section for charge exchange obtained from our data and compare it with the prediction using the forward dispersion relationships to calculate the real part and the optical theorem to calculate the imaginary part of the forward scattering amplitude. We used the most recent evaluation of the dispersion relation,[10] based upon new Saclay measurements that have been published by Amblard et al.,[11] to make the prediction. The band around the predicted curve is the estimate of the uncertainty on the smooth curve as determined in reference 9. The agreement is seen to be quite good.

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VIOLATION OF *CP* INVARIANCE AND THE POSSIBILITY OF VERY WEAK INTERACTIONS*

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The observation[1] of the decay $K_2^0 \to 2\pi$ provides evidence that the weak interactions are not invariant with respect to the operation CP. The required magnitude of this CP-violating term in the weak-interaction Hamiltonian and the implications for other possible observations depend upon the theoretical model for explaining the $K_2^0 \to 2\pi$ decay. Sachs[2] has provided such a model in which (1) the CP-violating term is maximal in the sense that the $\Delta Q = -\Delta S$ decay interaction is 90° out of phase with $\Delta Q = +\Delta S$ interaction, (2) CP violation would not occur in nonleptonic decays or in leptonic decays other than that of K^0, and (3) the strength of the CP-violating term is comparable to the CP-conserving term. In this note we wish to raise some possible objections to the model of Sachs and to suggest an alternative which essentially satisfies conditions (1) and (2) above but requires that CP-violating weak interactions are weaker than the CP-conserving ones by a factor of 10^7 to 10^8.

The Sachs model is equivalent to a weak interaction Hamiltonian of the following form[3]:

$$H_W = H_L + H_{L0} + H_{L1} + H_{N1} + H_{L,-1}', \tag{1}$$

where the first four terms are the usual weak Hamiltonian even under CP: H_L for purely leptonic processes, H_{L0} for $\Delta S=0$ leptonic, H_{L1} for $\Delta Q=\Delta S$ leptonic, and H_{N1} for $|\Delta S|=1$ nonleptonic. The additional term $H_{L,-1}'$ is odd under CP and yields $\Delta Q=-\Delta S$ leptonic decays. The K^0 eigenstates are written

$$|K_1^0\rangle = N(|K^0\rangle + r|\bar{K}^0\rangle),$$
$$|K_2^0\rangle = N(|K^0\rangle - r|\bar{K}^0\rangle),$$

where $|\bar{K}^0\rangle = CP|K^0\rangle$, and r is a complex admixture coefficient which would equal unity if CP invariance were valid. Since the CP invariance of H_{N1} assures that the amplitude for $K^0\to 2\pi$ equals that for $\bar{K}^0\to 2\pi$, the nonvanishing experimental ratio[1] of 2.3×10^{-3} for the amplitude of $K_2^0\to 2\pi$ with respect to $K_1^0\to 2\pi$ requires[2] $r=1+\epsilon$ with $|\epsilon|=4.6\times10^{-3}$. With Eq. (1) a nonzero value of ϵ is associated with the self-energy term of the form

$$\Delta_L' = \sum_a \frac{\langle K^0|H_{L,-1}'|a\rangle\langle a|H_{L1}|\bar{K}^0\rangle}{E_K - E_a},$$

where the intermediate states $|a\rangle$ contain a lepton pair plus strong-interaction particles. In order that $|\epsilon|\ll 1$, it is required that Δ_L' be much smaller than the usual CP-invariant self-energy term given by

$$\Delta_N = \sum_b \frac{\langle K^0|H_{N1}|b\rangle\langle b|H_{N1}|\bar{K}^0\rangle}{E_K - E_b}.$$

Our possible objections to the Sachs model are these: (1) It is impossible to write the Hamiltonian in the form of a current interacting with itself.[4] (2) $\Delta Q=-\Delta S$ decays are assumed to be of comparable probability with $\Delta Q=\Delta S$ decays although contrary evidence exists, at least for the axial-vector interaction.[5] (3) The argument that $\Delta_L' \ll \Delta_N$ is based on the fact that the width associated with $K\to 2\pi$ which occurs via H_{N1} is known to be much larger than the widths associated with the leptonic decays $K\to\pi+e+\gamma$ which occur via H_{L1} or $H_{L,-1}'$. Arguments with respect to the real parts of Δ_L' and Δ_N are much more difficult to make since both involve divergent integrals. In this connection Ioffe has pointed out[6] that, while in the case of Δ_N it is reasonable to use a cutoff around the nucleon mass M due to the strong interactions among all the particles in states $|b\rangle$, in the case of Δ_L' the states $|a\rangle$ contain a lepton pair so that one of the integrations can only be cut off by a "weak interaction cutoff," Λ, presumably much larger than M. The ratio (Δ_L'/Δ_N) thus contains a factor $(\Lambda/M)^2$ and cannot be said to be small.[7]

As an alternative we suggest that H_W be written in the standard current-current form

$$H_W = (G/\sqrt{2})J^\mu J_\mu^\dagger,$$
$$J^\mu = L^\mu + \mathcal{J}^\mu + \mathcal{S}^\mu - i\alpha T^\mu, \tag{2}$$

where L^μ, $\mathcal{J}^\mu$, and $\mathcal{S}^\mu$ are the usual leptonic, strangeness-conserving, and $\Delta Q=\Delta S$ strangeness-changing currents, respectively, so that H_W contains H_L, H_{L0}, H_{L1}, and H_{N1} in the usual way. The additional current T^μ is a $\Delta Q=-\Delta S$ strangeness-changing current so defined that the factor i assures that the following terms in H_W are odd under CP:

$$H_{L,-1}' = (i\alpha G/\sqrt{2})(L^\mu T_\mu^\dagger - T^\mu L_\mu^\dagger), \tag{3a}$$

$$H_{N1}' = (i\alpha G/\sqrt{2})(\mathcal{J}^\mu T_\mu^\dagger - T^\mu \mathcal{J}_\mu^\dagger), \tag{3b}$$

$$H_{N2}' = (i\alpha G/\sqrt{2})(\mathcal{S}^\mu T_\mu^\dagger - T^\mu \mathcal{S}_\mu^\dagger). \tag{3c}$$

In addition to the CP-violating $\Delta Q=-\Delta S$ leptonic term $H_{L,-1}'$ present in the Sachs model, we have a $|\Delta S|=1$ nonleptonic term H_{N1}' and a $|\Delta S|=2$ nonleptonic term H_{N2}'. The last of these contributes a CP-violating contribution of order αG to the self-energy,

$$\Delta_N' = \langle\bar{K}^0|H_{N2}'|K^0\rangle.$$

In order that the CP-violating factor $\epsilon=r-1$ have a magnitude of 5×10^{-3} it is necessary[8] that $|\Delta_N'/\Delta_N|\simeq 5\times10^{-3}$. Since both Δ_N and Δ_N' involve only strongly interacting particles, it is reasonable that mass factors and cutoffs be of the order of M so that as an order-of-magnitude result we have

$$|\Delta_N'/\Delta_N| \simeq \alpha G/G^2M^2 = 10^5\alpha,$$

or α is between 10^{-7} and 10^{-8}. While such order-of-magnitude arguments are notoriously unreliable, our results really depend only on the fact that α is extremely small.

The model given by Eq. (2) with this extremely small value of α has the following consequences:

(1) The probability of $\Delta Q=-\Delta S$ leptonic decays

is less than those of $\Delta Q = +\Delta S$ by a factor of the order of 10^{15}.

(2) Violations of CP invariance or of T invariance may occur in nonleptonic strangeness-changing decays (due to interference between H_{N1} and H_{N1}') but the relative amplitude of the violating term is only 10^{-7} to 10^{-8}.

(3) No violations of CP invariance or T invariance occur in leptonic decays except for the special case of the K^0. This follows as in reference 2, since H_{L1} and H_{L-1}' must interfere to give a violation, but this is not generally possible since they correspond to $\Delta Q = \Delta S$ and $\Delta Q = -\Delta S$, respectively. The conclusion would not be absolutely true if higher order weak interactions are considered.

(4) $|\Delta S| = 2$ nonleptonic decays are allowed in lowest order via H_{N2}', but this first-order probability is most likely less than the usual second-order probability.

(5) The only observable violations of CP invariance that are not of the order 10^{-7} are consequences of $r \neq 1$. These are effects of order 10^{-2} to 10^{-3}. In addition to $K_2^0 \rightarrow 2\pi$, for example, the ratio of the two charge states in the leptonic decays of K_2^0 would be about 1.006 instead of 1. However, even in these decays, the time-reversal violation would only be of order 10^{-7}. This is in striking contrast to reference 2, where the large effective coupling of $H_{L,-1}'$ allows for large time-reversal violations in K^0 decay.

If $\Delta Q = \Delta S$ is not to be violated at all, the most natural way to introduce CP violation is through a term H_{N1}' of order of magnitude $|\epsilon|$. In this case the CP-violating interaction would be intermediate in strength between that of the model discussed here and the "full strength" of the weak interaction as in reference 2.[9]

The most interesting point of the model discussed here lies in the possibility that the experiment of reference 1 may measure an interaction as much as 10^7 or 10^8 times weaker than the standard weak interactions. If this is the case it may prove extremely difficult to observe CP violation (or T violation) in independent ways.

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[8]We assume here that the only important CP-violating contribution to the self-energy matrix comes from the first-order term Δ_N'. In particular, the second-order term Δ_L', the relative smallness of which in the Sachs model was questioned above, now contains the small factor α so that in our model we believe $\Delta_L'/\Delta_N \ll 10^{-3}$. It is also assumed that the factor $|\zeta - 1| \ll 10^{-3}$, where ζ defined by Sachs[2] is $A(\bar{K}^0 \rightarrow 2\pi)/A(K^0 \rightarrow 2\pi)$, so that we obtain the same value for $|r-1|$ as Sachs. This assumption is based on the fact that $\zeta - 1$ is proportional to the ratio of the contribution of H_{N1}' to $K^0 \rightarrow 2\pi$ to that of H_{N1} and so is expected to be of order α. Since we find α to be between 10^{-7} and 10^{-8} our assumptions are justified even if our order-of-magnitude result for α is too low by three orders of magnitude.

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