feel that the two low-energy points are in disagreement with the theoretical mean free path. The high-energy point is in serious disagreement with theory only if the average energy of the electrons is 10 Bev. We feel that the average energy of the electrons cannot be this low but is more like 50 to 100 Bev.

5. CONCLUSIONS

There exist in the cosmic radiation heavy primaries of energies greater than 10^{14} ev per nucleon. The flux of such particles as determined from these three interactions and an estimate of the volume of emulsion exposed and scanned in our laboratory is of the order of 10^{-4} particle/m^2 sec steradian.

The mean free path for trident production measured in such high-energy showers is extremely sensitive to the energy of the electrons. Koshiba and Kaplon[19] have outlined the experimental difficulties involved in measuring such high energies. As Block and King[16] have pointed out, the correction for pseudotridents is particularly important at these high energies, especially within the first radiation length of the origin of the parent pair. Our results based on the 28 unresolved pairs found in this single high-energy event are in agreement with theory unless the average energy of the high-energy electrons is as low as 10 Bev. We have shown that the average energy of the electrons is of the order of 50 to 100 Bev rather than 10 Bev, thus giving no disagreement between theory and experiment.

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Scattering of K^+ Particles*

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An experiment has been performed to investigate the relative probability of scattering of $K_{\pi 2}$ and τ mesons. If, as is thought on the basis of the analysis of Dalitz and others, these particles differ in spin-parity properties, they may be expected to have different scattering cross sections, and the relative proportions of τ and $K_{\pi 2}$ mesons in a beam of scattered K particles would differ from their relative proportions in a beam of directly-produced particles. In the present experiment, a measurement was made of the composition of a K^+-particle beam in which it is estimated that more than $\sim 75\%$ of the particles had undergone scattering. Comparison with other results on the composition of beams consisting predominantly of directly-produced particles indicates that the relative numbers of τ and $K_{\pi 2}$ mesons are unchanged, within $\sim 30\%$. The results are therefore consistent with the assumption that the τ and $K_{\pi 2}$ are the same particle.

INTRODUCTION

As has been shown by Dalitz,[1] the energy distribution and angular correlation of the three charged pion secondaries of τ mesons provide a means of determining the spin and parity of the τ. There exists now a large amount of data which have been analyzed to obtain this information,[2] and the results indicate that the spin-parity properties of the τ meson differ from those of the θ or $K_{\pi 2}$ meson, which decays into two pions.[3–7] Most of the available data are

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[1] R. H. Dalitz, Phys. Rev. **94**, 1046 (1954); Proceedings of the Fifth Annual Conference on High-Energy Physics (Interscience Publishers, Inc., New York, 1955).

[2] Report of the Pisa Conference on Elementary Particles, 1955, Nuovo cimento (to be published); Feld, Odian, Ritson, and Wattenberg, Phys. Rev. **100**, 1539 (1955); R. Haddock, Phys. Rev. **100**, 1803(A) (1955); Bhowmik, Evans, Van Heerden, and Prowse, Nuovo cimento **3**, 574 (1956); Orear, Harris, and Taylor, Phys. Rev. **102**, 1676 (1956); Biswas, Ceccarelli-Fabrichesi, Ceccarelli, Gottstein, Varshneya, and Waloschek, Nuovo cimento **3**, 825 (1956); Heckman, Smith, and Barkas, University of California Radiation Laboratory Report UCRL-3291, February 22, 1956 (unpublished); See also Proceedings of the Sixth Annual Conference on High Energy Physics, (to be published).

[3] The experimentally established decay schemes, $\theta^0 \rightarrow \pi^+ + \pi^- + 214$ Mev[4] and $K_{\pi 2}^+ \rightarrow \pi^+ + \pi^0 + 219$ Mev,[5–7] indicate that since both θ^0 and $K_{\pi 2}^+$ decay into two pions, with Q values which agree within the statistical errors, it is reasonable to regard the θ^0 as the neutral counterpart of the $K_{\pi 2}$, and to discuss them as a single particle.

[4] Thompson, Burwell, Cohn, Huggett, and Karzmark, Phys. Rev. **95**, 661 (1954).

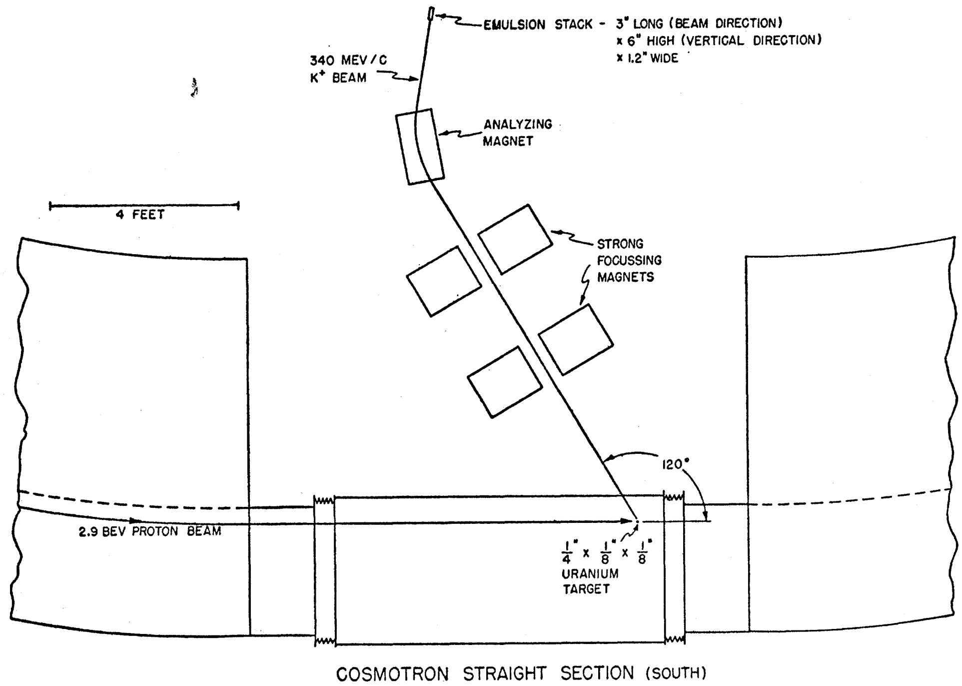

FIG. 1. Experimental arrangement.

probably consistent with the spin-parity assignments (0−) for the τ and (0+) for the θ. On this basis, it would seem that at least the τ and θ are distinct particles, while the other observed decays ($K_{\mu 2}$, $K_{\mu 3}$, K_{e3}, and τ' [8]) may be alternate modes of decay of one or both. It then is reasonable to expect to find some other measurable differences in properties or behavior of the τ and θ mesons. Recent experiments[5–7,9–13] have failed to detect any difference in mass and lifetime, and have also implied that there is no difference in their excitation curves or their distributions in angle and energy at production.

It is known that both τ and θ mesons are scattered by nuclei[14,15]; however, in view of the spin-parity difference, it would be surprising if their scattering cross sections were the same. The present experiment was performed in order to investigate the existence of a difference in scattering cross section, by comparing the relative proportions of τ and θ mesons in a beam of scattered K particles with their relative numbers in an unscattered beam. Because K-particle beam intensities are low, it was not possible to obtain a scattered beam simply by allowing directly-produced particles to strike a target. Instead, use was made of the scattering of K particles which occurs in the nuclei in which they are produced. Thus, to obtain a beam composed largely of scattered K particles, a magnetic channel was set up at an angle to the primary proton beam at which direct production of K particles in a nucleon-nucleon interaction was expected to be small, on kinematic considerations. From the observed K^+-particle scattering cross section,[15] a fairly large flux of particles scattered in secondary collisions in the target nuclei could be expected at such angles (backward in the laboratory system).

A difference in the $\tau/K_{\pi 2}$ ratios measured in such a beam and in a beam at an angle where direct production is dominant would provide a measure of the difference in scattering probability for the two particles.

EXPERIMENTAL DETAILS AND RESULTS

Two stacks of Ilford $G5$ emulsion strips were exposed in a magnetic strong-focusing and analyzing channel[16,17] to particles emitted from an uranium target at 120° to

[5] Ritson, Pevsner, Fung, Widgoff, Zorn, Goldhaber, and Goldhaber, Phys. Rev. **101**, 1085 (1956).

[6] G-Stack Collaboration, Nuovo cimento **2**, 1063 (1955).

[7] Crussard, Fouché, Hennessy, Kayas, Leprince-Ringuet, Morellet, and Renard, Nuovo cimento **3**, 731 (1956).

[8] By studying the energy distribution of the charged pion from the τ' decay and by comparison with the behavior of the negative (odd) pion from the decay $\tau^+ \rightarrow \pi^- + \pi^+ + \pi^+ + 75$ Mev (see footnote 2), the τ' has been established as an alternate mode of decay of the τ, with $\tau' \rightarrow \pi^+ + \pi^0 + \pi^0 + 84$ Mev. (See, for example, footnotes 5 and 9.) Therefore the total number of events $\tau + \tau'$ has been used to obtain the proportion of mesons which decay into 3 pions.

[9] Whitehead, Stork, Peterson, Perkins, and Birge, University of California Radiation Laboratory Report UCRL-3295, March 1, 1956 (unpublished).

[10] Hoang, Kaplon, and Yekutieli, Phys. Rev. **102**, 1185 (1956).

[11] L. Alvarez and S. Goldhaber, Nuovo cimento **2**, 344 (1955).

[12] Harris, Orear, and Taylor, Phys. Rev. **100**, 932 (1955).

[13] V. Fitch and R. Motley, Phys. Rev. **101**, 496 (1956), and V. Fitch, Bull. Am. Phys. Soc. Ser. II, **1**, 52 (1956).

[14] Yash Pal, Bombay Group, Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics, 1955 (Interscience Publishers, Inc., New York, 1955).

[15] Lannutti, Chupp, Goldhaber, Goldhaber, Helmy, Iloff, Pevsner, and Ritson, Phys. Rev. **101**, 1617 (1956).

[16] The magnetic strong-focusing and analyzing channel used in this experiment is the same as that used at 60° in several other experiments.[10,13,17]

[17] Harris, Orear, and Taylor, Phys. Rev. **101**, 1214 (1956).

TABLE I. Beam intensities.

	Experimental conditions	K^+-meson yield[a]	K^+/π^+ ratios (in the emulsions)
Present experiment	2.9-Bev internal proton beam, Cosmotron, U target—$\frac{1}{4}$ in.$\times\frac{1}{8}$ in.$\times\frac{1}{8}$ in. Secondary beam: 340 Mev/c at 120°. Path length—10 ft	$\sim$70/cm²/5$\times10^{12}$ protons	$\sim$1/400
Harris *et al.*[b]	2.9-Bev internal proton beam, Cosmotron, Cu target—$\frac{1}{2}$ in.$\times\frac{1}{8}$ in.$\times\frac{1}{8}$ in. Secondary beam: 290 Mev/c at 60°. Path length—10 ft	(280$\pm$40)/cm²/5.6$\times10^{12}$ protons	$\sim$1/600
Harris *et al.*[c] Kerth *et al.*[d]	6.2-Bev internal proton beam, Bevatron, Cu target. Secondary beam: 356 Mev/c at 90°. Path length—9 ft	(1310$\pm$150)/cm²/4.2$\times10^{12}$ protons	$\sim$1/60

[a] These yields are the numbers of K^+ mesons in the emulsions, per cm² perpendicular to the beam, for the given number of protons incident on the target
[b] See reference 17. The uranium target used in the present experiment contains approximately the same number of nucleons per cm² as the copper target used by Harris *et al.*
[c] See reference 12.
[d] Kerth, Stork, Birge, Haddock, and Whitehead, Phys. Rev. 99, 641(A) (1955).

the incident 2.9-Bev internal proton beam of the Brookhaven Cosmotron. Figure 1 shows the experimental arrangement. The plates were 10 feet from the target, which was $\frac{1}{4}$ in. thick in the beam direction, by $\frac{1}{8}$ in. by $\frac{1}{8}$ in. Uranium was used for the target, in order to have a high probability of K-particle scattering in the target nucleus. The magnetic channel was arranged to give positively-charged particles of momentum 340 Mev/c incident on the stacks.

The angle and momentum were chosen to give a predominantly scattered beam: For a K particle of momentum 340 Mev/c to be produced directly at 120° in a nucleon-nucleon collision, a target nucleon moving toward the incident proton must have a minimum Fermi energy of 27 Mev (momentum 227 Mev/c). If one assumes that the Fermi momenta follow a Gaussian distribution that corresponds to an average energy of 19.3 Mev,[18] only about 2% of the nucleons have momenta in the backward direction >227 Mev/c.

The total numbers of protons incident on the uranium target were 7×10^{12} for one stack, 1×10^{13} for the other. The K-meson yield was $\sim$70/cm²/5$\times10^{12}$ protons incident on the target, and the K^+/π^+ ratio in the emulsions was $\sim$1/400. Table I gives a comparison of these intensities with those observed under other experimental conditions.

In order to avoid scanning bias in finding different types of K-meson decays, along-the-track scanning was done. Tracks of the appropriate grain density were picked up at about 3 cm residual range, and followed to their ends in the stack. Each track end was carefully examined for secondary tracks. As the plates were very clear and well-developed, and the plateau blob density was $\sim$28 blobs per 100 μ, the efficiency for finding K_L mesons[19] was thought to be equal to the efficiency for finding τ and τ' particles and $K_{\mu3}$'s with low-energy secondaries, except for decays occurring near the emulsion surfaces. With the assumption that secondary tracks would be missed if they contained fewer than 10 blobs in the plate in which the decay occurred, a correction was made for the inefficiency for observing single secondaries near the surfaces. This correction amounted to 5% for K_L mesons.

τ mesons were identified by their characteristic decay into three coplanar charged π mesons. τ' and $K_{\mu3}$ mesons were distinguished by tracing all single gray or heavily-ionizing secondaries to the ends of their ranges, where their decays identified them as π's or μ's. Among the K_L mesons, the blob densities of those whose secondaries had true dip angles $<9°$ were carefully measured in order to distinguish $K_{\pi2}$ from $K_{\mu2}$ particles.

As a result of the along-the-track scanning, 566 K_L mesons, 28 τ mesons, 16 τ' mesons, and 2 $K_{\mu3}$ mesons (with secondary track blob densities greater than $\sim$1.7 minimum) were found. With the efficiency correction, the number of K_L mesons is 594. Of these, 72 had secondary tracks flat enough to satisfy the dip angle criterion. Approximately 1000 blobs were counted on each of these, near the decay, and their ionization densities g^*, relative to beam pion tracks in their neighborhoods, were determined.

The distribution in g^* of the 72 secondary tracks is shown in Fig. 2. The good separation of the two peaks was obtained by counting additional blobs on all secondary tracks for which 1000 blobs gave $1.04\leqslant g^*\leqslant 1.08$, in order to reduce the statistical uncertainty. All the particles included in the lower peak, $g^*\leqslant 1.05$, are

[18] Block, Harth, and Sternheimer, Phys. Rev. 100, 324 (1955); H. York, Phys. Rev. 75, 1467 (1949); E. M. Henley and R. H. Huddlestone, Phys. Rev. 82, 754 (1951).

[19] A meson is classified as a K_L particle if it has a single charged secondary of ionization smaller than $\sim$1.7 times minimum ionization. This class includes all $K_{\mu2}$, $K_{\pi2}$, and K_{e3} particles, and those $K_{\mu3}$ particles which decay into high-energy muons.

TABLE II. Relative frequencies, in percent, of the various modes of decay. The values found for a beam composed predominantly of scattered K^+ particles are compared with those found for beams consisting mainly of directly-produced K^+ particles.

	Scattered beam	Direct beams			
	Present experiment[a] 2.9-Bev internal proton beam, Cosmotron, U target. K^+ particles: 340 Mev/c at 120°. Path length—10 ft	Hoang *et al.*[b] 2.9-Bev internal proton beam, Cosmotron, Cu target. K^+ particles: 270 Mev/c at 60°. Path length—10 ft	Harris *et al.*[c] 2.9-Bev internal proton beam, Cosmotron, Cu target. K^+ particles: 290 Mev/c at 60°. Path length—10 ft	Ritson *et al.*[d] 6.2-Bev internal proton beam, Bevatron, Ta target. K^+ particles: 330 Mev/c at 90°.[f] Path length—9 ft	Whitehead *et al.*[e] 6.2-Bev internal proton beam, Bevatron, Cu target. K^+ particles: 330 Mev/c at 90°.[f] Path length—9 ft
$K_{\mu 2}$	60 ± 9	59 (±11)	...	55 ± 15	57.2 ± 5.0
$K_{\pi 2}$	30 ± 6	21 (±7)	...	30 ± 11	31.2 ± 3.5
$\tau+\tau'$	6.9 ± 1.0	8.7 (±2.3)	7.3 ± 1.4	7.6 ± 0.9	6.9 ± 0.8
$K_{\mu 3}$	2.7 ± 2.0	6 (±2)	...	5.0 ± 2.0	2.6 ± 1.1
K_{e3}	...	5 (±3)	...	1.7 ± 1.5	2.1 ± 1.5

[a] In obtaining the percentages of $K_{\mu 2}$ and $K_{\pi 2}$ mesons, it was assumed that none of the 72 K^+ particles whose secondary tracks were blob counted were K_{e3} or $K_{\mu 3}$ mesons. The electrons from K_{e3} would have $g^*\cong1.08$ (see Fig. 2), so the K_{e3}'s are included among the $K_{\pi 2}$ particles. The total number of $K_{\mu 3}$ particles was deduced from the observed number by assuming that the decay scheme is $K_{\mu 3}\rightarrow\mu+\pi^0+\nu$, and that the muon energy spectrum is determined entirely by the three body phase space factor.[18] The value of 2.7% is based on the two $K_{\mu 3}$ events which gave secondaries of energy <25 Mev ($g^*>1.7$).
[b] See reference 10. The percentages in the table are those given by the authors as most probable. By assuming that none of the K_L particles they analyzed were K_{e3} or $K_{\mu 3}$ mesons, they found as upper limits 65% $K_{\mu 2}$ and 24% $K_{\pi 2}$ particles. The errors given in the table in parentheses are standard statistical deviations estimated by us from the numbers in the quoted paper, as errors were not given there.
[c] See reference 17.
[d] See reference 5.
[e] See reference 9.
[f] With incident protons of 6.2 Bev, direct production of K^+ particles of the observed momentum at 90° in nucleon-nucleon collisions is highly probable, and the K^+-particle beam is most likely composed predominantly of directly-produced particles.

classified as μ's from $K_{\mu 2}$ decays; all in the higher peak, $g^*\geqslant1.08$, are classified as π's from $K_{\pi 2}$ decays. In eight cases, the identifications were checked carefully by blob counting a second section of the secondary track at 4 to 7 cm from the K-particle decay. No special effort has been made to identify electrons from K_{e3} decays or high energy muons from $K_{\mu 3}$'s among these 72 K_L secondaries, since these are too rare to affect appreciably the measured percentage of $K_{\pi 2}$ mesons.

Rough blob counts were made on about 100 additional K_L secondaries, in a search for secondaries with $1.2<g^*<\sim1.7$. One such track was found, which proved to be a muon of 27 mm range from a $K_{\mu 3}$.

The results obtained on the composition of the "scattered" beam are given in Table II, and comparison is made there with the results of similar measurements on beams consisting mainly of directly-produced K particles.

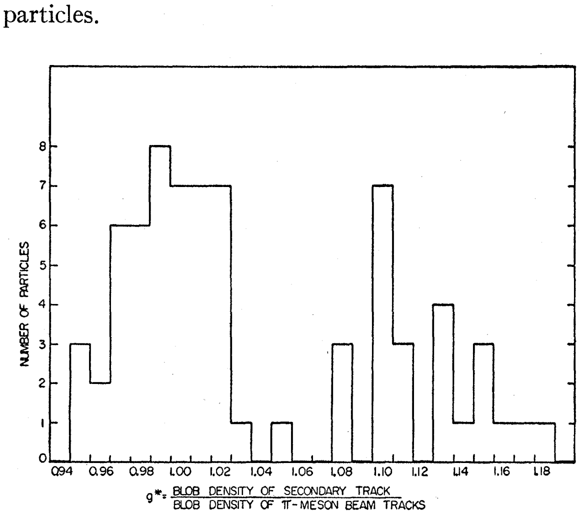

FIG. 2. The blob density distribution for the secondaries of 72 K_L mesons with true dip angles <9°.

DISCUSSION AND CONCLUSIONS

It is evident from Table II that, within the experimental accuracy, the relative proportions of τ and $K_{\pi 2}$ particles in the "scattered" beam are the same as in the "unscattered" beams.

The conclusions to be drawn from these results depend, of course, on the extent to which the 120° beam is scattered and the other beams are directly produced.

A rough estimate, based on an extrapolation of the results of Block, Harth, and Sternheimer[18] indicates that the number of K particles directly produced at 120° by 2.9-Bev protons in heavy nuclei is $\sim1/20$ of the number directly produced at 60°. As can be seen in Table I, the ratio of K-particle fluxes observed at 120° and 60° is $N_{120°}/N_{60°}\sim\frac{1}{4}$. Then, if f_θ is the fraction of directly-produced particles in an observed beam at a given angle θ, we have $f_{120°}/f_{60°}\cong(1/20)/(1/4)=1/5$. It is estimated that for production in copper, $f_{60°}\cong80\%$, so that the fraction of the beam at 120° which is directly produced is only $\sim16\%$. Thus, based on these considerations, the 120° beam is justifiably regarded as being largely a scattered beam, in contrast to the 60° beam. The calculations assume a Gaussian distribution of Fermi momenta in the nucleus, such that the average nucleon energy is 19.3 Mev[18]—a distribution with a much larger high-momentum tail could appreciably affect these values.[20]

The yield of K mesons at 120° resulting from a process in which a pion is first produced and then makes a K particle in the same nucleus has also been estimated. One would like to know the ratio R at 120° of the intensity of scattered K mesons to the intensity of those produced by secondary pions, but the detailed cross sections necessary for this calculation are not known.

[20] We wish to thank Dr. R. Sternheimer for helpful discussions concerning the estimate of the fraction of directly-produced particles at 120°.

However, the order of magnitude of R can be estimated from the following relation:

$$R \approx \frac{\sigma(pN,K^+)\sigma(K^+\,\text{scatt})t}{\sigma(pN,\pi)\sigma(\pi N,K^+)t'F},$$

where $\sigma(pN,K^+)$ and $\sigma(\pi N,K^+)$ are the cross sections for production of K^+ mesons in proton-nucleon and pion-nucleon interactions, respectively, $\sigma(pN,\pi)$ is the cross section for production of pions in proton-nucleon collisions, and $\sigma(K^+\text{scatt})$ is the cross section for scattering of K^+ mesons. The factor F gives the fraction of the total pion spectrum with sufficient energy to produce a 340-Mev/c K^+ particle at 120°. The minimum energy required, E_m, depends on the angle of pion emission, and is about 1.3 Bev in the lab for pions emitted within 30° of forward, assuming a nucleon energy of motion of 20 Mev. From the results on pion production of Block *et al.*[21] and of Niemann *et al.*,[22] we estimate $F \cong 1/10$. The factor t represents the average effective thickness of nuclear matter available for scattering of a K^+ produced in the nucleus, and is of the order of the radius of the uranium nucleus. Similarly, t' is the thickness of nuclear matter in which a pion can produce a K meson in the 120° beam, but t' is considerably less than the nuclear radius because a pion is soon degraded in energy to below E_m. It is estimated that $t/t' \cong 5$. For $\sigma(pN,\pi)$ we use the value 9 mb[21] obtained for single pion production in proton-proton collisions at 2.75 Bev, as multiply-produced pions very rarely have energies $>E_m$. For $\sigma(K^+\text{scatt})$ we use 6 mb.[15] Combining these values, we have $R \cong 30\sigma(pN,K^+)/\sigma(\pi N,K^+)$. If $\sigma(\pi N,K^+)$ should be found to be an order of magnitude greater than $\sigma(pN,K^+)$, then the K^+ intensity at 120° from secondary pions would be a sizable fraction of the total. However, at present the total cross section for production of heavy unstable particles in pion-nucleon collisions appears to be about 0.9 mb,[23] and in nucleon-nucleon collisions, ~0.4 mb,[21] in the appropriate energy ranges, so one expects $\sigma(\pi N,K^+)$ and $\sigma(pN,K^+)$ to be of the same order. In this discussion, it has been assumed that the cross sections are approximately isotropic in the center-of-mass system of each interaction. Forward-backward peaking would make K-production at 120° by secondary pions even more unlikely.

In view of all these considerations, it appears that about 75% or more of the K^+ mesons observed at 120° were scattered, the remainder being directly produced in nucleon-nucleon or pion-nucleon collisions. In contrast, the beam at 60° was ~80% directly-produced.

Within the possible limitations of the method, and the statistical uncertainty of ~30%, the results of this experiment indicate that τ and $K_{\pi 2}$ mesons have the same scattering cross section, as well as the same mass, lifetime, excitation curves and energy dependence in production. The results are therefore consistent with the assumption that they are the same particle—a particle of mixed parity, as proposed by Schwinger,[24] or a particle which can decay without parity conservation, as discussed by Yang and Lee.[25] If the τ and $K_{\pi 2}$ are different particles, then the similarity in their properties and behavior is surprising, and must probably be explained by some genetic relationship,[26,27] or by postulating that particles with odd-valued strangeness exist in doublets of opposite parity, as suggested by Lee and Yang.[28]

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[21] Block, Harth, Cocconi, Hart, Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **103**, 1484 (1956).

[22] Niemann, Bowker, Preston, and Street, Bull. Am. Phys. Soc. Ser. II, **1**, 172 (1956), and private communication.

[23] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **98**, 121 (1955). This cross section was measured for π^- mesons interacting with protons, while the singly-produced pions we must consider are a mixture of π^- and π^+ mesons (mainly π^+), interacting with both neutrons and protons.

[24] J. Schwinger (to be published).

[25] C. N. Yang and T. D. Lee (private communication).

[26] T. D. Lee and J. Orear, Phys. Rev. **100**, 932 (1955).

[27] R. Gatto, Nuovo cimento **3**, 318 (1956).

[28] T. D. Lee and C. N. Yang, Phys. Rev. **102**, 290 (1956).