In conclusion, we want to discuss the implications of CP and time-reversal invariance in the equations

$$\langle 2\,|\,T\,|K\rangle = e^{i\delta_2'} iA_2', \quad \langle 2\,|\,T\,|\bar{K}\rangle = -e^{i\delta_2'} iA_2'^*.$$

TCP invariance gives $\delta_2' = \delta_2$, whereas maximal TCP nonconservation gives $\delta_2' = \delta_2 \pm \frac{1}{2}\pi$. CP invariance gives $\mathrm{Im}A_2' = 0$ and maximal CP nonconservation gives $\mathrm{Re}A_2' = 0$, independently of TCP invariance. Thus, as in the previous analysis,[2] $\mathrm{Re}A_2'$ ($\mathrm{Im}A_2'$) contributes to a CP-conserving (CP-nonconserving) amplitude. The implications of time-reversal invariance are summarized in Table I.

Further discussion on the implications of Eq. (10) will be presented in a subsequent paper.

I wish to thank Dr. A. Di Giacomo for discussions.

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[2] For a review see J. S. Bell and J. Steinberger, in Proceedings of the Oxford International Conference on Elementary Particles, 1965 (Rutherford High Energy Laboratory, Chilton, Berkshire, England 1966); T. D. Lee and C. S. Wu, Ann. Rev. Nucl. Sci. 16, 511 (1966).

[3] W. D. Walker, J. Carrol, A. Garfinkel, and B. Y. Oh, Phys. Rev. Letters 18, 630 (1967).

[4] The phenomenological analysis of the $K \rightarrow 2\pi$ decays does not require substantial changes if TCP does not hold. The physical states $|K_L\rangle, |K_S\rangle$ may be written in the following form in terms of $|K_1\rangle, |K_2\rangle$: $|K_L\rangle \simeq |K_2\rangle + \epsilon_L |K_1\rangle$, $|K_S\rangle \simeq |K_1\rangle + \epsilon_S |K_2\rangle$. Here, independently of TCP invariance, a phase convention may be made so that ϵ_L is real (TCP invariance requires $\epsilon_L = \epsilon_S$). So the analysis of $K_L \rightarrow 2\pi$ is the same as in the case of TCP invariance. On the other hand, in the $K_S \rightarrow 2\pi$ decays the contribution from the $\epsilon_S |K_2\rangle$ term may be neglected as of the order of 10^{-6} and again the situation is the same as in the case of TCP invariance. The only significant change is in $\langle L\,|\,S\rangle \simeq \epsilon_L + \epsilon_S$, which may now be complex, whereas if TCP invariance is assumed $\langle L\,|\,S\rangle = 2\epsilon_L = \text{real}$. However, the experimental data on $\langle L\,|\,S\rangle$ are still affected by large errors, which are comparable with the theoretical errors arising by putting $\epsilon_S = \epsilon_L$. The same considerations hold for the phase φ_{+-}. A more detailed analysis of this point will be presented in a subsequent paper.

NEW EXPERIMENTAL LIMIT ON $\Delta S = -\Delta Q$ LEPTONIC DECAYS OF Σ^+ HYPERONS*

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(Received 30 October 1967)

No $\Sigma^+ \rightarrow n + l^+ + \nu$ decay was found in a rapid scan of 550 000 hydrogen bubble chamber pictures exposed to a stopping K^--meson beam. Based on the 260 $\Sigma^- \rightarrow n + l^- + \bar{\nu}$ events found in the same scan, the upper limit (90% confidence level) for the ratio of Σ^+ to Σ^- leptonic decay rates is 0.034.

We have scanned 550 000 pictures of the Brookhaven National Laboratory 30-in. hydrogen bubble chamber exposed to stopping K^- mesons at the Brookhaven alternating-gradient synchrotron for hyperon leptonic decays. A total of 260 strangeness-changing Σ^- leptonic decays have been found, but no corresponding Σ^+ leptonic decays. After correcting for the difference in production rates and effective observation time, this gives a limit[1] for Σ-hyperon leptonic decays

$$w(\Delta S = -\Delta Q)/w(\Delta S = +\Delta Q) \leqslant 3.4\%.$$

The film is estimated to contain two million Σ^- and one million Σ^+ hyperons produced in the reactions $K^- + p \rightarrow \Sigma^\pm + \pi$. The scan was for events in which the decay secondary from the hyperon looked like a lepton rather than a pion. The criterion for an electron candidate (positive or negative) was that it be distinguishable by ionization, spiral configuration (a turn through at least 180°), or having an energetic knock-on. The muons were required to stop in the chamber and then decay into electrons. The scan criteria were identical for Σ^+ and Σ^- events and the kinematics are nearly the same so we believe that the relative scanning efficiencies for Σ^+ and Σ^- leptonic decays are the same.

Each potential leptonic decay event was measured and then examined carefully by a physicist. The bubble density was measured for each positive electron track if there were any possibility that the track might have been caused by a muon or pion. Each stopping muon track was examined carefully for $\pi \rightarrow \mu$ kinks. In order to eliminate spurious background events, several criteria were used: (i) length of $\Sigma^{\pm} > 1$ mm; (ii) residual momentum of Σ^{-} at decay > 80 MeV/c; (iii) lepton has a dip $<60°$, or it is an obvious spiraling electron; and (iv) hypothesis $K^{-}+p \rightarrow \Sigma^{\pm}+\pi$ for production of the $\Sigma^{\pm}$ must have a good kinematic fit, and the Σ must be clearly visible in at least two views.

Further, each leptonic channel had an important additional criterion imposed on the momentum of the decay lepton in order to eliminate physical decay modes of Σ hyperons that are not of the type $\Sigma^{\pm} \rightarrow n+l^{\pm}+\nu$: (v) For electrons, $P_{e^{\pm}} > 70$ MeV/c; (vi) for stopping muons, 32 MeV/$c < P_{\mu^{\pm}} < 80$ MeV/c.

Condition (v) was imposed so as to eliminate the decays $\Sigma^{\pm} \rightarrow e^{\pm}+(\Lambda)+\nu$, where the Λ decays via the neutral mode. [We found five events of the type $\Sigma^{+} \rightarrow e^{+}+$ neutrals with $P_{e^{+}} < 70$ MeV/c as compared with four expected, corresponding to the sample of eight $\Sigma^{+} \rightarrow e^{+}+\Lambda+\nu$, $\Lambda \rightarrow p+\pi^{-}$, events satisfying criteria (i)-(iv), found in the same sample of the film.[2]]

The upper limit on P_{μ} in condition (vi) was imposed on the stopping-muon events so as to eliminate events of the type

$$\Sigma^{\pm} \rightarrow n+\pi^{\pm}, \quad \pi^{\pm} \rightarrow \mu^{\pm}+\nu, \quad \mu^{\pm} \rightarrow e^{\pm}+\nu+\bar{\nu}, \tag{1}$$

in which the $\pi \rightarrow \mu$ decay event is not detectable. One can never eliminate from the stopping-muon sample the rare but not completely negligible possibility of the type

$$\Sigma^{\pm} \rightarrow n+\pi^{\pm}+\gamma, \quad \pi^{\pm} \rightarrow \mu^{\pm}+\nu, \quad \mu^{\pm} \rightarrow e^{\pm}+\nu+\bar{\nu}, \tag{2}$$

in which again the $\pi \rightarrow \mu$ decay is not detectable. The lower limit on $P_{\mu^{+}}$ in condition (vi) is imposed so as to eliminate μ^{+}'s that arise from stopping π^{+}'s either from the reaction chain (2) or from other spurious reactions such as $K^{-}+p \rightarrow (\Lambda)+\pi^{+}+\pi^{-}$.

The criteria (i)-(v) for $\Sigma^{+} \rightarrow e^{+}+$ neutrals events go a long way toward eliminating non $\Delta S=-\Delta Q$ leptonic decay events, but inevitably a very small potential background remains. For example an event of the type $\Sigma^{+} \rightarrow p+\pi^{0}$, $\pi^{0} \rightarrow e^{-}+e^{+}+\gamma$, in which both the decay proton and the e^{-} from the Dalitz decay of the π^{0} are too short to be visible, would simulate a $\Sigma^{+} \rightarrow e^{+}+n+\nu$ event quite satisfactorily.

Table I lists the results of this experiment for the number of $\Sigma^{\pm} \rightarrow l^{\pm}+$ neutrals found to date. Not one candidate of the type $\Sigma^{+} \rightarrow l^{+}+n+\nu$, satisfying the criteria listed above, has been found. To convert these numbers to a ratio of $\Delta S=-\Delta Q$ and $\Delta S=+\Delta Q$ decay rates, one needs only to know the relative number of Σ^{-} and Σ^{+} decays in the film satisfying the required conditions on the Σ tracks. This relative number for Σ's produced from (K^{-},p) events at rest is the product of the factors[3]

$$a=\frac{\text{No. of } \Sigma^{-} \text{ produced}}{\text{No. of } \Sigma^{+} \text{ produced}}=\frac{0.45}{0.21},$$

and

$$b=\frac{\text{Mean time of } \Sigma^{-} \text{ in interval observed}}{\text{Mean time of } \Sigma^{+} \text{ in interval observed}}=1.80.$$

Hence

$$ab=\frac{\text{Effective number of } \Sigma^{-} \text{ observed}}{\text{Effective number of } \Sigma^{+} \text{ observed}}=3.9.$$

Our observation of 260 $\Sigma^{-} \rightarrow l^{-}+n+\nu$ events would imply that we should have seen $260/3.9=67$ $\Sigma^{+} \rightarrow l^{+}+n+\nu$ events, if the rates of $\Delta S=-\Delta Q$ and $\Delta S=+\Delta Q$ decays were equal. Having seen zero such events we can conclude that at the 90% confidence level, the $\Delta S=-\Delta Q$ rate is smaller than the $\Delta S=+\Delta Q$ rate by the factor $(2.3/67)=0.034$.

This result considerably sharpens the older results on hyperon leptonic decay[4,5] which implied an upper limit[6] of 0.08 for the ratio of $\Delta S=-\Delta Q$ to $\Delta S=+\Delta Q$ rates. A few events which are possible Σ^{+} leptonic decays have been reported (one e^{+},[4] one μ^{+} in emulsion[7] and another μ^{+} in a hydrogen bubble chamber[8]), but the number of these is not incompatible with the irreducible backgrounds described above.

Table I. Number of $\Sigma^{\pm} \rightarrow l^{\pm}+$ neutrals that satisfy the criteria described in the text.

			Events found	
			Σ^{-}	Σ^{+}
	$\Sigma^{\pm} \rightarrow n+e^{\pm}+\nu$	($P_e > 70$ MeV/c)	224	0
	$\Sigma^{\pm} \rightarrow n+\mu^{\pm}+\nu$	($32 < P_{\mu} < 80$ MeV/c)	36	0
Total	$\Sigma^{\pm} \rightarrow l^{\pm}+n+\nu$		260	0

As for $\Delta S = -\Delta Q$ leptonic decays for K mesons, the limit $w(K^+ \rightarrow \pi^+ + \pi^+ + e^- + \nu)/w(K^+ \rightarrow \pi^+ + \pi^- + e^+ + \nu) < 0.02$ has been set.[9] In $K_{e_3}{}^0$ decay, the most recent result[10] is $w(K^0 \rightarrow \pi^+ + e^- + \bar{\nu})/w(K^0 \rightarrow \pi^- + e^+ + \nu) = 0.07 \pm 0.05$, less than two standard deviations from zero.

We would like to thank Dr. D. Berley, Dr. A. Prodell, and the crews of the Brookhaven National Laboratory 30-in. hydrogen bubble chamber and the Brookhaven alternating-gradient synchrotron for their generous assistance, and our scanning staff for their persistent and reliable scanning efforts.

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*Work supported in part by the U. S. Atomic Energy Commission under Contract No. AEC-ORO-2504-114.

[1] Throughout this paper all upper limits will be 90% confidence limits.

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