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Test for *C*, *P*, and *T* Nonconservation in Gravitation

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The question of C, P, and T nonconservation in gravity is reexamined, and feasible experiments are suggested to test these effects.

Since the prediction by Lee and Yang[1] of possible parity nonconservation in β interactions, and the subsequent experimental verification of it by Wu *et al.*, physicists continue to be intrigued by the role of discrete symmetries in fundamental interactions. It is reasonably well established now that no such intrinsic symmetry violations exist in electromagnetic and strong interactions. That leaves one wondering about the question of discrete symmetries in gravitation. It should be emphasized that Einstein's formulation of gravitational interactions allows for these symmetries to be violated by an appropriate choice of the energy-momentum tensor[2] $T_{\mu\nu}$; but such violations are necessarily induced by other interactions, and hence do not amount to an intrinsic violation in gravity. In addition, such effects, if induced by other interactions, are expected to be too small to be observable at present.[3] I examine here the existing experimental support, if any, for assuming validity of discrete symmetries in gravity, and suggest experiments that are feasible at present, or likely to become feasible in the near future, to test for their violation.

Morrison and Gold[4] were the first ones to suggest the possibility of C nonconservation in gravity, which would manifest itself as unequal gravitational interactions for particles and antiparticles. Schiff[5] showed that consistency with the Eötvös experiment required that such nonconservation be less than 1 part in 10^4. Interestingly, this estimate coincides with an estimate of C nonconservation based on the observed perihelion motion of mercury to be given in this note. Leitner and Okubo[2] considered later the general question of discrete symmetries in gravity, and by considering a general potential of the form

$$U(r) = U_0(r)(1 + A\vec{\sigma}\cdot\hat{r}), \tag{1}$$

where $U_0(r)$ is the Newtonian potential, obtained the limit $A < 10^{-11}$ for protons and 10^{-7} for electrons based on the existing data on hyperfine structures. I show below that these limits are not fundamental measures of P and T nonconservation. Since no experiments so far have been performed to study the gravitational interactions of spinning objects, one has to conclude that there is little experimental justification to assume discrete symmetry invariance in gravitation. The proposed Everitt-Fairbank orbiting-gyroscope experiment[6] and the recently observed[7] binary pulsar system PSR 1913 + 16 offer us hope for observing such effects. In addition, Earth-based neutron-spin-precession effects are also analyzed here. Ramsey[8] has developed extremely accurate techniques to measure neutron spin precession, and I show that the magnitudes of such effects due to P and T nonconservation could already be in the vicinity of such accuracies.

Assuming G to be the only fundamental constant in gravitation, one can write down the most general C-, P-, and T-nonconserving potential for a two-body system (assuming CPT invariance):

$$U(r)=\alpha_1 \frac{GM}{c}\frac{\vec{s}^{(1)}\cdot\vec{r}}{r^3}+\alpha_2\frac{GM}{c^2}\frac{\vec{s}^{(1)}\cdot\vec{v}}{r^2}+\alpha_3\frac{GM}{c}\mu\frac{\vec{r}\cdot\vec{v}}{r^2}, \tag{2}$$

where M is the total mass, μ the reduced mass, $\vec{r}$ the relative displacement, $\vec{v}$ the relative velocity, and $\vec{s}^{(1)}$ the intrinsic spin of one of the objects. Terms for the other spin $\vec{s}^{(2)}$ can be written down by symmetry. I have deliberately omitted terms of the type $(\vec{s}^{(1)}\times\vec{s}^{(2)})\cdot\vec{r}$, etc., as these are expected to be very small. The α_1 term violates P and T conservation; α_2 violates P and C conservation; and α_3 violates C and T conservation. The Leitner-Okubo parameter A is related to α_1 via $A=\alpha_1 r^{-1}sm^{-1}c^{-1}$; for protons at Earth's surface $sr^{-1}m^{-1}c^{-1}=10^{-23}$ and we see that even if α_1 is 10^{12} the Leitner-Okubo limit is not violated.

I merely quote the results for the three categories of experiments mentioned before and present the details elsewhere. For the Ramsey neutron experiments, the angle of precession is given by

$$\Delta\vec{s} = -\alpha_1\left(\frac{GM}{Rc^2}\right)\left(\frac{c}{R\omega}\right)[(\Delta\hat{R}\times\hat{n})\times\vec{s}_0+\omega\Delta t(\hat{R}\cdot\hat{n})(\vec{s}_0\times\hat{n})]+\alpha_2\left(\frac{GM}{Rc^2}\right)(\Delta\hat{R}\times\vec{s}_0). \tag{3}$$

$\vec{s}_0$ is the initial spin orientation; $\Delta\hat{R}$ is the change in the local radius vector during Δt; and R, ω, and $\hat{n}$ are, respectively, the radius of Earth, its angular velocity, and the direction of its axis. The magnitude of the precession due to the first term is $\sim(10^{-3}\alpha_1$ rad)/(12 h). This averages to zero at the end of each day. The second term contributes a *cumulative* precession rate of $\sim 10^{-7}\alpha_1$ rad/sec. The latest measurement of the electric dipole moment corresponds to an accuracy in the measurement of 10^{-6} rad and we see that there is hope of measuring these effects. The last term produces a *noncumulative* effect of $\sim 10^{-9}\alpha_2$ rad per half Earth's rotation period.

For the Everitt-Fairbank gyroscope (EFG) and the spin precession in the Hulse-Taylor pulsar (HTP), the results are, assuming an elliptic orbit of semilatus rectum a, eccentricity e, and orbit normal $\hat{n}$,

$$\Delta\vec{s}=\alpha_1\left(\frac{GM}{ac^2}\right)^{1/2}(\Delta\hat{e}_r\times\hat{n})\times\vec{s}_0+\alpha_2\left(\frac{GM}{ac^2}\right)[(\Delta\hat{e}_r\times\vec{s}_0)-e\Delta\theta(\hat{e}_p\times\hat{n})\times\vec{s}_0]. \tag{4}$$

Here $\Delta\hat{e}_r$ refers to the change in the unit vector along the radius vector, and $\Delta\theta$ the corresponding change in the angle between $\hat{e}_r$ and the unit vector along the perihelion, $\hat{e}_p$. The magnitude of the spin precession is as follows: The first term causes a *noncumulative* effect of $\sim(2\times 10^{-5}\times\alpha_1$ rad)/(12 h) for EFG and $\sim 2\times 10^{-3}\alpha_1$ rad/half-revolution period for HTP. The second term also causes *noncumulative* effects per half-revolution periods of $\sim 2\times 10^{-9}\alpha_2$ rad for EFG and $2\times 10^{-6}\alpha_2$ rad for HTP. The last term causes a *cumulative* effect per revolution of $\sim 10^{-6}\alpha_2$ rad for HTP and none for EFG. The EFG techniques claim to be able to measure angles of at least as small as 10^{-9} rad and we see that both effects should be measureable.

The effects on the perihelion motion induced by the α_1 and α_2 terms are indeed small. The α_3 term, however, produces a *noncumulative* perihelion advance of $4e^{-1}\alpha_3(GM/ac^2)^{1/2}$ for orbits with $e>\alpha_3(GM/ac^2)^{1/2}$; the observed perihelion motion of mercury indicates that $\alpha_3<10^{-4}$! This is the same magnitude as the limit obtained by Schiff on possible C nonconservation. This makes the P- and T-nonconserving effects the best bet for observation. A positive effect of that type would absolve K mesons from being the sole violators of CP invariance.

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[8]N. Ramsey, unpublished. Also, see P. B. Miller, W. B. Dress, J. K. Baird, and N. F. Ramsey, Phys. Rev. Lett. 19, 381 (1967). It is, in principle, possible that for α's obtained by the neutron experiments are different from the ones obtained by EFG and HTP.

Precision Measurement of the Decay Rate of Orthopositronium in SiO_2 Powders*

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The decay rate of orthopositronium is found to depend linearly on the mass per free volume in powders of SiO_2 with grain radii of 35 and 70 Å. Three data points have a decay rate significantly less than both the theoretical free-space decay rate and the results of previous experiments. The value of λ_3 extrapolated to zero density, $7.104 \pm 0.006\ \mu sec^{-1}$, is $(1.9 \pm 0.1)\%$ below the theoretical value of the free-space lifetime. Possible interpretations of these results are discussed.

The measurement of the decay rate of the $n=1$ $^3S_1$ state of positronium (o-Ps) provides a clean test of quantum electrodynamics, since to high order the constituent leptons interact only through the electromagnetic interactions. The theoretical value of the decay rate of o-Ps including radiative corrections is[1-3]

$$\lambda_3^{\text{free}} = \lambda_3^{\text{free}}(0)[1 + (\alpha/\pi)(1.86 \pm 0.45)] = 7.242 \pm 0.008\ \mu\text{sec}^{-1}, \tag{1}$$

where

$$\lambda_3^{\text{free}}(0) = \frac{2}{9}\frac{\alpha^6}{\pi}\frac{mc^2}{\hbar}(\pi^2 - 9) = 7.212\ \mu\text{sec}^{-1} \tag{2}$$

is the decay rate neglecting radiative corrections.

Previous experiments to determine the free annihilation rate have been performed in gases at pressures ranging from about 1 to 10 atm. The decay rate of o-Ps is measured as a function of gas density and the free annihilation rate is interpreted as the decay rate obtained from a linear extrapolation to zero density. This requires an extrapolation of about 5% in λ_3. The results are $7.262 \pm 0.015\ \mu sec^{-1}$[4] and $7.275 \pm 0.015\ \mu sec^{-1}$.[5] Other results have been reported[6] but are not considered to be precision measurements of λ_3^{free}.[7] Thus, the average experimental value is about $2\frac{1}{2}$ standard deviations above theory.

We have attempted to determine the free annihilation rate in a low-density finely divided powder instead of a gas. The compact size (2 in. diameter) of the powder target permits a high γ detection efficiency which reduces noise and also allows, for the first time, a direct measurement of λ_3 by detecting all three of the annihilation γ rays in coincidence. In addition, the extrapolation to zero powder density is less than 1% of λ_3. The possibility that such an extrapolation may actually be interpreted as λ_3^{free} will be discussed at the conclusion of our paper where we present various interpretations of our data. We have selected two samples of silicon dioxide manufactured by Cabot Inc. (Cab-o-sil) which consist of roughly spherical primary particles with average radii of 35 and 70 Å. If Ps is excluded entirely from the powder grains[8,9] and interacts with the grains only during collisions, then the parameter analogous to the gas density is the mass per free volume of the powder. Hence we plot the annihilation rate as a function of the dimensionless variable

$$\rho^* = \rho/(\rho_{\text{solid}} - \rho), \tag{3}$$

which is proportional to the free-volume density of the powder. Here ρ_{solid} for SiO_2 is the solid aggregate density of 2.20 g cm^{-3}. The value of ρ^* is changed by compressing the powder over a density range of ρ of 0.03 to 0.26 g cm^{-3}.

The measurements were carried out with a multiple-detector delayed-coincidence γ-ray spectrometer. The system is used to measure the time interval between positron emission and the detection of a predetermined number (1 or 3) of the o-Ps annihilation γ rays. The time-interval measurements are made using an Ortec 467 time-to-amplitude converter (TAC) and a Nuclear Da-