

## New Experimental Limit on Velocity-Dependent Interactions of Clocks and Distant Matter\*

K. C. TURNER† AND H. A. HILL

*Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*

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An experiment analogous to that of Kennedy-Thorndike and the ammonia-beam experiment of Cedarholm, Bland, Havens, and Townes has been performed using the Mössbauer effect in Fe<sup>57</sup>. A Co<sup>57</sup> source was on the rim and an iron absorber near the center of a centrifuge. The frequency shift between the rotating source and absorber was measured as a function of the angular position relative to the fixed stars. An anomalous velocity-dependent interaction of clocks with a field derived from distant matter would be expected to cause a frequency shift  $\Delta\nu/\nu = 2\gamma\mathbf{u}\cdot\mathbf{v}/c^2$ , where  $\gamma$  is a constant,  $\mathbf{v}$  the relative velocity of source and absorber, and  $\mathbf{u}$  the velocity of the laboratory relative to a reference frame in which distant matter has an isotropic velocity distribution. The value of the component of  $\gamma\mathbf{u}$  lying in the earth's equatorial plane was found to be  $220 \pm 840$  cm/sec.

### I. INTRODUCTION

THE present approach to the problem of establishing an observational basis for general relativity is to consider a large class of theories, a class containing general relativity, and then to use all the observational material to narrow the class of possible theories.<sup>1</sup> One group of experiments used in this way are the so called ether drift experiments. The first of these experiments, the Michelson-Morely<sup>2</sup> and the Kennedy-Thorndike,<sup>3</sup> was motivated by the nineteenth century ether concept. In more modern terms, we might consider the effect of motion of the laboratory relative to distant matter. If there is a gravitational-tensor interaction in addition to that provided by the metric tensor, or possibly a vector interaction between matter in the laboratory and distant matter, the interaction will, in general, depend on the relative velocity of the two.<sup>1,4,5</sup> Thus the frequency of an atomic oscillator or the length of a rigid rod constructed from matter subject to such interactions may be dependent on this relative velocity.

The experiment reported here is one using the Mössbauer effect.<sup>6</sup> It is particularly interesting as it incorporates nuclear forces, strong electromagnetic forces in the nucleus, the electron structure of the atom, and the propagation of photons as ingredients which could conceivably be disturbed by the presence of distant matter. For this experiment, a Co<sup>57</sup> source was placed near the rim of a standard centrifuge with an iron absorber near the axis of rotation. The Mössbauer effect was used to look for any velocity dependence of

the frequency of the 14.4-keV  $\gamma$  rays as seen by the Fe<sup>57</sup> in the absorber.

For simplicity in thinking about the problem, we shall concentrate on only one aspect of it. Consider the nucleus to be thought of as a clock. If its proper clock rate is a function of its velocity relative to distant matter of the universe, it would be expected to vary in lowest order quadratically with the velocity. This is made a meaningful statement by making the comparison with a fixed clock of the same type using light pulses for the intercomparison.

This is effectively what the apparatus does. With the assumption that the electronic structure behaves in a proper Lorentz-invariant way and that light propagates on null geodesics, the  $\gamma$  ray from the source at the rim of the wheel may be compared directly with the absorber near the axis, after making allowance for the second-order Doppler shift.

The second-order Doppler shift is actually important for the experiment. Because of this effect the radiation from the source is red shifted substantially, and the probability of transmission through the filter varies linearly with any further shift (very small). If it were not for the initial shift induced either by the Doppler effect, a temperature difference, or some other cause, the effect would be quadratic in the frequency shift, hence unobservable.

One might rashly judge such experiments to be anti-relativity in conception, but such is far from the case. There is a definite observable difference between a laboratory moving with respect to the universe and one which is not. Namely, in the first case, galaxies are observed to stream toward us in one direction and away from us in the opposite direction. Since the galaxies have random velocities of a few hundred kilometers per second, and the motion of the sun associated with galactic rotation is of the same order of magnitude,<sup>7</sup> it is most unlikely that the earth is at rest with respect to distant matter. Because of this velocity  $\mathbf{u}$  of the labora-

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† Present address: Department of Terrestrial Magnetism, Washington, D. C.

<sup>1</sup> R. H. Dicke in *Lecture Notes of 1963 Les Houches Summer School*, edited by B. DeWitt (Gordon and Breach, New York, 1964).

<sup>2</sup> A. A. Michelson and E. W. Morley, *Am. J. Sci.* **34**, 333 (1887).

<sup>3</sup> R. J. Kennedy and E. M. Thorndike, *Phys. Rev.* **42**, 400 (1932).

<sup>4</sup> P. J. E. Peebles and R. H. Dicke, *Phys. Rev.* **127**, 629 (1962).

<sup>5</sup> P. J. E. Peebles, *Ann. Phys. (N. Y.)* **20**, 240 (1962).

<sup>6</sup> *The Mössbauer Effect*, edited by H. Frauenfelder (W. A. Benjamin, Inc., New York, 1962).

<sup>7</sup> C. W. Allen, *Astrophysical Quantities* (The Athlone Press, London, 1963).

tory relative to distant matter, the Mössbauer clock at the rim of the wheel has a time varying velocity  $\mathbf{u} + \mathbf{v}$  and the clock rate should vary with the angular position of the wheel as

$$\Delta\nu/\nu = 2\gamma uv \cos\theta. \quad (1)$$

Here  $v$  refers to the relative speed of the source and absorber and the angle  $\theta$  is that between the source velocity vector and the component of  $\mathbf{u}$  lying in the plane of the wheel. The magnitude of this component is designated as  $u$ . The  $\gamma$  is some small dimensionless number, a measure of the magnitude of the effect if any.

Inasmuch as both photon propagation and the mechanical structure of the wheel were involved in this experiment, it also sets limits on possible anomalies in these parts of the apparatus. The analysis would be very similar to that of the effect on the proper clock rate.

II. EXPERIMENTAL APPARATUS

The general plan of the present experiment is illustrated in Fig. 1. A source of  $\text{Co}^{57}$  is mounted at the rim of a centrifuge rotating with angular frequency  $\omega$ . An absorber of natural iron is placed near the center of the centrifuge. A NaI(Tl) crystal mounted on the centrifuge rotor detects the transmitted 14.4-keV  $\gamma$  ray of  $\text{Fe}^{57}$ .

A laboratory coordinate system is defined by a light beam which is reflected into a photomultiplier by four mirrors cemented to the rotor. This defines four quadrants and produces a pulse whenever the  $\text{Co}^{57}$  source moves from one quadrant to another. These quadrants are of four different sizes, all near  $90^\circ$ , and each pair of scalers counts only when the source is in the quadrant associated with that pair.

A block diagram of the experiment is shown in Fig. 2. The  $\gamma$ -ray pulses after amplification are sent to two

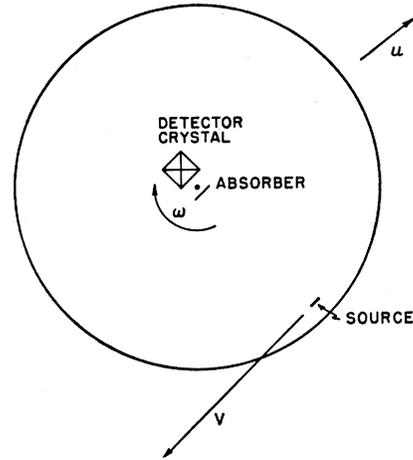


FIG. 1. Scheme of this experiment.

discriminators, one of which selects pulses in the 14.4-keV region (the differential discriminator), and the other (the integral discriminator) which counts all pulses above 22 keV. The pulses above 22 keV are almost entirely due to the 122-keV  $\gamma$  ray which is emitted in cascade with the 14.4-keV  $\gamma$  ray. The 122-keV pulses are used to measure the time spent in each quadrant since no resonance is possible.

The source was obtained as carrier-free  $\text{Co}^{57}$  from the Nuclear Science and Engineering Company of Pittsburgh, Pennsylvania. It was painted on 0.006-in. iron and annealed in a hydrogen atmosphere at  $1000^\circ\text{C}$  for 24 h. The absorber is a stack of three iron foils similarly annealed with each foil 0.00025 in. thick.

The source lies at the bottom of a collimating tube which together with the absorber holder are shown in Fig. 3. The sandwich construction of aluminum and

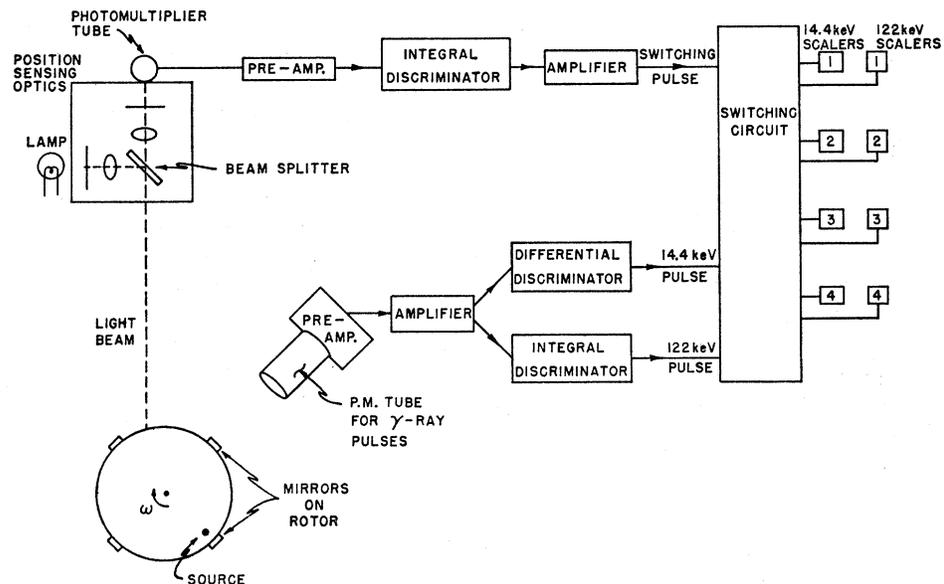


FIG. 2. Block diagram of experiment.

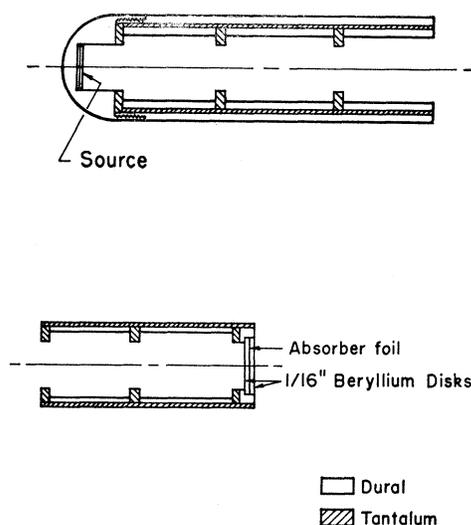


FIG. 3. Cross section of collimating tubes which hold the source and absorber.

tantalum has the following rationale: since the 122-keV  $\gamma$  ray is to be used to evaluate the time spent in each quadrant, it is absolutely essential that the counting rate of the 122-keV  $\gamma$  ray be position independent. The tantalum tube ensures that 122-keV  $\gamma$  rays do not pass through the aluminum rotor and Compton scatter off objects near the centrifuge back into the detector crystal introducing a position dependent counting rate. The tantalum tubes, with the tantalum washers, make the solid angle for the 14.4-keV  $\gamma$  ray and the 122-keV  $\gamma$  ray the same, so that if the source and/or absorber-holder tubes shift slightly, the ratio of the counting rates remains unchanged. This also reduces the 122-keV  $\gamma$ -ray pulse rate from what it would be if the 122-keV  $\gamma$  rays could scatter on the aluminum into the crystal. The aluminum inner tubes support the weaker tantalum tubes, and also reduce the 64-keV Ta x-ray, produced by the absorption of the 122-keV  $\gamma$  rays in Ta. The absorber foils are supported by a  $\frac{1}{16}$ -in. beryllium disk. A similar disk on top of them prevents the foils from being pushed to one side of the centrifugal forces acting on them.

The  $\gamma$  rays are detected by a thin (0.015-in thick) NaI(Tl) crystal cemented with Hysol Corporation Epoxy-Patch Kit No. 0151 into a Lucite light pipe. A  $\frac{3}{8}$ -in.-thick lucite disk was similarly fastened to the bottom of the crystal to prevent moisture from reaching the crystal, and also to preferentially filter out 6-keV Fe x-rays from the beam. The light pipe was designed for maximum light collection from the crystal. It is in the shape of an exponential spiral so that any light from the crystal reaching the wall of the light pipe is totally internally reflected toward the phototube. The non-rotating part of the optical system consists of a  $\frac{1}{4}$ -in Lucite light pipe and a Du Mont photomultiplier No. 6363 separated from the rotating light pipe by a  $\frac{1}{8}$ -in.

air gap. The resolution obtained with this geometry was as good or better than that of two Harshaw potted 0.015-in NaI(Tl) crystals.

It was necessary to locate the detecting crystal in the rotating portion of the apparatus in order to eliminate a position-dependent counting rate. If the crystal were not on the rotating part and not accurately perpendicular to the axis of rotation of the centrifuge, the effective crystal thickness would be a function of the position of the rotor and cause a position dependent counting rate.

The light pipe also has the effect of averaging the light output of the crystal over the whole surface of the photocathode of the photomultiplier tube. If this were not done, the pulse height for a given quadrant could depend on the orientation of the photomultiplier because of the nonuniformity of the photocathode.

The transmitted line shape was measured with the source and absorber actually used in the experiment. The half-width at half-maximum was 0.013 cm/sec; a  $v/c$  of about  $4 \times 10^{-13}$ .

The number for  $f$  defined in Eq. (2) was measured with the actual absorber used in the experiment, together with the beryllium supporting disks. This measured  $f$  was corrected for the loss of resolution produced by deterioration of the NaI crystal during the experiment, and the noise from the centrifuge motor. The corrected  $f$  is 0.0486.

The centrifuge was a Servall SS-4 superspeed centrifuge manufactured by Ivan Sorvall, Inc., and was operated at 15 000 rpm during the experiment. The angular velocity of the centrifuge was measured by a tachometer built into the machine. The scale could be read to about 100 rpm, and a check of the tachometer reading with a cycle counter looking directly at the tachometer output showed it to be accurate to this degree.

The center of the absorber foil was 0.45 in from the axis of rotation, and the source was at 3.95 in. This produced a second-order Doppler shift,  $s$ , of  $1.3 \times 10^{-13}$ , where  $s$  is defined by Eq. (6).

The apparatus can also be used to study the second-order Doppler shift although it was not designed specifically for that. A few measurements were made of this to check the apparatus. The observed change in the number of transmitted 14.4-keV  $\gamma$  rays in going from 0 to 15 000 rpm was  $(1.1 \pm 0.4)\%$  while the expected change was  $(0.9 \pm 0.1)\%$  (these measurements were made at a time when the value for  $f$  was somewhat higher than reported above). These measurements also show that if there were vibrations in the rotor, they caused shifts much less than the line width.

Data were taken in eight and nine minute pieces for periods of four to thirteen hours. The gain stability of the system was monitored by plotting the sum of the four channels for both the 14.4- and 122-keV  $\gamma$  rays. Every two hours or so, a pulse height spectrum in the

vicinity of the 14.4-keV  $\gamma$  ray was taken as an additional check. The photomultiplier tube was cooled with a mixture of dry ice and ethyl alcohol to prevent a temperature rise due to centrifuge air friction. A temperature rise raises the dark current, increasing the noise level above the 14.4-keV  $\gamma$  ray pulse.

### III. DATA ANALYSIS

The transmitted line shape of the 14.4-keV  $\gamma$  ray is Lorentzian and we may write for the counting rate  $r$  of the transmitted 14.4-keV  $\gamma$  rays

$$r = r_1 \left[ 1 - \frac{f}{1 + (\varphi/\Gamma)^2} \right], \quad (2)$$

where  $r_1$  is the counting rate with source and absorber lines well separated,  $f$  is the fractional change in  $r_1$  when the source and absorber lines are not separated,  $\Gamma$  the half width at half maximum of the transmitted line, and  $\varphi$  the equivalent Doppler shift of the source and absorber.  $\varphi$  is produced by the transverse Doppler shift together with the effect of interest given by Eq. (1). Thus we have

$$\varphi/c = \frac{v^2}{c^2} + 2\gamma \frac{\mathbf{u} \cdot \mathbf{v}}{c^2} \cos(\omega t + \alpha), \quad (3)$$

where  $\omega$  is the angular frequency of the centrifuge and  $\alpha$  is the angle between  $\mathbf{u}$  and the switching light beam which defines the laboratory coordinate system.

The observed quantities are the number of 14.4- and 122-keV  $\gamma$  rays taken in each quadrant for the 8- to 9-minute counting period. Labeling the quadrants by a number  $q$  ( $q=1, 2, 3, 4$ ), we have for the number of 122-keV counts in quadrant  $q$  simply

$$\int_q r_2 dt = \frac{r_2}{\omega} \int_q d\theta, \quad (4)$$

where  $r_2$  is the counting rate for the 122-keV  $\gamma$  rays and  $\theta = \omega t$ . For the number of 14.4-keV counts to 1st order in  $u$ , we have

$$\int_q r dt = \frac{r_1}{\omega} \left[ 1 - \frac{f}{1+s^2} \right] \int_q d\theta + \frac{\gamma u}{v} \frac{8r_1 f}{\omega} \frac{s^2}{[1+s^2]^2} \int_q \cos(\theta + \alpha) d\theta \quad (5)$$

where

$$s = \frac{1}{2} \left( \frac{v}{c} \right)^2 \frac{c}{\Gamma}. \quad (6)$$

The ratio  $R_q$  of the number of 14.4-keV  $\gamma$  rays to 122-

keV  $\gamma$  rays is then

$$R_q = \frac{r_1}{r_2} \left[ 1 - \frac{f}{1+s^2} \right] + \frac{\gamma u r_1}{v r_2} \frac{8fs^2}{[1+s^2]^2} \frac{\int_q \cos(\theta + \alpha) d\theta}{\int_q d\theta}. \quad (7)$$

The expression  $\int_q \cos(\theta + \alpha) d\theta / \int_q d\theta$  was evaluated as though each quadrant was exactly  $90^\circ$ . The error so introduced was considerably below the statistical error due to the finite number of counts in the experiment.

Using the abbreviations

$$A = \frac{r_1}{r_2} \left[ 1 - \frac{f}{1+s^2} \right] \quad (8)$$

and

$$B = \frac{\gamma u r_1}{v r_2} \frac{8fs^2}{[1+s^2]^2} \frac{2}{\pi}, \quad (9)$$

one arrives at the following equations for the four quadrants:

$$R_1 = A + B[-\sin\alpha - \cos\alpha], \quad (10)$$

$$R_2 = A + B[-\cos\alpha + \sin\alpha], \quad (11)$$

$$R_3 = A + B[+\sin\alpha + \cos\alpha], \quad (12)$$

$$R_4 = A + B[+\cos\alpha - \sin\alpha]. \quad (13)$$

Data were taken during the months of October and November in 1961. In analyzing these data, certain readings were eliminated. After the centrifuge had been running for several hours, occasional bursts of noise would occur originating in the centrifuge which was correlated with the angular position of the centrifuge. This would cause one of the channels to record many more pulses than the others. This showed up as a deviation, far outside statistics, from the quadrant ratios 1:1.06:1.06:1.02, which were calculated for each 8-minute period for both the 14.4-keV and 122-keV channels (the quadrant ratio is the ratio of the number of counts in quadrant  $q$  to quadrant 1).

After eliminating the data which did not comply with the quadrant ratio, we have left 536 measurements of  $R_q$  distributed over the four quadrants. Each of the  $R_q$  consisted of an 8- or 9-minute counting period, which yielded 5000–7000 14.4-keV counts and about 100 000 122-keV counts.

For each counting period, a least-squares analysis was made, treating  $A$ ,  $B \sin\alpha$ , and  $B \cos\alpha$  as independent variables. The quantities  $B \sin\alpha$  and  $B \cos\alpha$  were then transformed to yield effective velocities in the north and east directions for each eight or nine minute counting period.

The quantities so obtained were then divided into four groups, according to the time of day when the data was taken. These four groups of numbers, taken together, were then least-squares analyzed to yield three

final numbers: the components of the effective velocity  $\gamma u$  along  $x$ ,  $y$ , and  $z$  axes fixed in space. These axes, defined with respect to the earth's axis of rotation in the vicinity of November 1, 1961, are as follows: The  $z$  axis is parallel to the earth's axis of rotation, and points north; the  $x$  and  $y$  axes lie in the earth's equatorial plane, with the  $x$  axis pointing vertically upward at the equator at the longitude of Princeton (about  $75^\circ$ ) at 12 noon Eastern daylight time, and the  $y$  axis so oriented as to make up a right handed, mutually perpendicular system.

#### IV. RESULTS

When so analyzed, the following components for the effective velocity were obtained:

$$\begin{aligned}\gamma u_x &= -150 \pm 750 \text{ cm/sec,} \\ \gamma u_y &= -150 \pm 900 \text{ cm/sec,} \\ \gamma u_z &= +1340 \pm 900 \text{ cm/sec.}\end{aligned}$$

The errors quoted are standard deviations due to a finite number of counts. The mean square deviation of the  $R_i$  was slightly less than that predicted for the standard deviation from the finite number of counts. The error quoted for  $u_x$  is smaller than that for  $u_y$  and  $u_z$  because more data was taken at the time of day (six hours centered at 6:00 p.m.) when the apparatus was most sensitive to  $u_x$ .

It should be noted that the three components of  $u$  have not actually received equal treatment in the data reduction process. The rotation of the earth has permitted the reduction of systematic effects due to purely instrumental asymmetries in the case of the  $x$  and  $y$  components, but not the  $z$  component since this com-

ponent is parallel to the axis of rotation. Since we suspect that the components of the velocity  $u$  lying in the earth's equatorial plane contain less systematic error, we present as the final result, the component of the effective velocity in the equatorial plane as  $\gamma[u_x^2 + u_y^2]^{1/2} = 220 \pm 840$  cm/sec. The error,  $\pm 840$  cm/sec, quoted for the velocity in the equatorial plane is less than that given for the individual  $x$  and  $y$  components because the quoted errors in the components are not independent.

An estimate of  $\gamma$  can be made if the value for  $u$  were known. It is not unreasonable to set  $[u_x^2 + u_y^2]^{1/2} = 200$  kilometers/sec since the galaxies have random velocities of a few hundred kilometers/sec and the motion of the sun associated with galactic rotation is of the same order.<sup>7</sup> This gives a value of  $\gamma = (1 \pm 4) \times 10^{-5}$ .

The results of this experiment are somewhat better than the principal previous examination of Cedarholm, Bland, Havens, and Townes.<sup>8</sup> These workers were able to place an upper limit of 3000 cm/sec on  $\gamma u$ . It should be pointed out though that these experiments are complementary since one involves a nuclear oscillator and the other an atomic oscillator.

#### ACKNOWLEDGMENTS

This experiment was performed while one of us, K. C. Turner, was a graduate student of Professor R. H. Dicke, who pointed out the possibilities of a measurement using the Mössbauer effect, and suggested the problem.

<sup>8</sup> J. P. Cedarholm, G. F. Bland, B. L. Havens, and C. H. Townes, *Phys. Rev. Letters* **1**, 342 (1958).