Expressed in this unit, the result is

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

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.

We wish to express deep appreciation for the generosity, encouragement, and assistance with details of the experiment accorded us by our colleagues and the entire technical staff of these laboratories during the three months we have been preoccupied with it.

*Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission and by a grant from the Higgins Scientific Trust.

[1]R. V. Pound and G. A. Rebka, Jr., Phys. Rev. Letters 3, 439 (1959).

[2]A. Einstein, Ann. Physik 35, 898 (1911).

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

[4]R. V. Pound and G. A. Rebka, Jr., Phys. Rev. Letters 3, 554 (1959).

[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.

[8]T. E. Cranshaw, J. P. Schiffer, and A. B. Whitehead, Phys. Rev. Letters 4, 163 (1960).

TEMPERATURE-DEPENDENT SHIFT OF γ RAYS EMITTED BY A SOLID

B. D. Josephson
Trinity College, Cambridge, England
(Received March 11, 1960)

Recent experiments by Mössbauer[1] have shown that when low-energy γ rays are emitted from nuclei in a solid a certain proportion of them are unaffected by the Doppler effect. It is the purpose of this Letter to show that they are nevertheless subject to a temperature-dependent shift to lower energy which can be attributed to the relativistic time dilatation caused by the motion of the nuclei.

Let us regard the solid as a system of interacting atoms with the Hamiltonian

$$H = \sum p_i^2/2m_i + V(r_1, r_2, \cdots).$$

The Mössbauer effect is due to those processes in which the phonon occupation numbers do not change. It might appear that in such cases the energy of the solid is unaltered, but this is not so, as the nucleus which emits the γ ray changes its mass, and this affects the lattice vibrations. Suppose the nucleus of the ith atom emits a γ ray of energy E, its mass changing by $\delta m_i = -E/c^2$.

The change in energy, δE, of the solid is given by

$$\delta E = \langle \Delta H \rangle = \delta \langle p_i^2/2m_i \rangle = -\delta m_i \langle p_i^2/2m_i^2 \rangle$$
$$= (\delta m_i/m_i)T_i = (E/m_i c^2)T_i,$$

where T_i is the expectation value of the kinetic energy of the ith atom. The energy of the γ ray must accordingly be reduced by δE so there is a shift of relative magnitude $\delta E/E = T_i/m_i c^2$. The same formula can be deduced by regarding the shift as due to a relativistic time dilatation.

To estimate T_i we make the following assumptions: (i) The atoms all have the same mass, and the kinetic energy is equally distributed among them. (ii) The kinetic energy is half the total lattice energy, i.e., we assume that the forces coupling the atoms are harmonic. Under these assumptions $T_i/m_i = \frac{1}{2}U$, where U is the lattice energy per unit mass. The relative shift is thus given by $\delta E/E = U/2c^2$. For Fe at 300°K this has the value 8×10^{-13}. Clearly a compensating shift would occur for absorption provided source and absorber were identical and at the same temperature. A small difference in temperature between source and absorber leads to a relative shift per degree given by $\delta E/E = C_p/2c^2$ where C_p is the specific heat. For Fe at 300°K this is 2.2×10^{-15}/°K. This is sufficient for it to be necessary to take it into account in accurate experiments using the resonance absorption of γ rays, such as those to measure the gravitational red shift.[2,3]

I would like to thank Dr. Ziman, Professor O. R. Frisch, and Dr. W. Marshall for helpful discussions.

[1]R. L. Mössbauer, Z. Physik 151, 124 (1958).
[2]R. V. Pound and G. A. Rebka, Phys. Rev. Letters 3, 554 (1959).
[3]T. E. Cranshaw, J. P. Schiffer, and A. B. Whitehead, Phys. Rev. Letters 4, 163 (1960).

UPPER LIMIT FOR THE ANISOTROPY OF INERTIAL MASS FROM NUCLEAR RESONANCE EXPERIMENTS*

V. W. Hughes, H. G. Robinson, and V. Beltran-Lopez
Gibbs Laboratory, Yale University, New Haven, Connecticut
(Received March 2, 1960)

Mach's principle states that the inertial mass of a body is determined by the total distribution of matter in the universe; if the matter distribution is not isotropic, it is conceivable that the mass of a body depends on its direction of acceleration and is a tensor rather than a scalar quantity. Thus the matter in our galaxy is not distributed isotropically with respect to the earth, and hence the mass of a body on the earth may depend on the direction of its acceleration with respect to the direction towards the center of our galaxy. Cocconi and Salpeter[1] have proposed that the total inertial mass of a body on the earth be considered the sum of an isotropic part m and an anisotropic part Δm, and that the contribution to the mass of a body on the earth due to a mass $\mathfrak{M}$ a distance r away from the body is proportional to $\mathfrak{M}/r^\nu$ $(0 \leq \nu \leq 1)$. The ratio of Δm, due to a mass $\mathfrak{M}$ a distance r away, to m, due to the total mass in the universe, is

$$\frac{\Delta m}{m} = \frac{\mathfrak{M}}{r^\nu}\frac{3-\nu}{4\pi\rho R^{(3-\nu)}}, \tag{1}$$

in which ρ = average density of matter in the universe (10^{-29} g/cm^3) and R = radius of the universe (3×10^{27} cm).[2] If Δm is ascribed to our own galaxy, then $r = 2.5\times10^{22}$ cm and $\mathfrak{M} = 3\times10^{44}$ g, where the total mass of the galaxy is considered concentrated at its center. Hence for $\nu = 1$, $\Delta m/m = 2\times10^{-5}$ and for $\nu = 0$, $\Delta m/m = 3\times10^{-10}$.

Cocconi and Salpeter have suggested several experiments to test for this anisotropy of mass based on the observation that the contribution to the binding energy of a particle in a Coulomb potential due to the anisotropic mass term Δm is

$$\Delta E = (\Delta m/m)\overline{T}\,\overline{P}_2(\cos\theta). \tag{2}$$

Here $\overline{T}$ is the average kinetic energy of the particle, P_2 is the Legendre polynomial of order 2, and θ is the angle between the direction of acceleration of the particle (determined by the direction of an external magnetic field $\vec{H}$ and by the magnetic quantum state) and the direction to the galactic center. This equation is based on the assumption that Δm varies as $P_2(\cos\theta)$. The first experiment suggested was to observe the Zeeman splitting in an atom[1] and the second was to observe the Zeeman splitting in the excited nuclear state of Fe^{57} by use of the Mössbauer effect.[3] [The change in binding energy due to Δm will not be given exactly by Eq. (2) in the nuclear case, but if the nucleus is idealized as a single particle in a spherically symmetric square well potential a similar type of equation applies.] For both experiments effects are to be measured as a function of the angle θ. The models used for the atom and the nucleus are adequate for the order of magnitude estimate we require for ΔE.

In this Letter we report an experiment using nuclear magnetic resonance in the ground state of nuclei to test for the anisotropy of mass. This method gives a sensitivity some factor of 10^6 greater than could be achieved in the experiment suggested by Cocconi and Salpeter using the Mössbauer effect. In addition, we report experiments on the Zeeman effect in atoms of the first type suggested by Cocconi and Salpeter.