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 $2.2\times10^{-15}/°\mathrm{K}$. 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]

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

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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.

We discuss first the atomic Zeeman experiments. There are at least two methods of searching for the effect of mass anisotropy in an atomic state with orbital angular momentum quantum number $L \geqslant 1$ and with total angular momentum quantum number $J \geqslant 3/2$. One method is to observe, for example, the frequency of the Zeeman transition $M_J=+3/2 \leftrightarrow M_J=+1/2$ in the $^2P_{3/2}$ state as a function of the relative orientation of the direction of the magnetic field and the direction to the galactic center. In our experiment with our electromagnet fixed to the earth and with the magnetic field pointing approximately in the north-south direction, the change in relative orientation is achieved as a function of time due to the rotation of the earth. In New Haven at 41° latitude at a certain time in the sidereal day the south direction in the horizontal plane points within 22 degrees towards the center of our galaxy; 12 hours later this same direction along the earth's horizontal plane points 104 degrees away from the galactic center. It is important, of course, that the frequency standard with respect to which the Zeeman transition frequency is compared shall itself exhibit no mass anisotropy effect. Most Zeeman transition frequency measurements such as those quoted by Cocconi and Salpeter[1] have been referred to crystal oscillator secondary standards calibrated occasionally against the signal from WWV, and hence because of possible mass anisotropy effects in the crystal oscillator are not suitable for the present purpose. In our experiment a frequency derived from the cesium atomic frequency standard (National Company Atomichron) was used. The transition $(F, M_F)=(4,0) \leftrightarrow (3,0)$ used in this frequency standard[4] will not exhibit any mass anisotropy effect. The magnetic field is maintained constant with a proton resonance probe whose resonance frequency is compared with the Atomichron frequency. For a constant magnetic field the proton resonance frequency will exhibit no mass anisotropy effect. The transition $M_J=+3/2 \leftrightarrow M_J=+1/2$ with $M_I=+3/2$ in the $^2P_{3/2}$ state of Cl^{35} was observed over a twelve-hour period. No variation with time of the Zeeman transition frequency occurring at about 9190 Mc/sec in a magnetic field of 4730 gauss was observed within the experimental error of 30 kc/sec. If the electronic structure of chlorine, which is an atom lacking one electron to complete the outer $3p$ shell, is treated as a hole moving in a Coulomb potential due to the nucleus and electrons, the upper limit to $\Delta m/m$ of 10^{-10} is obtained.

A second method is to observe the frequencies of two Zeeman transitions where the intervals would be affected differently by any mass anisotropy. It is only necessary to observe the two transitions at the time at which the direction to the galactic center is such as to maximize the mass anisotropy effect. Simple experimental data of this type are available from the Zeeman transitions $\Delta M_J=\pm 1, \pm 2$ in the $^3P_2$ state of atomic oxygen.[5] From these data it can be deduced that $\Delta m/m \leqslant 10^{-10}$.

By far the most sensitive test is obtained from a nuclear magnetic resonance experiment on an appropriate nucleus in its ground state. Consider the Li^7 nucleus in its ground state which has nuclear spin $I=3/2$. In a magnetic field there will be four energy levels corresponding to the allowed values of the magnetic quantum number M_I. In the absence of any mass anisotropy, adjacent levels are equally spaced and a single nuclear resonance line will be observed. If the mass anisotropy effect is present, there will be three different intervals which will lead to a triplet nuclear resonance line, if the structure is resolved, or to a single broadened line if the structure is unresolved. Over a twelve-hour period, the resonance line for Li^7 was observed in a $1N$ water solution of $FeCl_3$ saturated with LiCl. The magnetic field of about 4700 gauss was stabilized against the proton resonance frequency with the Atomichron as a frequency standard. Only a single line was observed. The line width of 4.3 parts per million is due primarily to the inhomogeneity of the magnetic field and from the width of the proton resonance line should be (5.0 ± 1) parts per million. Hence a broadening of no greater than 8 cps could be due to the effect of mass anisotropy. If the nuclear structure of Li^7 is treated as a single $P_{3/2}$ proton in a central nuclear potential,[6] the limit $\Delta m/m \leqslant 10^{-20}$ is obtained. The increase in sensitivity over that which one could obtain from the Mössbauer effect is due to the far narrower line width obtainable for a transition with a nucleus in its ground state as compared with a nucleus in an excited state.

The limit here obtained of $\Delta m/m \leqslant 10^{-20}$ is far less than the value of 3×10^{-10} obtained by setting $\nu=0$ in Eq. (1). Hence it seems that within the framework of the Mach theory as discussed by Cocconi and Salpeter one should conclude that there is no anisotropy of mass of the type which varies as $P_2(\cos\theta)$ associated with effects of mass in our galaxy.

In the interest of completeness we intend to improve the sensitivity of the nuclear resonance experiment at least one order of magnitude by obtaining a narrower line width. We shall study the nuclear resonance signal of nuclei consisting of closed shells plus or minus one nucleon. Also we shall search for an anisotropic mass which varies other than as $P_2(\cos\theta)$ by studying nuclear resonance signals of nuclei with spin greater than 3/2. Finally, since in the spirit of this investigation it is not necessarily excluded that mass anisotropy could be associated with a point in the universe other than the center of our galaxy, we shall study the nuclear resonance signal with respect to any arbitrary direction.

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SIGNIFICANCE OF ELECTROMAGNETIC POTENTIALS IN THE QUANTUM THEORY IN THE INTERPRETATION OF ELECTRON INTERFEROMETER FRINGE OBSERVATIONS

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The effects of electromagnetic potentials in quantum theory recently discussed by Aharonov and Bohm[1] and also by Furry and Ramsey,[2] and a decade ago by Ehrenberg and Siday,[3] have been the subject of some lively discussion[4] regarding experimental observations. Interference fringes have been observed[5,6] in electron interferometers in which electron beams are split into separate component beams which travel along spatially separated paths before being recombined to produce the interference. One of the effects in question would be an observable shift of interference fringes produced by a quite small amount of magnetic flux passing between the two component beams, but confined completely to regions not penetrated by the beams, for example by means of a long solenoid. The presence of such a magnetic field would thus be detected in spite of the fact that none of the detecting apparatus ever actually entered any of the region of that field.

The question has arisen whether the existence of such an effect can be ruled out already, in the light of the fact that electron interference fringes have actually been observed. Marton has informed us that stray 60-cycle magnetic fields were present in his electron interferometer such that the magnetic flux passing between the beams was quite large in comparison with the very small amount of flux predicted to be needed to change the relative phase of the two component beams by 2π. It was thought at first that if the effect predicted by quantum theory referred to above had indeed been present, the interference fringes would have been shifted back and forth sixty times each second during the exposure by such large amounts that they could not possibly have been seen.[7] After considerable discussion at Princeton, National Bureau of Standards, Swarthmore, New York, and elsewhere, it was finally realized, during the New York meetings of the American Physical Society, that the change in length of the two component electron beams, due to their being bent in actually passing through