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EVIDENCE FOR THE $\Delta I = \frac{1}{2}$ RULE *

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It has been clear for some time that the experimental data relating to strange-particle decays are suggestively close to the values predicted by the $\Delta I = \frac{1}{2}$ selection rule.[1, 2] The largest discrepancy has been between the limits[3, 2]

$$0.28 \leq B \leq 0.38, \tag{1}$$

predicted for the neutral branching ratio $B \equiv P(K_1^0 \to \pi^0 + \pi^0)/[P(K_1^0 \to \pi^0 + \pi^0) + P(K_1^0 \to \pi^+ + \pi^-)]$, and the values $B = 0.14 \pm 0.06$ found in the Columbia propane bubble-chamber experiment,[4] and $B = 0.06$ (one event) in the MIT lead-plate cloud-chamber experiment.[5] The Prediction (1) is obtained, instead of the prediction $B = 1/3$ of the "pure" $\Delta I = \frac{1}{2}$ rule, if one assumes enough $\Delta I = 3/2$ to account for the decay $K^+ \to 2\pi$.

The particle-mixture theory of Gell-Mann and Pais predicts, for the fraction f of short-lived (K_1^0) decays,

$$f = K_1^0/(\text{all } K^0) = \tfrac{1}{2}. \tag{2}$$

This result is expected from CPT invariance alone, i.e., CP invariance is not needed.[6] If, as seems likely, the 2π modes constitute practically all the short-lived decays,[4] and $K_2^0 \to 2\pi$ is negligible,[7] Eqs. (1) and (2) can be combined to predict, for $\Delta I = \frac{1}{2}$,

$$0.31 \leq R_K \leq 0.36, \tag{3}$$

where $R_K = P(K_1^0 \to \pi^+ + \pi^-)/(\text{all } K^0.)$.

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The corresponding experimental results (previous to the present experiment) are $R_K = 0.42 \pm 0.05$ (Columbia),[4] and $R_K = 0.46 \pm 0.08$ (Michigan propane chamber).[8] These are only in fair agreement with the prediction (3), but when combined with Columbia's $B/2 = 0.07$ give $f = 0.49 \pm 0.08$, in good agreement with the particle-mixture prediction (2).

At the time of the CERN conference, we presented preliminary results, based on 450 decay events observed in our hydrogen bubble chamber, for R_K, and for the Λ branching ratio R_Λ.[8] The $\Delta I = \frac{1}{2}$ rule predicts[9] the value

$$R_\Lambda \equiv P(\Lambda \rightarrow p + \pi^-)/(\text{all } \Lambda) = 2/3. \quad (4)$$

Our preliminary values were in good agreement with the predictions (4) and (3). We reported no results on the $K_1^0 \rightarrow \pi^0 + \pi^0$ mode at that time and thus could not check the predictions (1) and (2).

We have now completed our analysis, and report on a total of 1091 events. Our data show no contradictions with the predictions of the $\Delta I = \frac{1}{2}$ rule. On the contrary they are in remarkable agreement with them.

We have observed 227 double events ($\mathbb{D} = 227$) in which both the Λ and the K^0 decay within the prescribed "fiducial volume" inside the chamber via their charged modes $\Lambda \rightarrow p + \pi^-$ and $K_1^0 \rightarrow \pi^+ + \pi^-$. There are 594 events in which only the Λ is observed to decay via its charged mode ($\Lambda = 594$), and 270 events in which only the K_1^0 is observed to decay via its charged mode ($K = 270$). For each of the 864 single V's, the production and decay dynamics of the observed particle checks with the hypothesis of associated production via either $\pi^- + p \rightarrow \Lambda + K^0$ (Λ production) or $\pi^- + p \rightarrow \Sigma^0 + K^0$ (Σ^0 production).

The branching ratios R_K and R_Λ, and the "true" number of associated productions, n(true), are given by

$$R_K = [D/(\Lambda + D)]\ \eta_K ,$$

$$R_\Lambda = [D/(K + D)]\ \eta_\Lambda ,$$

and

$$n(\text{true}) = [(\Lambda + D)(K + D)/D]\ \eta_0 ,$$

where η_K, η_Λ, and η_0 are escape corrections which would be unity for an infinite chamber. The η's are calculated by averaging over smoothed "true" distributions in the production position and angle. We require that for a Λ or K^0 to be "detectable" its charged decay must occur beyond 0.3 cm from the production point and must lie within the fiducial volume. The fiducial volume is defined by the requirement that all decay tracks be at least 2 cm in length. In the small fraction of single V's in which the production and decay dynamics of Λ and K^0 overlap when curvature and angle measurements alone are used, we measure ionization on the positive decay fragment, to distinguish protons (Λ decay) from π^+ (K_1^0 decay).

The calculated averages of the η's vary only a few percent over the entire incident-pion momentum range, and differ by only a few percent between the Λ and Σ^0 production modes. Therefore we quote here only the "grand average" over all the "true" distributions, which yields the calculated values $\eta_K = 1.249$, $\eta_\Lambda = 1.398$, and $\eta_0 = 1.097$. In performing the averages we use our lifetime values $\tau_K = 0.94 \pm 0.05 \times 10^{-10}$ sec and $\tau_\Lambda = 2.72 \pm 0.16 \times 10^{-10}$ sec. We also calculate the derivatives with respect to lifetimes, with the results $\Delta \ln R_K = + 0.193\ \Delta \ln \tau_\Lambda$ and $\Delta \ln R_\Lambda = + 0.149\ \Delta \ln \tau_K$. The contributions of uncertainties in lifetimes to the uncertainties in R_K and R_Λ are negligible.

The observed counts, D, Λ, and K must be replaced by D/ϵ_2, Λ/ϵ_1, and K/ϵ_1, where ϵ_2 and ϵ_1 are scanning efficiencies for finding double and single V's. By rescanning 30% of the film we find for "detectable" decays, $\epsilon_2 = 0.995 \pm 0.005$, and $\epsilon_1 = 0.976 \pm 0.008$.

The values of R_K and R_Λ obtained at the various beam momenta, 0.95 and 1.03 Bev/c (below Σ^0 threshold), and 1.09, 1.12, and 1.23 Bev/c (above Σ^0 threshold) agree within the errors. Similarly the momentum-averaged Λ-production results agree within one-third standard deviation with the Σ^0-production results. We therefore present only the grand average results, for the fractions of charged decays, and total number of associated productions,

$$R_K = 0.339 \pm 0.020, \tag{5}$$

$$R_\Lambda = 0.627 \pm 0.031, \tag{6}$$

$$n(\text{true}) = 2020 \pm 100. \tag{7}$$

We turn now to the decay $K_1^0 \rightarrow \pi^0 + \pi^0$. We have seen three events consistent with this decay mode; in each case there is an associated charged Λ decay. In one case a π^0 undergoes a "Dalitz decay" into $e^+ + e^- + \gamma$. In the other two cases one of the π^0-γ rays produces an electron pair in the liquid hydrogen. From our experimental K^0 momentum distribution we find the π^0-γ-ray spectrum by assuming isotropy in the K^0 and π^0 decay. Combining this with the known pair-production cross section per hydrogen atom, and including a probability for Dalitz-decay of 2.5×10^{-2} per K_1^0, we find a total detection efficiency per K_1^0 of 3.5×10^{-2}. Our three events thus correspond to $3/3.5 \times 10^{-2}$ = 86 ± 50 decays. The number of accidental counts due to chance coincidences from unassociated electron pairs is estimated from the frequency of pairs, and the chance of fitting the decay dynamics. The result is that less than 0.2 accidental count is expected. (No correction was made.) There were 227 decays $K_1^0 \rightarrow \pi^+ + \pi^-$, associated with charged Λ decays. Therefore, independent of assumptions as to the value of $f = K_1^0/(\text{all } K^0)$, and independent of escape corrections, we find for the fraction B of neutral K_1^0 decays

$$B = 86/(86 + 227) = 0.27 \pm 0.11, \tag{8}$$

which is consistent with Prediction (1). We combine the charged and neutral results (5) and (8) to obtain

$$f = 0.47 \pm 0.080, \quad (9)$$

in good agreement with the particle-mixture-theory prediction (2).

The disagreement between our results (5) and (8), and (9) and those of other groups may be expressed as follows: Both Eisler et al.[4] and we find the "expected" $f = \frac{1}{2}$, but disagree on the admixtures of charged and neutral K_1^0 decays. However, if we combine all experiments without imposing the contraint $f = \frac{1}{2}$ then our charged K_1^0 decays dominate statistically, whereas in the neutral decays the Columbia and MIT results prevail (7 + 1 = 8 events to our 3 events). The internal consistency is furthermore not bad--a χ^2 probability of 18% for the charged decays, and 20% for the neutral. The resulting charged and neutral world averages are R_K (U.C., Col.[4], Mich.[8]) = 0.354 ± 0.018, and B(U.C., Col.,[4] MIT[5]) = 0.141 ± 0.037. (The error on B reflects only the counting statistics.) In the absence of other decay modes of the (short lived) K_1^0 these combine to give $f = 0.424 \pm 0.026$, in disagreement with Prediction (2). If, instead, $f = \frac{1}{2}$ is assumed, then 18 ± 6% of the K_1^0 decays would have to occur by an as yet unknown mode. We believe it is instead more reasonable not to combine the experiments, and to attribute the disagreement to statistical bad luck or systematic error. The χ^2 probability that our charged fraction is consistent with the Columbia-MIT neutral fraction is then about 10^{-3}.

We next consider the decay $\Lambda \rightarrow n + \pi^0$. We have found two Dalitz decays and one γ conversion corresponding presumably, to this mode. In each case there was an associated charged K_1^0 decay. The three events correspond to 171 ± 100 neutral Λ decays. Combining these with the 227 double V's we find $R_\Lambda = 227/(227 + 171) = 0.57 \pm 0.14$. Since we have good reason for believing that the associated-production hypothesis is valid and that there are no prominent Λ decay modes other than the two considered here, this last result can be combined with Result (6) for the charged decays. We thus obtain the weighted average

$$R_\Lambda = 0.624 \pm 0.030. \tag{10}$$

Result (10) is in excellent agreement with the $\Delta I = \frac{1}{2}$ prediction $R = 2/3$, and with other determinations by groups at Columbia,[4,8] Michigan,[8] and MIT,[5,8] as well as with results of the Berkeley K^- -capture experiment.[8] A least-squares weighted average of these results gives R_Λ (U.C., Col., Mich., MIT) = 0.637 ± 0.020.

Finally, Dalitz[1] and Pais and Treiman[10] point out that if the $\Delta I = \frac{1}{2}$ rule is valid one expects $w(K_2^0 \rightarrow \pi^+ + \pi^- + \pi^0) = (2/5)w(K^+ \rightarrow 3\pi)$. Furthermore, the decay rate $w(K_1^0 \rightarrow \pi^+ + \pi^- + \pi^0)$ should be exceedingly small compared with the corresponding K_2^0 rate,[10] so that we may attribute any observed $\pi^+ + \pi^- + \pi^0$ decay to the K_2^0.

We have seen one such decay. The event was associated with a charged Λ decay. However, we would easily detect this decay mode if it occurred as a single V. Corresponding to the total number of associated productions, n(true) = 2020, there should be 1010 K_2^0's. Combining the known K^+ branching ratios[11] and lifetimes[12] and the $\Delta I = \frac{1}{2}$ rule one obtains the prediction $w(K_2^0 \rightarrow \pi^+ + \pi^- + \pi^0) = 2.4 \times 10^6\ \text{sec}^{-1}$. The average potential time for K^0's was 3.5×10^{-10} sec. We therefore expect to find $2.4 \times 10^6 \times 3.5 \times 10^{-10} \times 1010 = 0.85 \pm 0.10$ decays $K_2^0 \rightarrow \pi^+ + \pi^- + \pi^0$. Our single event is thus consistent with the $\Delta I = \frac{1}{2}$ rule.[13]

In summary, we find that our 1091 associated-production and decay events are in remarkably good agreement with the predictions of the $\Delta I = \frac{1}{2}$ rule.

This makes the total experimental evidence for $\Delta I = \frac{1}{2}$ fairly impressive: (a) The decay $\Xi^- \rightarrow n + \pi^-$ occurs, if at all, much less frequently than $\Xi^- \rightarrow \Lambda + \pi^-$. This can be understood if the Ξ has $I = \frac{1}{2}$ and the $\Delta I = \frac{1}{2}$ rule holds. (b) The strong inhibition of $K^+ \rightarrow 2\pi$ relative to $K_1^0 \rightarrow 2\pi$ follows from the $\Delta I = \frac{1}{2}$ rule, if the K has zero spin and $I = \frac{1}{2}$. (c) The admixture of $\Delta I = 3/2$ required to admit the observed $K^+ \rightarrow 2\pi$ rate is in good agreement with our $K_1^0 \rightarrow 2\pi$ branching ratios. (d) The Λ branching ratio agrees with (but does not require[9]) $\Delta I = \frac{1}{2}$. (e) The branching ratio[11, 2] $P(K^+ \to \pi^+ + \pi^- + \pi^0)/(P(K^+ \to \pi^+ + 2\pi^0)$ agrees with (but does not require[14]) $\Delta I = \frac{1}{2}$. (f) The results of Cool et al.[15] on $\Sigma^{\pm}$ decay asymmetry are most easily explained by (but do not require) $\Delta I = \frac{1}{2}$. (g) Our one $K_2^0 \to \pi^+ + \pi^- + \pi^0$ agrees (as well as one event can) with $\Delta I = \frac{1}{2}$.[13]

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