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DECAY PROPERTIES OF HEAVY MESONS AND HYPERONS

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INTRODUCTION

N the last two years, research in K-mesons and hyperons has been quite fruitful. These two large groups of unstable particles have been identified by the common designation "strange particles," which is closely linked with the somewhat unusual formalism of isotopic spin, applied to K mesons and hyperons. It is well known that an attempt to extend the concept of charge independence to these particles has led to the so called "theory of displaced isotopic multiplets," formulated first by Gell-Mann and Nishijima,[1-4]* which has played (and continues to play) a tremendous heuristic role. During the two years covered by this survey, the experimental data on the decay properties of K mesons and hyperons have gradually become more complete, and many qualitatively new results have been obtained. None of these contradict the Gell-Mann classification, and some are direct consequences of this classification. What are these results?

1. Final confirmation of the existence, predicted by Gell-Mann, of the Σ^0 hyperons, which decays rapidly ($\tau_{\Sigma^0} < 10^{-15}$ sec) into a Λ^0 particle and a γ quantum.

2. The first direct experimental evidence of the existence of a neutral cascade hyperon (Ξ^0) has been obtained, also predicted on the basis of the shifted charge multiplets scheme.

3. In agreement with the theory of Gell-Mann and Pais (page 127), a long-lived K_2^0 particle has been observed, differing in its decay properties from the hitherto known K_1^0 meson, and the existence of a $K^0 \rightarrow \widetilde{K}^0$ transition (so called Pais-Piccioni process) was experimentally proven.

4. It was shown experimentally that the decay of hyperons, like β decay, is not invariant under space reflection and charge conjugation.

5. Accordingly, there are no grounds at present for doubting parity nonconservation in K-meson decays as well. Thus, one can assume that the τ and θ mesons are really the same

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*For a further development of the ideas of Gell-Mann, in their mathematical formulation, see the survey articles (references 5, 6, 7) and also the monograph by M. A. Markov,[8] which also contains an exhaustive bibliography on the subject.

TABLE I. Decay properties of K-mesons and hyperons (data as of Nov. 1, 1958)

General designation		Symbol	Decay product	Branching ratio, q	Mass	Lifetime, τ
				%	Mev	sec
K-mesons	1	$\boldsymbol{K^+}$			493.98 ± 0.14	$(1.21 \pm 0.01) \cdot 10^{-8}$
		K_{μ_2}	$\mu^+ + \nu$	58.5 ± 3.0	494.2 ± 1.2	$(1.23 \pm 0.02) \cdot 10^{-8}$
		K_{π_2} (θ)	$\pi^+ + \pi^0$	27.7 ± 2.7	494.1 ± 1.0	$(1.21 \pm 0.02) \cdot 10^{-8}$
		K_{π_3} (τ)	$\pi^+ + \pi^+ + \pi^-$	5.56 ± 0.41	493.9 ± 0.9	$(1.18 \pm 0.03) \cdot 10^{-8}$
		K'_{π_3} (τ')	$\pi^+ + \pi^0 + \pi^0$	2.15 ± 0.47	~ 493	$\left(1.0^{+0.5}_{-0.3}\right) \cdot 10^{-8}$
		K_{μ_3}	$\mu^+ + \pi^0 + \nu$	2.83 ± 0.95	495 ± 2.1	$(0.88 \pm 0.23) \cdot 10^{-8}$
		K_{e_3}	$e^+ + \pi^0 + \nu(?)$	3.23 ± 1.30	494 ± 4	$(1.44 \pm 0.46) \cdot 10^{-8}$
		K_γ	$\pi^+ + \pi^0 + \gamma(?)$	~ 0.04		
	2	$\boldsymbol{K^-}$			493.9 ± 0.4	$(1.25 \pm 0.11) \cdot 10^{-8}$
		K_{μ_2}	$\mu^- + \tilde{\nu}$	65 ± 18		
		K_{π_2}	$\pi^- + \pi^0$	30 ± 12		
		K_{π_3}	$\pi^- + \pi^- + \pi^+$	5 ± 5		
		K'_{π_3}	$\pi^- + \pi^0 + \pi^0$			
		K_{μ_3}	$\mu^- + \pi^0 + \tilde{\nu}(?)$			
		K_{e_3}	$e^- + \pi^0 + \tilde{\nu}$			
	3	$\boldsymbol{K^0 \tilde{K}^0}$				
	a	K_1^0 (θ_1^0)	$\pi^+ + \pi^-$	86 ± 6	496 ± 3	$(0.98 \pm 0.08) \cdot 10^{-10}$
			$\pi^0 + \pi^0$	14 ± 6		
	b	K_2^0 (θ_2^0)	$e^\pm + \pi^\mp + \nu$	$21 \leqslant q \leqslant 91$	$m_{K_1^0} - m_{K_2^0}$ $\simeq 10^{-5}$ **ev**(?)	$\left(9.0^{+3.5}_{-2.5}\right) \cdot 10^{-8}$
			$\mu^\pm + \pi^\mp + \nu$	$9 \leqslant q \leqslant 78$		
			$\pi^+ + \pi^- + \pi^0$	$1.5 \leqslant q \leqslant 14$		
Hyperons	4	$\boldsymbol{\Lambda^0}$	$p + \pi^-$	63 ± 3	1115.2 ± 0.14	$(2.70 \pm 0.10) \cdot 10^{-10}$
			$n + \pi^0$	37 ± 3		
	5	$\boldsymbol{\Sigma^+}$	$p + \pi^0$	49 ± 3	1189.4 ± 0.2	$(0.79 \pm 0.10) \cdot 10^{-10}$
			$n + \pi^+$	51 ± 3		
	6	$\boldsymbol{\Sigma^0}$	$\Lambda^0 + \gamma$		$1190.5^{+0.7}_{-1.4}$	$\tau < 10^{-11}$
	7	$\boldsymbol{\Sigma^-}$	$n + \pi^-$		1196.4 ± 0.3	$\left(1.72^{+0.17}_{-0.10}\right) \cdot 10^{-10}$
	8	$\boldsymbol{\Xi^-}$	$\Lambda^0 + \pi^-$		1319 ± 3	$(4.6 < \tau < 200) \cdot 10^{-10}$
	9	$\boldsymbol{\Xi^0}$ (?)	$\Lambda^0 + \pi^0$		?	?
Anti-hyperons	10	$\boldsymbol{\tilde{\Lambda}^0}$	$\tilde{p} + \pi^+$		1114^{+3}_{-1}.	

particle, decaying in different ways with parity nonconservation.

6. The first event of a charge-conjugated analogue of the Λ^0 particle — the anti-lambda hyperon ($\tilde{\Lambda}^0$), decaying in accordance with the principle of charge conjugation into an antiproton and a π^+ meson, has been registered.

It must be noted that the experimental material used in this survey concerning the decay interactions of unstable particles was obtained essentially with accelerators. An exception is the information on the cascade Ξ hyperon, the only source of which are so far only cosmic rays.*

DECAY PROPERTIES OF K-MESONS

"The $\tau\theta$ Problem"

The difficulties arising in connection with a study of the τ and θ mesons are known to re-

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*A recently published communication states that two events of creation and decay of Ξ^--particle were recorded with the aid of a propane bubble chamber in a π-meson beam of a bevatron (5.5 Bev/c) (see page 135).

TABLE II

	$K_{\mu_2} \to \mu + \nu$	$K_{\pi_2} \to \pi^+ + \pi^0$	$K_{\pi_3} \to \pi^+ + \pi^- + \pi^+$	$K'_{\pi_3} \to \pi^+ + 2\pi^0$	$K_{\mu_3} \to \mu + \pi^0 + \nu$	$K_{e_3} \to e + \pi^0 + \nu(?)$
15	57.0±2.6	23.2±2.8	6.77±0.45	2.15±0.42	5.9±1.3	5.1±1.3
16	58.5±3.0	27.7±2.7	5.56±0.41	2.15±0.47	2.83±0.95	3.23±1.30

duce to the following. It was established experimentally that the masses and the lifetimes of τ and θ mesons are the same, within experimental error, and this gave grounds for assuming τ and θ to be the same particle, but decaying in different ways. On the other hand, it has been shown that the final states of the decays $\tau \to 3\pi$ and $\theta \to 2\pi$ have opposite parities, and this was evidence that the τ and θ could not be the same particle.

It was taken to be self-evident that in K-meson decays, like in all other weak interactions, parity was conserved.

This last statement, undoubted by anyone, was subjected to a critical review by Lee and Yang.[9] The subsequently performed experiments[10,11] have shown that parity is not conserved in β decay. Strictly speaking, these experiments could not be considered as direct proof that parity is not conserved in all weak interactions, including the τ and θ neutrino-less decays.

However, a direct experimental verification of the fact of parity nonconservation in K decay was quite difficult, since it is impossible to obtain polarized K mesons, in view of the zero spin of the latter (see page 125).*

On the other hand, it is obvious that the decays of K mesons and hyperons should have the same invariance properties (or non-invariance properties), since K mesons and hyperons are "bound" in the strong interaction of associated production, for which the aforementioned invariance properties take place. Therefore, after recent experiments have shown nonconservation of parity and violation of invariance under charge conjugation in hyperon decays (see page 139), there are no grounds for doubting that the same takes place in K_π decays.

It can thus be considered proved that there exists one K-meson which decays by different modes, and the fact that the final states of the τ and θ decays have different "parities," is simply the result of parity nonconservation in the decay interaction of K mesons. As to other attempts of resolving the "$\tau\theta$ problem,"[12,13,14] they have not found experimental verification.

Different Modes of K$^+$-Meson Decay

Table II lists the branching ratios for different modes of K$^+$-meson decay, obtained by the Dublin and Berkeley groups. Taking into account the data by the Amsterdam group[17] the average weighted branching ratios for the $K_{\mu_3}^+$ and $K_{e_3}^+$ decays is respectively (3.9 ± 0.5) and (5.1 ± 0.8) percent.

Most of the decays reported here have been sufficiently well investigated, and the latest researches add little to the old experimental data. An exception are K_{μ_3} and K_{e_3} decays, which have been receiving much attention of late.

As early as in 1951 O'Kelly proposed[18] that the simplest of the possible K_{μ_3} decays is $K_{\mu_3} \to \mu + \pi^0 + \nu$. However, only recently an experimental confirmation was obtained of the fact that one of the neutral products of the decay is a neutral pion. Several K_{μ_3}-decay events have been recorded,[19,20] in which the rare decay $\pi^0 \to e^+ + e^- + \gamma$ takes place (the so called "Dalitz pair") (see Fig. 1).

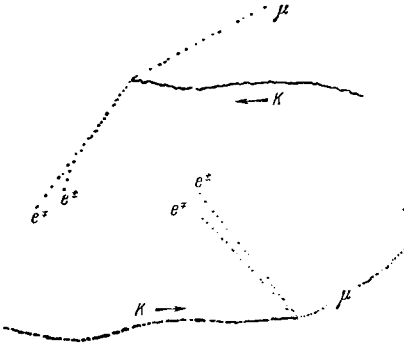

FIG. 1

Strictly speaking, the other neutral particle could be a γ-quantum instead of the neutrino. Since, however, there are good reasons for assuming the K^0-meson to be a boson, there is no doubt concerning the $K_{\mu_3}^+ \to \mu^+ + \pi^0 + \nu$ scheme. The μ^+-meson spectrum shown in Fig. 2 (reference 15) is also in good agreement with this decay scheme, by which the maximum energy is $E_\mu \sim$ 134 Mev.

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*From this point of view, the absence of any asymmetry whatever in the decays of 2697 analyzed K mesons,[246] is quite natural.

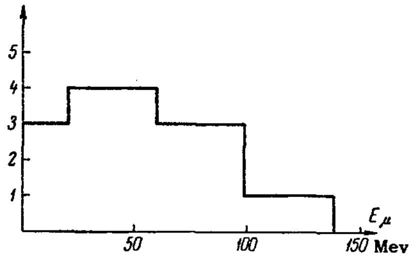

FIG. 2

As to the decay $K^+_{e_3} \rightarrow e^+ + ? + ?$, nothing specific can be said thus far concerning the nature of the neutral decay products. It must be assumed, however, that the $K^+_{e_3}$ is the charged analogue of $K^0 \rightarrow e^\pm + \pi^\mp + \nu$, observed among the decays of the long-lived K^0-meson component (see page 127).

For the $K^+_{e_3} \rightarrow e^+ + \pi^0 + \nu$ the maximum positron energy is 228 Mev. However, in four cases (out of the 45 recorded) the positron energy exceeds 228 Mev (references 15, 18, 21). Positrons of such energies could arise, in principle, through $K_{e_2} \rightarrow e + \nu$, but so far there are not enough experimental data in favor of the existence of such a decay. It is most likely that the presence of a positron with $E > 228$ Mev is the result of an experimental error. It must be noted that the spectrum of the positrons produced by the decay $K \rightarrow e^+ + \pi^0 + \nu$, calculated unter the assumption of a scalar K meson and a tensor decay interaction, has two peaks near 100 Mev and 210 Mev.[22,23,24] This spectrum is in good agreement with the experimental results reported at the Sixth Rochester Conference[18] (see Fig. 3) and with the data of the Dublin group.[15] In this connection cases with $E > 228$ Mev can be considered as a result of a "smearing" of the second (tensor) peak produced by large errors in the determination of E_{e^+}.

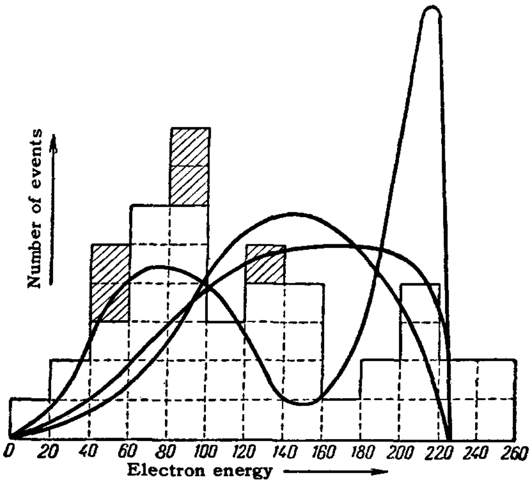

FIG. 3

Feynman and Gell-Mann,[25] and independently also Marshak and Sudarshan[26] as well as Sakurai,[27] have recently proposed a universal four-fermion interaction scheme, in which the coupling between the baryons and the electron-neutrino field is effected through the vector and axial-vector covariants (the so called V-A theory). Within the framework of this scheme, a satisfactory explanation was obtained for almost all the experiments on β decay, as well as experiments on the decay and capture of μ mesons. The only serious disagreement with experiment was connected with the $\pi \rightarrow e + \nu$ decay, predicted by the V-A theory, and not observed for a long time.[28,29,30] This difficulty was eliminated by recent experiments which have shown, in contradistinction to earlier investigations, that the $\pi \rightarrow e + \nu$ decay exists and that its probability is of the same order of magnitude as that predicted by the V-A theory.[31,32] These successes of the V-A theory make it very attractive to extend this theory to include also decay interactions of K-mesons and hyperons. In this connection, the presence of clearly pronounced tensor peaks in the K_{e_3} spectrum is somewhat discouraging. An estimate of the χ^2 probability* in a comparison of the experimental K_{e_3} spectrum with the V-A theory gives in the best case $\chi^2 \sim 0.07$. while the use of the S + T + (P) variant yields good agreement with experiment.[35,36]† On the other hand, the experimental value of the branching ratio for the $K^+_{\mu_3}$ and $K^+_{e_3}$ decays, namely $R_{K^+} = \frac{K^+ \rightarrow \mu^+ + \pi^0 + \nu}{K^+ \rightarrow e^+ + \pi^0 + \nu} = 0.8 \pm 0.2$ are in good agreement with the predictions of the V-A theory ($R_{K^+} \approx 1$).[37,38,39] It is therefore very important, in principle, to investigate further various angular correlations and energy distributions of the K_{e_3} and K_{μ_3} decays (particularly at fixed pion energy),‡ which give a wealth of possibilities for a final determination of the theory variant for the decay interaction for K mesons.[40–50]

Of exceptional interest are searches for the $K \rightarrow e + \nu$ decay, the branching ratio for which $\frac{w(K \rightarrow e + \nu)}{w(K \rightarrow \mu + \nu)}$ should, according to the V-A the-

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*Concerning the χ^2 criterion and in general concerning the maximum-likelihood method see, for example, references 33 and 34.

†It must be noted, however, that the calculations of the K_{e_3} and K_{μ_3} spectra within the framework of the V – A theory are of approximate nature, since these decays cannot be directly expressed in terms of the four-fermion interaction.

‡This is possible not only in the investigation of neutral $K^0_{e_3}$ and $K^0_{\mu_3}$ mesons, but also in the case of an investigation of the $K^+ \rightarrow \mu + \pi^0 + \nu$ decays in bubble chambers with heavy filler.

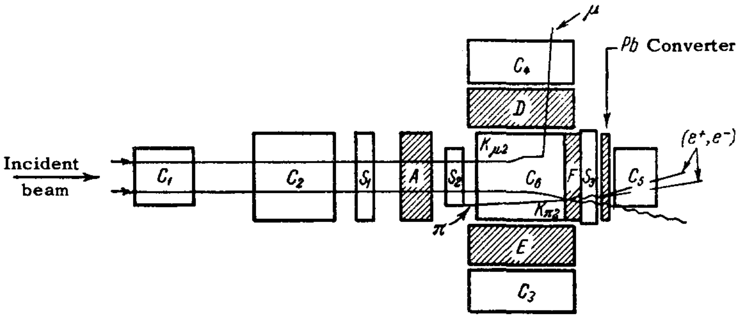

FIG. 4

ory, amount to 0.23×10^{-4} (references 37, 38).

It must also be noted that a study of the $K_{\mu 3}$ decay affords a rare opportunity of verifying the validity of time-reversal (T) invariance (or, what is the same, the conservation of the "combined" parity CP) in weak interactions. For this purpose it is necessary to ascertain the presence of polarization of the decay muon relative to the decay plane $\sigma_\mu (\mathbf{p}_\pi \times \mathbf{p}_\mu)$, which can be determined from the asymmetry of the $\mu \to e$ decays. The presence of such an asymmetry, subject to the condition that the K^+ mesons are not polarized,* would be evidence of the violation of the T (or CP) invariance in the decay of the K-meson.

Apparently such an experiment is best set up in bubble chambers with heavy fillers (such as xenon or freon), for in this case the direction of the decay pion ($\mathbf{p}_\pi$) can be determined by observing the conversion of the γ quanta that are created by the decay $\pi^0 \to 2\gamma$.

In recent years there were recorded two $K'_{\pi 3}$ events, in which, at the point of decay, there emerges not only a pion but also an electron-positron pair (e^+e^-), which is apparently the result of the $\pi^0 \to e^+ + e^- + \gamma$ decay.[52,53]

These facts, if one takes also into account the similarity between the positive-pion spectra in the $K'_{\pi 3}$ and $K_{\pi 3}$ decays[54] are direct evidence in favor of the $K'_{\pi 3} \to \pi^+ + \pi^0 + \pi^0$ decay.

Finally, quite recently there have been observed, among a large number of ordinary K^+ decays (1400), two $K'_{\pi 3}$ decays, in which positive pions were emitted with energies exceeding the maximum possible for the ordinary $K'_{\pi 3} \to \pi^+ + \pi^0 + \pi^0$ decay. The authors have proposed that what they recorded was an anomalous decay event of the type $K^+ \to \pi^+ + \pi^0 + \gamma$ (references 55, 56). However, as indicated in reference 56, the nearly equal decay-energy values in both cases (60 and 61.7 Mev) suggest the possibility of a two-particle decay $K^+ \to \pi^+ + x^0$, where x^0 is a hitherto unknown boson with mass of ~ 500 m_e, the neutral analogue of the particle recorded by the Alikhanyan group (see page 143).

Mention must also be made of an unsuccessful attempt of observing a hypothetical $K_2^+ \to \mu^+ + \mu^0$ decay among the decays of 400 K^+ meson.[57] This is evidence against the existence of a neutral muon with mass of $\simeq m_{\mu^\pm}$.

Average Lifetime of the K^+ Meson

Along with using the emulsion procedure for the determination of the lifetime of K mesons, counters have been successfully employed in recent investigations and this made it possible to obtain more accurate results.

Figure 4 shows schematically a system of counters used in reference 64 to measure the average lifetime of $K_{\pi 2}$, $K_{\mu 2}$, and $K_{\pi 3}$ decays. K^+ mesons with a momentum of 465 Mev/c were deflected by the magnetic field of an accelerator and focused with the aid of quadrupole magnetic lenses unto a system of Cerenkov and scintillation counters, located 4.5 meters from the target.

The Cerenkov counter located at the head of this system is sensitive only to charged particles with velocities from 0.62 to 0.78 c. To limit the number of K mesons registered by counter C_1, a second Cerenkov counter C_2 is connected in anticoincidence with C_1. The threshold of C_2 is so chosen that the pions with momentum of 465 Mev/c are registered by this counter, while the K mesons with the same value of momentum do not produce Cerenkov radiation in this counter. The K mesons are slowed down and are stopped in C_6, causing $C_1 - C_2 + S_1 + S_2 - S_3$ coincidences, and then decay with emission of a particle fast enough to actuate C_4. What is measured here is the delay between the pulses in C_1 and C_6, a delay that characterizes the lifetime of the decaying K meson.

The $K_{\mu 2}$ decay events are identified with the aid of one of the Cerenkov counters, sensitive to the muon. The thickness of the absorbers D and E is so chosen that the pions from the $K_{\pi 2}$ decay

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*Experimental data are evidence that the spin of K mesons is zero (see page 125).

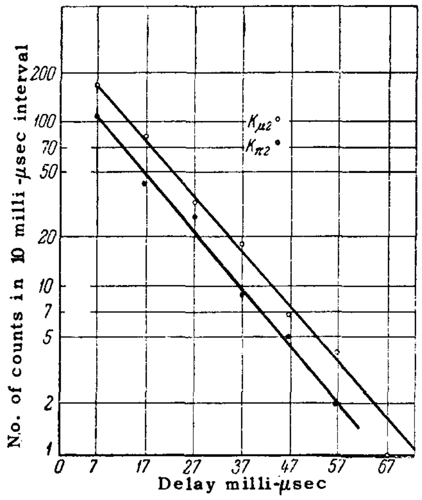

FIG. 5

are absorbed in them. Neither are most of the other types of decay, which have a low probability in any case, recorded. The K_{π_2} mesons that stop in F and decay into positive and neutral pions are simultaneously selected.

The neutral pions decay forthwith into two γ quanta, which are not recorded in S_3 and after passing through a lead converter they produce a pulse in C_5. Generally speaking, coincidences of this kind will occur also in $K_{\mu_3} \rightarrow \mu + \pi^0 + \nu$ and $K_{e_3} \rightarrow e + \pi^0 + \nu$ decays, but their relative probability is very small.

Figure 5 shows a curve of the delayed $C_1 + C_6$ coincidences in the registration of K_{π_2} and K_{μ_2} decays, from which it follows that

$$\tau_{K_{\mu_2}} = \left(1.17^{+0.08}_{-0.07}\right)\cdot 10^{-8}\ \text{sec},$$

$$\tau_{K_{\pi_2}} = \left(1.21^{+0.11}_{-0.10}\right)\cdot 10^{-8}\ \text{sec}.$$

A somewhat modified experimental setup was used by the same authors to measure the average lifetime of the K_{π_3} decay

$$\tau_{K_{\pi_3}} = \left(1.17^{+0.08}_{-0.07}\right)\cdot 10^{-8}\ \text{sec}.$$

An analogous setup was used by the Alvarez group,[67,69] which also obtained the same values for $\tau_{K_{\pi_2}}$ and $\tau_{K_{\mu_2}}$, within the experimental accuracy (see Table III).

It is known that the branching ratios for K_{μ_3} and K_{e_3} decays measured under different conditions, are equal within the limits of experimental error. This is evidence that $\tau_{K_{\mu_3}}$ and $\tau_{K_{e_3}}$ are of a magnitude nearly equal to the average lifetime (of the remaining decays). However, a direct measurement of $\tau_{K_{\mu_3}}$ and $\tau_{K_{e_3}}$ involves serious experimental difficulties in view of the low relative probability of these decays.

The Rochester group has undertaken an attempt

TABLE III

Reference	K-meson source	Detector	E_{K^+} Mev	Average lifetime in 10^{-8} sec					
				Δt 10^{-8} sec	K_{π_3}	K_{π_2}	K_{μ_2}	K_L	All K
58	Cosmic rays	Counters	80	1.6				0.96 ± 0.08	
59	” ”	”	80	4.3				1.40 ± 0.15	
60	” ”	Counters and cloud chamber	80	0.45				$1.10^{+0.41}_{-0.24}$	
61	” ”	Counters		10^2					$1.08^{+0.08}_{-0.22}$
62	” ”	”			$1.13^{+0.42}_{-0.23}$			1.09 ± 0.13	
63	” ”	”	80	1.5					0.8 ± 0.07
64	Cosmotron	”	190	2.9		$1.21^{+0.11}_{-0.10}$	$1.17^{+0.08}_{-0.07}$		
65	”	”	200	1.6	$5.17^{+0.08}_{-0.07}$				
66	”	Emulsions	356	1.3	$1.04^{+0.42}_{-0.23}$			$1.11^{+0.18}_{-0.11}$	
67	Bevatron	Counters	100÷140			1.3 ± 0.2	1.4 ± 0.2		1.3 ± 0.1
68	”	”	120		1.19 ± 0.046	1.21 ± 0.03	1.24 ± 0.018		
69	”	Emulsions	110	0.18	$1.0^{+0.7}_{-0.3}$				
70	”	”	110	2	$0.8^{+0.5}_{-0.2}$			$0.7^{+0.15}_{-0.10}$	
71	”	”	100÷170	1.3				$1.01^{+0.33}_{-0.21}$	
72	”	”	150	1.3				$1.27^{+0.14}_{-0.12}$	$1.35^{+0.16}_{-0.13}$
73	”	”			1.0 ± 0.2			1.24 ± 0.2	
	Weighted average				1.18 ± 0.03	1.21 ± 0.02	1.23 ± 0.02	1.11 ± 0.12	1.11 ± 0.10

to estimate the relative value of $\tau_{K_{\mu 3}}$ and $\tau_{K_{e3}}$ using as standards the $K_{\pi 2}$ and $K_{\mu 3}$ decays.[73] The results of these estimates are given in the table:

$$\tau_{K_{\mu 3}} = (0.88 \pm 0.23) \cdot 10^{-8}\ \text{sec};$$

$$\tau_{K_{e3}} = (1.44 \pm 0.46) \cdot 10^{-8}\ \text{sec}.$$

As can be seen from the table, the experimental values of the average lifetime of the various decays agree within the limits of experimental errors. This is in complete agreement with the assumed existence of a single K meson that decays by various modes.

Recently Treiman and Wyld advanced the hypothesis of a possible existence of a K^+ component with average lifetimes considerably less than 10^{-8} sec.[75]

However, thus far neither emulsions[76] nor cloud chambers[77] have recorded any noticeable number of short-lived K^+ mesons.

Mass and Spin of the K^+ Meson

The masses of K^+ mesons that decay by various modes, also agree within the limits of errors (see table).

The values of the masses obtained in the scanning of the same stack of emulsions, exposed to the K^+-meson beam of the bevatron, are:[78]

$$\begin{aligned} m(K_{\pi 3}) &= 966.6 \pm 1.9 m_e, \\ m(K_{\pi 2}) &= 966.9 \pm 2.0 m_e, \\ m(K_{\mu 2}) &= 967.2 \pm 2.2 m_e, \\ m(K_{\mu 2}) &= 969 \pm 5 m_e, \\ m(K_{e3}) &= 967 \pm 8 m_e. \end{aligned}$$

As is known, an analysis of the negative-pion momentum spectrum in $K_{\pi 3}$ decay can supply information on the spin of the K^+ meson.[79]

Several recently published papers contain such an analysis based on a considerable number of events,[80,81,82,83] and this makes it possible to draw the following conclusions:

1. The $K_{\pi 3}$ meson state in best agreement with the experimental data is (0^-).
2. The states 1^- and 2^+ are practically excluded.
3. The relative probability (for $K_{\pi 3}$) of the (1^+) state is negligible.
4. The state (2^-) cannot be excluded in principle, but an argument against this possibility is the absence of the $K^+ \to \pi + \gamma$ decay.[84]

It should be noted that an isotropic distribution of the decay products in $K_{\pi 2}$ and $K_{\mu 2}$ events[85,12] is also evidence in favor of $\sigma_K = 0$.

In addition, the presence of complete polarization (within 10%) of the μ meson in $K_{\mu 2}$ decay, which was observed, for example in reference 86 can, generally speaking, occur if the K-meson spin is zero. Thus, there is a considerable number of independent experimental facts to show that the K-meson spin is zero, although the proof cannot be considered rigorous.

The K^- Meson

The decay properties of K^- mesons are known in much less detail, since they interact strongly with matter and, when stopped, are usually captured by the nucleus before having a chance to decay. The few registered K^--decay events are essentially decays in flight.

Recently several $K^-_{\pi 3}$ decay events were recorded in a cloud chamber and in a bubble chamber.[87,88,89] The $K^-_{\pi 2}$ decay which was observed in an emulsion exposed in a K^--beam[89] can be considered as quite reliable.

A K^-_{e3} decay event was also registered in the same emulsion stack.

The Paris group has obtained certain experimental indications on the existence of $K^-_{\mu 2}$ and $K^-_{\mu 3}$ decays.[90] The Berne group has registered several $K^-_{\pi 2}$ and $K^-_{\mu 2}$ events and measured the energies of these decays: $Q_{\pi 2} = (109.5 \pm 3.0)$ Mev and $Q_{\mu 2} = (153 \pm 4)$ Mev. Thus, the existence of these types of decays can be considered as experimentally proven.[91] There are also other cases, registered with a cloud chamber, which can be interpreted as $K^-_{\pi 2}$ and $K^-_{\mu 2}$ decays.[87,99] The branching ratios for different modes of decay for the K^- meson is apparently the same as for the K^+ meson,[94] (see Table I), but owing to the poor statistics one cannot draw more definite conclusions. The average lifetime of the K^- meson $[\tau = (1.25 \pm 0.11) \times 10^{-8}\ \text{sec}]$[94] coincides, within the experimental accuracy, with τ_{K^+}. The existence of a short-lived K^- component with $\tau_{K^-} \sim 10^{-10}$ seconds, mentioned in references 96 and 97, was not confirmed by later experiments.[87]

And, finally, there was recently observed in an emulsion stack a three-particle K^- decay, in which, along with a negative meson, an electron-positron pair was emitted.[98] The most probable interpretation of this event is a $K^{-\prime}_{3\pi}$ decay with subsequent decay of one of the pions in accordance with the Dalitz scheme:

$$\begin{array}{l} K^-_{3\pi} \to \pi^- + \pi^0 + \pi^0 \\ \qquad\qquad\qquad\quad \searrow \\ \qquad\qquad\qquad\qquad e^+ + e^- + \gamma. \end{array}$$

An investigation of the capture reaction $K + p \to \Sigma^+ + \pi^-$ makes it possible to determine, with great accuracy, the mass of the K^- meson from

TABLE IV

$\tau_{K_1^0}$ $\times 10^{10}$ sec	Number of events	Detector, experimental conditions	Reference
$1.06\,^{+0.08}_{-0.06}$	259	Bubble propane chamber in π^- beam (1.3 Bev), cosmotron	170
$0.99 + 0.12$	89	Cloud chamber with plates in π^- beam (1.8 Bev), cosmotron	171
$0.93\,^{+0.10}_{-0.06}$	228	Bubble H chamber in π beam, bevatron	172
$0.81\,^{+0.23}_{-0.15}$	62	Bubble propane chamber in π^- beam (1.1 Bev), cosmotron	173
$1.15\,^{+0.45}_{-0.25}$	39	Cloud chamber in π^- beam (1.9 Bev), cosmotron	174
$0.98\,^{+0.08}_{-0.06}$	677	Weighted average	

the known masses of the remaining particles that enter into this reaction. The most accurate values of m_K were obtained by the Berkeley group[99,100] ($493.87 \pm 0.46\ m_e$) and by the Wisconsin group ($493.96 \pm 1.0\ m_e$)[101], giving a weighted average of $m_K = 493.6 \pm 0.4\ m_e$.

Thus, the same values of mass and lifetime of the K^+ and K^- mesons give full support to the hypothesis that these mesons form a particle-antiparticle pair.

The K_1^0 Meson

The most probable decay $K^0 \rightarrow \pi^+ + \pi^-$ was investigated quite thoroughly in the earlier researches (see references 102, 103, 104).

Recently, more accurate values were obtained only for the decay energy $Q_{K^0} = (217.0 \pm 4)$ Mev,[106] which, taking into account the earlier data[105] gives a weighted average $Q_{K^0_{2\pi}} = (215 \pm 2)$ Mev. More accurate values were also obtained for the lifetime (see Table IV).

Now that it has become possible to obtain "strange" particles from accelerators, attempts were undertaken to register the neutral decays $K^0 \rightarrow \pi^0 + \pi^0$ and $\Lambda^0 \rightarrow n + \pi^0$.

In many papers[108,109,110] an original method was used for the purpose, first devised by Garwin.[107]

The K^0 mesons escaping from the target (see Fig. 6) decay at a certain distance from it, producing in a case of a neutral decay π^0 mesons, which immediately ($\sim 10^{-15}$) decay into γ quanta.

Thus, γ quanta are emitted from a space not connected with the target and are registered by a well-collimated γ telescope.

Owing to the possibility of displacing the target relative to the collimator, it is possible to "view" the space at various distances from the target, both in front of it and behind it. Figure 7 shows the dependence of the intensity of γ radiation on the relative placement of the target and of the collimator axis.[109] The dotted lines show the intensity of the γ rays emitted directly from the target, obtained at an incident-proton energy smaller than the threshold for "strange" particle production.

From an analysis of these curves (and also of the curves obtained in reference 110 at various energies of incident protons) the authors conclude the existence of the decays $K^0 \rightarrow 2\pi^0$ and $\Lambda^0 \rightarrow n + \pi^0$.

Here the authors make quite arbitrary assumptions about the energy and angular distribution of the created particles, and disregard the contribution of the $\Sigma^+ \rightarrow p + \pi^0$ decay. These investigations cannot therefore, strictly speaking, be considered as experimental proof of the existence of the neutral K^0 decay. More direct experimental evidence of the presence of the $K^0 \rightarrow 2\pi^0$ decay were obtained in references 112 and 161.

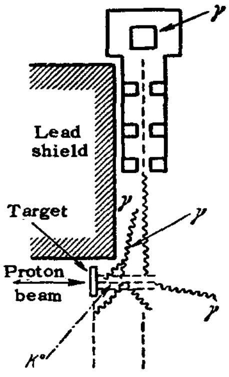

FIG. 6

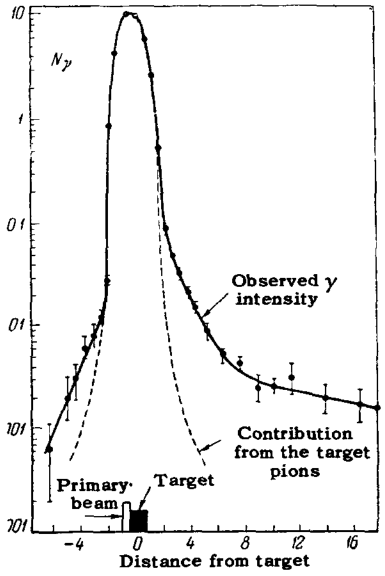

FIG. 7

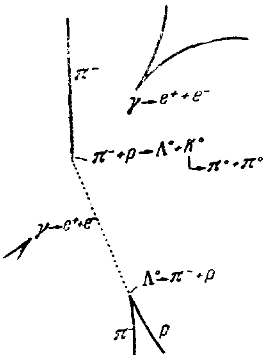

FIG. 8

The authors were able to photograph in a bubble chamber eight events of production of Λ^0 particle in π^-p interactions. These photographs show, in addition to the characteristic Λ^0 decay, also electron-positron pairs from converted γ quanta (Fig. 8). A kinematic analysis of these events is in good agreement with the assumption that the registered γ quanta are the result of a neutral decay of a K^0 meson produced in association with the Λ^0 particle in the following reaction: $\pi^- + p \rightarrow \Lambda^0 + K^0$. Figure 9 shows the energy distribution of the quanta obtained from these photographs.

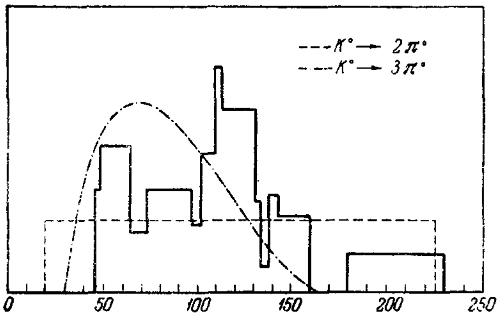

FIG. 9

An analysis of this distribution makes it possible to discard the possibility of decays of the type $K^0 \rightarrow 2\gamma$ and $K^0 \rightarrow \pi^0 + \gamma$, since the former gives (in the center of mass system) monoenergetic γ quanta (246 Mev), and the second yields a maximum at 229 Mev. Of the two possible decays, $K^0 \rightarrow 2\pi^0$ and $K^0 \rightarrow 3\pi^0$, apparently the former takes place, since a decay into three pions is considerably less probable from the point of view of the phase-space volume. Furthermore, if the decay interactions are invariant under time reversal, then the decay $K_1^0 \rightarrow 3\pi^0$ should in general be forbidden for the short-lived component (see page 129). The number of quanta registered simultaneously with decay was used to calculate the branching ratio for the decay:

$$R_{K^0 \rightarrow 2\pi^0} = \frac{\omega(K^0 \rightarrow 2\pi^0)}{\omega(K^0 \rightarrow 2\pi)} = 0.14 \pm 0.06.$$

Less direct estimates give $R_{K^0 \rightarrow 2\pi^0} = 0.07 \pm 0.02$,[258]

In any case, $R_{K^0 \rightarrow 2\pi^0}$ is apparently small, since in certain experiments, such as the exposure of a chamber with plates in the 1.8-Bev beam of negative pions, no neutral decays were observed at all ($R_{K^0 \rightarrow 2\pi^0} = 0.1 \pm 0.1$).[113]*

It must be noted that the $K^0 \rightarrow 2\pi^0$ decay is allowed only for an even spin of K^0 ($\sigma_{K^0} = 0, 2, 4, \ldots$). We can thus discard immediately, in the determination of the spin, the possibilities $\sigma_{K^0} = 1, 3, 5, \ldots$.

The latest experimental data give no grounds whatever for assuming the spin of K^0 to be other than zero.

Figures 10 and 11 show the angular distributions of the decays of K mesons produced in pairs with hyperons in π^-p interactions at 1.1 Bev.[115,116]

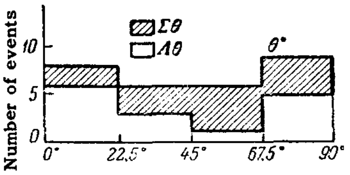

FIG. 10

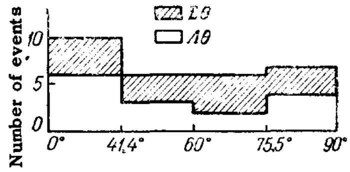

FIG. 11

From the given distributions it is seen that they have no clear anisotropy, in agreement with the assumption that $\sigma_{K^0} = 0$.

The previously obtained experimental indications that the K^0 decay might be anisotropic[116] are apparently the result of experimental errors.

It can therefore be assumed that the spin of the K^0 meson, like the spin of charged K mesons, is zero.

The Long-Lived K^0 Meson (K_2^0)

It was indicated even in the earlier investigations that there exist so called "anomalous" K^0 decays, different from $K^0 \rightarrow 2\pi$. Recently interest in the "anomalous" decays has grown in connection with the known investigations by Gell-Mann and Pais.[117] As is known, the application of the charge-conjugation operation to the K^0 particle has resulted in a rather unique situation. On the one hand it was established experimentally that the K^0 particle has a non-identical antiparticle, that is, the states K^0 and $\tilde{K}^0$ cannot have definite "eigenvalues" of the charge-conjugation operator. On the other hand it is known that K^0 and $\tilde{K}^0$ can go into the $\pi^+\pi^-$ state, which has a definite value of "charge" parity ($C = +1$). Furthermore, a slow conversion of the particle into an antiparticle through this state, $K^0 \rightleftarrows 2\pi \rightleftarrows \tilde{K}^0$, is possible. In seeking a way out of this difficulty,

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*More recent data from this group, namely $0.03 \leq R_{K^0 \rightarrow 2\pi^0} \leq 0.13$ were reported at the conferences in Venice and Padua.[114]

Gell-Mann and Pais have proposed that the states K^0 and $\tilde{K}^0$ are a superposition of two components, K_1^0 and K_2^0, which consist of linear combinations of the states K^0 and $\tilde{K}^0$. These states are made up in such a way that each has a definite value of C and, consequently, definite decay properties

$$K_1^0 = \frac{K^0 + \tilde{K}^0}{\sqrt{2}}, \quad K_2^0 = \frac{K^0 - \tilde{K}^0}{i\sqrt{2}}.$$

The first component K_1^0 as can be seen, is "charge even" $(C = +1)$ and can break up into $\pi^+\pi^-$, while the second is "charge odd," and its decay into $\overset{0}{\pi^+}\overset{0}{\pi^-}$ is forbidden.* It was also suggested that K_2^0 has a considerably longer lifetime and is therefore not observed in the associated production processes.

The classical experiment on the determination of the existence of a $K^0 \rightleftarrows \tilde{K}^0$ transition in vacuum was proposed by Pais and Piccioni, after whom this process is usually named.[118] They proposed to study the interaction of the K^0 mesons a sufficiently large distance from the point of production in order to permit the short-lived component to decay completely. If the remaining long-lived component actually represents the superposition $K_2^0 = \frac{K^0 - \tilde{K}^0}{i\sqrt{2}}$ then, as a result of the different character of the interaction of K^0 and $\tilde{K}^0$, such a superposition can "break apart," and cases of hyperon production can appear, for example, $\tilde{K}^0 + N \to Y + \pi$ or a charge exchange $\tilde{K}^0 + n \to K^- + p$.

It also becomes possible to observe near the point of the interaction $K^0 \to 2\pi$, decays that result from the separation of the K^0 and $\tilde{K}^0$, which have already interacted, from the superposition $K_2^0 = \frac{K^0 - \tilde{K}^0}{i\sqrt{2}}$. Danysh and Pontecorvo have proposed an interesting version of the experiment described above: observe the K^- at incident-nucleon (pion) energies below the threshold of K^- production (that is, below the threshold for the production of a pair of K-mesons), but at energy still sufficient for the associated production of $K^0 (K^+)$ with a hyperon.[119] In this case the K^- may result from the transition $K^0 \rightleftarrows \tilde{K}^0$ with subsequent charge exchange $K^0 \to K^-$ in a thick target (or as a result of an even more complicated process, namely $K^+ \to K^0 \to \tilde{K}^0 \to K^-$). An interesting situation arises with the $K_{\mu_3}^0 \to \mu^\pm + \pi^\mp + \nu$ and $K_{e_3}^0 \to e^\pm + \pi^\mp + \nu$ decays, which are allowed both for the K_1^0 and the K_2^0 particles,* since it is always possible to set up symmetrical and antisymmetrical states of the type

$$K_1^0 = A_1 [\Psi (e^+\pi^-\nu) + \Psi (e^-\pi^+\tilde{\nu})],$$
$$K_2^0 = iA_2 [\Psi (e^+\pi^-\nu) - \Psi (e^-\pi^+\tilde{\nu})].$$

As was noted by Treiman and Sachs,[121] the probability of decays of this type will be determined not only by the exponents of the K_1^0 and K_2^0 decays, but also by the interference term, which depends on the difference in the masses of K_1^0 and K_2^0

$$R (e^+\pi^-\nu) = \frac{1}{2} A_1^2 \exp(-\lambda_1 t) + \frac{1}{2} A_2^2 \exp(-\lambda_2 t)$$
$$+ A_1 A_2 \cos(\Delta\omega t) \exp\left[-(\lambda_1 + \lambda_2)\frac{t}{2}\right],$$
$$R (e^-\pi^+\nu) = \frac{1}{2} A_1^2 \exp(-\lambda_1 t) + \frac{1}{2} A_2^2 \exp(-\lambda_2 t)$$
$$- A_1 A_2 \cos(\Delta\omega t) \exp\left[-(\lambda_1 + \lambda_2)\frac{t}{2}\right],$$

where λ_1 and λ_2 are the decay constants of K_1^0 and K_2^0, and

$$\Delta\omega = \frac{(m_{K_1^0} - m_{K_2^0}) c^2}{h}.$$

It is seen from these equations, for example, that when $A_1 = A_2$ the decay $K^0 \to (e^-\pi^+\overline{\nu})$ will be in general forbidden during the initial instant of time $(t = 0)$.

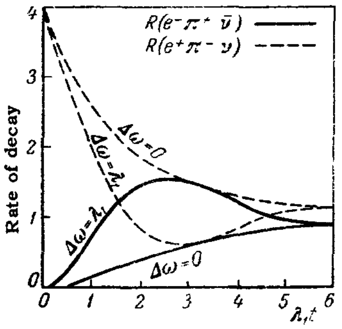

FIG. 12

We see from the curve (Fig. 12) that the time dependence of the probability of the decays $R(e^-\pi^+\overline{\nu})$ and $R(e^+\pi^-\nu)$ depends greatly on $\Delta\omega = \Delta M c^2/\hbar$. A study of this effect can there-

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*In accordance with experimental data, it is assumed here that the spin of the K meson is 0.

*The V – A theory predicts equal probabilities of the K_{e_3} and the K_{μ_3} decays[120] for the K_1^0 and K_2^0, that is,

$$w (K_1^0 \to \pi^\mp + \mu^\pm + \nu) = w (K_2^0 \to \pi^\mp + \mu^\pm + \nu),$$
$$w (K_1^0 \to \pi^\mp + e^\pm + \nu) = w (K_2^0 \to \pi^\mp + e^\pm + \nu).$$

It becomes therefore interesting to search for anomalous $K_1^0 \to {\mu^\pm \atop e^\pm} + \pi^\mp + \nu$ decays, for which the branching ratios should be (assuming the same experimental estimates as made for K_2^0)

$$\frac{w (K_1^0 \to \pi^\mp + \mu^\pm + \nu)}{w (K_1^0)} = \frac{w (K_1^0 \to \pi^\mp + e^\pm + \nu)}{w (K_1^0)} \sim 3 \cdot 10^{-4}.$$

fore yield information on the K_1^0 and K_2^0 mass difference.

An analogous time dependence was obtained by Okun'[122] for the probability of the $K^0 \rightarrow \mu^- + \pi^+ + \nu$ decay by assuming that the decay interactions $\pi^+ \rightarrow \mu^+ + \nu$ (a) and $K^+ \rightarrow \mu^+ + \nu$ (b) are the primary ones, and all the remaining interactions involving K, μ, ν are derived from the processes (a) and (b).[123] This assumption makes the decay $K^0 \rightarrow \mu^- + \pi^+ + \bar{\nu}$ forbidden, with the possibility of such a decay appearing as the result of the transformation of K^0 into a $\tilde{K}^0$ particle, the decay of which into $\mu^- + \pi^+ + \bar{\nu}$ is allowed.

Interference effects can also be investigated by registering not the decays but the products of the interaction of $\tilde{K}^0$ as was proposed in reference 124. It must also be noted that for large t, when only the long-lived component K_2^0 remains, a charge symmetry should exist in the K_2^0 decays, that is $R(e^-\pi^+\bar{\nu})/R(e^+\pi^-\nu) = 1$.

The experimental evidence on the noninvariance of decay interactions under charge conjugation has necessitated a review of the Gell-Mann and Pais theory. However, the main conclusions of this theory remain in force if the "combined parity" hypothesis is adopted. In fact, according to the ideas of Landau,[125] Lee and Yang,[126] spatial parity (P) and "charge" parity (C) are not separately conserved in weak interactions, but there exists only invariance under the aggregate of these operations (CP) ("combined inversion" in Landau's terminology). Then the states K_1^0 and K_2^0 can be considered as eigenstates of combined inversion with eigenvalues CP = +1 and CP = −1 respectively. Since the $\pi^+\pi^-$ state is even with respect to the CP operation, the decay $K_2^0 \rightarrow 2\pi$ is forbidden, as before. All the conclusion concerning the interference phenomena in the $K^0 \rightarrow e^\pm + \pi^\mp + \nu$ and $K^0 \rightarrow \mu^\pm + \pi^\mp + \nu$ decays, considered above, remain also in force. However, several new consequences appear upon the review of the $K_{3\pi}^0$ decay.[127,128]

1. The decay $K^0 \rightarrow 3\pi^0$ can occur only for K_2^0 (CP = −1) and not for the K_1^0 (CP = +1), since the $3\pi^0$ state is odd under CP conjugation.

3. The decay $K^0 \rightarrow \pi^+ + \pi^- + \pi^0$ is in principle allowed for the K_1^0, but such a decay is possible for the state $l = l' = 1$ (where l is the orbital momentum). Consequently this decay is approximately 100 times less probable than the K_0^2 $\pi^+ + \pi^- + \pi^0$, which can occur in the ground state. If at the same time the decay probabilities $w(K_{3\pi}^+)$ and $w(K_{3\pi}^0)$ are considered to be of the same order, then

$$\frac{w(K_1^0 \rightarrow \pi^+ + \pi^- + \pi^0)}{w(K_1^0 \rightarrow 2\pi)} \lesssim 10^{-5}.$$

Certain other consequences also appear and these will be reviewed in connection with the selection rule $|\Delta I| = \frac{1}{2}$ (see page 000).

It was subsequently shown[130] that the existence of the K_1^0 and the K_2^0 components with different lifetimes can follow from more general premises than the proposed invariance of the decay interaction under time reversal. In this case all the foregoing restrictions are lifted and the $K^0 \rightarrow 2\pi$ decay is found to be allowed for both the K_2^0 and for the K_1^0 component. And although these decays may in principle have different probabilities, it becomes necessary to explain somehow the great difference in the lifetimes of these components[131] and to introduce some sort of selection rules that forbid the $K_2^0 \rightarrow 2\pi$ decay.

In the case of violation of the CP invariance, charge asymmetry can occur also in the decays $K^0 \rightarrow {e^\pm \atop \mu^\pm} + \pi^\mp + \nu$ so that the relation $\dfrac{R(e^-\pi^+\bar{\nu})}{R(e^+\pi^-\nu)} = 1$ will no longer hold for the K_2^0 component.*

The first direct experimental evidence of the existence of a long-lived K_2^0 component was obtained by Lande et al.[129]

Figure 13 shows schematically the experimental setup used in that investigation. A cloud chamber was placed in a beam of neutral particles produced in the internal target of a cosmotron and passed through a lead collimator. The distance to the target was sufficient to allow practically all the Λ^0 and $K_{2\pi}^0$ particles to decay in flight. On the other hand the charged particles, traveling towards the chamber, were gathered by a strong

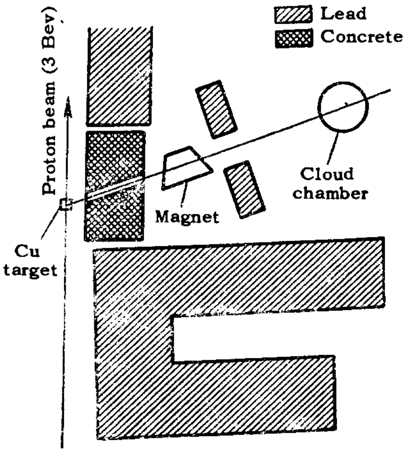

FIG. 13

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*Weinberg[132] believes, however, that such an asymmetry should be small ($\lesssim$ 10%) even if the decay interaction of the K meson is not invariant under CP.

deflecting magnet (40,000 gauss). As result, twenty-three V^0 events were registered, different from $K^0_{2\pi}$ and Λ^0 decays, and the lifetimes of these events ranged from 3×10^{-9} to 10^{-6} sec. A certain improvement in the experimental conditions[133,134,135] made it possible to increase the number of registered "anomalous" V^0 decays and to obtain more definite information on the mass of the decaying particle and on the character of these decays.

It was shown that the mass of the decaying particle is close to the K-meson mass and that its decay proceeds predominantly via the $e^{\pm}\pi^{\mp}\nu$ and $\mu^{\pm}\pi^{\mp}\nu$ states, and some of these decays were firmly identified.

Figure 14 shows the distribution of the transverse momenta of the positive, negative, and neutral decay products of the long-lived K^0_2 particles.

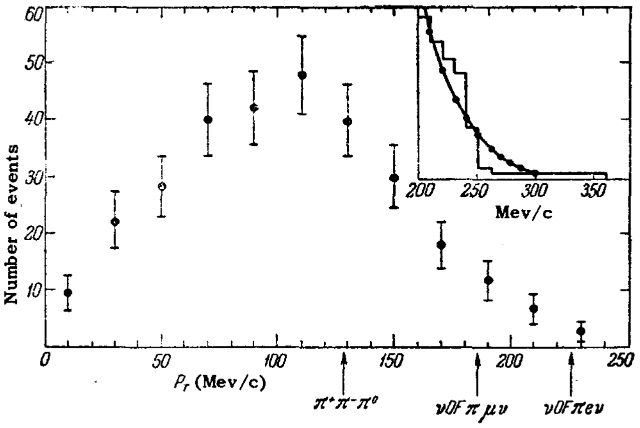

FIG. 14

As can be seen from the curve, the magnitude of the extreme momentum coincides with the maximum momentum in $K^0 \to e + \pi + \nu$ decay, which, along with the $K^0 \to \mu^{\pm} + \pi^{\mp} + \nu$ decay should be considered as the principal one. Naturally, one cannot exclude kinematically the $K^0 \to e^{\pm} + \mu^{\mp} + \pi^0$ decays, but such a possibility was disregarded since no such decays were observed among charged K mesons.

Two $K^0_2 \to \pi^+ + \pi^- + \pi^0$ decay events were registered, and a few other decays, which agree with this decay scheme, but do not contradict the $K^0_2 \to \pi^+ + \pi^- + \gamma$ decay.

Table V lists a number of various decays, identified by the Brookhaven group.[134] The table discloses the presence of a certain charge asymmetry in the K^0_2 decays, which, as noted earlier, may be the consequence of the violation of the CP (or T) invariance in the K^0_2 decays.

Considering also that the Berkeley group has recorded among the K^0_2 decays eight (8) events with e^- and not a single one with e^+, the summary charge asymmetry in the K^0_2 decays will be

$$\frac{w(\pi^+)}{w(\pi^-)} = \frac{38}{16} = 2{,}4.$$

The small number of registered events does not permit as yet to draw final conclusions on the nonconservation of CP(T), on the other hand, attempts are already being made to explain the possible charge asymmetry without foregoing the CP conservation in weak interactions, for otherwise (if CP is not conserved) the situation becomes even more complicated. However, no satisfactory solution has yet been found in this direction. Thus, Treiman and Wyld[136] proposed to revive the doublet theory and to attribute the possible charge asymmetry in the K^0_2 decays to interference between τ^0_2 and θ^0_2. It is assumed here that τ^0 and θ^0 are different particles, which is hardly likely now that τ and θ were found to be identical.

In experiments with cosmic rays, certain experimental data were also obtained regarding the "anomalous" K^0 decays. Using a cloud chamber, Kadyk et al.[137] observed 18 anomalous K^0 decays. In each individual case it was impossible to establish uniquely the type of decay, but it was shown that the majority of the registered decays were in good agreement with the schemes $K^0 \to e^{\pm} + \pi^{\mp} + \nu$, $K^0 \to \mu^{\pm} + \pi^{\mp} + \nu$, $K^0 \to \pi^+ + \pi^- + \gamma$, and possibly also $K^0 \to \pi^+ + \pi^- + \pi^0$. It was also established that the lifetime of these "anomalous" decays is much longer than the lifetime of the ordinary $K^0_{2\pi}$ decay. All this supports the assumption that these are decay events of the long-lived component K^0_2.

As to the observed differences in the number of associated productions and in the angular distributions of K^0_1 and K^0_2, this may be due to the different lifetimes.

TABLE V

Method of decay	$\pi^+e^-\nu$	$\pi^-e^+\nu$	$\pi^+\mu^-\nu$	$\pi^-\mu^+\nu$	$\pi^+\pi^-\pi^0$	π^+?	π^-?
Number of events	10	5	10	2	2	8	7
Total number of events with π^+ – 30 **Total number of events with π^- – 16**							

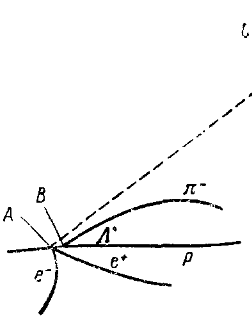

FIG. 15

Recently direct proof was obtained of the existence of associated production of a long-lived K_2^0 meson and a hyperon.[138] A photograph (shown schematically in Fig. 15) obtained with a propane bubble chamber shows the following to be emitted from the point of interaction between the π^- meson and the proton (A):

(1) A γ quantum giving rise to an electron-positron pair.

(2) A Λ^0 particle decaying near the point of interaction (B).

(3) A K^0 meson, which undergoes a three-particle decay at a considerable distance, equal to ten (10) times the average decay range of the K_1^0 particle (C). Thus, the entire accumulation of experimental data is evidence that the following reaction took place

$$\pi^- + p \longrightarrow K_2^0 + \Sigma^0 \searrow \Lambda^0 + \gamma$$

with a subsequent decay

$$K_2^0 \longrightarrow \begin{matrix} e^{\pm} \\ \mu^{\pm} \end{matrix} + \pi^{\mp} + \nu.$$

The data obtained by Planos et al.[139] permit an estimate of the relative number of K^0 mesons undergoing $K^0 \longrightarrow 2\pi$ decay. They took into account here both the charged $(\pi^+ + \pi^-)$ and neutral $(\pi^0 + \pi^0)$ decays, and the total number of K^0 mesons created was determined under the assumption that the only associated production to take place is: $\pi^- + p \longrightarrow \Lambda^0 (\Sigma^0) + K^0$ (i.e., the number of K^0 was taken equal to the number of Λ^0 decays).

As predicted by Gell-Mann and Pais, a ratio $\frac{w(K_1^0 \longrightarrow 2\pi)}{w(K_{1.2}^0)} = 0.49 \pm 0.08$ was obtained, i.e., half the K^0 mesons decay as the short-lived component K_1^0, and the second half, K_2^0, owing to its long lifetime, is not recorded in the chamber. The same paper contains an evaluation of the lower limit for the lifetime of the long-lived component $(\tau_{K^0} > 3 \times 10^{-8}$ sec).

In one of the later experiments of the Brookhaven group a direct measurement was made of the average lifetime of the K_2^0 particle.[140,141] For this purpose the distance from the target to the chamber was increased from 5.5 m to 21.5 m, this reducing the number of registered K_2^0 decays per single neutron interaction observed in the same chamber. Such relative measurements have made it possible to dispense with the need of corrections for the solid angle, for the intensity of the primary-particle beam, etc. The velocity spectrum of the K_2^0 was determined kinematically under the assumption of associated production of K mesons and hyperons in complex nuclei.[142]

The result obtained was $\tau_{K_2^0} = (9.0^{+3.5}_{-2.5}) \times 10^{-8}$ sec.

Several recently performed experiments have confirmed the existence of the transformation $K^0 \rightleftarrows \widetilde{K}^0$ in vacuo. Thus, as predicted by Pais and Piccioni, hyperon production was observed at a considerable distance from the target, resulting from the $K^0 \longrightarrow \widetilde{K}^0$ transformation, with the subsequent interaction $\widetilde{K}^0 + N \longrightarrow \Sigma^- + \pi$ in a cloud chamber.[133] More definite proof of the existence of the Pais and Piccioni process was observed in an analogous experiment with a bevatron, with the target bombarded by pions of energy lower than the threshold for production of the $\widetilde{K}^0$ particle.

At the same time was studied the interaction of the K^0 particle, which arises as the result of the Pais-Piccioni process in a propane bubble chamber, and which has led to the registration all together of not less than $14\,\Lambda^0$ and $15\,K^0$ decays.[134,143,144]

An event of exceeding beauty, recorded in a hydrogen bubble chamber by the Alvarez group, is the clearest illustration of the existence of the Pais-Piccioni process[145] (see Fig. 16).

This shows the negative-pion induced associated production of a Λ^0 particle, which decays right there, and of a K^0 meson. A kinematic analysis of this event makes it possible to determine uniquely the direction of emission of the K^0 meson, produced in association with the Λ^0 particle. The K^0 particle interacts, at a considerable distance from the place of production, with a proton, giving rise to a Σ^+ hyperon which undergoes the decay $\Sigma^+ \longrightarrow n + \pi^+$. It is obvious that the K^0 meson, having a "strangeness" $S_{K^0} = +1$, cannot cause the production of the hyperon $S_\Sigma = -1$, but such an interaction can result from the $K^0 \longrightarrow \widetilde{K}^0$ transition, which has indeed occurred in this case.

In emulsion stacks, irradiated at a considerable distance from the bevatron target, there were

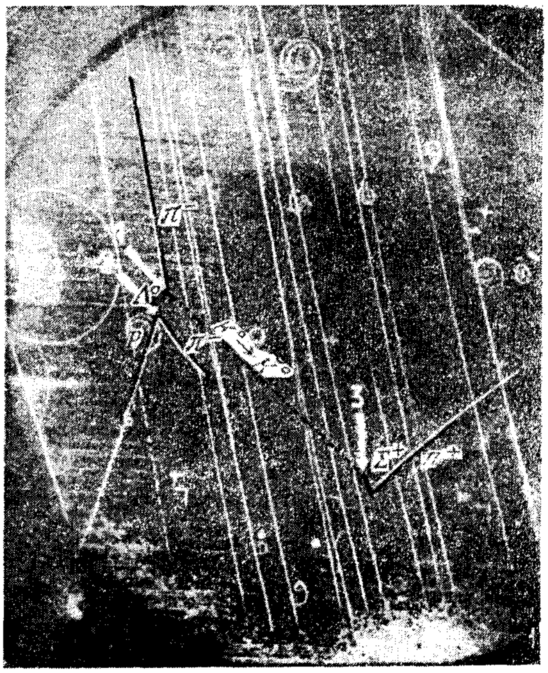

FIG. 16

also observed several events of production of unstable particles[146-154] and the production of hyperfragments[148,152] by a neutral particle. In some cases[149] it was found possible to estimate the mass of this neutral particle, which was found to be close to the K-meson mass.

All these cases are in good agreement with the assumption that the neutral particle producing these interactions is the $\tilde{K}^0$ meson, "formed" as the result of the Pais-Piccioni process via the long-lived K_2^0 component.

The most convincing experiments in this respect are those of Fry et al.[153,154] In emulsion stacks located near the target, exposed to a K^+-meson beam, there were observed 75 hyperfragments, which result from the following process:

$$K^0 \xrightarrow{\text{charge exchange}} K^0 \xrightarrow{\text{Pais-Piccioni process}} \tilde{K}^0$$

It must be noted that a further investigation of the K_2^0 decays is of considerable interest. It is particularly important to investigate the charge asymmetry in the $K_2^0 \rightarrow e^\pm + \pi^\mp + \nu$ and the $K_2^0 \rightarrow \mu^\pm + \pi^\mp + \nu$ decays, which apparently can solve the problem of CP-invariance in weak interactions.* Similar results can be obtained by investigating $3\pi^0$ decays, for example, in a xenon bubble chamber. In this case the presence of $K^0 \rightarrow 3\pi^0$ decays with a lifetime of $\tau_{K_1^0}$, would be evidence of violation of the CP(T) invariance.

It is also very important to investigate the Pais-Piccioni process and the associated interference phenomena, which can yield information on $\Delta m_{K^0} = (m_{K_1^0} - m_{K_2^0})$. For example, Okun' and Pontecorvo[155] discuss interesting experimental possibilities that arise if slow transitions with $|\Delta S| = 1$ and $|\Delta S| = 2$ have a comparable probability. In this case the $K^0 \rightarrow \tilde{K}^0$ transition should occur so rapidly ($\sim 10^{-16}$ sec), that a seeming violation of "strangeness" conservation could appear at production.

Recently the first experimental attempt of estimating Δm_{K^0} has been undertaken.[156] For this purpose the interactions of K^0 mesons with matter at various distances from their point of production have been investigated. As already noted, the presence of K^0 interactions in which hyperons are produced is evidence of the existence of the $K^0 \rightarrow \tilde{K}^0$ transition, and a study of the distribution of such interactions can give information on the value of Δm_{K^0}. A rough estimate, based on 12 events, yields $\Delta m_{K^0} \sim 10^{-5}$ ev, which corresponds to a transition time of $\sim 10^{-10}$ seconds. It was also noted there that no seeming violation of the conservation of "strangeness," caused by faster transitions, were observed (neither were they observed in the experiments of the Columbia and Princeton groups). In view of the very poor statistics these data must be approached very carefully. This is more so, because of the $K^0 \rightarrow \tilde{K}^0$ transition, with a time on the order of 10^{-10} sec, may not be at all due to the foregoing interference and result merely from the difference in the lifetimes of K_1^0 and K_2^0. Another interesting study, proposed in many papers, is an experimental investigation of various methods of regeneration of the K_1^0 meson, for example by scattering the long-lived K_2^0 meson[157] or by subjecting it to a magnetic field.[158] The latter proposal, however, is only of academic interest, since such a process is possible only if the magnetic moment and the spin of K^0 are not equal to zero.

As to an investigation of the regeneration of the K_1^0 meson by scattering the K_2^0 meson, this, as was shown by Good[159] can yield data on the mass difference of K_1^0 and K_2^0 particles.

DECAY PROPERTIES OF HYPERONS

The Λ^0 Hyperon

The principal decay of this hyperon, $\Lambda^0 \rightarrow p + \pi^-$, has by now been studied quite in detail. Noteworthy among the latest experimental data is a new value of the decay energy $Q_{\Lambda^0} = (37.9 \pm 0.4)$ Mev[105] (instead of the 36.9 Mev obtained in earlier investigations). This is of great importance

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*Cf., however, the footnote on page 129.

for a correct determination of the binding energy of the Λ^0 hyperon in hyperfragments, which, if the new value of Q_{Λ^0} is to be believed, is 1 Mev greater.

The first information on the neutral decay $\Lambda^0 \rightarrow n + \pi^0$ were obtained by Collins,[108] Osher et al.,[109] and Ridgeway et al.[110] However, as already indicated (see page 126) these data can in no manner be considered as experimental proof of the existence of the $\Lambda^0 \rightarrow n + \pi^0$ decay. Undoubtedly more convincing in this respect are the events registered with a propane bubble chamber in a π^--meson beam.[112,161] This experiment yielded five photographs of the production of a K^0 particle in π^-p interaction, and these photographs show, in addition to the $K^0_{2\pi}$ decay, also the converson of a γ quantum emitted on the hypothetical path of the Λ^0 particle. The direction of the emission of the Λ^0 particle was determined, in turn, from kinematic relations under the assumption that associated production takes place.

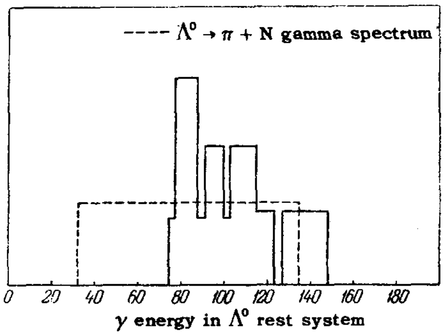

FIG. 17

The energy distributions of these five γ quanta, shown in Fig. 17, make it possible, in spite of the statistical paucity, to exclude the possibility of the $\Lambda^0 \rightarrow n + \gamma$ decay, which yields, in the center-of-mass system, monoenergetic γ quanta ($E_\gamma \sim$ 165 Mev), and at the same time does not contradict the $\Lambda^0 \rightarrow n + \pi^0$. By calculating the probability of the γ-quanta conversion, the authors have obtained a very rough estimate of the relative number of Λ^0 particles undergoing neutral decay

$$R_{\Lambda^0 \rightarrow n+\pi^0} = \frac{w\,(\Lambda^0 \rightarrow n + \pi^0)}{w\,(\Lambda^0)} = 0.18 \pm 0.09.$$

It is possible to obtain R_{Λ^0} in a more indirect manner from the ratio of the events of associated production of Λ^0 and K^0 to the number of events in which only one $K^0_{2\pi}$ is seen in the photograph, and the Λ^0 is assumed to decay into neutral products and is therefore invisible[161] ($R_{\Lambda^0} = 0.37 \pm 0.03$*).

The average lifetime of the Λ^0 particle was measured in many investigations. Tables VI and VII give the values obtained respectively in cosmic-ray experiments and with accelerators.

As can be seen from the tables, the average lifetimes of the Λ^0 particle measured in experiments with cosmic rays, is considerably greater than τ_{Λ^0} obtained with accelerators. One of the most probable causes of this discrepancy will be discussed in connection with the possible existence of a Ξ^0 hyperon (see page 136).

Σ Hyperons

The existence of charged Σ hyperons with decays $\Sigma^+ \begin{smallmatrix} \nearrow p + \pi^0 \\ \searrow n + \pi^+ \end{smallmatrix}$ and $\Sigma^- \rightarrow n + \pi^-$ was established experimentally relatively long ago, by ir-

TABLE VI

$\tau_{\Lambda^0} \times 10^{10}$	Number of events	Detector	Reference
3.5 ± 1.2	21	Cloud chamber with plates	162
2.5 ± 0.7	63	Cloud chamber in magnet	163
$3.7^{+3.9}_{-1.3}$	26	Cloud chamber in magnet	164
$3.6^{+1.1}_{-0.7}$	23	Cloud chamber in magnet	165
$4.0^{+3.7}_{-1.2}$	21	Cloud chamber with plates	166
$4.8^{+2.6}_{-1.2}$	22	Cloud chamber with plates	167
$2.14^{+0.8}_{-0.5}$	25	Cloud chamber with plates	168
$3.6^{+0.8}_{-0.5}$	31	Cloud chamber with plates	169
$3.5^{+0.3}_{-0.2}$	232	Weighted average	

TABLE VII

τ_{Λ^0} sec $\times 10^{10}$ sec	Number of events	Detector, experimental conditions	Reference
2.77 ± 0.2	304	Propane bubble chamber in π^- beam (1.3 Bev), cosmotron	139, 161
$2.75^{+0.40}_{-0.38}$	74	Cloud chamber in pion beam (1.9 Bev), cosmotron	174
3.05 ± 0.35	340	Hydrogen bubble chamber in π^- beam (000), bevatron	172
2.63 ± 0.21	188	Cloud chamber with plates in π^- (1.8 Bev), cosmotron	171
$2.08^{+0.46}_{-0.31}$	61	Propane bubble chamber in π^- beam (1.1 Bev), cosmotron	173
2.95 ± 0.4	76	Bubble chamber in beam of slow K^- mesons (bevatron)	175
2.70 ± 0.10	1043	Weighted average	

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*These are summary data obtained from 1399 events of associated production registered by various groups.[160]

radiating emulsions and cloud chambers in cosmic rays.

However, only the latest experiments, performed with accelerators, yielded more detailed information concerning the decay properties of the Σ^+ and Σ^- hyperons.

The most accurate values of the average lifetime τ_Σ were obtained in the study of Σ hyperons, produced as a result of K^--meson capture in bubble chambers and emulsions:

$$\tau_{\Sigma^+}=\left(0.95\ {}^{+0.31}_{-0\ 20}\right)\cdot 10^{-10}\ \text{sec},\quad \tau_{\Sigma^-}=\left(1.67\ {}^{+0,40}_{-38}\right)\cdot 10^{-10}\ \text{sec}$$

Glaser group,[176]

$$\tau_{\Sigma^+}=(0.69\pm 0.10)\cdot 10^{-10};\quad \tau_{\Sigma^-}=(1.6\pm 0.2)\cdot 10^{-10}\ \text{sec}$$

Alvarez group,[95]

$$\tau_{\Sigma^+}=\left(0.89\ {}^{+0.14}_{-0.10}\right)$$ Wisconsin group,[177]

and also in the investigations of the joint Columbia, Pisa, and Bologna groups[170]

$$\tau_{\Sigma^-}=\left(1.89\ {}^{+0,33}_{-0,25}\right)\cdot 10^{-10}\ \text{sec}$$

(bubble chamber in π^--meson beam). The weighted average of these values, given in Table I, is

$$\tau_{\Sigma^+}=(0.79\pm 0.10)\cdot 10^{-10}\ \text{sec},$$

$$\tau_{\Sigma^-}=\left(1.72\ {}^{+0.17}_{-0.10}\right)\cdot 10^{-10}\ \text{sec}.$$

The emulsion data yield, as a rule, lower values of τ_{Σ^-}. In connection with this, the hypothesis has been advanced that a short-lived Σ^- hyperon exists.[160] However, this hardly warrants serious consideration, for the above data are contradictory and are of low accuracy.

The branching ratios for various modes of Σ^+-hyperon decay were measured with sufficient accuracy and found to be close to unity

$$a_{\Sigma^+}=\frac{w(\Sigma\to p+\pi^0)}{w(\Sigma\to n+\pi^+)}=\frac{136}{154}=0.88\pm 0.12\,*.$$

Quite recently an even more accurate result, $R_{\Sigma^+} = 0.96 \pm 0.06$, was obtained[180] for the branching ratio for the $\Sigma^+ \to p + \pi^0$ and $\Sigma^+ \to n + \pi$ decays.

Worthy of attention is an unusual Σ^+ decay, observed by Ekspong and Nilsson[179] in an emulsion stack exposed to the K-meson beam of the bevatron. A characteristic feature of this decay is the presence of an electron-positron pair, emitted simultaneously with the proton.

It would be most natural to consider this electron-positron pair as a result of the $\pi^0 \to e^+ + e^- + \gamma$ decay, but such an interpretation raises difficulties connected with momentum conservation.

In accordance with the scheme of Gell-Mann and Nishijima, in which the Σ hyperon appears as a charge triplet $(I = 1)$, there should exist a neutral Σ^0 hyperon, which decays very rapidly $(\tau_{\Sigma^0} < 10^{-11}\ \text{sec})$* into a Λ^0 particle and a γ quantum. The latter circumstance makes a direct observation of the Σ^0 hyperon very difficult. First indirect indications of the existence of a Σ^0 particle were obtained even in earlier investigations,[181,182] when violation of momentum conservation was observed in two events of associated production $\pi^- + p \to \Lambda^0 + K^0$. This seeming nonconservation was readily eliminated by assuming the production of a Σ^0 particle: $\pi^- + p \to \Sigma^0 + K^0$ with subsequent decay $\Sigma^0 \to \Lambda^0 + \gamma$.

More detailed information on the existence of Σ^0 were found by Alvarez et al.,[183] who observed the continuous spectrum of Λ^0 particles resulting from capture of the stopped Σ^- particle by the proton. These results are in good agreement with the assumption that the reaction occurring is $\Sigma^- + p \to n + \Sigma^0 \searrow \Lambda^0 + \gamma$, and contradicts the $\Sigma^- + p \to \Lambda^0 + n$ reaction, since the latter reaction should yield monoenergetic Λ^0 particles ($E_{\Lambda^0} \sim 37$ Mev). Finally, recently[184] in a propane chamber placed in a π-meson beam there were recorded three events of associated production in which a γ quantum, which gives rise to an electron-positron pair, is emitted from the place of interaction between the negative pion and the nucleon in addition to a Λ^0_0 and K^0 (Fig. 18).

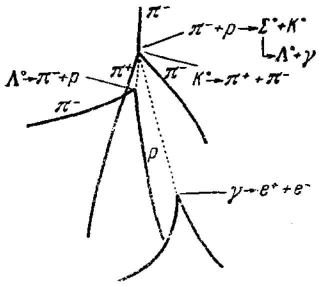

FIG. 18

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*Summary data from references 177 and 178.

*This value represents only an experimental limit. One must assume that τ_{Σ^0} is much less ($\sim 10^{-20} - 10^{-21}$ sec).

Twelve similar events are reported in references 138, 160, and 185. An analysis of these 15 events makes possible a sufficiently accurate determination of the decay energy of the Σ^0 particle:

$$Q_{\Sigma^0} = 75.3 \begin{smallmatrix}+0.9\\-1.4\end{smallmatrix} \text{ Mev}$$

and of its mass

$$m_{\Sigma^0} = 1190.5 \begin{smallmatrix}+0.9\\-1.4\end{smallmatrix} \text{ Mev.}$$

In one of the foregoing cases[185] of Σ^0 decay, a Dalitz pair ($\Sigma^0 \rightarrow \Lambda^0 + e^+ + e^-$) was emitted instead of a γ quantum. A study of the relative probability of such an anomalous Σ^0 decay is of considerable interest, since it would yield information on the relative parity of the Λ^0 and Σ^0 hyperons.[186] However, this calls for rich statistical experimental material.

Recently, exact values were also obtained for the masses of charged Σ hyperons, $m_{\Sigma^+} = (1189.5 \pm 0.3)$ Mev, $m_{\Sigma^-} = (1196.5 \pm 0.4)$ Mev[188] and $\overline{m}_{\Sigma^+} = (1189.3 \pm 0.3)$ Mev and $\overline{m}_{\Sigma^-} = (1195.8 \pm 0.5)$ Mev,[100] and also $\overline{m}_{\Sigma^-} = (1196.7 \pm 0.6)$ Mev.[187]

In Table I we give the weighted average of these results $m_{\Sigma^+} = (1189.4 \pm 0.2)$ Mev and $\overline{m}_{\Sigma^-} = (1196.4 \pm 0.3)$ Mev. As pointed out many times[189,190,191] the observed difference in the masses of the Σ^+ and Σ^- hyperons results from a difference in the intrinsic electromagnetic energy of these baryons, due in turn to the anomalous magnetic moments, as also happens in the case of the nucleon.[192,193] Using relations derived by Marshak et al.[190] as well as the latest experimental values of the masses of the uncharged and charged hyperons, we can estimate the magnetic moments of these hyperons, the values of which (in hyperon magnetons) are listed below:

$$\mu_{\Sigma^+} \simeq 1.5, \qquad \mu_{\Sigma^-} \sim 1 - 1.5, \text{ if } \mu_{\Sigma^0} > 0;$$

$$\mu_{\Sigma^+} = (-8) - (-11), \qquad \mu_{\Sigma^-} = 5 \div 8, \text{ if } \mu_{\Sigma^0} < 0.$$

Cascade Ξ Hyperons

The existence of a Ξ^- hyperon can be considered as experimentally proved, although the number of observed cascade decays $\Xi^- \rightarrow \Lambda \genfrac{}{}{0pt}{}{+\,\pi^-\ (a)}{\searrow\, p + \pi^-}$ are still very few. Until recently only 20 events* were recorded;[194-207] of these only 12 can be considered fully reliable, and all that can be said of the remaining is that they are in good agreement with the decay (a). Most cascade hyperons were recorded with cloud chambers in cosmic rays, and only four were recorded in emulsions, and in the latter no Λ^0 decay was observed, the identification being based on the characteristic energy of the Ξ^- decay.

The most valuable information on the properties of the Ξ^- particles are given by Trilling and Neubauer,[207] who analyzed six reliably registered Ξ^- hyperons. These data make it possible to estimate the relative probability of the production of the Ξ^-, which amounts to at least 20% of the probability of production of Σ^- (with allowance for the possible cases in which the decay of the Λ^0 particle, obtained as a result of the Ξ^- decay, occurs outside the effective volume of the chamber). Apparently, the registration hitherto of so few cases of Ξ^- is due (in addition to the high energy threshold for the production) also to the small efficiency with which two successive decays can be registered in a chamber of not too large size. Only in five previously-registered cases is a very rough direct measurement of the Ξ^- mass possible. However, since the decay scheme $\Xi^- \rightarrow \Lambda^0 + \pi^-$ has been reliably established, there is no need for direct measurement, and the mass of Ξ^- can be determined with sufficient reliability from the decay energy Q_Ξ. The weighted average of 18 Ξ^- decay events yields $Q_{\Xi^-} = (64.2 \pm 2.5)$ Mev, $m_\Xi = (1319 \pm 3)$ Mev. Until recently it was found impossible to measure the average lifetime of Ξ^- with any degree of accuracy. This is explained by the fact that in order to identify completely the Ξ^- it is necessary to observe also a Λ^0 decay, and this so to speak reduces the effective dimensions within which the measurement of τ_{Ξ^-} is possible. Only Trilling and Neubauer[207] make an estimate of the lower and upper limits of τ_{Ξ^-}, based on 7 analyzed Ξ^- decays. This estimate yields for the lower limit $\tau_\Xi = 4.6 \times 10^{-10}$ sec.*

An estimate of the upper limit $\tau_{\Xi^-} < 2 \times 10^{-6}$ sec was made from the number of K_1^0 decays that are not accompanied by a Ξ^- decay. It was assumed here that the Ξ^- is produced with two K-mesons. This last estimate is quite arbitrary and rather rough, and hardly deserves serious consideration. In spite of the quite large phase space volume, no $\Xi^- \rightarrow n + \pi^-$ (I) decay has been registered to date. The absence of such a decay has led Gell-Mann and Pais to the assump-

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*This number includes two cases registered with a propane bubble chanber, placed in a π^--meson beam ($E_{\pi^-} = 5.0 \pm 0.5$ Bev) of the bevatron.[205,206]

*The lifetimes of the Ξ^- hyperons, registered in the bevatron (1.1×10^{-10} sec and 4.8×10^{-10} sec), do not contradict these estimates.

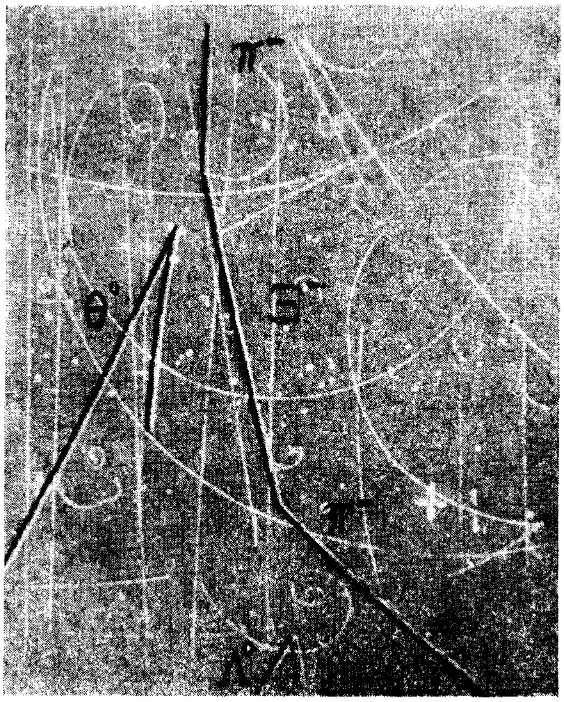

FIG. 19. Production and Decay of Ξ^- hyperon in a bubble chamber.[206]

tion that decays in which strongly-interacting particles participate are subject to the selection rule $|\Delta S| = 1$, which forbids decays (Type I) in which the "strangeness" changes by two. This selection rule calls for the strangeness of the Ξ^- hyperon to be $S_\Xi = -2$, since its decay products, Λ^0 and π^- have a total strangeness of -1.* Taking into consideration the well known relation

$$Q = I_3 + \frac{N}{2} + \frac{S}{2}$$

(where Q is the charge, I_3 is the third component of the isotopic spin, and N is the number of baryons minus the number of antibaryons) and, putting $S_\Xi = -2$, we find that $I_3 = -\frac{1}{2}$. It follows from this that under these assumptions the Ξ hyperon is a charged doublet, i.e., a Ξ^0 ($I_3 = +\frac{1}{2}$) should exist along with the Ξ^- ($I_3 = -\frac{1}{2}$).†

The preferred decay of this hypothetical particle is apparently the hard-to-observe $\Xi^0 \rightarrow \Lambda^0 + \pi^0$ decay. In connection with the possible existence of the Ξ^0 particle, attention should be called to the noticeable difference in the lifetime of the Λ^0 registered in cosmic rays, $\tau_{\Lambda^0} = (3.5^{+0.3}_{-0.2}) \times 10^{-10}$ sec and of Λ^0 particles, artificially obtained in accelerators [$\tau_{\Lambda^0} = (2.7 \pm 0.1) \times 10^{-10}$ sec]. In the former case it is possible to register, in addition to the Λ^0 particles produced directly in the primary act, also Λ^0 particles occurring as a result of the unobserved decay $\Xi^0 \rightarrow \Lambda^0 + \pi^0$. The primary interaction, in which hyperons are produced, is not observed here as a rule, and it is therefore impossible to distinguish between these two types of Λ^0 particles. This circumstance should lead an apparent increase in the measured τ_{Λ^0} over the actual value, and this increase should depend on the ratio of the probabilities for production of Ξ^0 and Λ^0 particles followed by their decay (for more details see reference 208).

At the same time, those experimenting with accelerators have dealt so far with Λ^0 particles that are "pure" in this respect, since the Ξ^0 hyperon could not be produced, from energy considerations.

This fact may be evidence in favor of the existence of the Ξ^0, although, naturally, the possibility of some systematic error cannot be excluded in this case.

The *only direct experimental indication in* favor of the existence of the Ξ^0 hyperon is an event recently obtained by exposing a cloud chamber in cosmic rays on Pique du Midi.[209] The photograph (Fig. 20) shows, in addition to the Λ^0

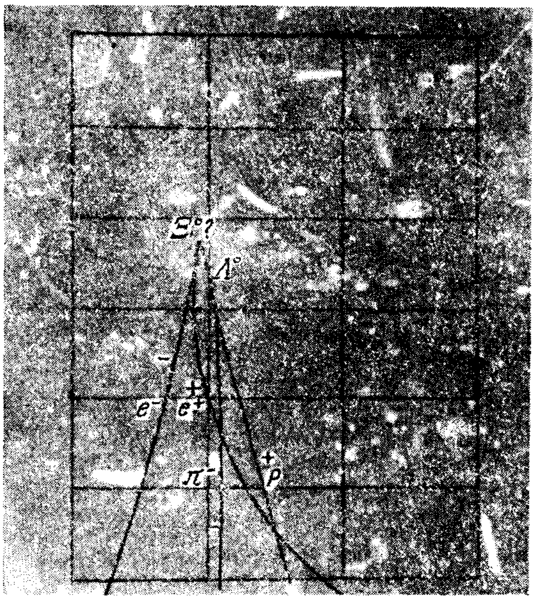

FIG. 20

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*An argument in favor of $S = -2$ seems to be the observed creation of Ξ^- with 2 K^0 mesons.[203] However, one must not overestimate this fact. First, there is no proof that both mesons are K^0 and not $\tilde{K}^0$; second, cases are known of a seeming violation of strangeness, when the K^0 mesons apparently decay outside the chamber or undergo neutral decay (for example, the production of a Ξ^- hyperon with one K^0 meson and in general without K mesons[204, 205, 206]).

†Within the framework of the Gell-Mann and Nishijima scheme, there exists, in principle, still another possibility: assign an isotopic spin $I = 0$ to the Ξ leading to an isotopic singlet with $S = -3$. In this case the selection rule can be modified: decays with $|\Delta S| = 1$ and 2 are allowed and those with $|\Delta S| = 3$ are forbidden.

particle, an electron-positron pair emitted from the point of the proposed Ξ^0 decay. The authors believe this to be the result of the decay $\pi^0 \rightarrow e^+ + e^- + \gamma$. The report contains no details whatever, and it is therefore not clear how it was possible to exclude, for example, the possibility of the $\Sigma^0 \rightarrow \Lambda^0 + e^+ + e^-$ decay or the possibility of associated production of Λ^0 and K^0 with subsequent decay $K^0 \rightarrow \pi^0 + \pi^0 \searrow e^+ + e^- + \gamma$.

The cascade hyperon is the most exotic and at the same time the least studied of all the hyperons, and therefore a further study of its properties is of exceeding interest. In addition to the investigation of the ordinary decay properties of the Ξ^-, important information can also be obtained by investigating the character of the interaction of the cascade hyperon with matter.[210] Thus, if the "strangeness" of the Ξ^- particle is really -2, then in the capture of the cascade hyperon by a proton of the nucleus, the reaction $\Xi^- + p \rightarrow \Lambda^0 + \Lambda^0$ may occur.* And this leads to a definite probability of both Λ^0 particles being captured by the nucleus, with the excitation energy (~ 30 Mev) emitted in the form of γ quanta and nucleons. A study of such a "double" hypernucleus offers a rare possibility of obtaining some information on the Λ^0-Λ^0 interaction.

Finally, a study of the Ξ^- decay gives one of the few actually realizable methods of verifying the conservation of the CP(T) invariance in weak interactions.[212]

The Hyperon Spin

It is known that at one time several observers[213,214] found a strong correlation between the planes of the production and decay of the Λ^0 particle, this being taken as evidence of the fact that the spin of the Λ^0 is greater than $\frac{1}{2}$. A further investigation of the angular distributions of one of the decay products of the hyperons relative to the direction of the π^- meson that causes this production has not confirmed the previously-obtained experimental data.[115,116,177,215,216,217] As indicated in reference 219, the results easiest to interpret are obtained if the analysis is confined only to the creation of hyperons at angles close to 0 and 180 degrees. In these cases the S wave predominates in the interaction and this simplifies considerably the analysis, and makes it unequivocal. A similar analysis was made in reference 215. Its results are given in Figs. 21 and 22. As can be seen from a comparison of the experimental data with the angular distributions, calculated for various values of the spin, the best agreement is obtained by assuming a spin $1/2$ for Λ^0 and Σ^-, in the case of spin $3/2$ there is a discrepancy 6 or 7 times greater than the standard error, and for larger spin values this discrepancy is even greater.

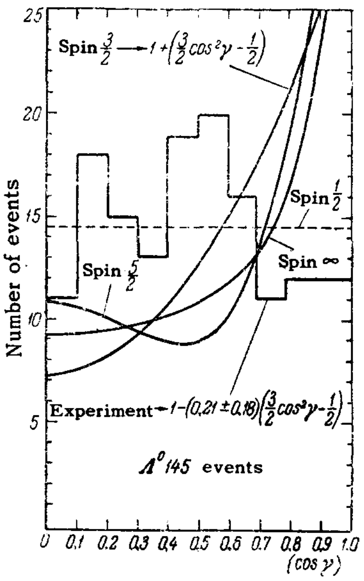

FIG. 21

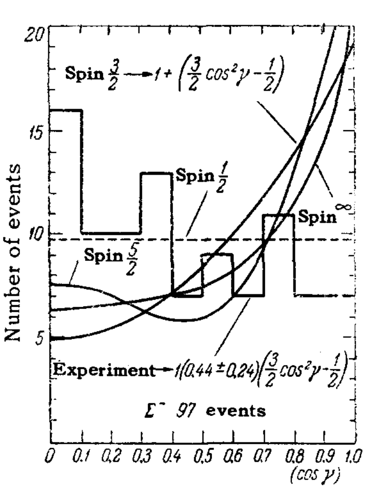

FIG. 22

When investigating the angular distribution of the Σ^- decays, produced in the $K^- + p \rightarrow \Sigma^- + \pi^+$ reaction,[177] none of the previously noted asymmetry was observed, this again being evidence of a spin $1/2$.[95] A measurement of the ratio of the number of non-mesonic to mesonic decays of hyperfragments (q) can yield, in principle, also information on the Λ^0 spin.[220] The latter data are in good agreement with $\sigma_{\Lambda^0} = \frac{1}{2}$, although certain difficulties arise in the analysis with the interpre-

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*According to the model of M. A. Markov,[211] in which the hyperons are considered as excited states of the nucleon, and the "strangeness" characterizes the degree of this excitation, the probability of such a process is negligibly small.

TABLE VIII

Type of decay	Probability of decay based on the V–A theory	Sensitivity of experiment
$\Lambda^0 \to P + e^- + \bar{\nu}$	5.3×10^7	1.1×10^7
$\Lambda^0 \to P + \mu^- + \bar{\nu}$	1.3×10^7	1.1×10^7
$\Lambda^0 \to P + 2$ leptons	6.6×10^7	1.1×10^7
$\Sigma^- \to N + e^- + \bar{\nu}$	29×10^7	9.4×10^7
$\Sigma^- \to N + \mu^- + \bar{\nu}$	14×10^7	9.4×10^7
$\Sigma^- \to N + 2$ leptons	43×10^7	9.4×10^7

tation of the non-mesonic decays.[221] An additional theoretical analysis, made under the assumption of a strong parity nonconservation in the Λ^0 decay (which does take place in reality) have shown that the experimental value of q can be reconciled with the calculated one only if $\sigma_{\Lambda^0} = \frac{1}{2}$.[222] A more general examination of the relation of the value of the spin to the degree of parity nonconvervation was made by Lee and Yang,[223] who showed that $\sigma_{\Lambda^0} = \frac{1}{2}$ follows from the experimentally observed large "up-down" asymmetry in the decay of the Λ^0 particle.

Thus, all the experimental data obtained during the past two years favor $\sigma_{\Lambda^0} = \frac{1}{2}$. In connection with this, the recently obtained[218] asymmetry in the angular distribution of the Λ^0 decay is somewhat puzzling, for it indicates that the spin of the Λ^0 particle is $3/2$. One must note, however, the insufficient statistical certainty of the observed asymmetry (28 events of associated production $\Lambda^0 + K^0$ were analyzed).

The authors themselves apparently do not trust their result, for in the analysis of the angular distribution of the K^0 decays they use a value of $\frac{1}{2}$ for the Λ^0 spin. Here they obtained, in accordance with other experimental data, a value $\sigma_{K^0} = 0$ for the spin of the K^0 meson. At the same time, if one assumes $\sigma_{\Lambda^0} = 3/2$, the angular distribution obtained for the K^0 is found to be incompatible with the value $\sigma_{K^0} = 0$. All this taken together calls for a certain caution in the approach to these data concerning the Λ^0 spin. As to the spins of Σ^0 and Σ^+, the experimental data now on hand, in spite of their paucity, are quite compatible with the assumption that the spins of these hyperons (like the spin of the Σ^-) are $\frac{1}{2}$. As indicated by Gatto,[224] a complete analysis of the angular distribution of the π^- meson produced by the Ξ^- decay can yield information on the spin of the cascade hyperon. However, the number of registered Ξ^- decay events is too small to permit any definite conclusions on the Ξ^- spin. As yet there are no grounds for assuming the Ξ^- spin to be different from $\frac{1}{2}$.

Leptonic Decays of Hyperons.

The question of the possibility of the existence of leptonic hyperon decays has long occupied both theoreticians and experimental physicists. Interest in this problem has become greater in connection with the success of the universal V-A interaction. This is quite natural: The "V-A theory" predicts quite definite probabilities for the leptonic decays of hyperons, and the comparison of these predictions with experiment is a criterion of the applicability of this theory to decay interactions of hyperons. The most thorough searches for leptonic decays of hyperons were made jointly by the Columbia and Pisa groups.[228] An analysis of 270 Λ^0 decays and 84 Σ^- decays registered in bubble chambers has disclosed no lepton emission in any of these. Table VIII shows the probabilities of the different leptonic decays, calculated from the V-A theory, and the sensitivity of the experiments corresponding to one decay (already unobservable).

A comparison of these two quantities shows that if the probability of leptonic decays were to correspond to the predictions of the V-A theory, such decays would have been observed by now.

Equally unsuccessful were the searches for leptonic decay of hyperons in many other investigations,[161,229,230] including among them the decays of the long-lived neutral particles.[134] So far, approximately 1500 decays of free and bound hyperons have been analyzed all together and not a single leptonic decay was observed.*

Although it is too early to draw any conclusion, this fact must be considered as a serious difficulty of the V-A theory as applied to hyperon decays (at any rate in its present form).

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*Disregarding the rather doubtful case reported in reference 231.

Attempts are being made now to circumvent somehow this difficulty (see, for example, reference 120). The same reference gives an estimate of the lower limits for the probability of leptonic decays of hyperons made on the assumption of no direct baryon-lepton interaction, the decay proceeding via the NΛK interaction with subsequent decay of the virtual K meson. These estimates yield:

$$\frac{w(\Lambda^0 \to p + e^- + \bar{\nu})}{w(\Lambda^0 \to p + \pi^-)} \geqslant 3 \cdot 10^{-4},$$

$$\frac{w(\Lambda^0 \to p + \mu^- + \bar{\nu})}{w(\Lambda^0 \to p + \pi^-)} \geqslant 5 \cdot 10^{-5}.$$

As a result of further research, two leptonic decays of the type $\Lambda^0 \to p + e + \nu$ were found in a thorough analysis of 1529 Λ^0 decays (instead of the 24 events predicted by the V-A theory).[292,293]

Parity Nonconservation in Hyperon Decay

Experiments performed at Columbia University[10,11] have demonstrated nonconservation of parity only for decays in which a neutrino participates, and the neutrino was assumed by many to be responsible for this effect.[126,232,233] It was therefore of considerable interest to verify experimentally the nonconservation of parity in neutrinoless decays, for example in hyperon decays. The first to point out the possibility in principle of verifying whether parity is conserved in hyperon decays were Lee and Yang.[14] Later on this possibility was analyzed in many theoretical papers.[234-237] Recently, experimental investigations have been reported in which, as suggested by Lee, Steinberger, et al.[238] the correlation between the production and decay angles was investigated in the following processes:

$$\begin{array}{l} 1)\ \pi^- + p \longrightarrow K^0 + \Lambda^0 \\ \qquad\qquad\qquad\qquad\quad \searrow p + \pi^-, \\ 2)\ \pi^- + p \longrightarrow K^0 + \Sigma^- \\ \qquad\qquad\qquad\qquad\quad \searrow n + \pi^-. \end{array}$$

The principal results of these experiments reduce to the following:

(1) A considerable "up-down" asymmetry was observed in the decay of Λ^0 particles polarized at production, indicating nonconservation of parity. The weighted average (based on the results of three investigations[239-241]) of the asymmetry is

$$\overline{P}\alpha_{\Lambda^0} = \frac{N_{\mathbf{up}} - N_{\mathbf{down}}}{\frac{1}{2}(N_{\mathbf{up}} + N_{\mathbf{down}})} = 0.52 \pm 0.10,$$

where N_{up} and N_{down} is the number of decay π^- mesons emitted upwards or downwards relative to the production plane $\overline{P}$ is the polarization of the Λ^0 particles at production averaged over all angles of emission, and α is the degree of asymmetry due to parity nonconservation. The possibility exists of estimating the upper limit of the polarization $\overline{P}$, by accounting for the angular distribution of the Λ^0 particles at production. Taking into account only S and P waves, and using the data by Adair[242] on the "front-back" anisotropy in the production of the Λ^0 particle (2.9 ± 0.4), it is possible to obtain for the polarization an upper limit $\overline{P} \leq 0.78 \pm 0.03$. From this, taking into account the experimental value of $\overline{P}\alpha_{\Lambda^0}$, it becomes possible to determine the lower limit of $\alpha_{\Lambda^0} \geq 0.67 \pm 0.13$.* The probability of the observed effect being the result of statistical fluctuations is $\sim 10^{-5}$.

(2) The result obtained is also evidence that both invariance under space reflection (P) and charge conjugation (C) are violated in Λ^0 decay.

To demonstrate this, Gatto[243] used a theorem by Lee, Oehme, and Yang,[130] by which an asymmetry connected with the pseudoscalar $\boldsymbol{\sigma}_{\Lambda^0} \times \mathbf{p}_\pi$ is forbidden if C is conserved and if the interaction in the final state is neglected. Gatto has calculated the maximum asymmetry possible with C conservation due to final state interaction between the decay products of the Λ^0 (proton and the π^- meson) and found it to be $\alpha \leq 0.18 \pm 0.02$. It is obvious that this quantity is incompatible with the experimental value $\overline{P}\alpha = 0.52 \pm 0.10$, since $\overline{P}$ cannot be greater than unity. This leads to the violation of the invariance under charge conjugation (C) in the decay of the Λ^0 particle.

(3) An analysis of 287 events disclosed no noticeable asymmetry connected with parity nonconservation in the decay of the Σ^- hyperon. This result is rather strange, considering the substantial asymmetry in Λ^0 decay, but this may be caused ty the absence of polarization at production of the Σ^-.†

One must also bear in mind that the degree of polarization P depends on the angle of emission (θ) of the created hyperon and may have opposite signs in different intervals of the angle θ, so that an averaging of $P(\theta)$ over all of θ may result in $\overline{P} \sim 0$. It is therefore of interest in the future to measure the anisotropy separately in different angular intervals.

(4) An analysis was made of the angular distribution of 114 decays of Λ^0 particles, which are

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*In recent experiments with the bevatron (bubble chamber in a beam of negative pions), a value $\alpha_{\Lambda_0} \geq 0.73 \pm 0.14$ has been obtained for the lower limit of the asymmetry coefficient (under the assumption that $\bar{P} \leq 1$).[160]

†Interesting possibilities of somehow "legalizing" the difference in the degree of asymmetry in the Λ and Σ decays are considered in references 244 and 245.

the product of Σ^0 decay, for the purpose of establishing parity nonconservation in the decay interaction of Σ^0 hyperon. No anisotropy beyond the limit of experimental error was observed here ($P\alpha_{\Sigma^0} = 0.17 \pm 0.17$).[160] In this case, however, one could not expect a considerable effect, since the decay Λ^0 particles retains only $\frac{1}{3}$ of the initial polarization of the Σ^0 hyperon.

Certain information with respect to the "up-down" asymmetry in Σ decays were also obtained with the aid of photoemulsions, in which $\Sigma^{\pm}$-hyperon decays were observed, resulting from the reactions

$$K^- + p \longrightarrow \Sigma^{\pm} + \pi^{\mp}.$$

In agreement with the data of the various groups, no anisotropy was observed in the Σ^- decay. At the same time a noticeable anisotropy $P\alpha_{\Sigma^+_{(0)}} = 0.36 \pm 0.21$ and $P\alpha_{\Sigma^+_{(+)}} = 0.37 \pm 0.19$ was observed for the decays $\Sigma^+ \rightarrow p + \pi^0$ and $\Sigma^+ \rightarrow n + \pi^+$, respectively.[247,248] However, the relative accuracy of these measurements leaves much to be desired.*

Lee and Yang called attention to the fact that the proton produced as a result of the Λ^0 decay should have, in the frame of reference where the Λ^0 is at rest, a longitudinal polarization equal to the coefficient of asymmetry α.[250]

When the Λ^0 particle decays in flight, a transverse polarization component appears in the decay proton, and this can be observed in "left-right" asymmetry on scattering.

From the value of this asymmetry, knowing the momentum and the angle of emission of the proton, it is possible to calculate the initial longitudinal polarization, i.e., α_{Λ^0}.

Thus, there is a possibility of measuring the coefficient of asymmetry of the Λ^0 decay directly, without need for any estimates of the degree of polarization of the Λ^0 particle at production. Furthermore, this method makes it possible to determine the sign of the asymmetry, something that cannot be done when measuring $\overline{P}\alpha$, owing to the lack of information on the sign of the polarization.

The first results of experiments employing this method have recently been published.[249,260] Thus, 54 events of the scattering of protons from the decay of Λ^0 particles have been observed in a cloud chamber with plates.[249] These data were used to determine[174] the coefficient of asymmetry $\alpha_{\Lambda^0} = -(0.85^{+0.15}_{-0.21})$.* The probability of the coefficient measured in this experiment having an opposite sign (i.e., "+") is $\frac{\omega(\alpha > 0)}{\omega(\alpha < 0)} = \frac{1}{24}$.

However, according to preliminary results obtained by the Berkeley group (21 scatterings of the decay protons in a bubble propane chamber) a more likely value is[160]

$$\alpha_{\Lambda^0} > 0 \left[\frac{\omega(\alpha > 0)}{\omega(\alpha < 0)} = 9.5 : 1 \right].$$

It was noted many times that a study of the asymmetry associated with parity nonconservation in hyperon decay can yield information on the character of their decay interaction.[236,252,253]

The foregoing experimental data regarding the asymmetry coefficient in Λ^0 decay is in good agreement (at least in magnitude) with the predictions of the V-A theory ($\alpha_{\Lambda^0} = -0.88$).[238,252] As to the sign of the asymmetry, the experimental data are contradictory and cannot lead for the present to unequivocal conclusions.

The asymmetry in the Σ-hyperon decays has not been investigated sufficiently to make a similar comparison with theory, and even the conclusions of the theory itself are less unequivocal in this case. Nevertheless, the existing data do exclude the scalar and pseudo-scalar covariants of the interaction, if it is assumed that the hyperon decay interaction is invariant under time reversal and if the parity conserving and parity nonconserving coupling constants are equal (the so called "one-to-one law"†).

We must mention finally that the V-A theory predicts a considerable magnitude for the asymmetry coefficient in the decay of Ξ^- hyperons ($\alpha_{\Xi^-} = -0.96$), which in principle can be measured experimentally.

Antihyperons

We can now consider that the division of all particles into antiparticles is one of the general laws of nature. Consequently no one doubts that

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*Quite recently more exact values of anisotropy were obtained for $\Sigma^{\pm}$ decays:[180]

$$\overline{P}\alpha\,(\Sigma^+ \longrightarrow p + \pi^0) = +\,(0.70 \pm 0.30),$$

$$\overline{P}\alpha\,(\Sigma^+ \longrightarrow n + \pi^+) = +\,(0.02 \pm 0.07),$$

$$\overline{P}\alpha\,(\Sigma^- \longrightarrow n + \pi^-) = +\,(0.02 \pm 0.05).$$

In this work there were selected the Σ hyperons emitted at production into a definite interval of θ ($45° < \theta_{cm} < 90°$). The experimental details are still unknown, and therefore the degree of reliability of these results is difficult to estimate.

*From the point of view of longitudinal polarization of the decay proton, a coefficient α with a minus sign means that the proton has a negative "helicity," i.e., its spin is directed opposite to its motion.

†Both conditions are apparently satisfied in β decay, but their validity for hyperon decay should, strictly speaking, be experimentally verified.

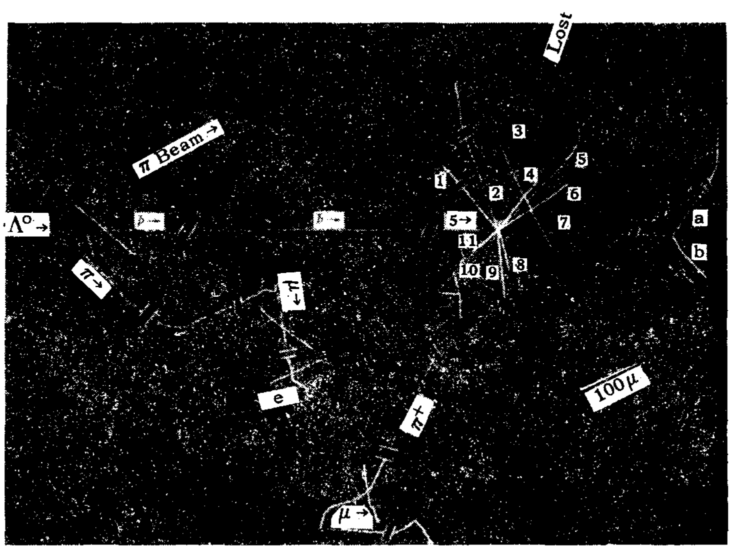

FIG. 23

hyperons, like all other fermions, have antiparticles. However, the observation of antihyperons involves considerable difficulties, owing to the high energy thresholds for their production.* It is apparently preferable to generate antihyperons not in the primary beam of accelerated protons, but in beams of secondary particles (π-K mesons, antiprotons), whose interactions afford considerably lower thresholds for antihyperon production. Nevertheless the production of sufficiently intense secondary-particle beams with sufficiently high energy, necessary to realize such a rare process as the creation of an antihyperon, is in itself a formidable problem.

Only one event that can be interpreted as the decay of an antihyperon has been recorded to date.[255] An emulsion stack irradiated in the π^--meson beam of the bevatron ($E_\pi = 4.6 \pm 0.3$ Bev) contained the decay of an anti Λ^0 particle, produced apparently in a reaction of the following type

$$\pi^- + p \rightarrow \tilde{\Lambda}^0 + \Lambda^0 + n.$$

Figure 23 shows the decay of a neutral particle into two charged ones — one of which undergoes the $\pi \rightarrow \mu + e$ decay characteristic of the π^+ meson, and the other gives a multiple-prong star with liberation of considerable energy (visible energy 783 Mev) and is almost certainly an antiproton annihilated in flight. The measurement of the angle of emission and of the energy of these two particles has made it possible to determine the decay energy $Q = (35^{+2.6}_{-0.9})$ Mev, which agrees, within experimental error, with the decay energy of a Λ^0 particle. Thus, there are all grounds for believing this case to be a decay of a $\tilde{\Lambda}^0$ particle, although the possibility of simultaneous production of $\tilde{p}$ and π^+ as the result of an interaction of some neutral particle with a neutron cannot be excluded in principle.

EXPERIMENTAL VERIFICATION OF THE SELECTION RULE $|\Delta I| = \frac{1}{2}$

The absence of the decay $\Xi^- \rightarrow n + \pi^-$, which is energetically more likely than the observed $\Xi^- \rightarrow \Lambda^0 + \pi^-$, may mean that in weak interactions, in which strongly-interacting particles participate, the "strangeness" can only change by unity ($|\Delta S| = 1$) or $|\Delta I_3| = 1$.* This circumstance was noted by Gell-Mann and Pais, who generalized this selection rule, by assuming that weak interactions of this type obey also $|\Delta I| = \frac{1}{2}$. This hypothesis leads to several consequences, which can be verified experimentally.

(1) The selection rule $|\Delta I| = \frac{1}{2}$ forbids the $K^+ \rightarrow \pi^+ + \pi^0$ decay, and at the same time allows the $K_1^0 \rightarrow 2\pi$ decay.†[257] Thus, within the framework of this selection rule we find an explanation for the great difference in the probabilities of these

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*The production of $\tilde{\Lambda}$ and $\tilde{\Sigma}$ hyperons directly in nucleon-nucleon collisions is at the limit of the energy rating of the bevatron, and the production of all the predicted antihyperons (including $\tilde{\Xi}$) in reactions of this type is possible at present only in the proton synchrotron of the Joint Institute of Nuclear Research.

*Strictly speaking, this argument is correct if $S_\Xi = -2$, but in principle the possibility of $S_\Xi = -3$ cannot be excluded at the present time.

†It is assumed here, in agreement with experiments, that the K-meson spin is zero (even).

decays, as observed experimentally.

(2) On the other hand, the experimentally estimated branching ratio for the neutral K^0-meson decay is

$$R_{K^0_{2\pi 0}} = \frac{w\,(K^0_1 \longrightarrow 2\pi^0)}{w\,(K^0_1 \longrightarrow 2\pi)} = 0.14 \pm 0.06\,{}^{*}$$

and noticeably contradicts the $|\Delta I| = \frac{1}{2}$ rule, according to which $R_{K^0_{2\pi^0}} = {}^1\!/_3$.[259] To satisfy the experimental value of $R_{K^0_{2\pi^0}}$ one must involve also transitions with $\Delta I = {}^3\!/_2$. It is obvious, however, that the accuracy of this measurement is too low to make any far reaching conclusions.

In the case of the experimental value

$$R_{K^0_{2\pi\pm}} = \frac{w\,(K^0_1 \longrightarrow \pi^+ + \pi^-)}{w\,(K^0_1 + K^0_2)} = 0.39 \pm 0.03$$

(weighted average of 1069 events, registered by various groups), the agreement with the rule $\Delta I = \frac{1}{2}$, which implies $R_{K^0_{2\pi}\pm} = {}^1\!/_3$, is somewhat better.

(3) The rule $|\Delta I| = \frac{1}{2}$ leads to the following branching ratios for the $K'_{3\pi}$ and $K_{3\pi}$ decays:[260,261]

$$R_{K_{3\pi}} = \frac{w\,(\pi^+ \longrightarrow \pi^0 + \pi^0)}{w\,(\pi^+ + \pi^+ + \pi^-)} = \frac{1}{4} \cdot 1.295 = 0.325\,{}^{\dagger}$$

This ratio is true if the wave functions of the 3π mesons is symmetrical under permutation of the π-meson momenta, as apparently is the case.[257,260] Experiment yields a value $R_{K_{3\pi}} = 0.32 \pm 0.08$, which is in good agreement with the values cited above.[11]

(4) It follows from the rule $|\Delta I| = \frac{1}{2}$ that the probabilities of 3π decays of K^+ and K^0 should be of the same order ($\tau \sim 10^{-7}$ sec) provided the predominant state of the 3π mesons is $I = 1$.‡ This selection rule leads also to other conclusions concerning the decay of the long-lived K^0 component, namely

$$R_{K^0_{3\pi}} = \frac{w\,(K^0_2 \to \pi^+ + \pi^- + \pi^0)}{w\,(K^0_2)} = 0.2, \qquad \text{(a)}$$

$$R_{K^0_{3\pi 0}} = \frac{w\,(K^0_2 \to 3\pi^0)}{w\,(K^0_2)} = 0.3 \qquad \text{(b)}$$

(provided that the state with $I = 1$ predominates).[141,260] The existing experimental data do not contradict the quantitative estimates given by (a) for $R_{K^0_{3\pi}}$, although one can hardly speak of agreement when dealing with so small a number of recorded events. As to the value of $R_{K^0_{3\pi^0}}$ given by (b), nothing can be said at all, since the $K^0_2 \to 3\pi^0$ decay has not yet been observed at all.

(5) The selection rules $|\Delta I| = \frac{1}{2}$ require that the branching ratio for the charged Λ^0 decay be

$$R_{\Lambda^0 \to p + \pi^-} = \frac{w\,(\Lambda^0 \to p + \pi^-)}{w\,(\Lambda^0)} = \frac{2}{3}\,{}^{*}$$

which is in good agreement with experiment ($R_{\Lambda^0} = 0.63 \pm 0.03$).[160]

(6) Considerably more complicated with respect to the selection rule $|\Delta I| = \frac{1}{2}$ is the situation with the Σ-hyperon decay. It appeared at first that the experimental values

$$R_{\Sigma^+} = \frac{w\,(\Sigma^+ \to p + \pi^0)}{w\,(\Sigma^+ \to n + \pi^+)} = 0.88 \pm 0.12$$

and $r = \tau_{\Sigma^-}/\tau_{\Sigma^+} = 2.2$ are incompatible if the selection rule $|\Delta I| = \frac{1}{2}$ is chosen.[261,262] The inclusion of arbitrary terms that account for parity nonconservation has expanded considerably the range of possible values of R_{Σ} and r, so that it became possible to satisfy the rule $|\Delta I| = \frac{1}{2}$.[263,264]

However, it is necessary to assume in this case a definite degree of parity nonconservation in Σ decays.[265,266,267]

As already mentioned (see page 139) the experimental data in this respect are quite indeterminate: no noticeable anisotropy was recorded at all in the Σ^- decays, while certain factors seemed to indicate that anisotropy exists in decays of the Σ^+ hyperon. Nothing can be said in either case concerning the asymmetry coefficients, since the degree of polarization is unknown. To avoid the need for estimating the polarization P to verify the selection rule $\Delta I = \frac{1}{2}$, use must be made of relations that include ratios of the magnitudes of the anisotropy ($P\alpha$), measured for different Σ decays under identical conditions.[268] The use of such relations shows that the existing experimental data (although still very skimpy) do not contradict explicitly the selection rule $\Delta I = \frac{1}{2}$.[269,270]

(7) An analysis of the isotopic relations, realized in the decay of Ξ^- and Ξ^0 hyperons under the assumption that a pure $\Delta I = \frac{1}{2}$ transition takes place, yields a value $\tau_{\Xi^-}/\tau_{\Xi^0} = \frac{1}{2}$ for the ratio of the average lifetimes of these hyperons (in the case of $\Delta I = {}^3\!/_2$, this ratio is $\tau_{\Xi^-}/\tau_{\Xi^0} = 2$).[261] This ratio can still not be verified, owing to the lack of experimental data.

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*Other experimental estimates of R_{K^0} (see page 127) yield even smaller values.

†The factor 1.295 is the correction for the difference in the phase space volumes of these decays.

‡The experimentally determined ratio $K'_{3\pi}/K_{3\pi}$ shows that this is apparently so.

*It must be noted that a similar result can be obtained if an appropriate combination of transitions with $|\Delta I| = {}^1\!/_2$ and $|\Delta I| = {}^3\!/_2$ is chosen.

(8) If the selection rule $\Delta I = \frac{1}{2}$ is extended to cover decay interactions that include leptons, as was done in reference 271, there arise several consequences, which can be experimentally verified:

$$w(K_1^0 \longrightarrow \pi^\pm + \mu^\mp + \nu) = w(K_2^0 \longrightarrow \pi^\pm + \mu^\mp + \nu)$$
$$= 2w(K^+ \longrightarrow \pi^0 + \mu^+ + \nu) = 6.6 \cdot 10^6 \ \mathbf{sec}^{-1},$$
$$w(K_1^0 \longrightarrow \pi^\pm + e^\mp + \nu) = w(K_2^0 \longrightarrow \pi^\pm + e^\mp + \nu)$$
$$= 2w(K^+ \longrightarrow \pi^0 + e^+ + \nu) = 8.4 \cdot 10^6 \ \mathbf{sec}^{-1}.$$

Bearing these relations in mind, it is easy to show that were the $K^0 \rightarrow \pi^\pm + \mu^\mp + \nu$ and $K^0 \rightarrow \pi^\pm + e^\mp + \nu$ the only possible means of decay of the K_2^0 meson, its lifetime should be $\tau_{K'} = 6.7 \times 10^{-8}$ sec. However, since other decays of the K_2^0 particle amount to not more than 20%,[279] the predicted lifetime of the K_2^0 meson is somewhat less ($\tau_{K_2^0} = 5 - 6 \times 10^{-8}$ sec). This quantity does not contradict clearly the experimental value ($\tau_{K_2^0} = (9 \pm 3) \times 10^{-8}$ sec). More definite conclusions necessitate more accurate measurements of the lifetime of the K_2^0 meson and of the branching ratios for the various modes of its decay.

Thus, in spite of the considerable experimental evidence in favor of the selection rule $|\Delta I| = \frac{1}{2}$, it is still difficult to conclude unequivocably, on the basis of the existing experimental data, that the decay interaction transforms in isotopic space as a spherical tensor of rank $\frac{1}{2}$. It must also be mentioned that the selection rule $\Delta I = \frac{1}{2}$ still has a purely phenomenological character. It would be quite interesting to justify it theoretically. The first steps in this direction have already been made.[273,274]

"NEW" PARTICLES

From time to time communications of the existence of new particles, differing from the hitherto known mesons and hyperons, are reported in the literature.

The detection in cosmic rays of a particle with mass $\sim 550\ m_e$ [(540 ± 35)[275]] has aroused considerable interest. Eleven such particles were recorded, an overwhelming majority of them (9) of negative sign; these particles stopped in the cloud chamber without producing any secondary particles. What is striking is the fact that these particles do not result from an interaction inside the chamber or above it, but apparently entered the chamber from the outside. This gives grounds for assuming that the observed particles can be products of decay of some other unstable particle. From among the known particles, such an unstable particle may be the K^- meson or the Ξ hyperon. However, a thorough search for a charged particle with mass $500\ m_e$ among the decay products of $5000\ K^+$ mesons produced no positive results[276] (see, however, reference 56). Among the particles generated in the bevatron target, no mesons with mass $500\ m_e$ were observed, so that only the upper limit for the production cross section of these particles could be estimated ($\sim 1/300$ of the production cross section of the K mesons).[176]

A search for similar particles with the Cornell synchrotron was is equally unsuccessful.[278] The upper limit for photoproduction of these particles, cited in the above reference, was $4 \times 10^{-33}\ \text{cm}^2$ per Be nucleus ($E_\gamma = 550 - 1100$ Mev). Nevertheless, Keuffel et al.[277] obtained certain additional data concerning the existence of such particles. In their experiment the mass spectrum of cosmic particles at high altitude was investigated using a system of scintillation and Cerenkov counters. In the region of $650\ m_e$ they observed a small peak including 15 particles, of which 8 comprised the background. However, this peak disappeared after the lead absorber located above the setup was removed. The observed fact signifies apparently (in contradiction to the experimental data of Alikhanyan's group) that the registered particles are produced in the direct vicinity of the target, although this may also be the result of a change in the background conditions.

The proceedings of the latest Geneva Conference on high-energy particle physics contain mention of three particles with $m \sim 500\ m_e$ registered in cosmic rays with the aid of a cloud chamber.[279]

However, five other groups (both chamber and emulsion), which also attempted to detect a particle with mass $500 - 600\ m_e$ in cosmic rays, have not found among 4700 stopped μ mesons a single "anomalous" particle.[280,281] On the other hand, assuming the relative probability derived by Alikhanyan and Shostakovich[275] for the appearance of a particle with $m = 500\ m_e$ (1 in ~ 200 stopped μ mesons), one would expect more than 20 such particles to be registered.

Thus, in order to reconcile all these results we must assume that the Alikhanyan group underestimated the relative flux of μ mesons by at least a factor of 20. Naturally, no correction for the unequal registration efficiency can eliminate this contradiction. It is obvious that the problem of the existence of a meson with mass $500 - 600\ m_e$ calls for additional experimental verification.

Sinhe and Sangupta,[284] with the aid of a cloud chamber exposed to cosmic rays, registered two decays of a neutral particle into two charged particles, one of which is apparently heavier than the π meson and decays in turn, yielding a weakly ionizing particle. Sinhe and Sangupta propose that a superheevy meson has decayed in accordance with the scheme $\lambda^0 \rightarrow \pi + K + 10$ Mev ($m_{\lambda^0} \sim 1270\ m_e$) with subsequent decay of the K meson. Here the new particle is considered as an excited bound state of the K particle and of the π meson, and use was made here of a model proposed some time ago by Powell.[285] It must be noted, however, that such an interpretation is far from unique, since there are no definite data on the nature of the proposed K meson. Therefore, for example, the possibility of the anomalous decay $K \rightarrow 2\pi + \gamma$ with subsequent decay of one of the pions cannot be excluded.

References 282 and 283 report two superheavy mesons, not neutral as in the foregoing paper, but charged. In the first of these events[282] a positively charged particle with mass $1200 - 1600\ m_e$ (measured by the ionization and momentum) is emitted from the wall of a diffusion chamber and decays into a neutral particle and a pion (or muon). The simplest decay scheme is

$$\lambda^+ \rightarrow K^0 + \pi^+$$

and under this assumption $m_{\lambda^+} = 1462 \pm 15\ m_e$.

In the second case[283] the "anomalous" meson is produced in the chamber as a result of π-nucleon interaction, and then undergoes a cascade decay. Of all the possible processes, the best agreement with the kinematic analysis is produced by the decay of a superheavy meson, $\lambda^- \rightarrow K^0 + \pi^-$, with a subsequent decay $K^0 \rightarrow \underset{e}{\mu^-} + \pi^+ + \nu$.

Experimental indications in favor of the possible existence of a superheavy meson are also contained in reference 286. There, in the scanning of emulsions exposed in the stratosphere, a star was observed from which a slow charged particle emerges. This particle interacts and gives rise to two tracks, one of which is assigned by the authors to the K^- meson. The justification for this is a measurement of the mass of this particle $(1160 \pm 180)\ m_e$. The track of the suggested K^- meson was traced to the end, but no charged particles were observed at the end of the track. According to the authors' assumptions, this event must be interpreted as the interaction between a superheavy meson (with $m \geq 1400\ m_e$) which results in the emission of a K meson. Earlier papers[288,289] described two other events, which can be interpreted as K-meson decay of a superheavy meson. In these two cases, like in the preceding ones, the K meson produces a prongless star at the end of its track. The probability of such an event, considering the number of prongless K^- stars (~ 0.18), is small (6×10^{-3}). This strange circumstance can be explained by assuming that the decay product is not a K meson but a still unknown fermion with mass close to the mass of the K meson, resulting from the decay of the K particle. Such a fermion, when stopped, should not give as a rule any visible interaction products, as happens also in the capture of a μ meson ($\mu^- + p \rightarrow n + \nu$).* It must be recalled in this connection that events registered by Harris et al.[55] and Prowse et al.[56] (see page 000) can also be interpreted as an anomalous decay of a K^- meson into a pion and an unknown neutral particle with a mass $\sim 500\ m_e$.

The events described in references 288 and 289, as well as those described in reference 287, can. also be interpreted as the decay (or interaction) of a superheavy hyperon $Y \rightarrow K + \Lambda\,(N)$. It must be pointed out that within the framework of the Gell-Mann scheme there can exist such a negatively charged hyperon with strangeness $S = -3$ (isotopic singlet), which would decay into a K meson and $\Lambda\,(\Sigma)$ or into a pion and Ξ particle. "Superheavy" mesons, which yield a K particle on decay, can also be included in the Gell-Mann scheme as isotopic singlets with $S = +2$ or $S = -2$.

Recently there was observed in a cloud chamber a case which, in the author's opinion agrees best with the assumption that a cascade decay occurs of a superheavy neutral hyperon,[290] $Y^0 \rightarrow \Sigma^{\pm} + \pi^{\mp}$, with subsequent decay $\Sigma^{\pm} \rightarrow \pi^{\pm} + n$.

However, this case does not contradict the other possibility that was previously discussed, namely:

$$\lambda^0 \rightarrow \pi^{\pm} + K^{\mp}$$

with subsequent decay

$$K^{\mp} \rightarrow \pi^{\mp} + ?$$

Furthermore, what might have happened was merely an interaction between the $\tilde{K}^0$ and the nuclei of the gas in the chamber, $\tilde{K}^0 + N \rightarrow \Sigma^{\pm} + \pi^{\mp}$.

This hypothetical "superhyperon" Y^0 has no place in the Gell-Mann — Nishijuma scheme. To describe the Y^0 within the framework of the foregoing scheme it would be necessary to introduce, in addition to the "strangeness," still another quantum number.

Mention should also be made of the decay, with anomalously large energy Q, which was registered

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*The particles with mass $\sim 550\ m_e$, registered by the Alikhanyan group, also show no visible tracks when stopped.

in cosmic rays with the aid of a cloud chamber.[291] The result of this decay, a positive particle with $p = (352^{+94}_{-61})$ Mev/c (with transverse momentum $p_T = 351$ Mev/c). is emitted at an angle of 95° to the direction of motion. Not one of the known decays of unstable particles can produce so large a decay energy, and therefore the authors are hard pressed to draw some sort of conclusion concerning the nature of the decaying particle.

Of the possible decays, the best agreement with the experimental value of p_T is given by the decay $\Xi \rightarrow n + \pi$ ($p_{\pi^+} \sim 320$ Mev/c), but in this case it becomes necessary to postulate a positive cascade hyperon.

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