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A time dilatation experiment based on the Mössbauer effect

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Abstract. Some experiments are described in which the time dilatation at the tip of a high speed rotor is measured and compared with the expectations of relativity theory. Mössbauer sources and absorbers are attached to the centre and tip (or vice versa) of the rotor and the time dilatation deduced from the variation of gamma ray transmission with rotor speed. A technique is described whereby using a source absorber combination with an appropriate inherent frequency shift the experiment takes on the features of a null experiment. A result $2{\cdot}1\% \pm 1{\cdot}9\%$ in excess of the expected dilatation is obtained.

1. Introduction

We describe here some measurements of the resonant absorption of gamma rays in a Mössbauer system fixed to a high speed rotor, with the source at the centre and the absorber at the tip of the rotor and vice versa. The aim of the experiments is to measure the effects of time dilatation in such a system and compare them with the expectations of relativity theory. These experiments, the earlier stages of which have been briefly reported before by Champeney, Isaak and Khan (1961, 1963 a), are complementary to the experiments with source and absorber at opposite tips which have been carried out in this laboratory by Champeney and Moon (1961) and Champeney, Isaak and Khan (1963 b).

On the grounds of relativity theory we expect the frequency of the radiation arriving at the absorber (as measured by a clock on the absorber) to vary with rotor speed according to

$$\frac{\nu_1}{\nu_0} = \left(\frac{1-\omega^2 r_s{}^2/c^2}{1-\omega^2 r_a{}^2/c^2}\right)^{1/2} \simeq 1 + \frac{\frac{1}{2}\omega^2(r_a{}^2 - r_s{}^2)}{c^2} \tag{1}$$

where ν_1 is the frequency measured at rotor angular velocity ω, ν_0 is the frequency of the emitted radiation as measured by a clock on the source, r_s and r_a are the radii of the source and absorber orbits and c is the velocity of light. If the amount of resonant absorption by the absorber has been previously measured as a function of incident frequency shift (by using shifts induced, say, by means of the first-order Doppler effect) then a measurement of the absorption in the rotor system as a function of rotor speed enables a direct test of the above equation.

It is worth considering how this formula is derived and what aspects of relativity we are testing in such an experiment. Equation (1) is commonly derived from the

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standard Doppler effect equations of special relativity; these may be written

$$\frac{\nu_1}{\nu_0} = \frac{(1-v_s^2/c^2)^{1/2}}{1-\mathbf{v}_s \cdot \mathbf{e}/c} = \frac{1-\mathbf{v}_a \cdot \mathbf{e}/c}{(1-v_a^2/c^2)^{1/2}} \tag{2}$$

where ν_0 and ν_1 are the frequencies of the emitted and received radiation as measured by clocks in the emitter's and receiver's reference frames, $\mathbf{v}_s$ is the velocity of the source as measured by the receiver, $\mathbf{v}_a$ is the velocity of the absorber as measured by the emitter and $\mathbf{e}$ is a unit vector along the ray path as seen, respectively, by the absorber and emitter in the first and second expressions in equation (2). For the situation with the source at the centre of the rotor and the absorber at the tip, and for the opposite case with source at tip and absorber at centre, the application of equation (2) is direct, for we have respectively $\mathbf{v}_a \cdot \mathbf{e} = 0$; $(\mathbf{v}_s \cdot \mathbf{e} \neq 0)$ and $\mathbf{v}_s \cdot \mathbf{e} = 0$; $(\mathbf{v}_a \cdot \mathbf{e} \neq 0)$, and equation (2) reduces to equation (1), giving a 'blue shift' when the source is at the centre and a 'red shift' when it is at the tip. Lee and Ma (1962) have pointed out that the Doppler effect equations can be simply adapted to the following form, suitable for use by a laboratory observer relative to whom both source and absorber are in motion:

$$\frac{\nu_1}{\nu_0} = \frac{1-\mathbf{v}_a \cdot \mathbf{e}/c}{1-\mathbf{v}_s \cdot \mathbf{e}/c}\left(\frac{1-v_s^2/c^2}{1-v_a^2/c^2}\right)^{1/2} \tag{3}$$

where $\mathbf{v}_s$, $\mathbf{v}_a$ and $\mathbf{e}$ are now the source and absorber velocities and the unit ray vector as measured by the laboratory observer. It is further a simple matter to show from geometrical considerations that for source and absorber fixed to a rotating disk (whether along the same diameter or not) we have $\mathbf{v}_a \cdot \mathbf{e} = \mathbf{v}_s \cdot \mathbf{e}$, so that the general result of equation (1) follows. These equations (2) and (3) are of course derived on the basis of systems in uniform relative motion, and in applying them to our experiment we are making tacit use of the hypothesis that, if an ideal clock moves non-uniformly through an inertial frame, then acceleration as such has no effect on the rate of the clock. Experiments such as ours are therefore combined tests of special relativity and of this hypothesis. In so far as this hypothesis may be justified for nuclear clocks such as ours by the general theory, then to that extent ours is an experiment in the general theory.

We need not work through the Doppler effect equations, as in the previous paragraph, but may derive our results directly from the time dilatation of special relativity if we make use of the above hypothesis. According to the time dilatation of special relativity, the time between two events at a clock moving with velocity v relative to some inertial frame is registered by this clock as $\tau = \tau_0(1-v^2/c^2)^{1/2}$, where τ_0 is the time as measured by clocks in the inertial system. In our rotor experiment difficulties do not arise from a variable distance between source and absorber, so that as measured in the laboratory system (regarded as the inertial frame) the frequency of the radiation at emission equals that at absorption. Thus the ratio of frequencies at emission and absorption as measured by source and absorber clocks is given by the inverse ratio of their time dilatations, i.e.

$$\frac{\nu_1}{\nu_0} = \left(\frac{1-v_s^2/c^2}{1-v_a^2/c^2}\right)^{1/2}$$

giving equation (1) directly.

Other Mössbauer experiments involving high speed rotors have been carried out by Hay *et al.* (1960, see also Hay 1961, Cranshaw and Hay 1963), by Kündig (1963), and by Turner and Hill (1964). Expressing the frequency shift as

$$\frac{\nu_1}{\nu_0} = 1 + \frac{\frac{1}{2}K\omega^2(r_a{}^2 - r_s{}^2)}{c^2}$$

where K has a value unity according to relativity theory, Hay *et al.* obtain a value $K = 1{\cdot}001 \pm 0{\cdot}013$ for 50% probability and $K = 1{\cdot}001 \pm 0{\cdot}062$ for 95% probability (their error curve was non-Gaussian), whilst Kündig obtains $K = 1{\cdot}0065 \pm 0{\cdot}011$ and we obtain $K = 1{\cdot}021 \pm 0{\cdot}019$. Although our random error is no smaller than these, we feel our result to be particularly free from unsuspected systematic errors, being essentially the combination of four independent sets of experiments using different source–absorber combinations and using, moreover, in one of these sets a technique having many of the features of a null experiment. Turner and Hill's experiment was designed to measure the angular dependence of any shift. As Ruderfer (1960, 1961) and Møller (1962) have pointed out, according to the classical idea of an aether drift, one would obtain an angle-dependent frequency shift of $\Delta\nu/\nu = (\mathbf{v}_s - \mathbf{v}_a) \,.\, \mathbf{V}/c^2$, where $\mathbf{v}_s$ and $\mathbf{v}_a$ are the source and absorber velocities relative, say, to the laboratory and $\mathbf{V}$ is the velocity of the laboratory relative to the aether. A positive sign for $\Delta\nu$ means that the received radiation is high in frequency. Alternatively, Turner and Hill point out that in more modern terms one can regard the experiment as sensitive to any dependence of clock rates on their velocities relative to distant matter. Assuming such a dependence, they obtain an angle-dependent shift $\Delta\nu/\nu = 2\gamma(\mathbf{v}_s - \mathbf{v}_a) \,.\, \mathbf{V}/c^2$ where γ is an unknown constant and $\mathbf{V}$ is now the laboratory velocity relative to distant matter. Interpreting the results according to the former model, for uniformity, the results of Cranshaw and Hay (1963) lead to a limit on the appropriate component of $\mathbf{V}$ of about 9 m sec^{-1}, and the results of Turner and Hill lead to $4{\cdot}4 \pm 16{\cdot}8$ m sec^{-1}.

Considering now experiments on the second-order Doppler effect which do not make use of rotors, Sherwin (1960) has pointed out that experiments on the thermal shift of Mossbauer radiation verify time dilatation in a manner somewhat analogous to that of the rotor experiments. Mention should also be made of the experiments of Mandelberg and Witten (1962), in which the second-order Doppler shift of the optical radiation from an ion beam was observed, and a value of $K = 0{\cdot}996 \pm 0{\cdot}050$ obtained.

These various results compare with our value of $K = 1{\cdot}021 \pm 0{\cdot}019$ and a limit on component velocity relative to an 'aether' of $1{\cdot}6 \pm 2{\cdot}8$ m sec^{-1}.

2. Method and apparatus

Experiments were performed with a source at the centre and absorber at the tip of a rotor, and vice versa, the case with source and absorber at opposite tips having been described by Champeney and Moon (1961) and Champeney *et al.* (1963 b). In the early experiments we used source–absorber combinations having no intrinsic shift, the increase in transmission with speed due to loss of resonance being compared with the corresponding results obtained by means of the first-order Doppler effect. Such a system is insensitive to the sign of the effect, and a combination having an inherent shift was therefore used. It became apparent, however, that a 'shifted' pair if properly chosen would possess marked advantages other than the settling of any ambiguity of sign. By choosing the shift to be of the correct magnitude and sign, one can arrange matters so that in going from low to high rotor speed one traverses the dip in the resonance and arrives at a speed at which the transmission is equal to the zero speed transmission. The experiment then takes on many features of a null experiment; if, moreover, the linewidth is chosen so that one is working approximately at the point of inflection, and if a comparison resonant absorber is fixed to the back of the source, then, as described below, one arrives at a system free from most of the systematic errors which might arise when using unshifted lines.

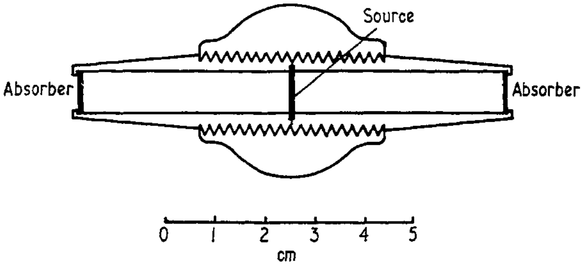

Figure 1. Diagram of the rotor.

The steel rotor is shown in figure 1. This consists of two hollow arms which can screw into a central portion. Sources or absorbers in the form of disks may be fixed at the centre of the rotor, clamped in position between the two arms, or at either tip resting against flanges. The rotor spins in vacuum, on a glass plate, about an axis through its centre pependicular to its length. The initial acceleration up to speeds of about 1400 c/s is induced by a rotating magnetic field provided by four coils external to the vacuum system; thereafter readings are taken during the gradual slow-down of the rotor (12 to 24 hours). A small electromagnet suspended in an oil dashpot just above the rotor provides an upward force of about 95% of the rotor's weight, thus reducing wear at the point of contact with the glass plate and providing a lateral centralizing force for the rotor. Having the magnet suspended in oil helps to dampen any wobble of the rotor.

The gamma rays could be detected by one or two xenon-filled proportional counters (with beryllium windows) placed outside the Melinex windows of the vacuum chamber, as shown in figure 2. The 14·4 kev gamma ray of interest was counted by conventional

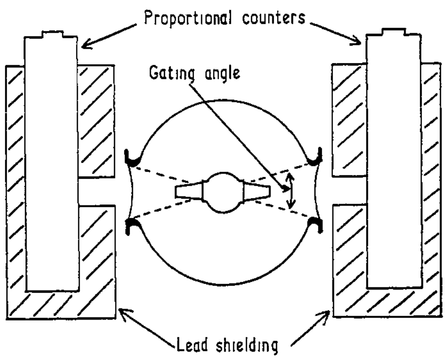

Figure 2. The rotor assembly, showing rotor, vacuum vessel and proportional counters.

amplifying and scaling systems involving single-channel pulse height analysers. The counting circuits were gated electronically so that they counted only during periods when the rotor was within a certain angular range 'pointing' at the counter. The opening and closing of the gate was controlled by the rotor intercepting two beams of light perpendicular to the plane of rotation. It was also arranged that during alternate open periods the gamma rays should be registered by different scalers. This allowed different absorber arrangements to be used in the two arms of the rotor, one of which could be used, as described below, to act as a 'dummy' or 'control'. For experiments with the source at the tip such a double gate is of course essential.

The various sources and absorbers used during the course of the experiments are described in the table. In this table R represents the ratio of the decrease in transmission at maximum absorption to the transmission far from resonance (after allowing for background), the linewidth is the total width at half height of the transmission dip expressed in terms of the Doppler velocity, and the shift is regarded positive for an absorber resonant frequency higher than the source frequency. Combination 5 was chosen as having a linewidth and shift satisfying the conditions for a null experiment outlined above. The enriched potassium ferrocyanide in the form of powder was mixed with Araldite and formed into a disk of diameter 7·5 mm and thickness 0·30 mm so as to fit into a tip of the rotor, up against a beryllium disk for mechanical strength. The other absorbers were either electroplated on beryllium backings or stuck on with Araldite. Apart from No. 4, the sources, in the form of foils about 10 micrometres thick, were embedded in Araldite between Dural and aluminium foils to form rigid disks suitable for use at the centre of the rotor. The 'copper' source, No. 4, was stuck on a beryllium backing suitable for mounting at a rotor tip.

Ref. No.	Source	Absorber	^{57}Fe in absorber (mg cm^{-2})	R (20 °c)	Linewidth (mm sec^{-1})	Shift (mm sec^{-1})
(1)	0·5 mc of ^{57}Co in ^{56}Fe matrix	52 % ^{57}Fe plated onto 0·005 in. thick Be	1·820	0·3676	0·4212	0·0
(2)	0·5 mc of ^{57}Co in in ^{56}Fe matrix	52 % ^{57}Fe plated onto 0·010 in. thick Be	0·884	0·2769	0·4082	0·0
(3)	0·5 mc of ^{57}Co in ^{56}Fe matrix	81 % ^{57}Fe foil Durofixed onto 0·010 thick Be	4·293	0·4520	0·5384	0·0
(4)	5 mc of ^{57}Co in Cu matrix	Stainless steel foil (20 % Ni, 25 % Cr, 55 % of 52 % enriched ^{57}Fe) Araldited to a 1 mm thick Be disk	1·43	0·45	0·78	−0·32
(5)	5 mc of ^{57}Co in Cr matrix	Anhydrous $K_4Fe(CN)_6$ made with 91 % enriched ^{57}Fe	0 325	0·250	0·402	+0·094

For combinations 1, 2 and 3, the source was mounted at the centre of the rotor, the resonant absorber at one tip and a non-resonant beryllium dummy at the other tip. Readings obtained from the dummy absorber enabled one to monitor and allow accurately for any effects of electronic drift, movement of rotor axis and change in gate width. Experiments with these combinations used only one proportional counter. With combination 4 the source was at one tip and the absorber at the centre; no dummy absorber was possible with this arrangement and the experiment was only performed with sufficient accuracy to confirm the sign of the effect. With combination 5 the source was mounted at the centre, a resonant absorber at one tip and an approximately matched resonant absorber was fixed at the centre of the rotor to the side of the source away from the first absorber. This arrangement of dummy eliminated the need for any correction due to changes in R resulting from the rotor temperature being different from that prevalent during the measurements of the resonance characteristics involving the first-order Doppler effect.

The experimental procedure involved taking low speeds readings for an hour or two at 100–200 c/s, then accelerating to about 1400 c/s and taking readings during the natural slow-down of the rotor (about 100 c/s per hour, but depending markedly on the condition of the glass plate). With combination 5 the readings were concentrated at low speeds and at high speeds (above about 1180 c/s) in order to find two speeds having equal transmission. A small correction enabled that speed to be derived corresponding to the same transmission as zero speed. During some of the runs readings were also taken at intermediate speeds giving information on the effects of rotor vibration.

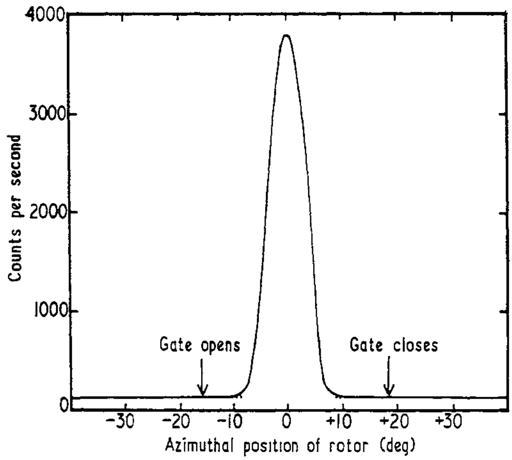

Figure 3. The observed counting rate as a function of rotor position (for combination 5) as determined in tests with the rotor stationary showing the angular acceptance of the gate. The dotted line indicates the counting rate with $\frac{1}{8}$ in. of aluminium placed in front of the counter.

A reading consisted of a ten-minute count, the parameter of interest being the ratio of the counts in the resonant and the dummy channels. These channels were interchanged between each reading to allow for any possible electronic asymmetry. The angular gate width was measured at half-hourly intervals by feeding timing pulses through the electronics and comparing the rate with that of ungated pulses. The rotor speed was continuously measured by feeding the gating pulses, from the interception of the light beams, into a ratemeter which was calibrated absolutely from time to time using a scaler and timer. The angular acceptance of the gate was made generously large so that the angular region of high counting rate, with the rotor 'pointing' at the counter, fell well within the acceptance region, and the system was therefore insensitive to small variations in position of rotor axis (see figure 3). Background corrections during the running of the rotor were based on the counting rate present when $\frac{1}{8}$ in. of aluminium was placed in front of the counter; as described in the next section, the true background was taken as 1·108 times this counting rate.

The measurement of resonance characteristics in terms of the first-order Doppler effect was carried out by mounting the various sources and absorbers on a linear motion device, capable of moving the absorber towards and away from the absorber with

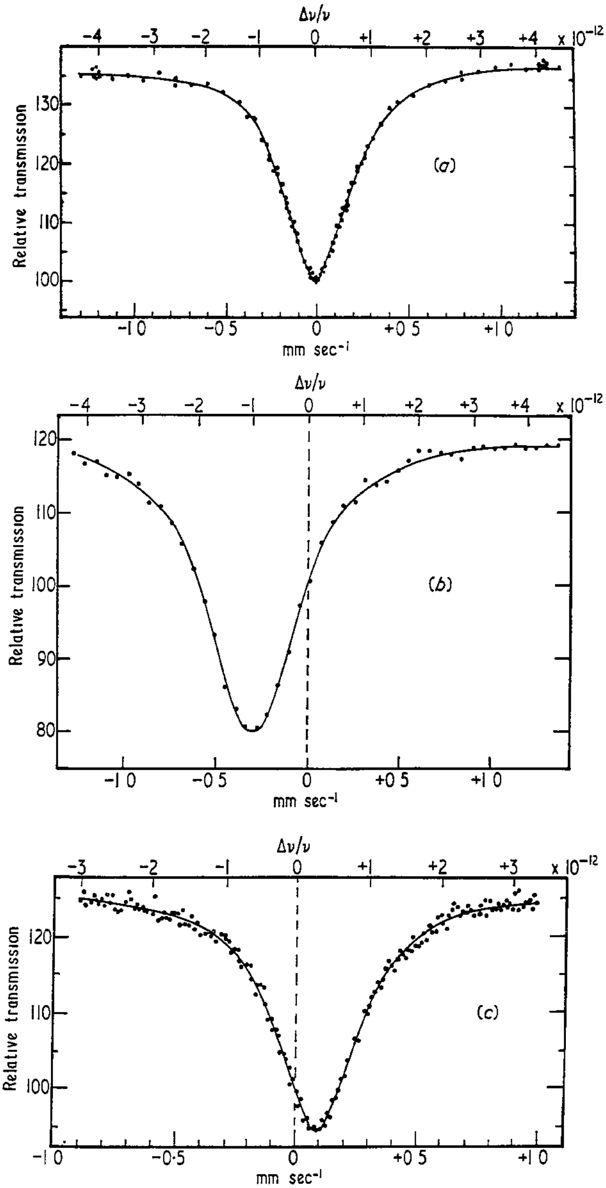

Figure 4. Samples of data obtained using a linear motion device, with (*a*) combination 2, (*b*) combination 4 and (*c*) combination 5. A positive velocity is taken to mean source and absorber approaching each other.

uniform velocity, the resulting gamma-ray transmission being measured as a function of this velocity. Two devices were used, based respectively on a screw and linear cam, driven by servo-controlled electric motors. The gamma-ray transmissions for the forward and backward motions were recorded on different scalers, the end parts of the motion, during the turn round, being gated out. The amplitude of motion (for the gates open) was measured by quasi-static measurements involving a travelling microscope, and the velocity during use was deduced by sending timing pulses from a quartz crystal oscillator through the gates. Some typical results are shown in figure 4. For many of the measurements readings were concentrated at three points on these curves (as described in the next section) and Lorentzian parameters derived analytically from these. For combination number 5 readings were concentrated at zero speed and near that velocity at which the counting rate equalled the zero speed counting rate, this velocity being the only information required about the line shape.

From the line shape data for combinations 1, 2 and 3, obtained from the first-order Doppler effect, curves showing the expected variation of transmission with rotor speed were calculated using the relation

$$\frac{\nu_1}{\nu_0} = 1 + \frac{\frac{1}{2}K\omega^2({r_a}^2 - {r_s}^2)}{c^2}.$$

By comparing the actual rotor data with such curves based on various values of K the best value of K was found by a least-squares technique. For combination 5 it was simply necessary to find the velocities v_L and v_R for the linear motion device and rotor respectively at which the transmissions equalled the zero speed transmissions, and to derive K as equal to $2cv_L/{v_R}^2$. Some typical rotor results are given in figure 5. Some corrections had to be applied and we consider these together with possible sources of error in the next section.

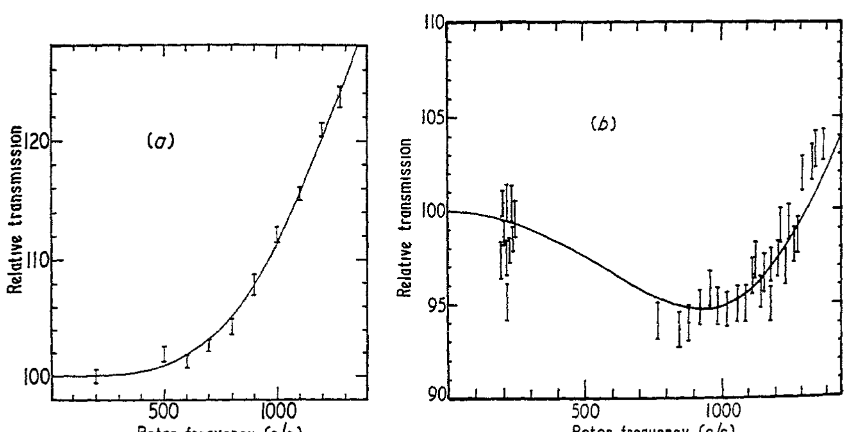

Figure 5. Samples of data obtained using the rotor, with (*a*) combination 3 (the accumulated data) and (*b*) combination 5 (one of sixteen runs). The full curves represent the expected variation in transmission with rotor frequency for $K=1\,00$. Figure 5 (*b*) represents one of the few runs when readings were taken at intermediate speeds (between 700 c/s and 1180 c/s) allowing an upper limit to be placed on the effects of rotor vibration.

3. Corrections and errors

We consider here effects which could have contributed to some error in K or which required correcting for.

3.1. *Frequency and speed measurements*

The accuracies of measurement of rotor frequency, and of speed on the linear motion device, were such as to contribute errors of less than 0·001 each in the value of K.

3.2. *Radius*

The absorber orbit radius was known to within $\pm 0{\cdot}13$ mm. This figure includes errors involved in static measurements of rotor and absorber dimensions, uncertainty of position of axis of rotation and the possible effects of stretching of the rotor arms and flexing of the sources and absorbers. This corresponds to an uncertainty of $\pm 0{\cdot}006$ in the value of K. A geometrical correction was necessary allowing for the finite size of the source amounting to 0·002 in K.

3.3. *Vibration*

There are two aspects to this: vibration on the linear motion device and vibration during the rotor runs. Measurements on the linear motion device were taken at zero speed (with the motor off), at points near the point of inflection of the Lorentzian and at relatively high speeds ($\sim 1{\cdot}2$ mm sec^{-1}). From three such coordinates the parameters of the unshifted Lorentzians were deduced analytically. The zero speed reading, with the motor off, would not have been subject to vibration, whilst the other two would have been insensitive owing to the low curvature of the Lorentzian at these points. It was estimated that peak vibration levels up to 25% of the velocity could be tolerated without K being altered by more than 0·001, and direct measurement of vibration with an electromagnetic pick-up showed this to be a generous allowance.

Vibration of the rotor arms (or of the source and absorber foils within the rotor) would cause an error if present. However, experiments with source and absorber at opposite tips (when no relativistic effect is expected) showed no change in counting rate, between low and high speed, to within an accuracy of 0·5%, thus allowing a limit to be placed on variation of vibration with speed. Further, a comparison of the transmission at low rotor speeds with that when the rotor was stationary on the bench indicated agreement to within 0·3%. We may deduce from these figures that rotor vibrations may have altered the value of K by at most 0·006. An independent estimate was used with combination 5. Rotor vibrations, if present, would have made the dip in transmission at intermediate speeds less prominent. A comparison of the observed reduction in transmission at intermediate speeds with the expected value allowed an estimate to be made of the effects of vibration on K. Under the pessimistic assumption of no vibration at low speed and a vibration level at high speeds equal to that deduced from the intermediate speed readings, K would have been affected by less than 0·005. The same constant vibration level at all rotor speeds would have affected K by less than 0·001.

3.4. *Thermal effects*

The rotor normally ran at a higher temperature than that prevalent during the use of the linear motion device, and a correction to allow for the change in R was necessary. This amounted to a correction in K of $+0{\cdot}022 \pm 0{\cdot}003$. With combination 5 the experiment was insensitive to such temperature difference.

3.5. *Background correction*

The background, arising from radiation other than the 14·4 kev gamma rays, was allowed for by interposing $\frac{1}{8}$ in. of aluminium in front of the counter and subtracting 1·108 times the residual counting rate from the readings. The figure 1·108 was arrived at experimentally by measuring transmissions with various thicknesses of aluminium and extrapolating the straight portion of a logarithmic plot, for thicknesses greater than 3 mm, to zero thickness. Suitable thicknesses of aluminium or Perspex placed in front of the counter window ensured that the effect of lower energy x rays was negligible. Errors in background allowance could not have affected K by more than 0·001. With combination 5 the experiment was insensitive to background allowance.

3.6. *Magnetic field*

On account of the rotor's ferromagnetic construction and the presence of the stabilizing magnet, the possibility of some polarization of source and absorber was considered which would effectively alter R. Bench tests showed that such effects would at worst alter K by less than $\pm 0{\cdot}003$. The combination 5, having an unsplit line, was insensitive to magnetic fields.

3.7. *Effects of strain*

The effects of bending or strain of the absorbers were such as to cause less than 0·0003 error in K, as estimated by calculations based on the results of Pound, Benedek and Drever (1961), and as a result of measurements of transmission through foils subjected to stresses up to 3000 kg cm^{-2} in excess of the actual stress.

3.8. *Effects of iron impurities*

The effects of iron impurities in the aluminium and beryllium foils were considered. In the case of combination 5 it was found that a correction of $-0{\cdot}014 \pm 0{\cdot}002$ in K was necessary, owing to an aluminium foil fixed to the dummy absorber (to produce a small mis-match and to help to distinguish the two counting rates) having a small iron impurity.

3.9. *Gate width*

Small variations in gate width ($\simeq 3\%$) occurred between low and high speed as a result of electronic time constants. From the known gate width and from data such as those in figure 3(a), corrections could be accurately applied. Typically this amounted to a correction in K of $0{\cdot}015 \pm 0{\cdot}001$. With combination 5 any correction was less than 0·001 in K.

3.10. *Electronic dead time*

A correction was applied for the differing dead times of the counting systems used with the rotor and linear motion devices. Typically this amounted to a correction in K of $0{\cdot}004 \pm 0{\cdot}001$. With combination 5 the experiment was insensitive to such effects.

4. Results

After applying corrections as necessary, values of K may be derived from combinations 1, 2 and 3 by comparing the rotor results with theoretical curves (as in figure 5(a)) and using a least-squares technique with K and the counting rate normalization as variables. We obtain for these three cases $K = 1{\cdot}067 \pm 0{\cdot}028$, $0{\cdot}951 \pm 0{\cdot}046$ and $1{\cdot}000 \pm 0{\cdot}030$. The values of $\chi^2 (= \Sigma(d_i^2/\sigma_i^2))$ were 9·5, 18·0 and 5·7 as compared with the expected value of 7·4. Here d_i is the deviation of a rotor reading (such as those in figure 5(*a*)) from the theoretical curve and σ_i is the standard error of the reading as calculated from the counting statistics. The errors quoted on K include both the statistical errors derived from the least-squares analysis and errors from causes mentioned in the previous section combined as though random. In this context one reading is typically the result of about sixty ten-minute readings obtained during several different runs, grouped according to speed range.

With combination 4 it was confirmed that with source at the tip and absorber at the centre a 'red shift' occurred. The transmission was found to decrease by $20\% \pm 1\%$ between 200 c/s and 1250 c/s, in agreement with an expected 19% decrease for a 'red shift'.

With combination 5 it was found that the transmission was restored to its zero speed value at a linear speed of $0{\cdot}1876 \pm 0{\cdot}0011$ mm sec^{-1} (approach) or by rotor frequencies of about 1313 c/s. From sixteen such values of rotor frequency obtained from sixteen runs, one was able to derive the value $K = 1{\cdot}020 \pm 0{\cdot}021$. This error included both statistical errors and other errors combined as though random. At intermediate rotor frequencies the transmission fell below the zero speed by 5·3%, confirming that with source at centre and absorber at tip a 'blue shift' occurs.

By combining these four values of K, weighted according to their standard deviations, we obtain the final value of $K = 1{\cdot}021 \pm 0{\cdot}019$.

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