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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

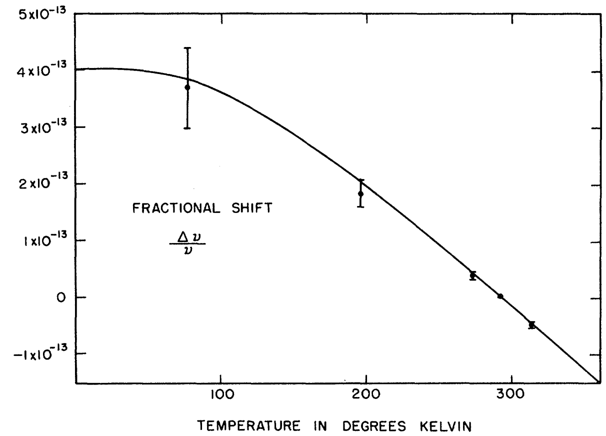

FIG. 1. Fractional shift of energy of 14.4-kev gamma-ray absorption of Fe^{57} vs absolute temperature of the metal. The solid line is derived from assuming a Debye temperature of 420°K.

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.

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