Neutral Decay Modes of the θ_1^0 and Λ^0*

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In a large multiplate cloud chamber, an event has been found which strongly indicates that the decay mode $\theta_1^0 \rightarrow 2\pi^0$ exists, and therefore that the spin of the K meson is even. Two showers are seen which, from their spatial angles and energies, must represent essentially the whole energy of the two π^0's from a θ_1^0 produced in association with a Λ^0. On the basis of this event, the fraction of θ_1^0 decays going by the $2\pi^0$ mode is $\sim$0.06, and the probability that this fraction could be consistent with the value of $\frac{1}{3}$ predicted by $\Delta I=\frac{1}{2}$ selection rule is 3%. Furthermore, the chance that the observed ratio is $\geqslant \frac{1}{4}$, a value possible with an admixture of $\Delta I=\frac{3}{2}$, is 10%. Our observation of single shower events attributable to $\theta_1^0 \rightarrow 2\pi^0$ give even smaller probabilities that the fraction of neutral decays is as large as $\frac{1}{3}$ or $\frac{1}{4}$, but the necessity of a background subtraction makes these results less significant. On the other hand, the fraction of Λ^0 decays going by a neutral decay mode is quite consistent with the value of $\frac{1}{3}$ predicted by the $\Delta I=\frac{1}{2}$ rule. The values obtained for this fraction are 0.22 ± 0.13 from the direct observation of showers (presumably from $\Lambda^0 \rightarrow n+\pi^0$), and 0.33 ± 0.06 from the number of Λ^0's not decaying by the charged mode.

1. INTRODUCTION

A STUDY of the possible neutral decay modes of the θ_1^0 (the short-lived component of the θ^0) and the Λ^0 can yield considerable information about these particles. First, if the neutral decay $\theta_1^0 \rightarrow 2\pi^0$ is observed at all, then the spin of the θ must be even. Secondly, if the neutral decays occur, then a measurement of the fraction, F_θ, of all θ_1^0 decays which go by the neutral mode, and of the similar fraction, F_Λ, of Λ^0 decays, provide a test of ideas concerning the decay mechanism.

For example, since the general features of the decay of hyperons and heavy mesons can be accounted for by the requirement[1] that the third component of isotopic spin change by one-half unit ($\Delta I_3=\pm\frac{1}{2}$) in a decay, it has been conjectured[2] that the stronger selection rule, $\Delta I=\frac{1}{2}$, may be operative. If the latter rule governs the decays of Λ's and θ's, F_θ and F_Λ both should have the value $\frac{1}{3}$,[3,4] neglecting electromagnetic effects. This total isotopic spin selection rule is appealing, since it provides at least a qualitative explanation[4–7] of the large difference between the $K^\pm$ and θ_1^0 lifetimes, and predicts[5–7] within experimental errors the τ'/τ branching ratio. A much weaker result is that, if parity nonconservation in the decays is assumed, the Σ^+/Σ^- lifetime ratio and the decay branching ratio, $(\Sigma^+ \rightarrow p+\pi^0)/(\Sigma^+ \rightarrow n+\pi^+)$, can be made[8,9] consistent with $\Delta I=\frac{1}{2}$.

Some other, more specific mechanisms proposed[3,10–12] to explain hyperon and heavy-meson decays can be looked upon as introducing larger changes in total isotopic spin.[5,9,13,14] In particular, we shall be concerned with the effect of an admixture of $\Delta I=\frac{3}{2}$ on F_θ. Since for a K of even spin the $K^\pm$ decay proceeds by $\Delta I=\frac{3}{2}$, the observed $K^\pm/\theta_1^0$ lifetime ratio provides a limitation on the amount of $\Delta I=\frac{3}{2}$ possible in the predominantly $\Delta I=\frac{1}{2}$ θ_1^0 decay. The result[13] is $0.26<F_\theta<0.41$. These limits may be altered somewhat by including the effect of the mass difference between the charged and neutral pions,[15] but estimates of this effect are at present necessarily somewhat arbitrary. Despite this uncertainty, it is still possible for a measurement of F_θ to provide a strong test of a considerable number of theories.

2. EXPERIMENTAL PROCEDURE

Since the details of the experiment will be given in another paper,[16] only a brief outline will be presented here. A π^- beam was brought out through the magnetic field of the Brookhaven Cosmotron, and after it was deflected through about 8° by a bending magnet, it entered a large multiplate cloud chamber. The chamber, which had a well-illuminated region of about 54 in. $\times$48 in.$\times$20 in., contained 17 iron plates $\frac{1}{2}$ in. thick. The incident pions, which interacted in the plates to produce hyperons and heavy mesons, had a median energy of approximately 1.5 Bev.

About 8000 sets of pictures were taken, each set

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consisting of three stereoscopic views. The pictures were scanned and measured on half-scale projectors, and the measurements were processed using an IBM 650. The results of the machine program included the spatial angle of the tracks, the coplanarities of V's with their origin, maximum and minimum track ranges, ionization corrections, and errors in these quantities from their over determination in three views. Using these results and calculated kinematics of the decays, about 260 Λ^0's and 120 θ^0's were definitely identified.

To measure F_θ, one looks for showers from $\theta^0 \rightarrow 2\pi^0$ when a $\Lambda^0 \rightarrow p+\pi^-$ is seen, but no $\theta_1{}^0 \rightarrow \pi^+ + \pi^-$ or K^+ is observed. While Λ^0+K^+ production can occur only by a secondary process or when a π^- is also produced, such possible K^+ productions were eliminated by discarding those events in which a charged track from the initial π^- interaction went out of illumination, or was consistent with being a K-particle decay. There then remained 166 "pure Λ^0" events. Similarly, to measure F_Λ, one looks for showers from $\Lambda^0 \rightarrow n+\pi^0$ in the vicinity of an observed $\theta_1{}^0 \rightarrow \pi^+ + \pi^-$ decay which is not accompanied by $\Lambda^0 \rightarrow p+\pi^-$ or by a K^-. The latter type of event, K-pair production, was again eliminated by discarding events which could contain charged K's, and there then remained 52 "pure $\theta_1{}^0$" events.

Some of the remaining events occurred in pictures having either such poor quality or so many other tracks that showers could have been missed, and therefore the number of events scanned for showers was reduced to 130 with Λ^0's and 47 with $\theta_1{}^0$'s. While showers had been searched for in the initial scan, each of these selected pictures was looked at again very carefully by at least one physicist.

Whenever a shower was found in the neighborhood of a Λ^0 or $\theta_1{}^0$, its axis was followed back and the shower discarded only if it definitely pointed to a π^- interaction other than the one producing the Λ^0 or the $\theta_1{}^0$. Some cases were included in which the shower axis passed near another origin as well as the strange-particle-producing one, and thus a few such events could be spurious.

For each shower the distance of closest approach between the shower axis and the origin of interest was determined. The shower was discarded if this distance exceeded 6 cm, since an analog computer analysis showed that the number of such showers having greater distances and caused by $\Lambda^0 \rightarrow n+\pi^0$ or $\theta_1{}^0 \rightarrow 2\pi^0$ decays would be negligible. Because of uncertainties in the shower axis direction, we were forced to include showers whose axis apparently passed through the origin, and hence could have been caused by π^0's produced in the π^- interaction, or by γ's from $\Sigma^0 \rightarrow \Lambda^0+\gamma$.

Since the shower sample is contaminated with showers direct from the origin and probably a few showers direct from a wrong origin, a background must be subtracted. This background can be found by looking for showers in the vicinity of interactions in which both a Λ^0 and a $\theta_1{}^0$ are seen, and which therefore can have no neutral strange-particle decays, except $\Sigma^0 \rightarrow \Lambda^0+\gamma$, which is a legitimate contributor to the background. We have 31 such events, of which 27 are suitable for the shower scan.

In order to avoid missing showers and to have shower axes which are reasonably well defined, we invoked the criterion that an event would be classed as a shower only if it consisted of at least three electron track segments. A segment is a section of track which appears in the gas space between two plates. For a direction of incidence normal to the iron plates, three electron segments correspond to the conversion of 80 ± 40 Mev[17] of γ-ray energy.

The probability of our seeing showers consisting of three or more electron segments each from the decays $\Lambda^0 \rightarrow n+\pi^0$ and $\theta_1{}^0 \rightarrow 2\pi^0$ was determined both analytically and by an analog computational method. The analytical procedure used the decay kinematics, along with a numerical integration over the geometry of the chamber. In the other method, a random sample of 20 $\theta_1{}^0 \rightarrow \pi^+ + \pi^-$ and 13 $\Lambda^0 \rightarrow p+\pi^-$ decays were treated as if they had been neutral decays, and an analog computer was used to find the probability for each of the decay γ rays to give three or more detectable electron segments. The results of the two methods are in good agreement, and the pertinent probabilities are (1) 79% for detecting at least one γ from each $\theta^0 \rightarrow 2\pi^0 \rightarrow 4\gamma$ decay, (2) 39% for detecting at least two such γ's out of the 4, and (3) 36% for detecting at least one γ from each $\Lambda^0 \rightarrow n+\pi^0 \rightarrow n+2\gamma$ decay.

3. SINGLE-SHOWER RESULTS FOR F_Λ

Nine showers were found accompanying 47 "pure" $\theta_1{}^0 \rightarrow \pi^+ + \pi^-$ decays, but a background has to be subtracted from this number of showers. The background could have been determined from associated $\Lambda\theta$ events, as explained in the previous section. However, as we shall see shortly, the $\theta_1{}^0 \rightarrow 2\pi^0$ decay is so rare that essentially all showers accompanying $\Lambda^0 \rightarrow p+\pi^-$ events are due to the background. Improvement in the statistical accuracy of the background subtraction is necessary because the background constitutes 40% of the total. The number of Λ^0's which decay by the neutral mode is then the net number of shower events, N, obtained after correcting for the background and the shower detection efficiency. To find F_Λ, N must be divided by the total number of Λ^0's which is N plus the number of associated $\Lambda\theta$ events, corrected for the inverse probability for the detection of $\Lambda^0 \rightarrow p+\pi^-$. On this basis,

$$F_\Lambda = 0.22 \pm 0.13.$$

However, F_Λ can be determined in another way, if one assumes that all unobserved Λ^0 decays are indeed

[17] W. E. Hazen, Phys. Rev. 99, 911 (1955); H. DeStaebler, Ph.D. thesis, Massachusetts Institute of Technology, 1954 (unpublished); P. A. Bender, Nuovo cimento 2, 980 (1955).

due to $\Lambda^0 \rightarrow n+\pi^0$. For this purpose, all "pure" events can be used, not just those scanned for showers. As before, the number of $\Lambda^0 \rightarrow p+\pi^-$ events is determined from the number of associated $\Lambda\theta$ events corrected for the inverse probability of seeing $\Lambda^0 \rightarrow p+\pi^-$. However, the total number of Λ^0's is now found from the observed $\Lambda\theta$ events (uncorrected) plus the observed $\theta_1^0 \rightarrow \pi^+ + \pi^-$ events, corrected for scanning efficiency, for the small contamination of $\theta^0+\Sigma$ and $\theta^0+\bar{\theta}^0$ events (in which the Σ or the second θ^0 are not seen), and for the rare $\theta_1^0 \rightarrow 2\pi^0$ decays. The number of neutral decays is then the total number of Λ^0's minus the number of $\Lambda^0 \rightarrow p+\pi^-$ decays. By this second method,

$$F_\Lambda = 0.33 \pm 0.06.$$

These results are in agreement with those of the Columbia bubble chamber group,[18] who find $F_\Lambda = 0.18 \pm 0.09$ from the direct observation of showers and $F_\Lambda = 0.35 \pm 0.05$ from the assumption that unobserved Λ^0's decay by the $n+\pi^0$ mode.

4. SINGLE-SHOWER RESULTS FOR F_θ

Nine single showers were seen accompanying the 130 Λ^0 events which were scanned for showers. For the same size sample, the background (based on showers seen with $\Lambda\theta$ events) is 24 ± 11 showers, and thus the result is consistent with $F_\theta = 0$. The probability of obtaining this result if F_θ is as large as $\frac{1}{3}$ is $(1^{+22}_{-1})\%$, or if F_θ is as large as $\frac{1}{4}$ the probability is $(4^{+28}_{-4})\%$. The uncertainties given correspond to standard deviations in the probabilities, and they reflect the large statistical error in the background subtraction.

5. TWO-SHOWER EVENT

While the single-shower result is consistent with no $\theta_1^0 \rightarrow 2\pi^0$ decay at all, we have observed one event which gives very good evidence that this decay mode does indeed exist. It so happens that with our chamber the probability of seeing two or more showers from a $\theta_1^0 \rightarrow 2\pi^0$ decay is about the same as the probability of seeing only one shower from the decay. Hence it is not surprising that the single-shower results, after a large background subtraction, could be consistent with $F_\theta = 0$, whereas one two-shower event was actually observed. However, the particular event seen was a very fortunate one.

A drawing of one view of the event is shown in Fig. 1. Track a is the incoming π^-, which interacts in the third iron plate. No charged secondaries come out of the interaction, but a Λ^0 does, and its line of flight is b. Both the Λ^0 decay products, the proton (c) and the π^- (d, e, and f), stop and are coplanar with the origin to within 4.4°, and therefore the Λ^0 is identifiable with certainty. The lines of flight, h and i, of two γ rays which produce the large showers shown intersect in space. If these γ rays arise from the decay of a neutral particle produced in the π^- interaction, then g would represent its line of flight.

Now g is coplanar with h and i to within 4.5°, making it seem as if the showers were caused by the 2γ decay of a neutral particle. The mass of such a particle can be estimated from the angle between h and i and the energies of the two showers, which are 280 ± 90 Mev and 470 ± 120 Mev, as determined[17] from the number of electron segments.[19] Since this mass is 340 ± 80 Mev, the two γ rays cannot have come from a single π^0 (135 Mev), and the chance is only 5% that they could have come from the 2γ decay of a θ^0 (494 Mev).

Instead, the small angle of uncoplanarity suggests that the showers may be from a θ_1^0 which decays into two π^0's (in 0.8×10^{-10} sec), each π^0 then promptly decaying in such a way that one γ ray goes in the direction of that π^0, carrying nearly all of the π^0 energy. This supposition is borne out by a calculation of the π^0 energies, assuming g is the direction of the θ_1^0 and h and i are the directions of the π^0's. These calculated energies are 295 ± 10 Mev and 600 ± 35 Mev, in good agreement with the shower energies, and hence with the idea that essentially all the energy of each π^0 went into one γ in the forward direction. Further evidence for this interpretation is provided by the information that the incident π^- is coplanar, within 6°, with the lines of flight of the Λ^0 and supposed θ^0 (indicating that neither particle scattered appreciably in the production nucleus), and that the energies and production angles of the Λ^0 and θ^0 can be made kinematically consistent

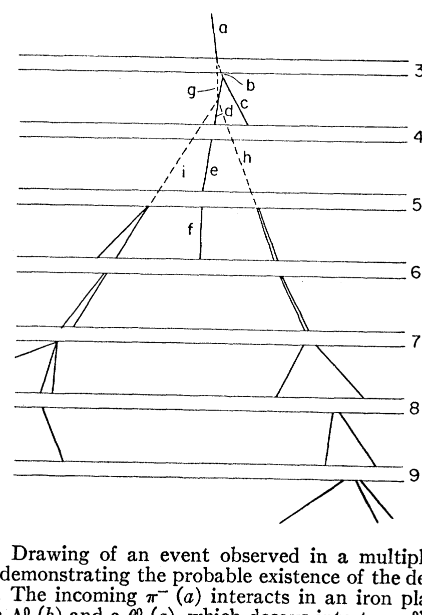

FIG. 1. Drawing of an event observed in a multiplate cloud chamber demonstrating the probable existence of the decay mode $\theta_1^0 \rightarrow 2\pi^0$. The incoming π^- (a) interacts in an iron plate (3) to produce a Λ^0 (b) and a θ^0 (g), which decays into two π^0's, each of which gives essentially all its energy to one forward γ ray (h and i), which then produces a shower in subsequent plates.

[18] M. Schwartz, *Proceedings of the Seventh Annual Rochester Conference on High-Energy Nuclear Physics, 1957* (Interscience Publishers, Inc., New York, 1957), Chap. V, p. 28.

[19] Note that all 17 of the electron segments of the large shower are not distinguishable in the drawing of Fig. 1.

with the simple reaction $\pi^- + p \rightarrow \Lambda^0 + \theta^0$, if the Fermi momentum of the target proton is considered.

While we feel that this event gives strong evidence for the $\theta_1{}^0 \rightarrow 2\pi^0$ decay, it is impossible to rule out a $3\pi^0$ decay in which one π^0 gets essentially no energy. However, no $\pi^\pm + \pi^\mp + \pi^0$ decays have been found, and at least on the basis of phase space, these ought to be about as frequent as $3\pi^0$ decays, and of course considerably easier to observe. Other evidence for the $\theta_1{}^0 \rightarrow 2\pi^0$ decay, and hence for even spin for the θ,[20] is furnished by the counter experiments of Osher, Moyer, and Parker[21] and of Ridgway, Berley, and Collins,[22] and by the Columbia-Brookhaven bubble chamber work.[18]

The more interesting question now is the relative abundance of $2\pi^0$ decays, and we can get a value for F_θ from the observation of the two-shower event, without the necessity of a background subtraction. Using the known probability for observing two showers (see Sec. 2) and the number of $\Lambda\theta$ events, corrected by the inverse probability for seeing $\theta_1{}^0 \rightarrow \pi^+ + \pi^-$, one gets

$$F_\theta = 0.06.$$

This value is certainly not in disagreement with the Columbia-Brookhaven bubble chamber result,[18] $F_\theta = 0.14 \pm 0.06$. The significance of our result for F_θ is best expressed by the statement that the chance of our having observed only one such two-shower event if F_θ were $\frac{1}{3}$ or larger is only 3%, and only 10% if F_θ were $\frac{1}{4}$ or larger.

6. CONCLUSIONS

Our result for the fraction of Λ^0's decaying by a neutral mode, as obtained from the percentage of "missing" Λ^0's, is $F = 0.33 \pm 0.06$, which would be in agreement with the value of $\frac{1}{3}$ predicted by the $\Delta I = \frac{1}{2}$ selection rule if all the neutral decays were $\Lambda^0 \rightarrow n + \pi^0$. While we have observed showers consistent with the $n + \pi^0$ decay mode, we cannot rule out other shower-producing modes. Furthermore, while the direct observation of showers (assuming the decay is $\Lambda^0 \rightarrow n + \pi^0$) gives $F = 0.22 \pm 0.13$, which is not in disagreement with $\frac{1}{3}$, we have not proved that all the missing Λ^0's decay by a shower-producing mode. The same qualification applies to the Columbia-Brookhaven result.[18]

The conclusion that the $\theta_1{}^0$ decays by the $2\pi^0$ mode, and that therefore its spin is even, has been strengthened by the observation of a decay which is consistent with nearly all of the energy of each π^0 going into a forward γ ray. Because of the large probability of seeing more than one shower from each $2\pi^0$ decay in our chamber, the observation of only one two-shower event indicates that the fraction of $\theta_1{}^0$'s going by the $2\pi^0$ mode is small, this one event giving a value $F_\theta = 0.06$. The chance that F_θ is actually $\geqslant \frac{1}{3}$ is 3%, and that it is $\geqslant \frac{1}{4}$ is 10%. The results from single-shower events give even smaller probabilities [(1^{+22}_{-1})% that F_θ is $\geqslant \frac{1}{3}$ and (4^{+28}_{-4})% that it is $\geqslant \frac{1}{4}$], but are more uncertain because a background subtraction had to be made.

On the basis of these results and those of Columbia-Brookhaven,[18] it seems unlikely that F_θ is as large as $\frac{1}{3}$, as predicted by a change in total isotopic spin of $\frac{1}{2}$. Although the present result could be explained as an unusual statistical fluctuation, this explanation is quite unlikely, and it seems profitable to look for another basis for the determination of the decay branching ratios. One such possibility is the $V-A$ universal Fermi interaction,[23] which was recently shown to be consistent with the observed[24] longitudinal polarization for protons from Λ^0 decay, and which predicts[25] $\frac{1}{3}$ for F_Λ.

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[20] Now that there is no reason to believe that the θ and τ are different particles, the analysis of τ decays [R. H. Dalitz, Phil. Mag. 44, 1068 (1953); Phys. Rev. **94**, 1046 (1954). E. Fabri, Nuovo cimento **11**, 479 (1954)], which gives strong evidence that the τ spin is zero, can be considered as similar evidence for the θ spin.

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