butions are anisotropic, and in particular that of the nucleons is strongly peaked in the forward-backward directions. Similar angular distributions are found for the baryons in the three-body reactions $pp \rightarrow YNK$.

The main conclusions from this experiment are: The dominant process of Λ production is associated with $Y_1^*(1385)$ formation, i.e., Λ is mainly produced by the reaction $pp \rightarrow Y_1^*NK \rightarrow \Lambda\pi NK$. Other possible modes of Λ production like direct production or as a decay product from nucleonic resonances $N^* \rightarrow YK$ are small or unimportant in $pp \rightarrow YNK\pi$ at 5.52 GeV/c.

In the present work it is difficult to detect the formation of $Y_0^*(1405)$ resonance via the neutral (i.e., $\Sigma^0\pi^0$) decay mode. The only type of events identified as Σ^0 events are those in which there are no invisible neutral particles. The number of Σ^0 events thus identified is small and in agreement with a minor contribution of Σ^0 production through nonresonating states.

It seems that in events of the type $pp \rightarrow \Sigma^0(\Lambda)NK$, where either the Σ^0 or the Λ does not belong to a Y_1^*, the N-π pair is associated with the formation of the $N_{3/2}^*(1235)$ resonance.

The lack of direct evidence for the K^* resonance formation and the small cross section for K-$\bar{K}$ production show that the formation of mesonic resonances in the pp reaction at 5.52 GeV/c is unimportant.

We would like to express our gratitude to CERN and to the hydrogen bubble chamber crew for enabling us to have the p-p exposure, and to the CERN programming group for help in the adaptation of CERN programs to our computer.

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[1]A similar experiment was carried out at 2.85 GeV by R. I. Louttit et al., Phys. Rev. 123, 1465 (1961).

[2]For the evaluation of the total cross section and beam contamination, see B. Haber, M.S. thesis, The Weizmann Institute of Science, Rehovoth, Israel, 1964 (unpublished).

[3]This is in good agreement with the value of 41.6 ±0.6 mb at 5.83 GeV/c by A. N. Didden et al., Phys. Rev. Letters 9, 32 (1964).

[4]However, the large amount of $Y_1^*(1385)$ formation (see further in the text) supports the identification of the Λ^0 events in the experiment.

[5]C. Robinson, M.S. thesis, The Weizmann Institute of Science, Rehovoth, Israel, 1964 (unpublished); and private communication. The calculations follow E. Ferrari [Phys. Rev. 120, 988 (1960)] and E. Ferrari and F. Selleri [Nuovo Cimento, Suppl. 24, 453 (1962)], extended to 5.5 GeV/c, and using recent data on πN and KN interactions.

POSSIBILITY OF CP VIOLATION IN $\Delta I = \frac{3}{2}$ DECAY OF THE K^0 MESON*

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The existence of the decay mode $K_2^0 \rightarrow \pi^+ + \pi^-$ has recently been reported by Christenson, Cronin, Fitch, and Turlay.[1] This establishes the violation of CP invariance. The branching ratio of $K_2^0 \rightarrow \pi^+ + \pi^-$ relative to $K_1^0 \rightarrow \pi^+ + \pi^-$ is 2.6 $\times 10^{-6}$. In view of this small branching ratio Sachs[2] proposes that this small effect may be an indirect consequence of the maximum violation of CP in the leptonic decay of the K^0 meson. Interesting consequences of this assumption can be readily checked by experiments as discussed by Sachs.

In this note we take a somewhat different viewpoint. We assume that in the (strangeness-changing) decay of the K meson which obeys the $\Delta I = \frac{1}{2}$ rule, CP is conserved, while in the decay which violates this rule CP is violated. Our motivation is inspired by the fact that there is evidently a connection between the strength of interactions and their symmetry property. The presence of the $\Delta I = \frac{3}{2}$ amplitude, as evidenced by the decay of $K^+ \rightarrow \pi^+ + \pi^0$, is at least one order of magnitude smaller than that which obeys the $\Delta I = \frac{1}{2}$ rule.[3] Admittedly, our assumption is quite speculative; however, if checked experimentally it might provide some insight to the weak decay mechanism. We have implicitly assumed that the existence of the decay mode $K^+ \rightarrow \pi^+ + \pi^0$ is not a consequence of electromagnetic violation of a strict $\Delta I = \frac{1}{2}$ weak interaction. Schwinger[4] has recently constructed a model for the decay of $K^+ \rightarrow \pi^+ + \pi^0$ without invoking electromagnetic effect, and pointed out the difficulty in a model with strict $\Delta I = \frac{1}{2}$ rule. The recent experiment on $K^+ \rightarrow \pi^+ + \pi^0 + \gamma$ by Cline and Fry[5] indicates that the rate and charged-pion spectrum are quite consistent with the inner bremsstrahlung and that there is no evidence for the amplitude for direct emissions of the photon from the decay vertex which would be expected to be large if the decay $K^+ \to \pi^+ + \pi^0$ was due to electromagnetic violation of the $\Delta I = \frac{1}{2}$ rule. We shall show below that our assumption can be tested easily by measuring the branching ratio b_2 of $K_2^0 \to \pi^+ + \pi^-$ relative to $K_2^0 \to \pi^0 + \pi^0$. In the Sachs model as well as in the model with small CP violation in both $\Delta I = \frac{1}{2}$ and $\Delta I = \frac{3}{2}$ amplitudes, this ratio is expected to be the same as the branching ratio b_1 of $K_1^0 \to \pi^+ + \pi^-$ to $K_1^0 \to \pi^0 + \pi^0$. Our model predicts that b_2 departs substantially from this value.

We shall define the states $|K_1^0\rangle$ and $|K_2^0\rangle$ as follows[6-9]:

$$|K_1^0\rangle = (p|K^0\rangle + q|\bar{K}^0\rangle)/(|p|^2 + |q|^2), \tag{1a}$$

$$|K_2^0\rangle = (p|K^0\rangle - q|\bar{K}^0\rangle)/(|p|^2 + |q|^2), \tag{1b}$$

where p and q are the off-diagonal elements, and are given by[6]

$$p^2 = \sum_n \frac{\langle K_0|H_w|n\rangle\langle n|H_w|\bar{K}_0\rangle}{E_0 - E_n - i\epsilon}, \tag{2a}$$

$$q^2 = \sum_n \frac{\langle \bar{K}_0|H_w|n\rangle\langle n|H_w|K_0\rangle}{E_0 - E_n - i\epsilon}, \tag{2b}$$

where the sum is extended over all intermediate states. We define the following amplitudes[7,9]

$$\langle K^0|H_w|2\pi, T=0\rangle = C_0 e^{i\delta_0},$$

$$\langle K^0|H_w|2\pi, T=2\rangle = C_2 e^{i\delta_2}. \tag{3a}$$

It follows that

$$\langle \bar{K}^0|H_w|2\pi, T=0\rangle = C_0^* e^{i\delta_0},$$

$$\langle \bar{K}^0|H_w|2\pi, T=2\rangle = C_2^* e^{i\delta_2}. \tag{3b}$$

We write

$$C_2 = |C_2| e^{-i\varphi_2},$$

$$C_0 = |C_0| e^{-i\varphi_0},$$

$$C_2/C_0 = x\, e^{-i(\varphi_2 - \varphi_0)},$$

where

$$x = |C_2/C_0| \text{ and } (q/p)^2 = \eta^2 e^{2i\theta}$$

with η real. The value of x is estimated by using the experimental information on the decay rate of $K^+ \to \pi^+ + \pi^0$ and $K_1^0 \to \pi^+ + \pi^-$: $x \simeq 0.04$. The branching ratio R of $K_2^0 \to \pi^+ + \pi^-$ relative to $K_1^0 \to \pi^+ + \pi^-$ is

$$R = \left| \frac{\sqrt{2}[1 - \eta e^{i(2\varphi_0 - \theta)}] - x\, e^{i(\delta_2 - \delta_0 + \varphi_0 - \varphi_2)}[1 - \eta e^{i(2\varphi_2 - \theta)}]}{\sqrt{2}[1 + \eta e^{i(2\varphi_0 - \theta)}] - x\, e^{i(\delta_2 - \delta_0 + \varphi_0 - \varphi_2)}[1 + \eta e^{i(2\varphi_2 - \theta)}]} \right|^2, \tag{4}$$

while the branching ratio b_2 of $K_2^0 \to \pi^+ + \pi^-$ relative to $K_2^0 \to 2\pi^0$ is

$$b_2 = \left| \frac{\sqrt{2}[1 - \eta e^{i(2\varphi_0 - \theta)}] - x\, e^{i(\delta_2 - \delta_0 + \varphi_0 - \varphi_2)}[1 - \eta e^{i(2\varphi_2 - \theta)}]}{[1 - \eta e^{i(2\varphi_0 - \theta)}] - \sqrt{2}x\, e^{i(\delta_2 - \delta_0 + \varphi_0 - \varphi_2)}[1 - \eta e^{i(2\varphi_2 - \theta)}]} \right|^2, \tag{5}$$

and a similar expression for b_1 (CPT invariance has been assumed throughout). The Sachs' model corresponds to putting $\varphi_0 = \varphi_2 = 0$; therefore, b_2 is identical to b_1, the branching ratio of $K_1^0 \to \pi^+ + \pi^-$ and $K_1^0 \to \pi^0 + \pi^0$. This is certainly also true if $\varphi_0 = \varphi_2$, i.e., CP violates equally in $T = 0$ and $T = 2$ states. In our model, since $\varphi_0 = 0$ but $\varphi_2 \neq 0$, and $\varphi_2 \gg \theta$, η is expected to be near unity. It is clear that, although x is small, the quantity $x[1 - \eta e^{i(2\varphi - \theta)}]$ can be comparably larger than $\sqrt{2}(1 - \eta e^{-i\theta})$ by making the phase φ_2 substantially larger than θ. This means that while the $T = 2$ amplitude is not important in the branching ratio b_1 of K_1^0, it is quite important in the K_2^0 decay. This should provide a sensitive test of our model. The remaining part of this Letter is devoted to the construction of such a model to illustrate our point of view.

Our task is to calculate the quantities p^2 and q^2 as defined by Eqs. (2a) and (2b). We shall make the usual assumption that the two-pion mode in the $T = 0$ state dominates the dispersion integral because of its larger coupling constant and its low mass.[10] Under the assumption of a strict $\Delta S = \Delta Q$ rule, the leptonic processes do not contribute to p^2 and q^2. The contribution of these processes would be nonvanishing if there was a violation to this rule, i.e., the existence of a $\Delta S = -\Delta Q$ transition, but there are no firm experimental evidences that this amplitude is large.[11] The $\Delta I = \frac{3}{2}$ amplitude as obtained from the decay rate of $K^+ \to \pi^+ + \pi^0$ is comparable to the $\Delta S = \Delta Q$ amplitude, so it must be taken into account. Denote p_0^2, q_0^2 the off-diagonal contribution to the self-energy dispersion integral due to the two pion in $T = 0$ state, and similarly p_2^2, q_2^2, due to the two pion in the $T = 2$ state. We have $p^2 = p_0^2 + p_2^2$, $q_0^2 + q_2^2 = q^2$. We shall assume that the pion-pion interaction is obtained by summing the bubble graphs corresponding to an interaction Lagrangian $-4\pi\lambda(\phi\cdot\phi)^2$. The effect of crossing is neglected.[12] The K-2π interaction is assumed to be of the point type. Typically, we have to evaluate the following type of the self-energy operator:

$$\pi(s) = \frac{C^2}{\pi}\int_4^\infty ds' \frac{[(s'-4)/s']^{1/2} |1/D(s')|^2}{(s'-s-i\epsilon)}, \qquad (5)$$

where

$$1/D(s) = \exp\frac{s-s_0}{\pi}\int_4^\infty ds' \frac{\delta(s')}{(s'-s-i\epsilon)(s'-s_0)}.$$

It was shown[13] that this integral can be split into two parts. One involves the product of right- and left-hand cuts in the pion-pion scattering equation, and the other is expressed in terms of the discontinuity across the left-hand cut of the $1/N$ function. In our model, we have

$$\pi(s) = C^2/ND(s), \qquad (6)$$

where N is the N function and is simply a constant.

The real and imaginary part of p_0^2 is simply related

$$\mathrm{Re}p_0^2/\mathrm{Im}p_0^2 = \cot\delta_0,$$
$$\mathrm{Re}p_2'^2/\mathrm{Im}p_2'^2 = \cot\delta_2, \qquad (7)$$

and similar relations for q_0^2 and $q_2'^2 \cdot p_2'^2$ and $q_2'^2$ are related to p_2^2 and q_2^2 by $p_2^2 = p_2'^2 e^{-2i\varphi_2}$, $q_2^2 = q_2'^2 e^{2i\varphi_2}$. It is clear that $p_2'^2 = q_2'^2$ and $p_0^2 = q_0^2$. Since the imaginary part of p^2 is related to the decay rate, we have

$$|p_2/p_0|^2 = |C_2/C_0|^2 \cot\delta_2/\cot\delta_0. \qquad (8)$$

The expressions for $\cot\delta$ are given by Chew and Mandelstam.[12] In our model the mass difference Δm is mainly determined by tht two-pion $T = 0$ state. Taking the value of $\Delta m \approx 1/\tau_1'$,[14] τ_1 being the lifetime of K_1^0, we obtain the pion-pion coupling constant $\lambda = -0.12$,[15] which corresponds to scattering lengths $a_0 = 1.0$ and $a_2 = 0.3$ (in unit of pion-Compton wavelength). At the mass of K meson $\cot\delta_2/\cot\delta_0 = 2.45$; therefore $|p_2/p_0|^2 \approx 1/200$. It is simple to see that

$$\theta = 2|p_2/p_0|^2 \sin 2\varphi_2, \qquad (9a)$$

$$1-\eta e^{-i\theta} = |p_2/p_0| \sin 2\varphi_2 \times[-2\sin(\delta_0-\delta_2) + i|p_2/p_0|]. \qquad (9b)$$

Using the experimental data on the branching ratio $R = 2.6\times10^{-6}$, we obtain $\varphi_2 = 0.033$ radian. The branching ratio b_2 is equal to 0.85 instead of 2. The charge asymmetry[5] in the leptonic decay of K_2^0 is simply $1-|q/p|^2$ and is equal to 0.4% in our model. (If we assume that CP violation is due mainly to the $\Delta I = \frac{1}{2}$ transition, the phase $\varphi_0 \simeq 1.8\times10^{-3}$, which is considerably smaller. The charge asymmetry is zero.) One can see that although the angle φ_2 is very small, which corresponds to a small CP violation, it can produce a large effect in the branching ratio b_2. The charge asymmetry is quite small and may be difficult to measure.

To end this Letter we would like to argue that even if there is a large $\Delta S = -\Delta Q$ amplitude, our conclusion remains valid as long as there is no maximum violation of CP invariance in the leptonic processes,[2] and that the contribution of the leptonic interactions to the real part of the self-energy matrix is of the same order as its imaginary part.[2,10,13] Our assumption of the existance of CP violation in $\Delta I = \frac{3}{2}$ transition might induce a CP violation in the leptonic decays of K^0 (see the model by Schwinger[4]). Since the phase angle φ_2 is already quite small, we do not expect a large CP violation here. If our theory is correct, there is no reason why it should be applied only to the decay of K meson. Experimental checks on the possibility of CP violation in $\Delta I = \frac{3}{2}$ decay of Λ, Σ, and Ξ are of great interest.

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Note added in proof.—Several authors[16] have proposed that the occurrence of the $\pi^+\pi^-$ decay mode of the long-lived components of the neutral K^0 in reference 1 can be explained in a CP-invariant way. Cosmological effects have been assumed. We wish to point out a rather obvious point that if experimental results show b_2 different from b_1 there is no doubt that CP is violated in the two-pion decay mode independent of any cosmological or regeneration effects. If b_2 is equal to b_1 our theory of CP violation in $\Delta I = \frac{3}{2}$ decay is incorrect, but no conclusion can be reached whether CP is actually violated or not. Needless to say, the experiment proposed here is of great interest.

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[1]J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964).

[2]R. G. Sachs, to be published.

[3]To simplify our discussion we assume that the $\Delta I = \frac{5}{2}$ amplitude is zero.

[4]J. Schwinger, Phys. Rev. Letters 12, 630 (1964). The effect of the strong interaction due to the pion-pion interaction in the $T = 2$ state can be taken into account by the method of Fermi [E. Fermi, Nuovo Cimento, Suppl. 2, 17 (1955)]. It is simple to translate the Fermi enhancement factor into the dispersion-relation language. This factor is simply $e^{u(m_K^2)-u(-\Lambda)}$, where $e^u = 1/D$ and Λ is the inverse of the square of the decay radius. Using the formula for the scattering length as given by reference 12, the enhancement factor is

$$\frac{\dfrac{1}{a_2}+\dfrac{2}{\pi}\left(\dfrac{y}{y-1}\right)^{1/2}\ln[(y-1)^{1/2}+y^{1/2}]}{\dfrac{1}{a_2}+\dfrac{2}{\pi}\left(\dfrac{\nu_K}{\nu_K+1}\right)^{1/2}\ln\left[\nu_K^{1/2}+(\nu_K+1)^{1/2}-i\left(\dfrac{\nu}{\nu+1}\right)^{1/2}\theta(\nu)\right]},$$

where $\Lambda = 4(y+1)$ and $m_K^2 = 4(\nu_K+1)$. If a_2 is small and the radius of decay not too small, this factor is close to unity so that Schwinger is justified in neglecting the pion-pion final-state interaction.

[5]D. Cline and W. F. Fry, Phys. Rev. Letters 13, 101 (1964).

[6]T. D. Lee, R. Oehm, and C. N. Yang, Phys. Rev. 106, 340 (1957).

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[11]L. Kirsch, R. J. Plano, J. Steinberger, and P. Franzini, Phys. Rev. Letters 13, 35 (1964); U. Nauenberg, P. Schmidt, J. Steinberger, S. Marateck, and R. J. Plano, Phys. Rev. Letters 12, 679 (1964).

[12]G. F. Chew and S. Mandelstam, Phys. Rev. 119, 467 (1960).

[13]Tran N. Truong, to be published.

[14]For the latest experimental data on K_1^0-K_2^0 mass difference, see International Conference on Fundamental Aspects of Weak Interactions (Brookhaven National Laboratory, Upton, New York, 1963).

[15]This choice of λ corresponds to attractive pion-pion interactions and $\Delta m < 0$, K_2^0 heavier than K_1^0. At present, the experimental status of the sign of Δm is not settled (see reference 14). Should it turn out that $\Delta m > 0$, we should choose λ positive, corresponding to repulsive interactions.

[16]F. Gürsey and A. Pais, unpublished; J. Bernstein, N. Cabibbo, and T. D. Lee, to be published. Gürsey and Pais have explicitly pointed out that their model predicts b_2 equal to b_1.