are 10^7 times lower than those required for the vacuum to become dichroic. Since the period of oscillation of a light wave is about 2×10^{-15} sec, only a very short-duration electrical field could be used to demonstrate this dichroism, and dissolution might be avoided.

Pulsed laser beams have been generated whose power is about 500 MW. If this beam could be focused to an area of the order λ^2, λ being the wavelength of light, the resulting intensity would be $\sim2\times10^{17}$ W/cm^2 corresponding to an alternating electric field of amplitude $\sim10^{10}$ V/cm. This is just comparable with the highest field encountered in field evaporation work.

The field strengths in question ($\sim10^{16}$ V/cm) are comparable with those existing at the surface of the nucleus of an atom. $E=e/r^2$, for a proton is $\sim2\times10^{18}$ V/cm, assuming a proton radius $\sim2.5\times10^{-13}$ cm. However, the nuclear electric field is confined to a very small volume. Furthermore, these fields are usually shielded by the surrounding clouds of negative charge due to bound electrons. Therefore a light wave having wavelength much greater than the size of an atom would not sense the strong nuclear field. It seems unlikely that at present the dichroism of the vacuum can be observed.

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Parity, Charge Conjugation, and Time Reversal in the Gravitational Interaction*

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Some consequences of possible violation of parity (P), charge conjugation (C), time reversal (T), and TCP invariance in the gravitation interaction are discussed and compared with existing experimental evidence. The evidence is suggestive of TCP (or CP or C) invariance, but one cannot rule out separate violation of P, C, and T.

I. INTRODUCTION

STRONG evidence[1] exists indicating that parity (P), time reversal (T), and charge conjugation (C) are absolute invariance properties of the strong and electromagnetic interactions. Further, P and C are known to be violated[2] in weak interactions, but T (or PC, related to T by the TCP theorem[3]) is apparently conserved.[4] It has long been conjectured that the relative lack of symmetry in the weak interactions is somehow connected with (or even responsible for) the relative weakness of the force. Additional evidence for such a symmetry-strength correlation[5] may be found if one considers other symmetries referring to internal properties such as isospin (I) and strangeness (S). For instance, only the strong interaction conserves both I and S; the electromagnetic (EM) interaction conserves S but not I, while the weak interaction violates both S and I.

A presumed symmetry-strength correlation provides the phenomenological justification for the "perturbation" approach toward understanding the known hierarchy of interactions. This approach attributes the breakdown of isotopic spin symmetry, i.e., multiplet mass splittings, to the isospin-violating, relatively weak EM interaction. Similarly, one usually attributes the supermultiplet mass splitting, i.e., the breakdown of the new SU_3 symmetries,[6] to an unspecified but presumably relatively weak part of the strong interactions. The assumption of weakness, together with transformation properties analogous to those of the EM interaction, led to the Gell-Mann–Okubo mass formula.[7] The recent

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[1] For references see, for example, K. Gotow and S. Okubo, Phys. Rev. **128**, 1921 (1962).

[2] For references see, for example, J. Jackson, *The Physics of Elementary Particles* (Princeton University Press, Princeton, New Jersey, 1958), Chap. 8–10.

[3] G. Lüders, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **28**, 5 (1954). Also see W. Pauli, in *Niels Bohr and the Development of Physics* (Pergamon Press, Ltd., London, 1955). For direct evidence of the validity of CPT, see R. G. Sachs, Phys. Rev. **129**, 2280 (1963).

[4] For evidence in β decay, see M. Burgy, V. Krohn, T. Novey, G. Ringo, and V. Telegdi, Phys. Rev. Letters **1**, 324 (1958). For evidence in Λ decay, Σ decay, and Ξ decay, see J. Cronin and O. Overseth, Phys. Rev. **129**, 1795 (1963). E. F. Beall, B. Cork, D. Keefe, P. Murphy, and W. Wentzel, Phys. Rev. Letters **8**, 75 (1962), and H. K. Ticko, Proceedings International Conference on Fundamental Aspects of Weak Interactions, Brookhaven National Laboratory p. 410, 1963 (unpublished).

[5] See, for example, the discussion of Pais at the Fifth Rochester Conference and of Gell-Mann and Schwinger at the Sixth Rochester Conference (unpublished).

[6] M. Gell-Mann, California Institute of Technology, Internal Report CTSL-20 (unpublished); Phys. Rev. **125**, 1067 (1962). Y. Ne'eman, Nucl. Phys. **26**, 222 (1961).

[7] S. Okubo, Progr. Theoret. Phys. (Kyoto) **27**, 949 (1962).

spectacular verification of both SU_3 and the mass formula[8] seems to us further evidence[9] of the vitality of the presumed symmetry-strength correlation.

At any rate, the presumed correlation has led us to inquire whether gravitation, by far the weakest of all forces, shares the symmetry violations of other weak forces.

Ordinarily, it is of course assumed that the gravitational interaction is described by Einstein's equation in the large, and locally by the classical Newtonian equation, so that such an inquiry is usually answered in the negative. It is interesting to note, however, that even within the framework of the Einstein formulation, strict P and C conservation cannot be a feature of the theory, owing to the presence of two-component neutrino fields which enter into the energy tensor. Of course, for ordinary test bodies, the effect of such symmetry violation must be very small compared with the symmetry exhibited by the Newtonian force, because neutrino coupling contributes corrections of a higher order in the gravitational coupling constant G. Thus, one normally takes the gravitational interaction to be P, C, and T conserving.

On the other hand, there exists very little experimental evidence which has a direct bearing on the question of symmetry violation in the gravitational interaction.

The purpose of this note is to investigate the consequences of a presumed T, C, or P violation in the gravitational interaction; in particular, to analyze existing experimental information and consider possible experiments which could shed light on questions of symmetry.

In what follows, we shall consider gravitation to be similar to other elementary-particle interactions, i.e., describable by some phenomenological field theory in a flat space.[10] Within this framework, one may consider a large number of possibilities for T, C, and P invariance. It turns out that present experimental evidence indicates that one or more of the operations TCP, CP, and C is conserved. Assuming TCP invariance, since this is the most general of the three, the possibilities[11] for separate T, C, and P symmetries, and the symmetries connected with their products, are shown below:

Conserved operators (aside from TCP+permutations)	Nonconserved operators	
P, C, T	None	(1)
T, CP, PC	C, P	(2)
P, CT, TC	C, T	(3)
C, PT, TP	P, T	(4)
None	$P, C, T.$	(5)

We shall see that present experimental evidence *does not conclusively rule out* any of these possibilities, although it suggests that (4) is unlikely.

II. POSSIBLE TWO-BODY POTENTIALS AND P, T INVARIANCE

In this section, we investigate some simple potentials which might be present in a two-body gravitational interaction, where P and/or T are violated. It is well known[12] that one must construct pseudoscalar observables to detect P violation, and observables which are odd functions of $\boldsymbol{\sigma}$ and momenta to detect T violation. Because of this, we shall study spin-dependent potentials between two point particles "1" and "2." Because of translational and rotational invariance, these potentials can only be functions of the *relative* coordinate $\mathbf{r}=\mathbf{r}_1-\mathbf{r}_2$, and the spin variables $\boldsymbol{\sigma}_1$, $\boldsymbol{\sigma}_2$. For simplicity we assume that both particles have spin $\frac{1}{2}$. Then, the effective potential $U(r)$ can always be expressed as a linear combination of the following terms:[13]

$$U_0(r)\,, \tag{6}$$

$$(\boldsymbol{\sigma}_1\pm\boldsymbol{\sigma}_2)\cdot\mathbf{r}U_1(r)\,, \tag{7}$$

$$(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\cdot\mathbf{r}U_2(r)\,. \tag{8}$$

Here, $U_j(r)$ $(j=0, 1, 2)$ are arbitrary scalar functions of the relative coordinate $|\mathbf{r}|$. The spin-independent term $U_0(r)$ clearly represents the Newtonian potential[14]

$$U_0(r)=G(m_1m_2/r)\,.$$

The invariance properties represented by (6), (7), (8) may be inferred from the well-known behavior of $\mathbf{r}$, $\boldsymbol{\sigma}_i$ under P and T, namely, $P:\mathbf{r}\rightarrow-\mathbf{r}$, $\boldsymbol{\sigma}_i\rightarrow\boldsymbol{\sigma}_i$, $T:\mathbf{r}\rightarrow+\mathbf{r}$, $\boldsymbol{\sigma}_i\rightarrow-\boldsymbol{\sigma}_i$. Thus, we see that (7) violates both P and T separately but conserves the product TP; (8) violates P only, and of course, (6) conserves everything.

Because of the extreme weakness of gravitation, the effects of a particle-particle interaction between microscopic objects cannot be experimentally detected. From this point on, therefore, we shall consider the gravitational effects of a macroscopic body (such as the earth) upon a test particle "1." The effective potential of such an interaction will involve the average over-all constituent point particles "2" contained in the earth. Since the earth is unpolarized as a whole, all terms containing $\boldsymbol{\sigma}_2$ will disappear as the result of such averaging. Thus, the effective earth-particle potential can be written

$$U(r)=U_0(r)+(\boldsymbol{\sigma}_1\cdot\mathbf{r})U_1(r)\,, \tag{9}$$

where $\mathbf{r}$ is a unit vector from the center of the earth to a test particle.[14]

[8] V. Barnes, P. Connolly, D. Crennell, B. Culwick, W. Delaney *et al.*, Phys. Rev. Letters **12**, 204 (1964). For a review of previous evidence, see the article by G. Chew, M. Gell-Mann, and A. Rosenfeld, Sci. Am. **210**, No. 2, 74 (1964).

[9] Specific models of the symmetry-breaking force implied in SU_3 have been proposed recently. See, for example, Y. Ne'eman, Phys. Rev. **134**, B1355 (1964).

[10] S. N. Gupta, Rev. Mod. Phys. **29**, 334 (1957).

[11] T. D. Lee, R. Oehme, and C. N. Yang, Phys. Rev. **106**, 340 (1959).

[12] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

[13] This follows from the methods of L. Eisenbud and E. P. Wigner, Proc. Natl. Acad. Sci. U. S. **27**, 381 (1941). Also see S. Okubo and R. F. Marshak, Ann. Phys. (Paris) **4**, 166 (1958).

[14] For convenience, we choose the arbitrary constant of potential equal to 0 here. We include it in the more general expression (11).

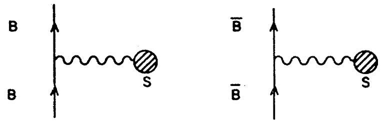

FIG. 1. Single graviton exchange diagram.

At the surface of the earth ($r=R$), letting

$$A=U(R)/U_0(R)\,, \tag{10}$$

we have

$$U(R)=U_0(R)[1+A\boldsymbol{\sigma}\cdot\mathbf{r}]+\bar{c}\,, \tag{11}$$

where A then represents the degree of both P and T violation, and $\bar{c}$ is an arbitrary constant. The potential (11) shows that the energy levels of a test proton will be split depending upon the orientation of its spin with respect to the radius vector from the center of the earth. Suppose the proton were situated in the nucleus of a hydrogen atom when an electron in an excited state makes a transition to its ground state. In this process, the proton spin may either flip or retain its direction, so we should expect to see a line splitting of the emitted photons of the amount[15] $2U(R)$. If the magnitude of A were anywhere near unity, the size of this splitting would be $\sim 2U_0(R)$. Surprising as it might seem, at the surface of the earth $2U_0(R)$ is large, namely of the order of two electron volts for a proton. Such a large splitting is clearly ruled out on the basis of the hyperfine structure observed for many elements.

We can, in fact, use the hyperfine splitting[16] of the ground state ($^1S_{1/2}$) of hydrogen (1420.4057 ± 0.00001 Mc/sec) to place an upper limit on A. The former is usually used[17] to determine the value of the fine structure constant α; it gives $\alpha^{-1}=137.037\pm0.001$. This value agrees with that obtained from the $^2S_{1/2}\rightarrow{}^2P_{1/2}$ fine structure splitting to an accuracy of 2 parts in 10^5. Then the maximum gravitational splitting consistent with observation would be $1420\times2\times10^{-5}$ Mc/sec, from which one finds

$$A\equiv[U(R)/U_0(R)]\leq10^{-11}. \tag{12}$$

We thus conclude that the P and T violating term $\boldsymbol{\sigma}\cdot\mathbf{r}U(r)$ can be present in a proton's potential only to the extent of 1 part in 10^{11}. A similar argument for the electron, taking account of its smaller mass, gives $A_{\text{electron}}\leq10^{-7}$.

This argument does not, of course, prove that P and T are separately conserved in gravitation, but only that the simplest experimentally detectable symmetry-violating term seems to be absent to a high degree of accuracy.

[15] The splitting is independent of the arbitrary zero of potential, as it should be.

[16] These values are taken from H. Bethe and Salpeter, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1959), Vol. 35, pp. 193–200.

[17] See J. Jauch and F. Rohrlich, *The Theory of Photons and Electrons* (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1955), p. 360.

III. C, CP, OR TCP INVARIANCE

In this section we shall investigate the question of C or CP or TCP invariance in the gravitational interaction. The most direct test of C invariance, for example, would involve the study of the gravitational interaction between particle and antiparticle. Since this does not seem possible experimentally, we turn to a comparison of the interaction of a macroscopic body (such as the earth or sun) with a particle and its antiparticle.

We note, firstly, that the extreme weakness of gravitation makes it likely that one can neglect the contributions of multiple graviton exchange. Then the interaction between a point particle "B" or its antiparticle "$\bar{B}$" and a macroscopic body S, can be graphically represented as a single graviton exchange in Feynman's sense (as shown in Fig. 1).

In the usual description, one might consider the interaction to be described by the linearized Einstein equation.[10] Here, the gravitational field would be represented by a symmetric tensor $g_{\mu\nu}$, and its interaction with a matter field would be $\Lambda g_{\mu\nu}T_{\mu\nu}$, where $T_{\mu\nu}$ is the energy-momentum stress tensor, and Λ is the gravitational coupling constant. With such an interaction, the gravitational energy of B and $\bar{B}$ is given by

$$\begin{aligned} U_B&=\Lambda\langle B|T_{\mu\nu}|B\rangle\,,\\ U_{\bar{B}}&=\Lambda\langle\bar{B}|T_{\mu\nu}|\bar{B}\rangle\,. \end{aligned} \tag{13}$$

Actually, identical expressions would be obtained from a more phenomenological point of view in which the interactions were ascribed to a (weak) unspecified gravitational Hamiltonian ΛH_G.

Let us consider a general case in which B is an unstable particle decaying through weak interactions described by the usual weak Hamiltonian H_w.[18] In the absence of both H_w and H_G, $|B\rangle$ and $|\bar{B}\rangle$ are degenerate eigenstates[18] of the strong Hamiltonian with (inertial) masses m_0 and definite parity. In the normal case, the decay products of B have charge or baryon number different from the corresponding decay products of $\bar{B}$, so the states B and $\bar{B}$ cannot be mixed by either H_w or H_G. Then the energies of the B and $\bar{B}$ eigenstates after perturbation are given to first order by

$$E_K=m_0+\langle B|H_w|B\rangle+\Lambda\langle B|H_G|B\rangle\,, \tag{14a}$$

$$E_{\bar{K}}=m_0+\langle\bar{B}|H_w|\bar{B}\rangle+\Lambda\langle\bar{B}|H_G|\bar{B}\rangle\,. \tag{14b}$$

The last terms of (14a) and (14b) represent the gravitational energies of B and $\bar{B}$, just as in Eq. (13).

If one makes the assumption that H_G is invariant to CPT or CP or C, the matrix elements of H_G are con-

[18] In this note, H_w represents the effective weak Hamiltonian up to the second-order perturbation rather than the original weak interaction itself. This is necessary because the first-order effect does not given any mass difference between K_0 and $\bar{K}_0$, as is well known. Also, for the sake of simplicity, we consider spin-0 particles in what follows, although the results may be generalized easily to include any spin.

nected by the relation[19]

$$\langle B|H_G|B\rangle=\langle\bar{B}|H_G|\bar{B}\rangle. \quad (15)$$

This equality, together with Eqs. (14a) and (14b), implies that the gravitational energies of B and $\bar{B}$ must be identical. The equality of U_B and $U_{\bar{B}}$ thus provides a test of either C, CP, or CPT invariance in the gravitational interaction.

Speculations concerning the relation between "gravitational mass" of particle and antiparticle have been widely discussed.[20] Particular attention has been paid to the possibility that the gravitational mass of $\bar{B}$ is equal to that of B, but with opposite sign. Investigation[21,22] of the consistency of existing experimental data with such a hypothesis have shown it to be incorrect. We consider below the possibility that the K^0 and $\bar{K}^0$ may have only a slightly different interaction with the gravitational field, and we show that it is inconsistent with experiment.

Our analysis is based on a generalization of Good's[22] argument which pointed out that a gravitationally induced difference in the De Broglie frequency between a K^0 and $\bar{K}^0$ would mix the usual K_1, K_2 eigenstates. The new eigenstates could then both decay by the two-pion mode, contradicting experimental observation.

If, after the perturbation $H_1=H_w+H_G$, we denote the eigenstates of the K^0, $\bar{K}^0$ system by $\psi_\pm=\begin{pmatrix}p\\q\end{pmatrix}$, then p and q are given by[23]

$$\begin{pmatrix}(H_1)_{KK} & (H_1)_{K\bar{K}}\\(H_1)_{\bar{K}K} & (H_1)_{\bar{K}\bar{K}}\end{pmatrix}\begin{pmatrix}p\\q\end{pmatrix}=M_\pm\begin{pmatrix}p\\q\end{pmatrix}, \quad (16)$$

where the eigenvalues $M_\pm$ represent the mass of the eigenstates. Assuming CP invariance for the weak interactions, we have

$$(H_w)_{KK}=(H_w)_{\bar{K}\bar{K}}$$

and

$$(H_w)_{K\bar{K}}=(H_w)_{\bar{K}K}=\tfrac{1}{2}\Delta m\,, \quad (17)$$

where Δm is the eigenstate mass difference due to weak interaction alone. Since $\Delta S=2$ nonleptonic weak transitions do not occur,[24] we know that $(H_w)_{K\bar{K}}\approx g_w^2\approx$ (rate for 2π decays) $\approx\hbar/\tau_1$, so Δm must be $\frac{1}{2}(\hbar/\tau_1)\approx 10^{-5}$ eV.

For the gravitational interaction, we assume[25]

$$(H_G)_{K\bar{K}}=(H_G)_{\bar{K}K}=0 \quad (18)$$

and, in accord with our hypothesis, allowing the K^0 and $\bar{K}^0$ to have different gravitational energies,

$$\begin{aligned}(H_G)_{KK}&\equiv U_1=m_K{}^G[GMe/R]+\bar{c}\,,\\(H_G)_{\bar{K}\bar{K}}&\equiv U_2=m_{\bar{K}}{}^G[G'Me/R]+\bar{c}\,.\end{aligned} \quad (19)$$

In this analysis, the observable quantities are the total energies U_1 and U_2. Any difference in these energies can be ascribed either to a difference in "gravitational mass" ($m_K{}^G\neq m_{\bar{K}}{}^G$) or gravitational coupling ($G\neq G'$). In view of the apparent equality of inertial and (passive) gravitational mass[26] for ordinary matter, it seems to us that the $G\neq G'$ description is more appropriate.

In any event, using the conditions (17), (18), and (19), one finds from Eq. (16) the eigenstates:

$$\begin{aligned}|\psi_+\rangle&=p\{|K^0\rangle+((\Delta U+\Delta M_\pm)/|\Delta m|)|\bar{K}^0\rangle\}\,,\\|\psi_-\rangle&=p\{|K^0\rangle+((\Delta U-\Delta M_\pm)/|\Delta m|)|\bar{K}^0\rangle\}\,,\end{aligned} \quad (20)$$

where

$$\Delta M_\pm=|M_+-M_-|=[(\Delta U)^2+(\Delta m)^2]^{1/2} \quad (21)$$

is the eigenstate mass difference and

$$\Delta U=U_1-U_2$$

is the K^0, $\bar{K}^0$ gravitational energy difference. Since the measured mass difference[27] of the eigenstates is of the order of Δm, the weak-interaction mass difference itself, we see immediately from (21) that ΔU cannot be much greater than Δm. Assuming CP invariance for the weak interaction, which insures that the K^0 and $\bar{K}^0$ amplitudes for 2-pion decay are equal, Eq. (20) implies that the ratio of 2π decay rates of the eigenstates ψ_- and ψ_+ is

$$R_{2\pi}=\frac{\Gamma(\psi_-\to 2\pi)}{\Gamma(\psi_+\to 2\pi)}=\frac{||\Delta m|+\Delta U-[(\Delta m)^2+(\Delta U)^2]^{1/2}|^2}{||\Delta m|+\Delta U+[(\Delta m)^2+(\Delta U)^2]^{1/2}|^2}. \quad (22)$$

Examination of (22) reveals that $R_{2\pi}\approx 0.2$ for $\Delta U=\Delta m$, which clearly contradicts experiment.[28] Thus, to obtain

[19] This follows from the general result $\langle f|H_G|i\rangle=\pm\langle\bar{i}|H_G|\bar{f}\rangle^*$ given in Refs. 11 and 30. One should keep in mind here that we are evaluating the matrix element in the rest system, and that spin inversion due to TC or TCP can be compensated by space rotation, since the energy is independent of its spin orientation. Finally, we note that for this particular case in which $i=f$, only the $+$ parity part of H_G can connect i with itself.

[20] P. Morrison and T. Gold, *Essays on Gravity* (Gravity Research Foundation, Boston, New Hampshire, 1957), p. 45.

[21] L. I. Schiff, Phys. Rev. Letters **1**, 254 (1958).

[22] M. Good, Phys. Rev. **121**, 311 (1961).

[23] This follows from degenerate perturbation theory, along the lines outlined in Ref. 10.

[24] This conclusion is usually based upon the observed magnitude of Δm itself (see Ref. 30) in connection with the argument of L. Okun and B. Pontecorvo, Zh. Eksperim. i Teor. Fiz. **32**, 1587 (1957) [English transl.: Soviet Phys.—JETP **5**, 1297 (1957)]. In order to avoid using circular reasoning, we may consider the absence of $\Xi^-\to n+\pi^-$ decay to be sufficient evidence for $\Delta S\neq 2$. See M. Ferro-Luzzi *et al.*, UCRL-10547 (unpublished).

[25] This is the assumption one usually makes concerning the gravitational interaction, as in Fig. 1. However, the analysis can be carried out without this restriction, and the results hold with the replacement $\Delta m^2\to\Delta m^2[1+(2(H_G)_{K\bar{K}}/\Delta m)]$.

[26] R. H. Dicke, Sci. Am. **205**, No. 6, 84 (1961).

[27] F. Muller, R. Birge, W. Fowler, R. Good, W. Hirsch *et al.*, Phys. Rev. Letters **4**, 418 (1960). Also see W. F. Fry, Proceedings International Conference on Fundamental Aspects of Weak Interactions, Brookhaven National Laboratory, 1963, p. 3 (unpublished).

[28] D. Neagu *et al.*, *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester*, edited by E. C. G. Sudarshan, J. H. Tinclot, and A. C. Melissious (Interscience Publishers, Inc., New York, 1960), p. 603.

an upper limit on ΔU, we may expand (22) for the case $\Delta U \ll \Delta m$ to first order in $\Delta U/\Delta m$; this gives

$$R_{2\pi} \approx \tfrac{1}{4} |\Delta U/\Delta m|^2. \tag{23}$$

The best experimental limit[28] is $R_{2\pi} \leq 3\times 10^{-3}$, and taking $\Delta m \approx 10^{-5}$ eV, one finds

$$\Delta U \leq 1.2\times 10^{-9}\ \mathrm{eV}. \tag{24}$$

This result is independent of the arbitrary constant $\bar{c}$, as it should be. To obtain a fractional difference which is also independent[29] of $\bar{c}$, we form the ratio

$$f_G = \frac{\Delta U(\mathrm{earth}) - \Delta U(\infty)}{U_1(\mathrm{earth}) - U(\infty)} \tag{25}$$

and take $\Delta U(\infty) = 0$, corresponding to no gravitational energy difference in the absence of matter. From (24) and (25) we find

$$f_G \lesssim 3\times 10^{-9}, \tag{26}$$

indicating the equality of the gravitational masses of the K^0 and $\bar{K}^0$ to be better than 3 parts in 10^9.

As emphasized earlier, assuming CP invariance for the weak interaction, this result is indicative of either C, CP, or CPT invariance in the gravitational interaction. Since CPT is the most general of these,[30] it is perhaps not imprudent to ascribe the result to the latter.

Similar considerations apply to the photon-graviton interaction, if we consider it to be described by the interaction of Fig. 1. Denoting the state vectors of right- and left-handed circularly polarized γ rays of momentum $\mathbf{k}$, by $|\gamma_L(\mathbf{k})\rangle$, $|\gamma_R(\mathbf{k})\rangle$, respectively, TCP (or TP) invariance gives[30]

$$\langle \gamma_L(\mathbf{k}')|H_G|\gamma_L(\mathbf{k})\rangle = \langle \gamma_R(\mathbf{k})|H_G|\gamma_R(\mathbf{k}')\rangle. \tag{27}$$

For $\mathbf{k}=\mathbf{k}'$, we see that the gravitational energy of the photon is independent of its polarization, if H_G is TCP (or TP) invariant. To the best of our knowledge, there exists no evidence for such a polarization effect within the red-shift spectrum from massive stars, as one might expect if the gravitational interaction were not TCP (or TP) invariant. Equation (27) leads immediately to the polarization independence of the scattering cross sections of photons from a symmetrical gravitational source like the sun. The scattering of right- and left-handed photons is given by

$$\sigma_L(\mathbf{k}\to\mathbf{k}') \propto |\langle \gamma_L(\mathbf{k}')|H_G|\gamma_L(\mathbf{k})\rangle|^2,$$
$$\sigma_R(\mathbf{k}\to\mathbf{k}') \propto |\langle \gamma_R(\mathbf{k}')|H_G|\gamma_R(\mathbf{k})\rangle|^2.$$

Since we are neglecting the multiple graviton exchanges, or equivalently, the effect of the final-state interactions, we can rewrite Eq. (27) as

$$\langle \gamma_L(\mathbf{k}')|H_G|\gamma_L(\mathbf{k})\rangle = (\langle \gamma_R(\mathbf{k}')|H_G|\gamma_R(\mathbf{k})\rangle)^*.$$

Therefore, we find

$$\sigma_L(\mathbf{k}\to\mathbf{k}') = \sigma_R(\mathbf{k}\to\mathbf{k}').$$

As in the previous case, there seems to be no evidence one way or the other for polarization dependence in the scattering of light by the sun. In principle though, the polarization of light deflected by the sun's gravitational field could serve as a test of TCP (or T or TP) invariance. Furthermore, such a test is also possible (in principle) by means of a "Pound-type"[31] terrestrial red-shift experiment, taking advantage of the known hyperfine structure[32] spectrum of Fe^{57}. For example, the $\Delta m = \pm 1$ right and left circularly polarized emission lines could be red-shifted by different amounts, if Eq. (27) were violated. Of course, such an effect would be difficult to detect even if it were large because one must resolve to about one part in 1000 of the linewidth.

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Note added in proof. Since the submission of this paper, a new measurement of the $K_2^0 \to 2\pi$ rate has been reported [J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters **13**, 138 (1964)] in which it is found that $[(K_2^0 \to 2\pi)/(K_2^0 \to \text{all other modes})] \approx 2\times 10^{-3}$. This new result has a significant bearing on the conclusions reached in Sec. III of this paper.

Using $R_{2\pi} \approx 10^{-5}$ in Eq. (23), we find that a gravitational energy difference of $\Delta U \approx 10^{-10}$ eV can account for the apparent "CP mixture" nature of the K_2^0. More specifically, if we maintain the assumption of CP invariance in the weak interactions, and attribute the apparent breakdown of CP invariance manifested in K_2^0 decay to the gravitational mixing effect, we conclude that the difference in the K^0 and $\bar{K}^0$ gravitational couplings (or gravitational masses) must be $\sim 10^{-10}$ eV [see Eq. (25)]. We emphasize, however, that *any* "superweak" force which differentiates between K^0 and $\bar{K}^0$ would be sufficient to explain the effect. Furthermore, it must be shown that the weak interaction is indeed a CP-conserving one (present evidence is only good to $\sim 10\%$) before the gravitational mixing hypothesis can be taken seriously.

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[29] See Good's paper, Ref. 22, for another point of view. Note, however, that if one adds the potential of the sun, galaxy, etc., the limit given in (26) will be even smaller.

[30] See K. Nishijima, *Fundamental Particles* (W. A. Benjamin Inc., New York, 1963), p. 329 ff.

[31] R. V. Pound and G. H. Rebka, Phys. Rev. Letters **4**, 337 (1960).

[32] S. S. Hanna, J. Heberle, C. Littlejohn, G. Perlow, R. Preston, and D. Vincent, Phys. Rev. Letters **4**, 177 (1960).