SIGN OF THE GRAVITATIONAL MASS OF A POSITRON*

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It has been suggested recently by several physicists[1] that an antiparticle may have the opposite sign of gravitational mass from its corresponding particle. The purpose of the present note is to point out that this sign can be determined experimentally in the case of a positron by reference to the well known work of Eötvös.[2] In these experiments the ratio of gravitational to inertial mass was measured for several substances, and the attempt made to detect differences in this ratio between one substance and another. No definite evidence for such differences was found. In several cases, the uncertainties in the fractional differences of the ratios were less than one part in 10^8.

The Coulomb field of an atom polarizes the vacuum and produces virtual electron-positron pairs. The reality of this effect is attested to by its contribution of -27 Mc/sec to the Lamb shift, and the agreement between theory and experiment within $\frac{1}{2}$ Mc/sec.[3] The virtual positrons contribute to the gravitational energy of the atom in the field of, say, the earth. The lowest order in which this contribution appears is first order in the gravitational potential, and second order in the atomic electrostatic potential. Three cases, which correspond to different assumptions concerning the effect of gravity on a positron, are considered in this note. (1) A positron behaves in the same way as an electron. (2) The gravitational rest mass of a positron is equal to and opposite in sign from that of an electron, but its kinetic energy is acted on normally by a gravitational field. (3) Both the rest mass and kinetic energy of a positron have equal and opposite gravitational sign from those of an electron.

Case (1) corresponds to the equivalence principle. As would be expected, the gravitational mass of the atom, including virtual pairs, is found to be equal to $1/c^2$ times the total energy of the atom, which is the inertial mass. The pair contribution diverges, and must be included as part of the renormalization of the atomic mass. In case (2), the difference between the gravitational mass and the renormalized atomic (inertial) mass is finite. As might be expected, the gravitational mass is the smaller, and by an amount of order $m(Z/137)^2$, where m is the electronic mass and Z the atomic number. This case is discussed in more detail below. In case (3), the difference between the two masses diverges logarithmically, and is indeed just equal to the pair contribution to the atomic mass. With a reasonable cutoff, the mass difference here is much larger than in case (2).

A straightforward calculation leads to the following expression as a good approximation for the mass difference in case (2):

$$(3/8\pi)m(Z/137)^2\int_0^\infty |F(q)|^2 dq/(q^2+4\mu^2)^{\frac{1}{2}}. \qquad (1)$$

Here, $\mu = mc/\hbar$, and $F(q)$ is the Fourier transform or form factor for the nuclear charge distribution, normalized to unit total charge [i.e., $F(0) = 1$].[4] For a rough computation, we may assume that $F(q) \approx 1$ for $q < R^{-1}$, and $F(q) \approx 0$ for $q > R^{-1}$. Then the integral in Eq. (1) is roughly equal to $\ln(\hbar/mcR)$.

Among other substances, Eötvös and his collaborators compared magnalium (90% Al, 10% Mg), Cu, and Pt. The fractional differences of the ratios of gravitational to inertial mass were somewhat greater than the probable errors quoted, but did not exceed $\frac{1}{2}$ part in 10^8. In comparison, the ratio of Eq. (1) to the atomic mass, in units of 10^{-8}, is equal to 10, 20, and 43, respectively, for Al, Cu, and Pt. Thus on the basis of case (2), we would expect fractional differences of the ratios of 10, 23, and 33 parts in 10^8, respectively, for Al-Cu, Cu-Pt, and Al-Pt. As pointed out above, these numbers would be even larger in case (3).

We therefore conclude that the Eötvös experiment precludes the possibility that the gravitational mass of a positron is equal to and opposite in sign from that of an electron. A full account of this work, and a discussion of related questions, will be published elsewhere.

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[1]Most of these suggestions are unpublished; see, however, D. Matz and F. A. Kaempffer, Bull. Am. Phys. Soc. Ser. II, 3, 317 (1958). We refer in this note entirely to what H. Bondi [Revs. Modern Phys. 29, 423 (1957)] calls the passive gravitational mass.

[2]For a summary of these experiments see Eötvös, Pekár, and Fekete, Ann. Physik 68, 11 (1922).

[3]See for example Schweber, Bethe, and de Hoffmann, Mesons and Fields (Row, Peterson and Company, Evanston, 1955), Vol. 1, p. 299. This places the

positron computation of this note on a much firmer basis than a similar computation for an antinucleon, which would presumably give a much larger effect.

[4]In actuality, screening of the nuclear charge by the atomic electrons will cause $F(q)$ to decrease from 1 to 0 as q decreases from the reciprocal atomic radius to zero; this has a negligible effect on the value of the integral in Eq. (1).

EXPERIMENTAL TEST OF TIME-REVERSAL INVARIANCE IN STRONG INTERACTIONS

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A comparison of the polarization (P) and the asymmetry (A) in the scattering of protons by nuclei can be used as a test of invariance under Wigner time reversal in the nuclear interaction. The target nucleus cannot be chosen arbitrarily for a significant test; for example, if the nucleus has zero spin, time-reversal invariance has no bearing on the equality of P and A. Bell and Mandl[1] have considered the case in which the target nucleus has spin 1/2. They show that invariance under time reversal and spatial rotation constitutes a necessary and sufficient condition for equality of P and A. In the case of p-p scattering, they further deduce a relationship that gives a lower limit to the magnitude of the T-noninvariant term of the scattering matrix, when one knows $|P-A|$, the differential cross section, and a certain combination of the invariant amplitudes. Finally, Phillips[2] has shown that, if the first four partial waves are sufficient to describe p-p scattering, the T-noninvariant term can be specified by one real parameter that is directly related to $|P-A|$.

The first experimental evidence on this point can be found in the original p-p polarization measurements of Oxley.[3] In the course of the experiment, asymmetries in double scattering were obtained for a first target of carbon and a second target of hydrogen, as well as for the targets in opposite sequence. On the assumption that $P=A$ for the carbon scattering, one observes that the former measurement gives A and the latter P for the hydrogen scattering. From Oxley's results, one finds that $P - A = 0.01 \pm 0.06$, and can conclude that the T-noninvariant term is not large at the angle and energy of the measurement.

Recently, Hillman[4] and collaborators have reported a more precise determination of the hydrogen polarization. At 180 Mev and at 30.9 degrees center of mass, they obtain $P = 0.264 \pm 0.014$; they compare this with $A = 0.257 \pm 0.018$, deduced for their energy from an interpolation of existing data.

We have independently measured P and A in p-p scattering at 210 Mev and 30 degrees center of mass. Our procedure was again essentially that of Oxley and of Hillman. A liquid hydrogen target of thickness 0.8 g/cm^2 was used, and we employed carbon both as the polarizer in the A measurement and as the analyzer in the P measurement. The incident unpolarized beam in the P measurement was degraded with CH_2 so as to have the same energy at the center of the hydrogen target as the polarized beam had in the A measurement. The detection geometry after second scattering was the same in both measurements, a precaution that tended to reduce systematic errors associated with finite solid angle. The analyzing power of the carbon target for the energy at which it scattered in the P experiment was separately determined by a double-scattering experiment in which both targets were carbon and the first-scattered beam was degraded to the appropriate energy. The polarizing power of the carbon target in the A measurement is well known from previous work at this laboratory.

As a result of these measurements, we obtain $A = 0.308 \pm 0.005$ and $P = 0.279 \pm 0.017$, the latter being the average of data taken at two scattering angles in the analyzer. The errors are statistical. We note that the asymmetry is in good agreement with the result of Baskir,[5] who obtained $A = 0.311 \pm 0.010$ at the same energy and angle.

If we assume that the energy dependence of the polarization-asymmetry difference is not rapid, the results of this experiment can be combined with the 31° results of Hillman et al.[4] to obtain $P - A = -0.014 \pm 0.014$. Woodruff,[6] using the method of Phillips[2] and the nucleon-nucleon potential of Gammel and Thaler, has developed formulas from which the T-noninvariance parameter λ, defined by Phillips, can be deduced. For the energy and angle of these experiments, the expression developed is $I_0(P - A) = 0.9 \sin 2\lambda$, where I_0 is the p-p differential cross section. From the $(P - A)$ result given above, we find λ to have the value 2.0 ± 2.0 degrees. It can then be concluded that the T-noninvariant term of the scattering matrix has a magnitude no more than a few percent of the average magnitude of invariant terms.