the coefficient k at different rotor radii R in obvious contradiction to their equation (7).

However, in their criticism with regards to our experiments (Kholmetskii *et al.*, 2009; Yarman *et al.*, 2016), Friedman *et al.* (2016, 2017) obviously forget that, in our setup, just like in all other Mössbauer rotor experiments with ordinary sources, only the *relative* vibrations between the source and the absorber, that are both fixed on the rotor, are essential – which totally invalidates their evaluation of absolute rotor vibrations (Friedman *et al.*, 2016, 2017) vis-à-vis the analysis of our results.

Namely, we have already shown above that the random component of relative vibrations is approximately 60 times smaller in comparison with absolute rotor vibrations, and the same estimation remains in force with respect to the non-random component of rotor vibrations, too (Kholmetskii *et al.*, 2018*a*). Thus, taking the shift of the resonant line at the 0.60 mm s^{-1} value due to the non-random vibration component as obtained by Friedman *et al.* (2016) in their synchrotron experiment, we derive the corresponding shift of the resonant line in a Mössbauer rotor experiment with a point-like source as 60 times smaller, *i.e.* an inconsequential 0.01 mm s^{-1}.

This value is anyway about 20 times smaller than the proper width of the resonant line (0.19 mm s^{-1}), and therefore negligible in every respect in Mössbauer experiments using ordinary sources fixed on a rotor. Hence, the assumption about the random character of vibrations for this kind of experiment is perfectly fulfilled. We emphasize that this conclusion completely agrees with the observation by Kündig (1963) about the symmetrical shape of the resonant line at all angular velocities up to the highest values.

Conjointly, such a conclusion supports the correctness of our experimental results (4), (5), which indicate that the maximal acceleration, even if it existed, should have a considerably larger value in comparison with the *ad hoc* estimation (8) by Friedman & Gofman (2010), to the extent that the dependence of the coefficient k on the rotor radius R according to equation (7) becomes immeasurable. Even so, in contrast to this outcome, Friedman *et al.* (2019) reported the observation of '. . . *a stable statistically significant relative shift between the spectra of the two states with opposite acceleration*'. In order to connect this result with the hypothesis about maximal acceleration, Friedman *et al.* (2016, 2017) assumed that none of the numerous instrumental factors confounding their setup could be responsible for the observed shift of the spectra in the two states of the absorber the way mentioned above. However, as we have recently shown (Kholmetskii *et al.*, 2018*a*), the most important instrumental factor which could be responsible for the shift of the spectra in the states (a) and (b) beyond the hypothesis about maximal acceleration has been unfortunately missed by Friedman *et al.* (2016, 2017).

Our paper (Kholmetskii *et al.*, 2018*a*), which addresses the quandary, was published after the submission date of the latest paper by Friedman *et al.* (2019) but before the date of its acceptance for publication. For the convenience of the readers, we now reproduce the principal points of our criticism of the experiments by Friedman *et al.* (2016, 2017).

Remarkably, Friedman *et al.* (2016, 2017) have overlooked the fact that a rotor cannot be perfectly balanced on its rotational axis, and, thus, during the rotor run, the axis inevitably fluctuates near its equilibrium position due to imbalance. The range of such fluctuations δr is conditionally shown in Fig. 1, along with the angular positions of the semi-circular absorber in the states (a) and (b) in the experiment conducted by Friedman *et al.* (2016). One can then immediately realize that the linear Doppler shift of the absorption

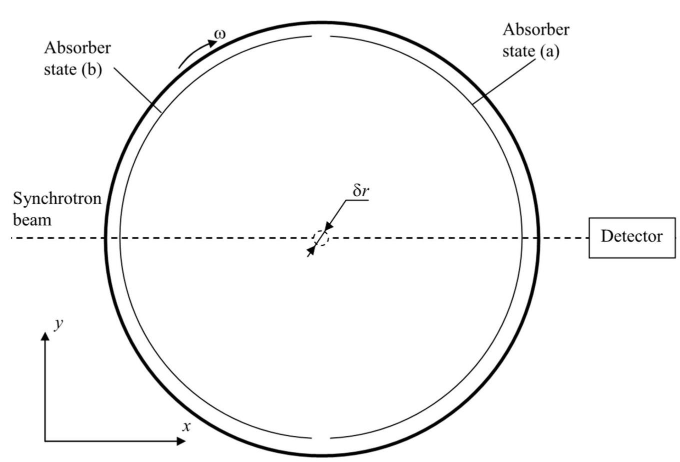


Figure 1
Angular positions of the semi-circular absorber in state (a) and state (b) in the experiment (Friedman *et al.*, 2016), and the range of the fluctuation δr of the position of the rotational axis during the rotor run.

resonant line should be different for the states (a) and (b) at a finite value of δr, and the crucial point here is the evaluation of the admissible range of values of δr which do not affect the observed shift of the spectra in the two states of the orbiting resonant absorber.

It is easy to formulate that the difference of the linear Doppler effects along the x-axis (directed along the synchrotron beam) for the states (a) and (b) at any finite value of δr is equal to

$$\delta v_{ab} = \omega r \frac{\delta r}{r} = \omega \delta r. \tag{10}$$

At this point, it can be seen that Friedman *et al.* (2016, 2017, 2019) totally missed the instrumental factor (10) in their analysis. This is why we find it especially important to estimate its possible influence on the measured shifts of the resonant lines in the states (a) and (b). In particular, Friedman *et al.* (2017) observed such a shift at the maximum value

$$\Delta v_{ab} = 0.41 \text{ mm s}^{-1} \tag{11}$$

at the maximal rotational frequency 200 rev s^{-1} ($\omega = 2\pi \times 200$ rad).

Substituting the indicated numerical values into equation (10), we obtain

$$\delta r \simeq 0.3 \ \mu\text{m}. \tag{12}$$

As a consequence, in order to claim that the result (11) has a physical origin, reflecting the existence of a maximal acceleration, one has to ensure the strong inequality $\delta r \ll 0.3$ µm.

However, the right-hand side of equation (12) already constitutes a tiny value, as it is much smaller than the width of the synchrotron beam (about 5 µm) – and it assuredly cannot be well controlled up to any degree of satisfaction in the experiments reported by Friedman *et al.* (2016, 2017).

Nevertheless, if one continues to insist on further improvement of the methodological side of Mössbauer rotor experiments with a synchrotron source as suggested by Friedman *et al.* (2016, 2017, 2019), they have to ensure that the instrumental factor (10) – related to the spatial fluctuation of the rotor axis during its rotation – remains insignificant even at the expected lowest limit of the maximal acceleration (9).

In order to obtain a corresponding numerical estimation, we adopt a natural assumption that the variation of the count rate of the detector of resonant γ-radiation is linearly proportional to the energy shift of the resonant line at small shifts. Next, we recall that the energy shift between the states (a) and (b) at the value (11) corresponds to the estimated maximal acceleration

$$a_{\rm m} = 1.2 \times 10^{17} \text{ m s}^{-2}, \tag{13}$$

as derived in the experiment by Friedman *et al.* (2017). Hence, under a realistic estimation of $a_{\rm m}$ according to equation (9), the amplitude of the fluctuation of the rotor axis should be less than the value (12) by the ratio of the right-hand side of equations (9) and (13), *i.e.*

$$\delta r \le 0.3 \text{ Å}. \tag{14}$$

This constraint on the admissible fluctuation of the rotor axis belongs to the atomic scale, and its implementation is absolutely unrealistic. Thus, the impracticable inequality (14) totally invalidates the idea by Friedman *et al.* (2016, 2017, 2019) to compare the intensity of resonant radiation traversing the orbiting resonant absorber in its states (a) and (b) for an evaluation of a supposed maximal acceleration in nature.

4. Conclusion

The latest publication by Friedman *et al.* (2019) advocates the application of a synchrotron source of resonant radiation to measure the Mössbauer effect in a rotating system, but without any presentation of the actual state-of-the-art technique in this novel branch of experimental activity. This motivated us to present our own analysis on the subject, where we indicated a number of principal points missed by Friedman *et al.* in both their previous publications (Friedman *et al.*, 2016, 2017) and their latest paper (Friedman *et al.*, 2019).

In particular, we highlighted the low sensitivity of the experiments conducted by Friedman *et al.* (2016, 2017) – based on a synchrotron source of resonant radiation – to the relative energy shift between emission and absorption lines, which ruins any attempt to directly measure the coefficient k in equation (1). Such impracticality is explained by the huge broadening of the observed resonant line as a consequence of the linear Doppler effect between emitted and absorbed resonant radiation alongside absolute rotor vibrations.

The impossibility to evaluate the coefficient k in equation (1) via the setup of Friedman *et al.* (2016, 2017) using resonant synchrotron radiation renders practically useless such experiments in the verification of a full set of competing hypotheses with respect to the controversial origin of the extra-energy shift between an emitted and an absorbed radiation emerging in a rotating system beyond the usual relativistic dilation of time.

Nevertheless, one can still test the hypothesis about the possible existence of a maximal acceleration in nature (Friedman & Gofman, 2010) in a special configuration where the intensity of resonant radiation passing across an orbiting absorber is compared against its two particular angular positions – characterized by the opposite signs of the projection of centrifugal accelerations upon the direction of the synchrotron beam.

Corresponding measurements carried out by Friedman *et al.* (2016, 2017) allowed them to conclude '. . . *a stable statistically significant relative shift between the spectra of the two states with opposite acceleration*'. Being motivated by such an observation, recently Friedman *et al.* (2019) presented an '*indispensible*' plan with regard to the performance of a decisive Mössbauer rotor experiment using synchrotron radiation aimed to confirm their hypothesis about the existence of a maximal acceleration in nature.

However, despite the seemingly detailed analysis of various instrumental factors which could affect their measurement results (Friedman *et al.*, 2019), we have shown above that the most significant instrumental factor, *i.e. a spatial fluctuation of* *the rotor axis due to unavoidable mechanical imbalance*, has been missed by Friedman *et al.* (2019), which invalidates any further attempts to assess the value of a maximal acceleration via their measurements, especially vis-à-vis its recent realistic estimation (9).

This allows us to suppose that the presence of the EES, as confirmed by our experimental results (4), (5), is not related to the hypothesis about maximal acceleration and has another physical origin (see, for example, Yarman *et al.* 2015). Further progress in this area can be made via the direct measurement of the coefficient k in equation (1) – which, as we mentioned above, can nowadays be achieved either in Mössbauer rotor experiments utilizing an ordinary point-like source fixed on the rotor along with a similarly situated resonant absorber or in modified experiments with a synchrotron beam, where at least some of the γ-optical elements should be fixed on a rotor to avoid the linear Doppler effect between the source and the absorber and to minimize the influence of rotor vibrations on the shape of measured resonant line.

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