Conjecture on Maximal Violation of T Invariance in Dilepton Production by Neutrinos*

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The conjecture is that CP and T invariances are maximally violated by the weak currents associated with the new ("superstrange") class of hadrons suggested by dilepton production by neutrinos. This accounts for the phenomenon of CP nonconservation in K^0 and $\bar{K}^0$ decay, and the magnitude of η_{+-} is consistent with a superstrange hadron mass within the energy range of the neutrino experiments. Tests of T invariance in such neutrino experiments are suggested.

It has been suggested[1] that the recently observed dimuon production by neutrinos[2] and antineutrinos[3] is evidence for the existence of hadrons having a new quantum number. The purpose of this note is to offer the conjecture that time-reversal invariance is violated maximally by the weak interactions of this new class of hadrons, which I shall call[4] "superstrange hadrons," and to show that not only can the observed CP and T nonconservation of the K^0, $\bar{K}^0$ system be accounted for in this way, but also the magnitude of the Wu-Yang parameter, η_{+-}, measuring that violation can be used to estimate the mass of the lightest superstrange hadron. Furthermore, this conjecture would mean that direct effects of T nonconservation might be manifest in the production of leptons (either in pairs or singly) by neutrinos, and I shall suggest such experiments which should make it possible to verify the conjecture.

The superstrange hadron acting as an intermediary in the dilepton production might be either a boson or a fermion. Only the former will be considered for the sake of simplicity, since the results to be obtained here are independent of that choice. The hadron is assumed to undergo decay by means of a superstrange weak current formed by combining the superstrange field with the field associated with an "ordinary" (i.e., either a nonstrange or a strange) particle. Because of accumulating evidence[5] that a strange particle is associated with dilepton production, I shall use examples of superstrange (ss) currents formed between superstrange- and strange-particle fields, although this has no significant effect on the conclusions to be drawn here. Thus, the ss current associated with a ss boson (B) will be formed by combining the B field with the K-meson field. Examples of the resulting description of dilepton production by neutrinos and antineutrinos are shown in Fig. 1.

My conjecture includes three assumptions: (I) The ss weak current is maximally T and CP nonconserving. (II) That is the only source of a T- and CP-nonconserving interaction. (III) The mass of the ss hadron is greater than the kaon mass, m. CPT invariance is assumed implicitly. The notion of a "maximally" violating current is not uniquely defined, but a useful measure of the degree of violation will be introduced later.

The properties of the neutral kaons to be accounted for are the data[6,7] on the complex parameters η_{+-} and η_{00}. It is well known that assumptions II and III lead to the same predictions for these parameters as the superweak[8] theory, namely

$$\eta_{+-} = \eta_{00} = \epsilon, \tag{1}$$

where ϵ is the parameter[9] describing the mixing of the K^0 and $\bar{K}^0$ states to form the K_S and K_L.

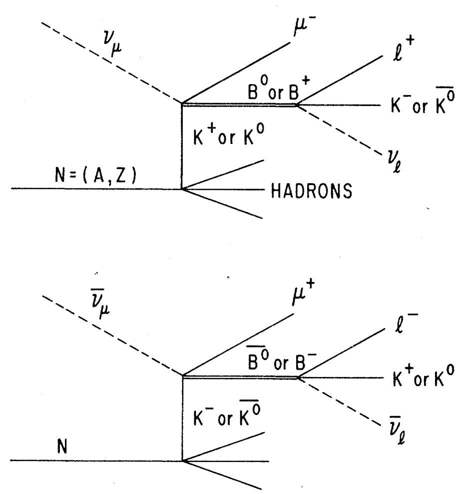

FIG. 1. Dilepton production processes via a superstrange boson.

This parameter may be obtained by the standard solution[10] of the mixing problem in terms of the elements of the mass matrix.

The mass matrix is made up[10] of a dispersive part Δ and an absorptive part Γ:

$$M = \Delta - (i/2)\Gamma . \tag{2}$$

The expressions

$$2i\mu = \langle \bar{K}^0|\Delta|K^0\rangle - \langle K^0|\Delta|\bar{K}^0\rangle \tag{3}$$

and

$$2i\gamma = \langle \bar{K}^0|\Gamma|K^0\rangle - \langle K^0|\Gamma|\bar{K}^0\rangle \tag{4}$$

define real quantities μ and γ in terms of which ϵ may be expressed as

$$\epsilon = \exp(i\varphi_0)(\mu - \tfrac{1}{2}i\gamma)[(\Delta m)^2 + \tfrac{1}{4}\Gamma_S{}^2]^{-1/2} . \tag{5}$$

The "natural" (or "superweak") phase[11] φ_0 appearing here is defined by

$$\tan\varphi_0 = 2\Delta m/(\Gamma_S - \Gamma_L), \tag{6}$$

where $\Delta m = m_L - m_S$, and where m_L and m_S and Γ_L and Γ_S are the masses and decay rates of the long-lived and short-lived neutral kaons, respectively.

It can also be shown easily that assumptions II and III lead to $\gamma = 0$ so that ϵ depends only on the dispersive quantity μ:

$$\epsilon = \mu \exp(i\varphi_0)[(\Delta m)^2 + \tfrac{1}{4}\Gamma_S{}^2]^{-1/2} . \tag{7}$$

These results are consistent with the experimental data on CP nonconservation, but they do not, of course, account for the magnitude[6] $|\eta_{+-}| = 2.3\times 10^{-3}$ of the effect. This additional information will be used here to estimate the mass of the ss hadron by making use of the definition of μ, which also determines $|\eta_{+-}|$ in accordance with Eqs. (1) and (7). The expression, Eq. (3), defining μ may be written in terms of the virtual decay amplitudes[9,10] $A_c(E)$ and $\bar{A}_c(E)$ of the K^0 and $\bar{K}^0$ into channel c at energy E as

$$\mu = \frac{1}{2\pi} \mathrm{P} \int \frac{dE}{E-m} \,\mathrm{Im}\,F(E), \tag{8}$$

with

$$F(E) = \textstyle\sum_c A_c{}^*(E)\bar{A}_c(E) . \tag{9}$$

Equation (7) and the relationship $\Delta m \approx \frac{1}{2}\Gamma_S$ between the measured values[6] yields the result

$$|\epsilon| = \mathrm{P}\int \frac{dE}{E-m}\,\mathrm{Im}\,F(E)/2\sqrt{2}\,\pi\Delta m . \tag{10}$$

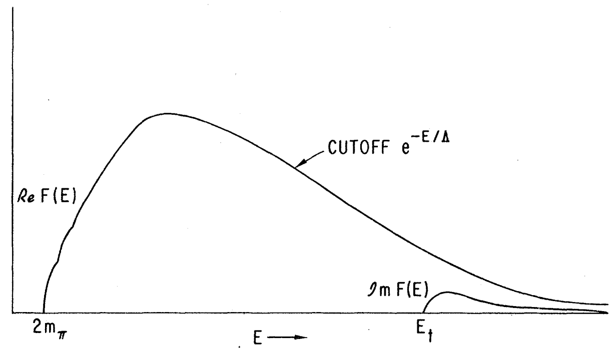

FIG. 2. Schematic illustration of the shapes of $\mathrm{Re}F(E)$ and $\mathrm{Im}F(E)$.

Furthermore, it is easily shown that

$$\Delta m = \frac{1}{\pi}\mathrm{P}\int \frac{dE}{E-m}\,\mathrm{Re}\,F(E) . \tag{11}$$

Therefore, the small value of $|\epsilon|$ is determined by the relative sizes of $\mathrm{Im}\,F(E)$ and $\mathrm{Re}\,F(E)$. $\mathrm{Im}\,F(E)$ is different from zero only for T-nonconserving intermediate states. The essential assumption here is that these superstrange states arise only at high energy, so that $\mathrm{Im}\,F(E)$ will compare with $\mathrm{Re}\,F(E)$ as shown schematically in Fig. 2. The threshold E_t for $\mathrm{Im}\,F(E)$ is determined by the mass of the ss hadron which, in turn, is to be set high enough so that the relative values of the integrals Eqs. (10) and (11) are such as to give $|\epsilon| = 2.3\times 10^{-3}$.

To obtain a rough estimate of the mass, I have made simplifying assumptions about the form of $F(E)$; assumptions which do, however, include the physical content of the model. $\mathrm{Re}\,F(E)$ is taken to be a smooth function with threshold at $2m_\pi$ (the $\Delta S = \Delta Q$ rule excludes the lower semileptonic threshold) and normalized by the known decay rate which gives $\mathrm{Re}\,F(m) \approx \frac{1}{2}\Gamma_S$ by virtue of the dominance of the 2π decay.

The other condition to be satisfied by $\mathrm{Re}\,F(E)$ is that Eq. (11) should lead to the value $\Delta m = \frac{1}{2}\Gamma_S$. However, when $F(E)$ is calculated from Eq. (9) using the usual weak interactions, the integral in Eq. (11) diverges. Therefore, it is necessary to introduce a cutoff to obtain a finite Δm.

Since $\mathrm{Im}\,F(E)$ arises only from T-nonconserving interactions, the ratio $\mathrm{Im}\,F(E)/\mathrm{Re}\,F(E)$ is the measure of T nonconservation. Maximal violation then means that this ratio shall be comparable to the ratio of the number of T-nonconserving channels to the number of T-invariant channels at energy E. Thus, aside from kinematic factors, I shall set $\mathrm{Im}\,F(E) \sim \kappa\,\mathrm{Re}\,F(E)$, where κ is the measure of the degree of violation.

I assume that there are two or more particles in the lowest intermediate state. Consideration of the alternative of a single, neutral ss boson of spin 0 does not change the conclusions. Then $\mathrm{Im}\,F(E)$ vanishes below a threshold, E_t, where E_t is the sum of the particle masses. For $E > E_t$, I assume

$$\mathrm{Im}\,F(E) = \kappa[(E - E_t)/E_t]^{1/2}\,\mathrm{Re}\,F(E). \qquad (12)$$

The ss mass has been estimated by taking $\mathrm{Re}\,F(E)$ to be a smooth function of the form

$$\mathrm{Re}\,F(E) = \tfrac{1}{2}\Gamma_S\left(\frac{E - 2m_\pi}{m - 2m_\pi}\right)^{1/2} \exp\left(-\frac{E - m}{\Lambda}\right), \qquad (13)$$

and Λ has been determined by the condition that Eq. (11) gives $\Delta m = \frac{1}{2}\Gamma_S$ with the result[12] $\Lambda = 7.7m_\pi$.

This expression for $\mathrm{Re}\,F(E)$ may now be used in Eq. (12) to obtain a relationship between κ and the desired mass by requiring that Eq. (10) yield $|\epsilon| = 2.3\times 10^{-3}$. The results[12] for values of κ in the interesting range are as follows:

$$\begin{aligned} E_t &= 14m_\pi \text{ for } \kappa = 0.08, \\ E_t &= 16m_\pi \text{ for } \kappa = 0.1, \\ E_t &= 18m_\pi \text{ for } \kappa = 0.2, \\ E_t &= 20m_\pi \text{ for } \kappa = 0.25, \end{aligned} \qquad (14)$$

Thus, a ss hadron mass of the order of several nucleon masses and a value of κ in the range between $\frac{1}{10}$ and $\frac{1}{3}$ is consistent with the magnitude of the observed CP nonconservation. That range of κ is certainly consistent with the notion of a T-nonconserving ss current comparable in strength with the other weak current.

The range of masses for the ss hadron suggested by this conjecture is consistent with the range of energies accessible in neutrino experiments, in particular in the dilepton experiments. Time-reversal tests in such experiments should provide a means for verifying the conjecture. Although tests of T invariance in processes such as those illustrated in Fig. 1 are complicated by the lack of symmetry between incoming and outgoing states, it is possible to take advantage of the fact that the neutrino acts only through the weak interactions to arrive at some simple conditions which might be subject to test in neutrino experiments.

As long as the reaction cross section involves the weak interaction only in first order, it is proportional to the squared modulus of the matrix element $\langle \mu, X, \text{out}\,|H_w|\,\nu_\mu, N\rangle$, where N is the target nucleus and X includes all outgoing particles except the primary muon. The Coulomb interaction between the muon and hadrons will be neglected here. Then the condition of time-reversal invariance has the same form[13] as it does for weak decay amplitudes:

$$\begin{aligned} &\langle \mu, X, \text{out}\,|H_w|\,\nu_\mu, N\rangle \\ &\quad = \exp(2i\delta_X)\langle -\mu, -X, \text{out}\,|H_w|-\nu_\mu, -N\rangle, \end{aligned} \qquad (15)$$

where the minus signs indicate that the momenta and spin quantum numbers of the particles have been reversed and where $2\delta_X$ is the eigenphase of the S matrix for the hadron system in the final state.

It follows that the condition *imposed by time reversal invariance* on the cross section is

$$\sigma(\nu_\mu, N \to \mu, X) = \sigma(-\nu_\mu, -N \to -\mu, -X). \qquad (16)$$

Then, for example, in the inclusive (ν_μ, μ) reaction on an unpolarized target, only the momenta and spins of the neutrino and muon need be considered in applying Eq. (16). Thus, the existence of an odd term of the form $\vec{p}_\nu \times \vec{p}_\mu \cdot \vec{\sigma}_\mu$ in the inclusive cross section would indicate T nonconservation. Therefore, a *measurement of the polarization of the muon normal to the (ν, μ) production plane provides a test of T invariance.*

This test applies to single lepton as well as to dilepton production. In dilepton production, the secondary lepton is presumed to arise from decay of the ss hadron. Since the amplitude for the decay would satisfy a condition similar to Eq. (15) for a T-invariant interaction, the condition Eq. (16) can be assumed to include the decay products. Therefore, in a (ν, l) inclusive experiment, *polarization of the secondary lepton normal to its production plane is also forbidden by T invariance.*

It is also of interest to consider inclusive dilepton events, those in which both leptons are observed in coincidence but all other particle parameters (except those of the incident neutrino) are averaged. Then the term $(\vec{p}_\nu \cdot \vec{p}_\mu \times \vec{p}_l)$ is excluded by T invariance according to Eq. (16), which suggests a *search for correlation between the normal to the dilepton plane and the direction of the incident beam.*

Finally, in the dilepton case, the spin correlation $(\vec{p}_\nu \cdot \vec{\sigma}_\mu \times \vec{\sigma}_l)$ is excluded by T. Therefore, it is useful to define a "dilepton polarization" as the expectation value $\vec{P} = \langle \vec{\sigma}_\mu \times \vec{\sigma}_l\rangle$ and to *measure the component of $\vec{P}$ along the direction of the in-*

cident neutrino. A nonzero value again implies T nonconservation.

It should be emphasized again that these tests depend directly on the assumption that the reaction amplitude (S-matrix element) is the matrix element of H_w, which is Hermitian. In very-high-energy neutrino interactions, the appearance of these apparently T-nonconserving terms could, instead, be a signal that the weak interactions are no longer weak enough to be treated only in lowest order.

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[9]The mixing parameter, virtual decay amplitudes, etc., are defined here as in R. G. Sachs, Prog. Theor. Phys. 154, 809 (1975).

[10]See, for example, P. K. Kabir, *The CP-Puzzle* (Academic, New York, 1968), Appendix A, p. 99 ff.

[11]T. D. Lee and L. Wolfenstein, Phys. Rev. 138, B1490 (1965); B. G Kenny and P. K. Kabir, Phys. Rev. D 2, 257 (1970).

[12]The integrals were evaluated by means of the computer language SPEAKEASY with the help of S. Cohen, M. Macfarlane, and S. C. Pieper.

[13]See Kabir, Ref. 10, Appendix C, p. 113 ff.

Copious Direct Photon Production: A Possible Resolution of the Prompt-Lepton Puzzle*

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We propose that all direct leptons not due to vector meson decay can be attributed to the decay of virtual photons. At $p_\perp \approx 3$ GeV/c, we expect γ/π, the ratio of direct photons to pions, to be about 10 to 20% for $\sqrt{s} \approx 20$-60 GeV.

The copious production of prompt leptons in hadronic collisions[1-6] has thus far evaded a satisfactory explanation. The problem has been to explain simultaneously the large value of l/π, roughly 10^{-4}, the lack of any threshold or low-$p_\perp$ turnover, at least for electrons, and the apparent equality of the e/π and μ/π ratios. If there were sizable production at large $p_\perp$ of low-invariant-mass virtual photons, which internally converted to lepton pairs, the large l/π ratio and its lack of structure could be explained.[7] At first sight, however, there are two problems with such an explanation: The γ/π ratio required at large $p_\perp$, $\sim 10^{-1}$, seems too large, and e/π should be considerably larger than μ/π, contrary to experimental evidence.[2]

In what follows we present a picture of large-$p_\perp$ bremsstrahlung where, in fact, the γ/π ratio naturally becomes as large as 10^{-1} at large $p_\perp$. In this picture e/μ is really ≈ 2 or 3, the apparent equality of e/π and μ/π being explained as an artifact of the interpretation of the experiments. That is, the large-$p_\perp$ experiments reporting $e/\pi \simeq 1\times 10^{-4}$ have not measured the "true" e/π ratio, since they either overestimated the π^0 spectrum by assuming that there are no η's or direct γ's,[2] or they rejected the low-mass pairs which are responsible for making e/π larger than μ/π.[3] We also show that the low-$p_\perp$ data are qualitatively consistent with this picture.

Now we describe our picture in more detail. At low c.m. momentum, γ/π is surely of order α. However, if it is true that short-distance quark-gluon dynamics becomes important as the momentum transfer increases, we expect γ/π to increase with $p_\perp$ because of the weakening of the strong interactions relative to electromagnetism. Furthermore, dimensional-counting arguments[8] imply that the cross section for large-$p_\perp$ pion production should fall faster by one power of s that that for γ production at fixed x and $\theta_{\text{c.m.}}$, i.e., at 90°, $\gamma/\pi \sim sf(x_\perp)$. Thus there are two