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The validity of an experiment testing the influence of acceleration on time dilation using a rotating Mössbauer absorber and a Synchrotron Mössbauer Source

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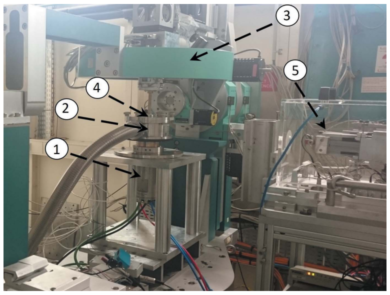
Three experiments are reviewed, performed (in 2014–2016) at ID18 of ESRF to measure the influence of acceleration on time dilation by measuring the relative shift between the absorption lines of two states of the same rotating absorber with accelerations anti-parallel and parallel to the incident beam. Statistically significant data for rotation frequencies up to 510 Hz in both directions of rotation were collected. For each run with high rotation, a stable statistically significant 'vibration-free' relative shift between the absorption lines of the two states was measured. This may indicate the influence of acceleration on time dilation. However, the measured relative shift was also affected by the use of a slit necessary to focus the beam to the axis of rotation to a focal spot of sub-micrometre size. The introduction of the slit broke the symmetry in the absorption lines due to the nuclear lighthouse effect and affected the measured relative shift, preventing to claim conclusively the influence of acceleration on time dilation. Assuming that this loss of symmetry is of first order, the zero value of the relative shift, corrected for this loss, falls always within the experimental error limits, as predicted by Einstein's clock hypothesis. The requirements and an indispensable plan for a conclusive experiment, once the improved technology becomes available, is presented. This will be useful to future experimentalists wishing to pursue this experiment or a related rotor experiment involving a Mössbauer absorber and a synchrotron Mössbauer source.



1. Introduction

Time dilation due to the velocity of a moving object is the fundamental prediction of Einstein's theory of Special Relativity (Einstein, 1905). A natural way to detect this is by using a uniformly rotating absorber. Since time is directly connected to frequency, the absorption spectrum of a uniformly rotating absorber will be shifted by the transverse Doppler shift. For regular subluminal velocities, this shift is very small, so one needs very accurate techniques to measure it.

After the discovery of the Mössbauer effect in 1958, quantitative measurements of the relativistic time dilation, expressed by the shift of the absorption line due to the rotation of a Mössbauer absorber, were carried out in the 1960s (Hay *et al.*, 1960; Hay, 1962; Cranshaw *et al.*, 1960; Cranshaw

& Hay, 1963; Champeney & Moon, 1961; Champeney *et al.*, 1965).

In Mössbauer absorption spectroscopy, an absorber which is at rest is exposed to a radiation beam from a Mössbauer source placed on a transducer. A detector measures the intensity of the beam transmitted through the absorber for different velocities of the transducer. The observed absorption line exhibits the transmission intensity as a function of the velocity of the transducer. For a rotating absorber it was predicted that the time dilation due to the transverse Doppler shift causes a change in the resonant frequency with respect to the absorber at rest. Although this change is tiny, the extremely narrow spectral line widths of the Mössbauer absorption lines would allow one to detect this tiny change. In most of these experiments, the Mössbauer source was fixed to the center of a fast rotating disk, and the absorber was attached to its rim. The predicted shift was based on the absorption value at the frequency of the source. In the analysis of these experiments, it was assumed that the absorption line of the rotating absorber had a Lorentzian shape with the same width as its spectrum at rest, and that the spectral line shift is due to time dilation only.

Kündig, in his ingenious experiment (Kündig, 1963), was the first to obtain experimentally a few points of the Mössbauer absorption line of a rotating absorber by placing the source on a transducer at the center of a rotating disk. He discovered a broadening of this line during the rotation and attributed this broadening to the vibrations in the rotor. He also assumed that this broadening does not affect the position of the absorption line. This assumption is valid for random vibrations of the rotor, but Kündig already suspected the possibility of non-random vibrations caused by the rotor bearing.

The question arises: is there an additional time dilation due to the acceleration of the absorber? According to Einstein's Clock Hypothesis (Einstein, 1911) the answer is definitely no and the rate of an accelerated clock is equal to that of a co-moving unaccelerated clock. On the other hand, if acceleration also influences time, relativistic dynamics predicts the existence of a maximal acceleration $a_{\rm m}$ (Friedman & Gofman, 2010) and a Doppler type shift due to acceleration (Friedman, 2011). This Doppler type shift is similar to the one due to the velocity, where velocity and the maximum velocity are replaced by acceleration and maximal acceleration, respectively. Since a rotating Mössbauer absorber is exposed to centripetal acceleration, it may also be used to test the effect of acceleration on time dilation.

The relativity of a rotating disk is not yet well understood (Rizzi, 2004; Alba & Lusanna, 2010; Klauber, 2007). There are several models for the relativistic effects of a rotating disk, but all of them present some theoretical as well as experimental problems. Therefore, any experiments that will measure relativistic effects of a rotating disk could contribute to reveal the real relativistic model of a rotating disk.

For technical reasons it is very complicated to keep the balance of a fast rotating disk with a Mössbauer source on a transducer on it. Therefore, in order to detect the influence of time dilation of a rotating disk, the source has to be installed outside the rotating disk. Using such a setup, it was claimed (Friedman & Nowik, 2012) and confirmed experimentally (Friedman *et al.*, 2015) 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 center of rotation of the disk. This necessitates the use of a strong Mössbauer source (which is not available in a regular laboratory) with the capability to be focused to the center of the disk. The SMS (Potapkin *et al.*, 2012) at the Nuclear Resonance Beamline ID18 (Rüffer & Chumakov, 1996) of ESRF, together with the KB optics (Kirkpatrick & Baez, 1948) to focus this beam, seemed to us as an ideal choice for such an experiment.

Using the SMS, we set the rather ambitious task to investigate the influence of acceleration on time dilation using a Mössbauer absorber attached on the inside rim of a rotating disk. The aim was to measure the relative shift between the absorption lines of two states of the absorber: for acceleration anti-parallel and parallel to the direction of the SMS incident beam. To achieve this goal, we conducted three experiments HC-1361 (July 2014), HC-1898 (July 2016) and HC-3065 (July 2017) at the Nuclear Resonance Beamline ID18 of ESRF. By using a semicircular absorber and a system to separate out the two states of the detected transmitted radiation, we were able to obtain the entire absorption line for each one of these two states. Einstein's Clock Hypothesis and all currently known relativistic models for rotating systems predict the same absorption line for both states. If all the extraneous effects that could generate a difference between the absorption lines of these two states were under control, according to the Clock Hypothesis, our experiment should have resulted in a null experiment.

The importance and elegance of the experiment was pointed out by Professor Rainer Weiss of MIT, the recipient of the 2017 Nobel prize in physics. After the goal, description and our initial findings were presented to him during a private visit, he wrote: '. . . your notion of actually doing an experiment to see if there is a new mechanism involved when acceleration is present is clearly worth doing. What I thought was elegant about your experiment is the idea that you were using a Mössbauer absorber to determine frequency shifts in a spectrally narrow synchrotron X-ray beam. That already is a major tour de force. The experiment is clearly being done carefully with great attention to systematic problems.'

In this paper we present (i) a comprehensive review of the experiment, (ii) a critical review of the validity of the experiment to achieve its intended goal, and (iii) conclusions regarding the feasibility of a conclusive experiment. Although the experiment proved to be finally inconclusive, it nevertheless revealed important observations, unexpected unwanted effects never discovered before, as well as the requirements for a conclusive experiment once improved technology becomes available. This will save hours of expensive beam time and weeks of heavy thinking for future experimentalists who will intend to pursue such or related rotating Mössbauer experiments.

2. Challenges and ways to overcome them

Testing the influence of acceleration on time dilation using a Mössbauer source and a rotating absorber presented several challenges. These challenges and our recommended way to overcome them are as follows.

2.1. Challenge 1

The time dilation due to velocity expressed by the Transverse Doppler (TD) shift is of second order in v/c. The conjectured time dilation due to acceleration is also of second order. However, if the direction of the X-ray beam is not perfectly perpendicular to the absorber velocity at the point of incidence, there is also a first-order Longitudinal Doppler (LD) shift due to the component of the velocity in the direction of the ray. Since the disk rotates about its axis of rotation, only photons passing through this axis are not exposed to the LD shift. Thus, to avoid this unwanted LD shift, one must concentrate source beam to the disk's rotation axis.

As shown by Friedman & Nowik (2012), the absorption line of a rotating absorber depends on (i) its absorption line at rest, (ii) the rotation frequency, and (iii) the distribution of the distances of the rays in the beam from the axis of rotation. Assuming that the absorption line at rest and the distribution of the rays in the incoming beam (with respect to their distance from the axis of rotation of the disk) are both Lorentzian, then the absorption line of the rotating absorber will also be a Lorentzian. For a rotation frequency ω, denote the width at half absorption intensity by γ_ω and the depth of the absorption curve by A_ω. Then, assuming the isomer shift at rest is zero, the connections between these parameters to their corresponding values γ_0 and A_0 at rest, for a beam of width d, are

$$\gamma_\omega = \gamma_0 + \omega d, \qquad A_\omega = A_0 \frac{\gamma_0}{\gamma_\omega}. \tag{1}$$

The absorption line undergoes an additional shift (in addition to the one due to time dilation), named the *alignment shift* (AS), given by

$$\mathrm{AS} = \pm \omega b_0, \tag{2}$$

where b_0 denotes the distance of the center of the beam to the axis of rotation. The dependence of the sign of the alignment shift on the direction of rotation and the sign of b_0 is given in Table 1.

Table 1
Sign of the alignment shift.

b_0	CW	CCW
+	−	+
−	+	−

In the light of these circumstances, for any distribution of the rays in the incoming beam, the absorption line of a rotating absorber should not depend on whether the acceleration is anti-parallel or parallel to the incident beam. Without the acceleration influence, one would expect the absorption lines for two states with opposite accelerations to be identical, thereby implying a null-experiment for testing the Clock Hypothesis.

The flattening of the absorption lines may lead to total loss of information of this line. To avoid this one needs a way to eliminate the X-rays from the source which are distant from the axis of rotation. In order to obtain statistically significant absorption curves for rotations of 300 Hz (lowest frequency revealing relativistic effects) or higher, the limitations on widening and flattening of the absorption lines require that the width of the beam at the axis of rotation should be about 1–3 µm (see Appendix *A*). Thus, if one would use conventional Mössbauer spectroscopy with manual collimators to eliminate the distant rays, the count rate would be extremely low to collect statistically significant data in a reasonable time period.

This necessitates the use of a strong Mössbauer source with the capability to focus the beam to the axis of rotation. The SMS together with the KB optics to focus this beam at the Nuclear Resonance Beamline ID18 of ESRF was the only choice for such an experiment. However, since the focusing by the available KB optics is not sufficient, the insertion of an additional slit above the axis of rotation would eliminate the distant rays to further narrow the beam and permit statistically meaningful absorption lines.

2.2. Challenge 2

In addition to the above challenge caused by the first-order effects while measuring a second-order effect, there is an additional challenge caused by the imperfectness of a mechanical system. It is obvious that any mechanical system is subjected to vibrations, which in turn affect the absorption lines. This requires a 'vibrationless' rotor system, to eliminate as much as possible the unwanted vibrations and means to trace the remaining vibrations.

Although the random vibrations of the rotor system cause the widening of the absorption lines, they do not shift them. However, the non-random vibrations resulting from the lack of coincidence between the axis of rotation of the disk and the center line of the bearing system may induce such a shift. The insertion of a vibration monitoring system would enable these non-random vibrations to be detected. It is well known that these non-random vibrations follow the Jeffcott model of rotor/bearing system with non-zero eccentricity (Yoon *et al.*, 2013), hence they could be monitored and their effect on the observed shifts could be calculated. Furthermore, monitoring the vibrations can identify the rotation frequencies far from the self-resonant frequencies of the rotor system (where the shift due to vibrations do not affect significantly the measurements) and perform measurements only at these frequencies. The use of active damping can further reduce significantly the size of vibrations.

2.3. Challenge 3

In addition to the above chalenges, there is a further challenge, to align the beam to the axis of rotation of the disk and to maintain this alignment during the data collection. By using formula (2) one can calculate the position of the beam b_0 with respect to the axis of rotation from the measured alignment shift. By moving the rotor in the direction opposite to b_0, one can align the axis of rotation with the center of the beam. Since the increase in the rotation frequency increases the sensitivity of the absorption lines to the misalignment of the system, one needs to improve the alignment if necessary. To maintain this alignment, the mounting of the components of the setup must be as rigid as possible.

2.4. Challenge 4

Another possible challenge could stem from the nuclear lighthouse effect of the rotating absorber, discovered by Ralf Röhlsberger *et al.* (Röhlsberger, 2000; Röhlsberger *et al.*, 2000, 2001; Roth *et al.*, 2005). As in the case of nuclear forward scattering, the synchrotron radiation creates a collectively excited state (nuclear exciton) in the Mössbauer studied isotope absorber. In a rotating sample, these excited states acquire a phase shift while evolving in time. The radiative decay proceeds therefore in a deflected direction. This is called the nuclear lighthouse effect of the rotating absorber. The deflection angle depends on (i) the rotation frequency, (ii) the direction of rotation and (iii) the closeness of the photon frequency to the resonant frequency of the absorber. Since the deflection angle is small, if one uses a detector large enough to detect also the deflected photons, this effect should not affect results, providing that no additional slit is used to complement the deficiency of the currently available KB optics. The availability of suitable KB optics with a sub-micrometre size focal point would eliminate the use of an additional slit altogether, hence exclude the consideration of the nuclear lighthouse effect.

3. Technical details and procedure

The experimental setup is a combination of a mechanical and optical systems basically comprising the SMS, KB optics, rotor system containing a disk with a semicircular Mössbauer absorber on its rim, detector, state separation optical system, vibration monitoring system, data processing unit, slit and supporting electronics (see Fig. 1).

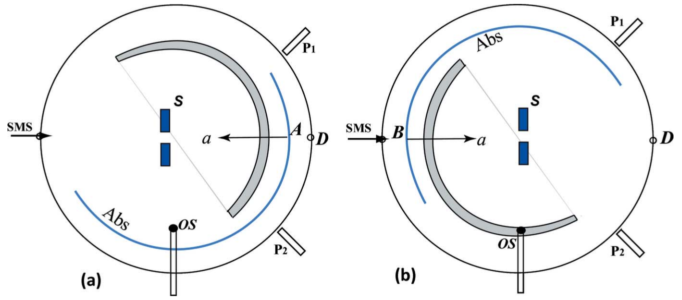


Figure 1
The setup and two states (*a*) and (*b*), SMS source, slit S, semicircular absorber Abs, optical sensor OS, proximity sensors P_1, P_2 and detector D.

The SMS comprises a number of optical elements with the key element being an anti-ferromagnetic and almost ideal single crystal of iron borate $^{57}FeBO_3$, which is used in pure nuclear (111) reflection, which is forbidden for electronic scattering but allowed for nuclear scattering. This crystal is maintained under an external magnetic field and is heated a bit above its Néel temperature, where the magnetic hyperfine structure collapses to a single-line spectrum. The SMS at ESRF provides the ^{57}Fe resonant radiation at 14.4 keV within a bandwidth of 15 neV. In contrast to radioactive sources, the beam emitted by the SMS is almost in full resonance (without background lines), fully polarized, has high brilliance and can be focused by KB optics to a 10 µm × 5 µm spot size. The transmitted radiation was counted by an APD detector diametrically opposed to the SMS.

The rotor system contained a 50 mm-radius circular disk made of titanium 6Al-4v, with 108 slots carefully cut by an electric discharge machining (EDM) process distributed uniformly around its perimeter. The disk was driven by a high-speed air-bearing spindle produced by Colibri Spindles Ltd, Israel. The rotor system was specially designed to preserve both clockwise (CW) and counterclockwise (CCW) constant rotation frequencies of up to 1 kHz, and enable the direction of rotation to be changed by the flick of a remote switch. This also allowed us to eliminate first-order effects (in rotation frequency) by averaging the results produced by the two opposite directions of rotation. A semicircular-shaped enriched potassium ferrocyanide ^{57}Fe (95%) $K_4Fe(CN)_6{\cdot}3H_2O$ single-line absorber was placed on the inside rim of the disk.

The disk was lowered inside a vacuum chamber, with the high-speed air-bearing spindle located outside the chamber. The vacuum conditions, which are essential for high-speed rotation, low friction and acoustic noise, were maintained by an automatically controlled vacuum pump when the air pressure was kept to be below 5.5 bar to avoid the overheating of the rotor system. The spindle was located outside the vacuum chamber, while the driving shaft crossed the chamber wall through a carefully designed bore, leaving a gap of 50 µm between the static (chamber) and the dynamic (shaft) parts. The chamber had two openings each of width 2 mm covered by transparent Mylar to allow the beam from the SMS to cross the chamber.

A state separation optical system using an optical sensor (OS) facing the disk mounted on top of the chamber produced one type of signal when the system was in state (*a*) and another signal in state (*b*), depending on the direction of the acceleration at the point of incidence of the beam with the absorber. The data processing unit of the SMS was suitably modified to send the data from the detector to the memory unit, defined by both the state of the system as well as the velocity of the iron borate crystal of the SMS. This provided us two absorption lines for each run.

The vibration monitoring system consisting of two proximity sensors (by Micro-Epsilon Ltd) placed orthogonal to one another was used to measure the radial displacement of the disk. Collecting simultaneously the data from these sensors and the optical sensor allowed us to monitor the non-random vibration at any point of the disk.

In order to reduce line broadening, we focused the SMS beam to the axis of rotation of the disk using the KB optics. In addition, we also mounted an adjustable slit with the possibility to align its position with the axis of rotation, in order to further narrow the beam from the KB optics. In order to adjust the slit, it was installed outside the vacuum chamber. This was achieved by inserting a mini-chamber, also with two transparent openings, in the center of the vacuum chamber.

Initially we used a metal slit provided by ESRF. We then used a gold-plated slit of width 10 µm and thickness 15 µm produced by lithography at the nano-center of the Hebrew University of Jerusalem, Israel, and further improved by the Intel Israel facility. By rotating it we were able to obtain any effective width below 10 µm. We also used an additional high-quality Pt slit of width 2.5 µm and thickness 50 µm produced by Sylvain Petitgirard at Bayerisches Geo-Institut, which enabled us to obtain absorption lines at higher rotation frequencies and also to check the sensitivity of the relative shift on the choice of the slit.

The dynamical rotor system was finely balanced before it was incorporated in the beamline. We assembled it together with the vacuum chamber and mounted them on a six-circle Huber diffractometer in the experimental laboratory. Firstly, we ran it at different rotation frequencies to obtain its vibration map by the use of the Schenck VIBORTEST 60 tester and our vibration monitoring system. We identified the frequencies remote from the unwanted resonant frequencies, for which the effect of the vibrations on the relative shift is minimal. This enabled us to safely reach rotations up to 510 Hz in both directions.

A HUBER 5102-05 *xy*-stage facilitated the mounting and adjustment of the slit with its specially designed holder (see Fig. 2). Once this was completed, we finally assembled the system for the separation of states and modified the SMS for this separation.

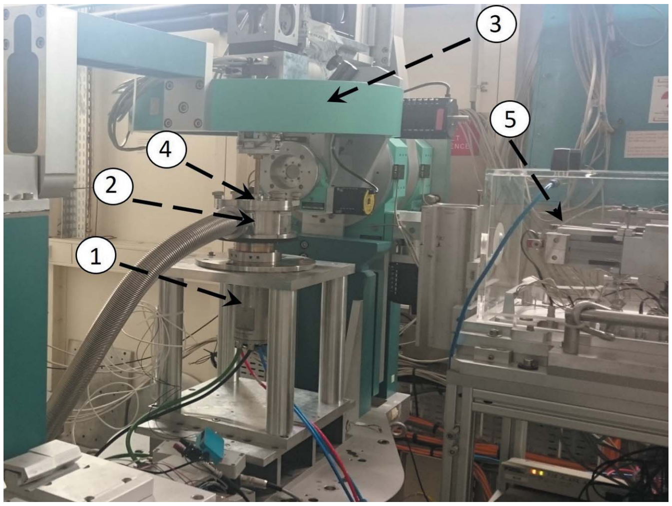


Figure 2
The experimental setup. The rotor system (1) together with the disk in the vacuum chamber (2) were all mounted on a six-circle Huber diffractometer (3). The slit (4) with its holder on top of the vacuum chamber and KB optics (5).

Once the beam shutter was opened, the incident SMS beam focused by the KB optics to the axis of rotation of the disk crosses the disk along its diameter. As the disk rotates, the beam then hits the slit prior to hitting the fast rotating absorber when the system is in state (*a*), or it first hits the absorber and than it hits the slit in state (*b*). In these states the radial acceleration of the absorber is alternately directed anti-parallel and parallel to the beam wavevector (see Fig. 1), yielding opposite signs for the postulated additional frequency shift due to this acceleration. The state separation optical system identifies these respective states, and the SMS data acquisition system was suitably modified to yield simultaneously the absorption spectra corresponding to each state. The absorption curves were measured by recording the transmitted intensity as a function of the Doppler detuning of the SMS.

4. Achievements and unexpected deficiencies

In our first two experiments (Friedman *et al.*, 2015, 2017) we developed a method of how to systematically align the axis of rotation with the center of the beam using the alignment shift, and how to obtain the entire resonant absorption line of a rotating absorber. We obtained absorption lines for the two states (*a*) and (*b*) and the relative shift between them. We discovered that the non-random vibrations due to the imbalance of the rotor/bearing system also cause an unwanted shift which may significantly affect the relative shift. Using the vibration monitoring system, we monitored these vibrations, demonstrated that they conform with the well known forced steady state response of a Jeffcott rotor/bearing system. We estimated their effect and found a way to correct them in order to obtain the 'vibration-free' relative shift. We found (Friedman *et al.*, 2016) that the shift due to the non-random vibrations was often comparable with the observed shift. Nevertheless, in two runs of CW rotations at 200 Hz, where the vibrations were negligible, we observed a statistically significant 'vibration-free' relative shift of 0.41 mm s^{-1} which is much larger than the one predicted by any model. This indicated the influence of acceleration on time dilation, and motivated us to persevere and perform the third experiment with the accusative knowhow.

Our last experiment allowed us to collect more statistically significant data and rotating absorber spectra up to 510 Hz in both states (*a*) and (*b*) (Fig. 1) for several rotation frequencies in both CW and CCW directions with different slits. We checked the reproducibility of the relative shift for the CW run at 200 Hz keeping almost the same configuration, and reproduced our earlier 'vibration-free' relative shift of 0.41 mm s^{-1}, described above. Even though in this run the system was improved by re-balancing it close to the run and also by using the advanced gold plated slit, the 'vibration-free' relative shift was unaltered.

We found a way to increase significantly the count rate by changing the temperature of the iron borate crystal. This

Table 2
Parameters of resonant spectra and vibration shifts for states (*a*) and (*b*) at 360 Hz rotation.

Run	Effect (%)	γ (mm s^{-1})	Shift (mm s^{-1})	Relative shift (mm s^{-1})
63*a*	8.02 (2)	3.04 (13)	0.01 (7)	–
63*b*	8.78 (2)	2.72 (11)	0.16 (6)	−0.15 (10)
64*a*	7.77 (2)	3.04 (15)	0.40 (7)	–
64*b*	8.91 (3)	2.62 (13)	0.03 (7)	0.37 (10)

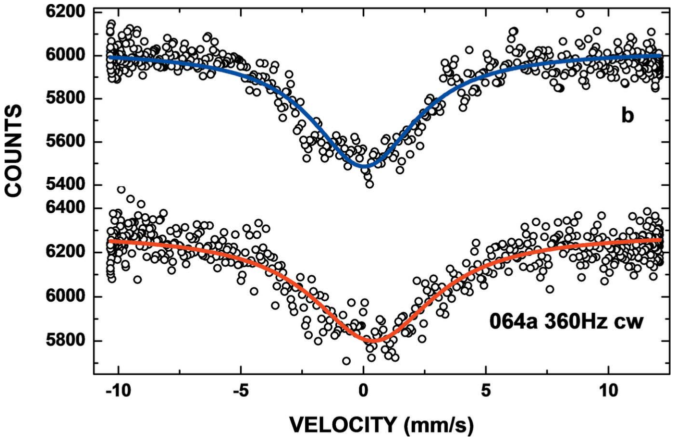


Figure 4
The resonant lines for states (*a*) and (*b*) at 360 Hz CW rotation.

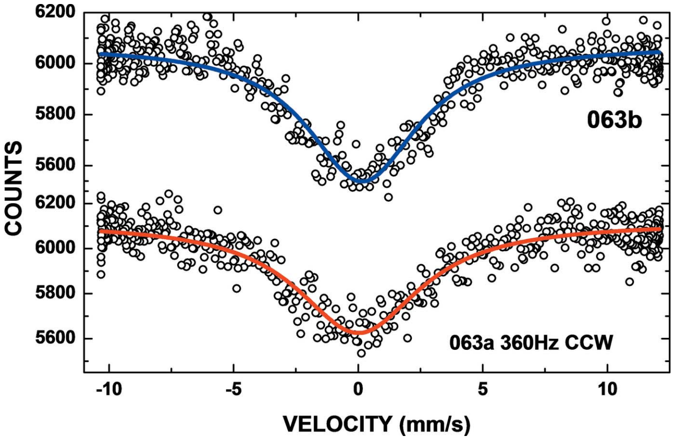


Figure 3
The resonant lines for states (*a*) and (*b*) at 360 Hz CCW rotation.

allowed us to collect statistically significant data over a much shorter time. This change caused widening of the absorption curve at rest from $\gamma_0 = 0.5$ mm s^{-1} to $\gamma_0 = 0.86$ mm s^{-1}, producing a slight change in the width γ_ω of the rotating absorber (see Appendix *A*). This preferable condition avoids larger widenings, caused by the loss of alignment of the system during the long measurements time.

Although we managed to measure a sufficiently large number of counts at 510 Hz, we observed a drift due to the loss in alignment of the beam and the rotor system during the long runs. The latter was due to the limitation in the stability of the relative positioning of the rotor disk and the slit system. This drift caused a widening of the spectrum, which in turn reduced significantly the accuracy of the observed relative shift.

We collected several files for rotations of 300 Hz, 360 Hz and 510 Hz in both directions. For example, in runs 63 and 64 at 360 Hz CCW and CW, respectively, we obtained spectra by using the 2.5 μm slit rotated by 10° to obtain an effective slit of about 1 μm (see Figs. 3 and 4). Table 2 summarizes the parameters of the absorption lines in the figures.

We repeated the experiment with different slits with the expectation that this change should not affect the relative shift. As stated above, the purpose of the slit is to collimate the beam emerging from the KB optics, thereby reducing the widening of the absorption lines at higher rotational frequencies. Indeed, the use of a narrower slit reduced this widening, as expected. Use of a slit should not affect the relative shift for the following reason. For any ray of the beam, the first-order shift depends only on *b*, the distance of the ray from the rotation axis. As shown by Friedman *et al.* (2015), the alignment shift for each ray is ωb where ω is the angular velocity vector of the rotating disk. The alignment shift of the beam is obtained by integrating this shift over the distribution of all the rays in the beam with respect to *b*. Since each (unbent) ray which passes the slit spends the same time in each state, it has equal probability to be in either state (*a*) or (*b*). Hence, the shift of the absorption lines in each state is expected to be identical and the relative shift should not be affected.

Furthermore, since the wavelength of the beam is 0.86 Å and the slit width is about 1 μm, the diffraction of the beam from the slit is also negligible. It is reasonable to assume that this diffraction, if occurs, will cause a widening of the absorption line in state (*a*) where the beam first hits the slit, and the resulting diffraction increases the widening of the absorption line (see Fig. 1). On the other hand, in state (*b*), the diffraction of the beam emerging from the absorber does not affect the absorption line, since the detector is wide enough to record even the diffracted rays. The observed slight widening of the absorption line in state (*a*) in comparison with that in state (*b*) (see Table 1) supports our assumption. Furthermore, it is natural to assume that the diffraction does not break the symmetry between the two states; therefore, the choice of slit should not affect the relative shift. Even if the diffraction by the slit would break the symmetry, changing the direction of rotation would produce the same relative shift with an opposite sign.

We discovered, however, that our expectation was incorrect. Without altering any components of the system, different slits produced different relative shifts for the same rotation frequency. Moreover, we have noticed that, even in the 'absence of vibrations' and using the same slit, both the magnitude and sign of the relative shift changed with the direction of rotation. For example, as shown in Table 1, at 360 Hz the relative shift changed from 0.37 (10) mm s^{-1} to −0.15 (10) mm s^{-1} for CW to CCW, respectively. This discovery revealed the existence of a new unwanted first-order relative shift, which cannot be ignored.

We assume that this unwanted relative shift is due to the nuclear lighthouse effect. As mentioned above, the radiative decay of a rotating absorber proceeds in a deflected direction which depends on: (i) the rotation frequency, (ii) the direction of rotation and (iii) the closeness of the photon frequency to the self-resonant frequency of the absorber.

In state (*b*) the beam from the KB optics is partially absorbed by the absorber and the emerging beam is deflected due to the nuclear lighthouse effect depending on the above three factors. This deflected beam hits the slit, which blocks out part of it before reaching the detector. Thus, the deflection due to the nuclear lighthouse effect affects the observed absorption line. On the other hand, in state (*a*), however, the beam from the KB optics is first partially blocked (and partially diffracted) by the slit and then undergoes a deflection after passing the absorber. This later deflection does not affect the collected data, since the detector is relatively large with respect to the size of the beam and is close to the absorber in this state. Hence, our assumption, presented above, that each (unbent) ray not blocked by the slit has equal probability to be in either state (*a*) or (*b*), is not valid. This loss of symmetry explains the dependence of the relative shift on both the choice of the slit and also on the direction of rotation.

We attempted to estimate quantitatively this shift caused by the nuclear lighthouse effect and take it into account as done by Friedman *et al.* (2016) for the relative shift due to non-random vibrations, discussed above. The non-random vibrations can be measured and hence the relative shift due to them could be calculated. On the other hand, the relative shift due to the nuclear lighthouse effect depends on many parameters of the system, which make its estimation impossible.

As in the previous experiments, we also observed a drift in the spectrum for long runs at high rotation frequencies. We discovered that this drift was substantially reduced after tightening the rotor system to the plate holding it. One must have a rigid table that connects perfectly to our rotor system and thereby preventing the loss in the alignment of the system.

The above-mentioned unwanted effects could overshadow the relative shift due to acceleration, and thus prevent us claiming conclusively the influence of acceleration on time dilation using the currently available technology.

5. An indispensable plan for a conclusive experiment

Based on our observations and their implications acquired in this series of experiments, we suggest the following indispensable plan for a conclusive experiment, in order to test the influence of acceleration on time dilation using a rotating absorber and a synchrotron Mössbauer source (SMS).

(i) Measure the spectral absorption lines for two separate states (*a*) and (*b*) of the rotor (see Fig. 1) differing only in the direction of their respective accelerations in order to observe the relative shift between them.

(ii) Monitor the non-random vibrations and quantify their effect on the relative shift.

(iii) Check the reproducibility of the relative shift.

(iv) Repeat the experiment with a configuration that should not affect the relative shift.

(v) Explore other effects that also lead to a relative shift, in case the change in configuration affects it.

(vi) Obtain the corrected relative shift by eliminating any unwanted side contribution.

(vii) Repeat the experiment with different configurations to verify that the corrected relative shift is independent of the configuration.

(viii) Check that the relative shift is unaffected by measuring a different absorber and/or rotor system.

(ix) Study the dependence of the relative shift on the rotation frequency and disk size.

The experiment revealed the following requirements to perform step (i) of the above plan:

(i) One needs preferably a perfect single-line Mössbauer absorber. This absorber needs to be large enough to cover the full or half circumference of a rotating disk. Using a semicircular absorber allows one to obtain the spectra for *two states* (*a*) and (*b*) when the acceleration is anti-parallel and parallel to the SMS radiation. If a circular absorber is used, the observed spectrum will be some convolution of the spectra for the two states.

(ii) It is preferable that the disk will be transparent to the SMS radiation. For this reason, beryllium is the best candidate for such a disk; however, due to its high Poisson degree, its fabrication is limited. Therefore, one is forced to use a non-transparent disk with windows on its circumference. These windows must be built with very high accuracy in order not to block the radiation. Moreover, for high rotations, air turbulence causes problems so the rotating disk must be lowered into a vacuum chamber and a suitable vacuum pump is desired.

(iii) A ‘vibrationless’ rotor system with the capability to rotate the disk for a range of rotation frequencies in both directions is required. We used an air-bearing in our experiments; however, one could use a magnetic bearing. In order to be able to obtain a reliable Mössbauer absorption line, the radial velocity of the vibrations must be less then 0.01 mm s^{-1}. Furthermore, to minimize these vibrations, an active damping of the vibrations should be applied.

(iv) One needs an SMS producing a coherent narrow beam for several frequencies in the neighborhood close to the Mössbauer resonant frequency.

(v) The system should be stable to preserve the alignment for long runs with a sub-micrometre accuracy. This beam must be focused to the center of rotation of the disk. In order to be able to observe a statistically meaningful spectral line without using a slit (which turned out to be problematic), the focal point must be of sub-micrometre size.

(vi) In order to separate the two states, one needs an optical system that provides one type of signal when the system is definitely in state (*a*), another signal when it is in state (*b*), and a third one when it is in the transition between the two states. The data processing needs to send the data from the detector to the memory unit defined by both the state of the system as well as the velocity of the iron borate crystal of the SMS.

(vii) The detector must be large enough to count also the photons which are deflected by the nuclear lighthouse effect.

(viii) A vibration monitoring system using fast proximity sensors with the ability to measure radial velocities of less then 0.01 mm s^{-1} must be employed. Alternatively, a Michelson interferometer may be used to monitor the vibrations.

(ix) The the rotor system must have the possibility to be moved both in the x an y directions in order to be able to align the axis of rotation of the disk with the focal point of the beam. The y alignment is by use of the observed alignment shift, and the x position should be defined as the position with the minimal value for observed γ_ω.

6. Discussion and conclusions

By measuring the relative spectral shift between the resonant absorption lines of a rotating absorber in two states with opposite accelerations to the SMS radiation, we aimed to test experimentally the influence of acceleration on time dilation.

We discovered the importance of focusing the SMS beam to the axis of rotation and developed a method to systematically align this axis with the center of the beam using the observed shift of the absorption line. This allowed us to obtain the entire resonant absorption line of the rotating absorber. Next, we measured the absorption lines for the two states (a) and (b) with opposite accelerations and the relative isomer shift between them. We discovered that non-random vibrations may affect significantly the relative shift; we monitored them, estimated their effect and found a way to correct them to obtain the 'vibration-free' relative shift.

We checked the reproducibility of the relative shift. In the second experiment we measure a non-zero statistically significant 'vibration-free' relative shift for the CW run at 200 Hz. In the third experiment, keeping almost the same configuration as the second one, but with a re-balanced rotor system and improved slit, we measured almost the same relative shift.

Using all the experience and the knowhow we acquired, we managed to gather stable statistically significant data for rotation frequencies up to 510 Hz in both directions of rotation, and using different slits. For each high-frequency rotation run, we observed a stable statistically significant relative shift between the spectra of the two states with opposite acceleration. Although this seemed to indicate the influence of acceleration on time dilation as anticipated, unfortunately, even after exhausting every bit of knowhow acquired and the currently available technology, this claim is not conclusive. Unexpectedly, we found that the measured relative shift is also affected by both the choice of the slit and the direction of rotation. The use of a slit imposes a loss of symmetry in the absorption lines in the two states due to the nuclear lighthouse effect when using a slit. The relative shift arising from the symmetry break could overshadow the relative shift caused by the acceleration, the object we were looking for. Hence, we cannot claim conclusively the affect of acceleration on time dilation.

Assuming that the loss of symmetry caused by the use of the slit is a first-order effect on the relative shift as a function of the rotation frequency ω, the averaging of the measured relative shift of two runs with the same frequency but with opposite directions of rotation yields an estimation for the 'corrected' relative shift. We observed that for accelerations up to 5×10^5 m s^{-2}, in all our experiments, the zero value of the 'corrected' relative shift falls within the experimental errors limits, as predicted by Einstein's Clock Hypothesis.

The experiment revealed the impossibility of conducting such an experiment using a slit for reducing the widening of the absorption lines, and also the importance of maintaining the alignment between the optical and the dynamical rotor system for long runs. Thus, a successful experiment requires an improved KB optics with a sub-micrometre size focal point. A more rigid mounting of the rotor system would also improve the accuracy of the measurements and avoid spectral drift and widening of the spectrum. The application of active damping to further reduce the vibrations of the rotating disk and the implementation of a Michelson interferometer to measure these vibrations accurately is also recommended.

Although these experiments brought inconclusive results, they nevertheless revealed the challenges in reaching their goal, as well as unexpected effects never discovered before and how to correct for them where possible. They also revealed the absolute requirements as well as an indispensable plan for a successful conclusive experiment, once the improved technology becomes available. Hopefully, these findings will prove useful to future experimentalists wishing to pursue this experiment, or a related rotor experiment involving a Mössbauer absorber and SMS.

Interest in the effects of acceleration on time dilation is ongoing. Using the fact that acceleration contributes to the temperature dependence of the center shift, W. Potzel (Potzel, 2016) applied our maximal acceleration model by measuring the temperature shift of high-resolution 93.3 keV Mössbauer resonance in ^{67}ZnO and β'-brass to test the clock hypothesis. He came up with a lower limit for the maximal acceleration as $a_{\rm m} > 1.5 \times 10^{21}$ m s^{-2}, a value which is two orders of magnitude higher than the ones obtained earlier. To reach this limit, he claims that 'future ^{57}Fe Mössbauer experiments will be highly demanding but should also furtheron intensively be examined using synchrotron radiation experiments in combination with high-speed centrifuges at modern synchrotron facilities like PETRA III at DESY which can cover the relatively high Mössbauer energy necessitated in these experiments'. Our series of experiments provide some estimates of $a_{\rm m}$ which seem to indicate the validity of his claim. From the data in Table 2 for 360 Hz CW and CCW rotations of our last experiment, we obtain a 'corrected' relative shift of $\sim$0.11 mm s^{-1} which yields an estimate of $a_{\rm m} \simeq 1.4 \times 10^{18}$ m s^{-2} (see Appendix B). This value is one order of magnitude higher from the 200 Hz estimation in our second experiment (Friedman *et al.*, 2017).

Recently, Benedetto & Feoli (2018) attempted to interpret the measured relative shift in our second experiment by assuming the existence of a first-order time-dependent Doppler shift for an accelerated absorber due to the interaction time between the beam of photons and the nuclei in the absorber. This model allowed them to calculate the average interaction time τ of a rotating absorber from the observed relative shift relative shift as τ = (relative shift)/a, where a is the acceleration of the absorber. Alternatively, assuming that τ is affected by the acceleration, they suggested calculating it from the half-width absorption intensity line γ of a rotating absorber. They used the γ value from our experiment to calculate τ, and showed that the values deduced from both ways are close. Although their approach is logically correct, it does not confirm experimental results obtained by members of the current team headed by Ralf Röhlsberger at PETRA III at DESY, Hamburg, in 2013, which measured the effect of acceleration on the time spectrum (time delay) of a rotating Mössbauer sample. This experiment showed that the increase of rotation frequencies does not reduce the time delay (see Friedman & Steiner, 2017). For example, for rotation frequencies of 6–14 kHz of a thin sample, no change in the time spectrum and hence in the average interaction time τ was observed. Furthermore, the widening of the Mössbauer absorption lines of a rotating absorber was predicted by Friedman & Nowik (2012) and was verified experimentally at ESRF by Friedman *et al.* (2015). The reason for this widening is the longitudinal Doppler shift. Hence, the use of our experimental γ (Benedetto & Feoli, 2018) to estimate the value of τ of a rotating absorber is misleading.

Finally, our experiment is the first trial to measure directly the time dilation of a rotating absorber without assuming *a priori* the effect of vibrations on the absorption lines. Even though our experiment was designed to measure the influence of acceleration on time dilation, the experimental setup can also be used to test the influence of velocity on time dilation expressed by the TD shift, a topic still of interest nowadays (see Friedman *et al.*, 2015, and references therein). A single run cannot define the TD shift because of the alignment shift. However, since the direction of rotation does not affect the TD shift but changes the sign of the alignment shift, if one repeats runs with the same setup and the same angular velocity but changes only the direction of rotation, averaging the shifts of the absorption lines of the two opposite directions annihilates the effect of the alignment shift. As this procedure does not require the separation of two states, we can use the absorption line obtained from combining the counts of both states. Assuming, as above, that the loss of symmetry due to the nuclear lighthouse effect when using a slit is a first-order effect in ω, the TD shift can be obtained by averaging the measured shift of the lines at the same rotation frequency in two opposite directions. From the data in Table 2 for 360 Hz CW and CCW rotations of our last experiment, we obtained a TD shift of 0.15 (13) mm s^{-1} (see Appendix *C*). The theoretical TD shift predicted by Special Relativity is 0.04 mm s^{-1}, which falls within the confidence interval.

APPENDIX *A*
Example of calculation of γ_ω and A_ω

The parameters of our single line absorber were γ_0 = 0.5 mm s^{-1} and A_0 = 72%. For 300 Hz rotation $\omega = 2\pi\nu$ = 1885 s^{-1}. If d = 1 µm = 10^{-3} mm, then from (2) we obtain γ_ω = 0.5 + 1885 × 10^{-3} mm s^{-1} = 2.385 mm s^{-1} and A_ω = 72 × 0.5/2.385 = 15.1%.

If d = 3 µm = 3 × 10^{-3} mm, then γ_ω = 0.5 + 1885 × 3 × 10^{-3} mm s^{-1} = 6.155 mm s^{-1} and A_ω = 72 × 0.5/2.385 = 5.9%.

APPENDIX *B*
Calculation of the maximal acceleration based on 360 Hz rotations

From Friedman (2011) we know that the relative shift RS = $2rc\omega^2/a_{\rm m}$, where r is the radius of the disk. Assuming RS = 0.11 mm s^{-1} for 360 Hz rotation, this yields an estimate value for $a_{\rm m}$ of

$$a_{\rm m} \simeq \frac{2(2\pi \times 360)^2 \times 0.05 \times 3 \times 10^8}{0.11 \times 10^{-3}} \quad {\rm mm\,s^{-2}}$$
$$= 1.4 \times 10^{18}\ {\rm m\,s^{-2}}. \qquad (3)$$

APPENDIX *C*
Calculation of the transverse doppler shift based on 360 Hz rotations

The shift of the total absorption line (without separation of states) is the average of the shifts of the two states. Thus, for run 63 (CCW) this shift is 0.08 (12) mm s^{-1} while for run 64 (CW) this shift is 0.22 (14) mm s^{-1}. Averaging the shifts in the two opposite directions to cancel the alignment shift and other first-order shifts yields a TD shift 0.15 (13) mm s^{-1}. The TD shift predicted by Special Relativity is v^2/c, which for 360 Hz (v = 113 m s^{-1}) rotation is 0.04 mm s^{-1}.

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