GRAVITATIONAL RED-SHIFT IN NUCLEAR RESONANCE

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It is widely considered desirable to check experimentally the view that the frequencies of electromagnetic spectral lines are sensitive to the gravitational potential at the position of the emitting system. The several theories of relativity predict the frequency to be proportional to the gravitational potential. Experiments are proposed to observe the timekeeping of a "clock" based on an atomic or molecular transition, when held aloft in a rocket-launched satellite, relative to a similar one kept on the ground. The frequency ν_h and thus the timekeeping at height h is related to that at the earth's surface ν_0 according to

$$\Delta\nu_h = \nu_h - \nu_0 = \nu_0 gh/c^2(1+h/R) \approx \nu_0 h \times (1.09\times10^{-18}),$$

where R is the radius of the earth and h is the altitude measured in cm. Very high accuracy is required of the clocks even with the altitudes available with artificial satellites. Although several ways of obtaining the necessary frequency stability look promising, it would be simpler if a way could be found to do the experiment between fixed terrestrial points. In particular, if an accuracy could be obtained allowing the measurement of the shift between points differing as little as one to ten kilometers in altitude, the experiment could be performed between a mountain and a valley, in a mineshaft, or in a borehole.

Recently Mössbauer has discovered[1] a new aspect of the emission and scattering of γ rays by nuclei in solids. A certain fraction f of γ rays of the nuclei of a solid are emitted without individual nuclear recoil. Instead, the recoil momentum is delivered to the crystal lattice as a whole resulting in negligible Doppler shift. Such γ rays are in resonance with nuclei similarly bound in a lattice and a similar fraction f of the electromagnetic resonant cross section

$$\sigma_R = 2\pi\lambda^2\left(\frac{2I_e+1}{2I_g+1}\right)\frac{1}{1+\alpha},$$

where I_e and I_g are the spins of the emitting and the ground states, respectively, and α is the internal conversion coefficient, pertains to the scattering. Calculations based on the Debye model of lattice vibrations yield for f at temperatures T much less than the Debye temperature θ_D

$$f = \exp\left\{-\tfrac{3}{2}\frac{E_\gamma^{\,2}}{2Mc^2k\theta_D}\left[1+\tfrac{2}{3}\left(\frac{\pi T}{\theta_D}\right)^2\right]\right\},$$

where E_γ is the energy of the γ ray, M is the nuclear mass, and k is Boltzmann's constant. The factor $(E_\gamma^{\,2}/2Mc^2k\theta_D)$ is the ratio of the recoil energy that would be taken up by the free nucleus to $k\theta_D$. For γ rays much above the 129 kev employed by Mössbauer the factor f becomes very small even at absolute zero.

The most striking evidence for the existence of this effect is the observation that the attenuation of the 129-kev gamma rays of Ir^{191} in passing through an iridium absorber is reduced if the source is moved. The speed required to reduce the part of the attenuation caused by resonant scattering to one-half its maximum value was found to be approximately 1.5 cm/sec. From this a half-life of the excited state is derived to be 0.1 mμsec. Others have repeated this experiment, and extended it to helium temperatures.[2,3] One other case is reported,[3] that of W^{182} wherein a half-life of 0.6 mμsec is inferred by the Doppler width of the resonance. This is half the accepted lifetime as measured by delay coincidence techniques. It is not clear whether this discrepancy represents a limit of the technique or whether it is largely an instrumental problem, as the authors suggest, enhanced by the complex array of other γ rays in the Ta^{182} source. Of course, as has been suggested, one should expect to see effects caused by hyperfine structure in these spectra when lifetimes are long enough to allow them to be important. All the effects discussed in connection with the directional correlation of cascade γ rays should have an influence. For example, it would seem desirable to use a source that has a good chance of being in a normal lattice site and electronic state at the time of emission of the final γ ray in question. One could have serious aftereffects from β decays, from prior emission of high-energy γ rays, or from electron captures as well as broadening from imperfections in the crystal lattice or short spin-lattice relaxation.

Even if the further development of the technique does not yield still narrower resonances, those already observed have fractional widths in frequency well below those of all the reference lines yet proposed for "atomic clocks." If the scattering is reduced to one-half its maximum by relative motion of the source and scatterer with velocity v, the Q, the ratio of the frequency to the full width at half-height of the resonance line being observed, is just $c/2v$. In the case of Mössbauer's experiment Q is about 1×10^{10} and in the case of W^{182} it is 7×10^{10}. In general $Q = 1.10E_\gamma(\mathrm{Mev})\,\tau_{1/2}(\mathrm{m\mu sec})\times10^{12}$.

A measurement of the gravitational red shift could be performed by transmitting γ rays from a source to a scatterer at an altitude different by h and by observing what relative velocity yields maximum scattering. For the predicted shift to be a full half-width of the line, the altitude difference h must be $h_{1/2} = [4.18/E_\gamma(\mathrm{Mev})\,\tau_{1/2}(\mathrm{m\mu sec})]$ km. Thus, for the width reported for W^{182}, 66 km difference of height would be required.

It is exciting to speculate about the possibilities opened up if cases of even less breadth can be found. For example, Fe^{57}, for which $E_\gamma = 0.0144$ Mev and $\tau_{1/2} = 100$ mμsec, would require only 2.9 km separation were it to yield its natural breadth. Another example might be Zn^{67} with an excited level at 0.093 Mev, of half-life 9400 mμsec. For this, if the natural breadth were obtained, $h_{1/2}$ would be 4.74 meters. This possibility represents a considerable extrapolation from present data. We are undertaking to examine these and other isotopes in various environments with the aim of selecting an isotope suitable for a gravitational experiment. Among other things equivalence of or absence of hyperfine structures in the sources and scatterers would be desirable.

Obviously one of the difficulties with large separations between source and scatterer arises from the inverse-square law of intensity. As a consequence of the participation of a large number of identical nuclei in an individual recoil-free scattering process, one anticipates the existence of intense Bragg diffraction from thin crystals. Thus one has the possibility of some degree of focusing with bent crystals. Furthermore one may use the Bragg reflection from thin crystals to separate the γ rays emitted without recoil from all others. In this way irrelevant background γ rays could be eliminated from the detector.

Total external reflection of low-energy γ rays at grazing angles of incidence offers a possibility of a "light-pipe" to increase the effective solid angle that the scatterer subtends at the source. Within the limits set by the small angle of total reflection, this pipe need not be optically straight.[4]

The fixed baseline used for an experiment of this type reduces unwanted Doppler shifts to only those resulting from thermal, seismic, or similar disturbances. To equal the predicted gravitational shift the fractional change required in the height difference is 3.27×10^{-8} per second. Perturbing effects must be kept well below this value but this is also true for the other methods of measuring the red shift. Relative motion could be separated from the red shift by simultaneous observations of beams traveling in both directions.

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[1] R. L. Mössbauer, Z. Physik 151, 124 (1958); Naturwissenschaften 45, 538 (1958); Z. Naturforsch. 14a, 211 (1959).

[2] Craig, Dash, McGuire, Nagle, and Reiswig, Phys. Rev. Letters 3, 221 (1959).

[3] Lee, Meyer-Schutzmeister, Schiffer, and Vincent, Phys. Rev. Letters 3, 223 (1959).

[4] We wish to thank E. M. Purcell for this suggestion.

RESONANT ABSORPTION OF THE 14.4-kev γ RAY FROM 0.10-μsec Fe^{57}†

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We wish to report experiments on the resonant scattering of a recoil-free γ ray[1] which appears to be sharp enough to be used for an experimental determination of the "gravitational red-shift," as proposed in our recent note.[2]

Our initial work has been with the 14.4-kev γ ray of 0.10-microsecond Fe^{57}. Although we first worked with a source of the 270-day parent Co^{57} extracted from an iron foil kindly irradiated for us with the deuteron beam at the MIT cyclotron, an intense background of Co^{56} rendered that source poor for our purposes. Most of our work has been with Co^{57} obtained commercially.

About 50 microcuries of Co^{57} was electroplated together with added iron onto one face of a one-centimeter square of thin Armco iron.

Initial studies of the absorption of a 0.001-in. thick iron foil at temperatures of liquid nitrogen and at room temperature indicated that the desired resonant absorption was present, that the ratio of about 3:2 of the magnitudes at the two temperatures was in reasonable agreement with theory, but that the absorption was small and the line was broad compared to its natural breadth. In these experiments crude 60-cycle magnetic vibrators were used to destroy resonance and to observe the line widths. The increase in intensity available by the use of low temperatures is so small that we henceforth operated at room temperature, in the interest of stability.

The supposition that the hyperfine structure splittings of the ferromagnetic source and absorber were not fully equivalent led us to try heat treatments of the source and absorber foils. A dramatic improvement resulted after the source had been held at 950°C for an hour, which treatment was expected to result in diffusion of the cobalt, if it were retained on the surface initially, into the lattice a mean distance of about 3×10^{-5} cm, or 1000 lattice spaces. We have discovered that there was probably about 0.1 mg of stable cobalt carrier present in our source which may be important in making such treatment necessary. With the absorber foil first used, which was found to contain 3% silicon, replaced by one rolled from Armco iron to 11.5 mg/cm^2 thickness, and annealed, the line shown in Fig. 1 was obtained.

These data represent counts above background of the 14.4-kev γ ray as made with a scintillation spectrometer, using a 0.040-in. by $\frac{3}{4}$-in. NaI(Tl) crystal[3] and a single-channel pulse-height analyzer set to accept most of the full-energy peak.

All but about fifteen percent of the counts in the channel arose from the γ ray, from evidence obtained with absorbing foils. Each point is based on about 2.3×10^5 counts shared equally between conditions with the source fixed and with it moving toward and away from the absorber at constant speed. The motion was produced by a moving-coil magnetic transducer on which the source was cemented and which was supplied with a ten-cycle-per-second triangular waveform of current of adjustable amplitude.

The resonant absorption is halved by a Doppler speed of $|v_{1/2}|=0.017$ cm/sec (which, incidentally,

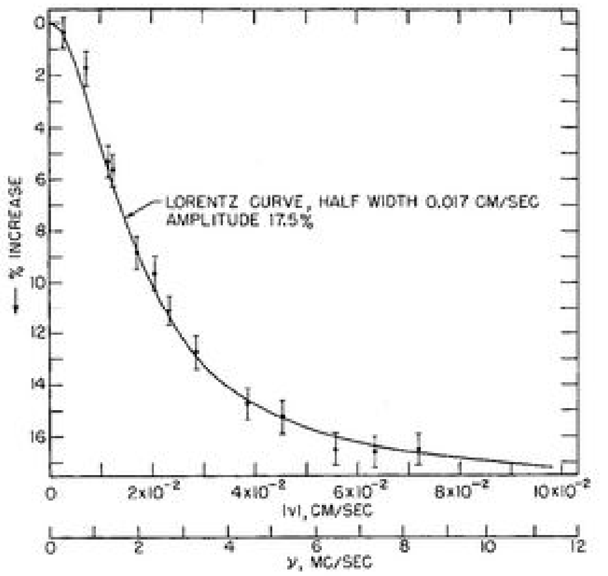

FIG. 1. The percentage increase in intensity of the 14.4-kev γ ray as a function of the absolute value of the velocity of the source. A velocity of 0.01 cm/sec corresponds to a frequency displacement of 1.16 Mc/sec.

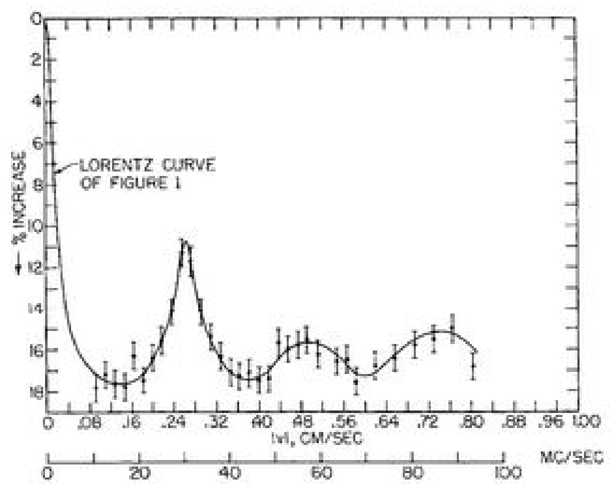

FIG. 2. The increase in intensity for velocities large enough to show hyperfine structure. There appear to be three principal satellites which probably correspond to the hyperfine structure interaction of the 0.10-μsec metastable, spin 3/2, nucleus with the internal effective magnetic field.

corresponds to only 0.0009 cm peak-peak amplitude at 10 cps). This is to be compared to 0.0095 cm/sec to be expected from energy and lifetime considerations for a "thin" absorber if no broadening exists other than from the lifetime. We are not certain that our initial difficulties with effects from the surface or the cobalt carrier are entirely eliminated and we are inclined to attribute the residual broadening by a factor of approximately two at least partly to such causes.

Our experimental width at half-height is approximately 10^{-12} times the velocity of light and represents a 100-fold reduction compared to the example reported by Mössbauer[1] and others.[4,5]

It is known that hyperfine splitting exists in ferromagnetic metals. The 14.4-kev γ ray is thought to be a magnetic dipolar transition and, with an excited state spin of 3/2 and ground-state spin of 1/2, the radiation ought to consist of six hyperfine components and the absorber should have a matched set of six lines. With appropriate Doppler speeds at the source, displacements should be found that produce partial overlaps of the lines, yielding a form of hyperfine satellites. In a limited study, we have found some structure we believe to be of this type. The results are shown in Fig. 2. We do not wish to take the space here to give the straightforward theoretical description of the hyperfine structure which we will do in a more complete report later. There appear to be three satellite lines, the innermost occurring at a speed $|v| = 0.26$ cm/sec, corresponding to a frequency shift of 30.5 Mc/sec. The g factor of the ground state of Fe^{57} is known to be small,[6,7] although 20 Mc/sec of splitting has been observed in stable Fe^{57} as an impurity in silicon.[8] If the ground-state splitting is negligible—or contributes only to the line widths observed—the three satellite lines of integrated intensities 3/4, 1/2, and 1/4 times that of the center line would fall at Doppler frequencies equal to one, two, and three times the Larmor frequency of the spin 3/2 excited state in the effective classical magnetic field at the nucleus in the ferromagnet. According to this interpretation the Larmor frequency of the excited state is about 30 Mc/sec and its magnetic moment is large compared to that of the ground state. The breadth of the satellites may be caused in part by inconstancy of the speed of the transducer during a modulation cycle. We are engaged in improving this as well as in processing a source of much larger activity in the interest of gathering more detailed data. Until we know the details of the hyperfine structure more fully, we cannot make an exact comparison of the magnitude of the scattering with theory because the cross sections depend upon the degree of resolution of the lines.

We are now confident that we can perform the gravitational experiment inside the laboratory using this γ ray from Fe^{57}. With the line width we have found, a measurable shift of the line center is predicted by the principle of equivalence[9] for the height difference available to us inside this laboratory.

With a source of limited strength, statistical fluctuations decrease the definition of the line, owing to decreased counting rates, in a way that just compensates, assuming the inverse square law to apply over the path, the linear increase in shift as the height difference between source and absorber is increased. Use of very large vertical distances do not appear to offer much increase in precision.

[†] Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

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[3] We wish to thank Professor L. Grodzins of Massachusetts Institute of Technology for the loan of this crystal.

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VARIATION WITH TEMPERATURE OF THE ENERGY OF RECOIL-FREE GAMMA RAYS FROM SOLIDS*

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The 14.4-kev γ ray emitted without recoil by 0.1-μsec Fe^{57} in metallic iron[1-4] excited great interest as the most precisely defined electromagnetic frequency yet discovered. It may be adequately well defined to allow measurement of the influence of a gravitational potential on frequency[5] and of other small effects hitherto beyond the sensitivity available in the laboratory. As a preliminary step in the operation of an experimental system designed to measure the gravitational effect, we have been making tests to find out whether other influences than the one intended might lead to systematic errors by introducing important frequency shifts not taken into account.

So far the largest such effect found is that of temperature. That temperature should influence the frequency exactly as we observe is very simply explained. Thermally excited vibrations cause little broadening through first order Doppler effect under the conditions obtaining in the solid because the value of any component of the nuclear velocity averages very nearly to zero over the nuclear lifetime. The precision of the γ ray of Fe^{57} requires the second order Doppler effect also to be considered. A shift to lower frequency with increased temperature results from this because the also well-defined average of the square of the velocity of the particle increases in direct proportion to the average kinetic energy. As a consequence one would expect a temperature coefficient of frequency in a homogeneous solid,

$$(\partial\nu/\partial T) = -\nu C_L/2Mc^2,$$

where C_L is the specific heat of the lattice and M is the gram atomic weight of iron. In the high-temperature classical limit where $C_L = 3R$,

$$(\partial\nu/\partial T)_{T\to\infty} = -2.44\times10^{-15}\nu \text{ per °K.}$$

At lower temperatures one would expect a coefficient reduced by the value of the appropriate normalized Debye specific heat function. For iron, at 300°K one should find about 0.9 times, and at 80°K about 0.3 times, the above classical value.

The temperature dependence has been measured by counting the γ rays from our 0.4-curie Co^{57} source transmitted through enriched Fe^{57} absorbing films (0.6 mg Fe^{57}/cm^2). The Co^{57} of the source is distributed in about 3×10^{-5} cm thickness below the surface of a 2-in. diameter iron disk, made in the manner described earlier.[1] Small frequency shifts that result when the source and absorber are held at different temperatures were measured by using a transducer to move the source sinusoidally at ten cps toward and away from the absorber at a peak speed of about 0.01 cm/sec. A gate pulse and mercury relays were used to make one counter record during 25 milliseconds of the modulation period symmetrically disposed about the time of maximum velocity toward the absorber. Another counter recorded the corresponding counts with the source going away from the absorber. The difference of the counts in the two registers should be proportional to the relative frequency shift of the absorber and source for shifts small compared to the line width. Quantitative knowledge of the parameters of the system that are involved in determining the constant of proportionality is rendered unnecessary by adding through a clock-driven hydraulic system a continuous relative motion of 6.3×10^{-4} cm/sec directed oppositely during each of the two halves of the time for a given datum point. In this way the sensitivity to frequency shift originating in the Doppler effect is measured simultaneously with the shift sought. The algebraic sum of the counting rate differences for the two halves of the run are proportional to the shift and the difference to the sensitivity.

The shift at liquid nitrogen relative to room temperature is comparable to the line width and for that point the two counting rates were recorded at a series of values of the sinusoidal modulation amplitude. From these a value of the shift and of the apparent line width could be obtained although difficulties of calibration under the conditions of operation have contributed strongly to the uncertainties. There is evidence that the line appears to broaden with such a temperature difference by perhaps a factor of 2.3 which might be evidence that the hyperfine structure splittings are temperature sensitive to some extent, as must be expected.

The data are plotted in Fig. 1. A solid line representing the effect expected with a Debye temperature of 420°K is also drawn. The agreement can be regarded as an experimental demonstration of the second order Doppler effect using thermal velocities rather than a centrifuge. It might be remarked that crystalline anisotropy might make this source of high velocities useful for experiments to the end of detecting such spatial anisotropies as might accompany ether drift or an inertial frame.

The temperature sensitivity at room temperature [experimentally $(-2.09\pm0.24)\times10^{-15}$ per degree C, theoretically -2.21×10^{-15} per degree C] is highly relevant to the interpretation of data from our experiment on the effect of gravitational potential. A temperature difference of 1°C between the top and the bottom of our 22-meter tower would result in a shift about equal to that predicted by the principle of equivalence. For smaller height differences correspondingly smaller temperature differences would be required. It is now clear that correction for or control of the temperature difference and perhaps other parameters must be included in the instrumentation of experiments intending to utilize the extreme frequency discrimination available with gamma rays of this type.

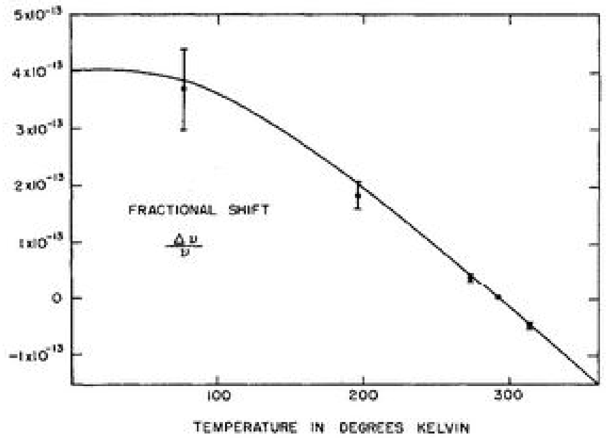

FIG. 1. Fractional shift of energy of 14.4-kev gamma-ray absorption of Fe^{57} vs absolute temperature of the metal. The solid line is derived from assuming a Debye temperature of 420°K.

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APPARENT WEIGHT OF PHOTONS*

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As we proposed a few months ago,[1] we have now measured the effect, originally hypothesized by Einstein,[2] of gravitational potential on the apparent frequency of electromagnetic radiation by using the sharply defined energy of recoil-free γ rays emitted and absorbed in solids, as discovered by Mössbauer.[3] We have already reported[4] a detailed study of the shape and width of the line obtained at room temperature for the 14.4-kev, 0.1-microsecond level in Fe^{57}. Particular attention was paid to finding the conditions required to obtain a narrow line. We found that the line had a Lorentzian shape with a fractional full-width at half-height of 1.13×10^{-12} when the source was carefully prepared according to a prescription developed from experience. We have also investigated the 93-kev, 9.4-microsecond level of Zn^{67} at liquid helium and liquid nitrogen temperatures using several combinations of source and absorber environment, but have not observed a usable resonant absorption. That work will be reported later. The fractional width and intensity of the absorption in Fe^{57} seemed sufficient to measure the gravitational effect in the laboratory.

As a preliminary, we sought possible sources of systematic error that would interfere with measurements of small changes in frequency using this medium. Early in our development of the instrumentation necessary for this experiment, we concluded that there were asymmetries in, or frequency differences between, the lines of given combinations of source and absorber which vary from one combination to another. Thus it is absolutely necessary to measure a change in the relative frequency that is produced by the perturbation being studied. Observation of a frequency difference between a given source and absorber cannot be uniquely attributed to this perturbation. More recently, we have discovered and explained a variation of frequency with temperature of either the source or absorber.[5] We conclude that the temperature difference between the source and absorber must be accurately known and its effect considered before any meaning can be extracted from even a change observed when the perturbation is altered.

The basic elements of the apparatus finally developed to measure the gravitational shift in frequency were a carefully prepared source containing 0.4 curie of 270-day Co^{57}, and a carefully prepared, rigidly supported, iron film absorber. Using the results of our initial experiment, we requested the Nuclear Science and Engineering Corporation to repurify their nickel cyclotron target by ion exchange to reduce cobalt carrier. Following the bombardment, in a special run in the high-energy proton beam of the high-current cyclotron at the Oak Ridge National Laboratory, they electroplated the separated Co^{57} onto one side of a 2-in. diameter, 0.005-in. thick disk of Armco iron according to our prescription. After this disk was received, it was heated to 900°-1000°C for one hour in a hydrogen atmosphere[6] to diffuse the cobalt into the iron foil about 3×10^{-5} cm.

The absorber made by Nuclear Metals Inc., was composed of seven separate units. Each unit consisted of about 80 mg of iron, enriched in Fe^{57} to 31.9%, electroplated onto a polished side of a 3-in. diameter, 0.040-in. thick disk of beryllium. The electroplating technique required considerable development to produce films with absorption lines of width and strength that satisfied our tests. The films finally accepted, resonantly absorbed about 1/3 the recoil-free γ rays from our source. Each unit of the absorber was mounted over the 0.001-in. Al window of a 3 in. × 1/4 in. NaI(Tl) scintillation crystal integrally mounted on a Dumont 6363 multiplier phototube. The multiplier supply voltages were separately adjusted to equalize their conversion gains, and their outputs were mixed.

The required stable vertical baseline was conveniently obtained in the enclosed, isolated tower of the Jefferson Physical Laboratory.[7] A statistical argument suggests that the precision of a measurement of the gravitational frequency shift should be independent of the height. Instrumental instability but more significantly the sources of systematic error mentioned above are less critical compared to the larger fractional shifts obtained with an increased height. Our net operating baseline of 74 feet required only conveniently realizable control over these sources of error.

The absorption of the 14.4-kev γ ray by air in the path was reduced by running a 16-in. diameter, cylindrical, Mylar bag with thin end windows and filled with helium through most of the distance between source and absorber. To sweep out small amounts of air diffusing into the bag, the helium was kept flowing through it at a rate of about 30 liters/hr.

The over-all experiment is described by the block diagram of Fig. 1. The source was moved sinusoidally by either a ferroelectric or a moving-coil magnetic transducer. During the quarter of the modulation cycle centered about the time of maximum velocity the pulses from the scintillation spectrometer, adjusted to select the 14.4-kev γ-ray line, were fed into one scaler while, during the opposite quarter cycle, they were fed into another. The difference in counts recorded was a measure of the asymmetry in, or frequency-shift between, the emission and absorption lines. As a precaution the relative phase of the gating pulses and the sinusoidal modulation were displayed continuously. The data were found to be insensitive to phase changes much larger than the drifts of phase observed.

A completely duplicate system of electronics, controlled by the same gating pulses, recorded

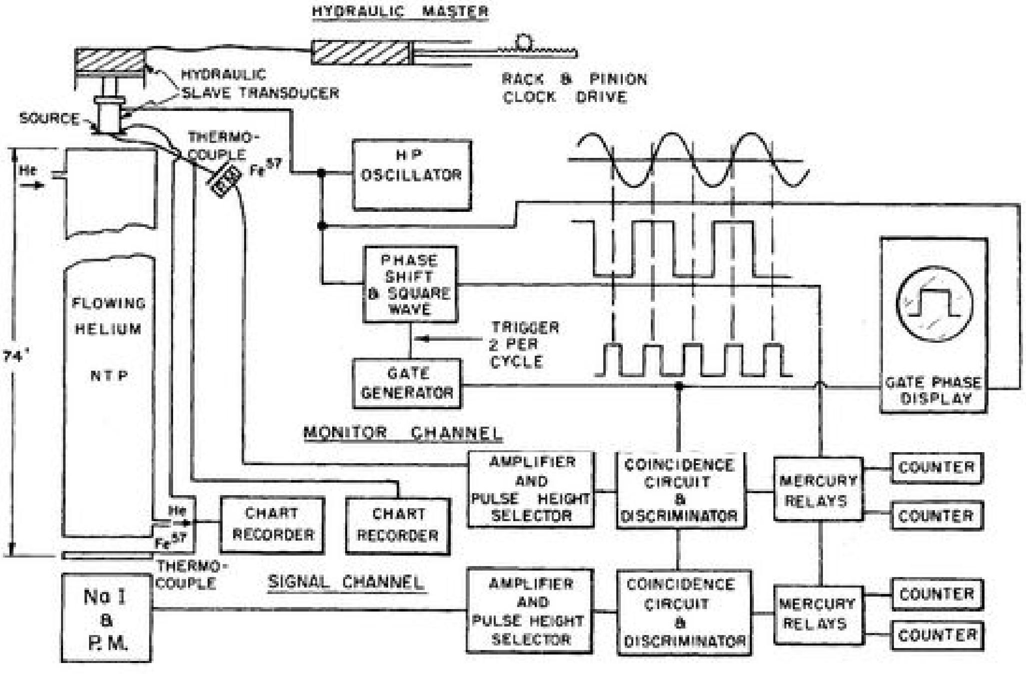

FIG. 1. A block diagram of the over-all experimental arrangement. The source and absorber-detector units were frequently interchanged. Sometimes a ferroelectric and sometimes a moving-coil magnetic transducer was used with frequencies ranging from 10 to 50 cps.

data from a counter having a 1-in. diameter, 0.015-in. thick NaI(Tl) scintillation crystal covered by an absorber similar to the main absorber. This absorber and crystal unit was mounted to see the source from only three feet away. This monitor channel measured the stability of the over-all modulation system, and, because of its higher counting rate, had a smaller statistical uncertainty.

The relation between the counting rate difference and relative frequency shifts between the emission and absorption lines was measured directly by adding a Doppler shift several times the size of the gravitational shift to the emission line. The necessary constant velocity was introduced by coupling a hydraulic cylinder of large bore carrying the transducer and source to a master cylinder of small bore connected to a rack-and-pinion driven by a clock.

Combining data from two periods having Doppler shifts of equal magnitude, but opposite sign, allowed measurement of both sensitivity and relative frequency shift. Because no sacrifice of valuable data resulted, the sensitivity was calibrated about 1/3 of the operating time which was as often as convenient without recording the data automatically. In this way we were able to eliminate errors due to drifts in sensitivity such as would be anticipated from gain or discriminator drift, changes in background, or changes in modulation swing.

The second order Doppler shift resulting from lattice vibrations required that the temperature difference between the source and absorber be controlled or monitored. A difference of 1°C would produce a shift as large as that sought, so the potential difference of a thermocouple with one junction at the source and the other at the main absorber was recorded. An identical system was provided for the monitor channel. The recorded temperature data were integrated over a counting period, and the average determined to 0.03°C. The temperature coefficient of frequency which we have used to correct the data, was calculated from the specific heat of a lattice having a Debye temperature of 420°K. Although at room temperature this coefficient is but weakly dependent on the Debye temperature, residual error in the correction for, or control of, the temperature difference limits the ability to measure frequency shifts and favors the use of a large height difference for the gravitational experiment.

Data typical of those collected are shown in Table I. The right-hand column is the data after correction for temperature difference. All data are expressed as fractional frequency shift $\times 10^{15}$. The difference of the shift seen with γ rays rising and that with γ rays falling should be the result of gravity. The average for the two directions of travel should measure an effective shift of other origin, and this is about four times the difference between the shifts. We confirmed that this shift was an inherent property of the particular combination of source and absorber by measuring the shift for each absorber unit in turn, with temperature correction, when it was six inches from the source. Although this test was not exact because only about half the area of each absorber was involved, the weighted mean shift from this test for the combination of all absorber units agreed well with that observed in the main experiment. The individual fractional frequency shifts found for these, for the monitor absorber, as well as for a 11.7-mg/cm^2 Armco iron foil, are displayed in Table II. The considerable variation among them is as striking as the size of the weighted mean shift. Such shifts could result from differences in a range of about 11% in effective Debye temperature through producing differences in net second order Doppler effect. Other explanations based on hyperfine structure including electric quadrupole interactions are also plausible. Although heat treatment might be expected to change these shifts for the iron-plated beryllium absorbers, experience showed that the line width was materially increased by such treatment, probably owing to interdiffusion. The presence of a significant shift for even the Armco foil relative to the source, both of which had received heat treatments, suggests that it is unlikely one would have, without test, a shift of this sort smaller than the gravitational effect expected in even our "two-way" baseline of 148 feet. The apparently fortuitous smallness of the shift of the monitor absorber relative to our source corresponds to the shift expected for about 30 feet of height difference.

Recently Cranshaw, Schiffer, and Whitehead[6] claimed to have measured the gravitational shift using the γ ray of Fe^{57}. They state that they believe their 43% statistical uncertainty represents the major error. Two much larger sources of error apparently have not been considered: (1) the temperature difference between the source and absorber, and (2) the frequency difference inherent in a given combination of source and absorber. From the above discussion, only 0.6°C of temperature difference would produce a shift

Table I. Data from the first four days of counting. The data are expressed as fractional frequency differences between source and absorber multiplied by 10^{15}, as derived from the appropriate sensitivity calibration. The negative signs mean that the γ ray has a frequency lower than the frequency of maximum absorption at the absorber.

Period	Shift observed	Temperature correction	Net shift
	Source at bottom		
Feb. 22, 5 p.m.	-11.5 ± 3.0	-9.2	-20.7 ± 3.0
	-16.4 ± 2.2[a]	-5.9	-22.3 ± 2.2
	-13.8 ± 1.3	-5.3	-19.1 ± 1.3
	-11.9 ± 2.1[a]	-8.0	-19.9 ± 2.1
	-8.7 ± 2.0[a]	-10.5	-19.2 ± 2.0
Feb. 23, 10 p.m.	-10.5 ± 2.0	-10.6	-21.0 ± 2.0
			Weighted average = -19.7 ± 0.8
	Source at top		
Feb. 24, 0 a.m.	-12.0 ± 4.1	-8.6	-20.6 ± 4.1
	-5.7 ± 1.4	-9.6	-15.3 ± 1.4
	-7.4 ± 2.1[a]	-7.4	-14.8 ± 2.1
	-6.5 ± 2.1[a]	-5.8	-12.3 ± 2.1
	-13.9 ± 3.1[a]	-7.5	-21.4 ± 3.1
	-6.6 ± 3.0	-5.7	-12.3 ± 3.0
Feb. 25, 6 p.m.	-6.5 ± 2.0[a]	-8.9	-15.4 ± 2.0
	-10.0 ± 2.6	-7.9	-17.9 ± 2.6
			Weighted average = -15.5 ± 0.8
			Mean shift = -17.6 ± 0.6
			Difference of averages = -4.2 ± 1.1

[a] These data were taken simultaneously with a sensitivity calibration.

Table II. Data on asymmetries of various absorbers in apparent fractional frequency shift multiplied by 10^{15}. In the third column we tabulate the Debye temperature increase of the absorber above that of the source which could account for the shift.

Absorber	$(\Delta\nu/\nu)\times 10^{15}$	$\Delta\theta_D$ in °K
No. 1	-8.4 ± 2.5	+15 ± 4
No. 2	-24 ± 3.5	+41 ± 6
No. 3	-28 ± 3.5	+48 ± 6
No. 4	-19 ± 3.5	+33 ± 6
No. 5	-24 ± 3.5	+41 ± 6
No. 6	-17 ± 2.5	+29 ± 4
No. 7	-19 ± 3.5	+33 ± 6
Weighted mean of No. 1-No. 7	-19 ± 3.0	+33 ± 5
Monitor absorber	+0.55 ± 0.15	-0.95 ± 0.26
Armco foil	+10 ± 3.5	-17 ± 6

as large as the whole effect observed. Their additional experiment at the shortened height difference of three meters does not, without concomitant temperature data, resolve the question of inherent frequency difference. Their stated disappointment with the over-all line width observed would seem to add to the probability of existence of such a shift. They mention this broadening in connection with its possible influence on the sensitivity, derived rather than measured, owing to a departure from Lorentzian shape. Clearly such a departure is even more important in allowing asymmetry.

Our experience shows that no conclusion can be drawn from the experiment of Cranshaw et al.

If the frequency-shift inherent in our source-absorber combination is not affected by inversion of the relative positions, the difference between shifts observed with rising and falling γ rays measures the effect of gravity. All data collected since recognizing the need for temperature correction, yield a net fractional shift, $-(5.13 \pm 0.51) \times 10^{-15}$. The error assigned is the rms statistical deviation including that of independent sensitivity calibrations taken as representative of their respective periods of operation. The shift observed agrees with -4.92×10^{-15}, the predicted gravitational shift for this "two-way" height difference.

Expressed in this unit, the result is

$$(\Delta\nu)_{\text{exp}}/(\Delta\nu)_{\text{theor}} = +1.05 \pm 0.10,$$

where the plus sign indicates that the frequency increases in falling, as expected.

These data were collected in about 10 days of operation. We expect to continue counting with some improvements in sensitivity, and to reduce the statistical uncertainty about fourfold. With our present experimental arrangement this should result in a comparable reduction in error in the measurement since we believe we can take adequate steps to avoid systematic errors on the resulting scale. A higher baseline or possibly a narrower γ ray would seem to be required to extend the precision by a factor much larger than this.

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[5] R. V. Pound and G. A. Rebka, Jr., Phys. Rev. Letters 4, 274 (1960).

[6] We wish to thank Mr. F. Rosebury of the Research Laboratory of Electronics, Massachusetts Institute of Technology, for providing his facilities for this treatment.

[7] See E. H. Hall, Phys. Rev. 17, 245 (1903), first paragraph.

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