V. Thursday Afternoon: Properties of Heavy Mesons and Hyperons,

L. Alvarez presiding.

LEPRINCE-RINGUET gave the introductory summary covering most of the published results on heavy mesons and hyperons. Since most of these data have been published, details will be spared in this report. Fig. 1. shows the mass measurements of K^+'s.

Observer	$K^+_{\mu 2}$	$X^+(K_{\pi 2})$	χ^+	τ'	Remarks
G-Stack	977±6	966 ± 3			Baroni R-E curves
	20.57±0.24	11.8±0.15			
Ritson et al	964±6	964±4		964±8	Barkas R-E curves
	20.48±25	11.51±0.15			
	957±7	960±9			Momentum-range on primary.
Barkas	962.5±3.2	972.2±4.5	951.2±10.6	951±11	Compares mass of τ = 966
Crussard	952±3(15)	969±4(9)			Barkas R-E curves
	20.2±0.15	11.8±0.17			

Fig. 1

In Fig. 1. the range of the secondary in cm of emulsion is given under the masses where appropriate. The Barkas values obtained by comparing the and K ranges are essentially independent of R-E (range-energy) curves. Baroni R-E curves give slightly higher masses than the Barkas R-E curves. M.I.T. has also performed an experiment to obtain ($\tau^+ - K^+$) mass difference and found $4 \pm 4\ m_e$. Fig. 2 shows the mass determinations for K^- mesons. Bon.

Observer	Mass	Method
Brookhaven (Hornbostel and Salant)	931 ± 24	Momentum and range
Berkeley (Chupp *et al*)	964	$\frac{\text{Mass } K^-}{\text{Mass } K^+} = 0.998 \pm 0.013$

Fig. 2

The details of the Berkeley experiment on K-masses are given later in this report by S. Goldhaber. Fig. 3 shows the lifetimes of K^+'s as measured by emulsions and counters using machine K^+ beams. It should be pointed out that Keuffel and Mezzeti, Robinson and Hyams have made the first such measurements using the cosmic radiation. Their results are in very good agreement with those shown in Fig. 3. Bon.

Particle	Lifetime	Observers	Method
τ^+	$0.8 {+0.5 \atop -0.2} \times 10^{-8}$	Harris *et al*	Emulsion - Brookhaven K-Beam
	$1 {+0.7 \atop -0.3}$		
$K^+_{\mu 2}$	1.4 ± 0.2	Alvarez *et al*	Counters - Berkeley K-Beam
	$1.17 {+0.08 \atop -0.07}$	Fitch *et al*	Counters - Brookhaven K-Beam
χ^+	1.3 ± 0.2	Alvarez *et al*	Counters - Berkeley K-Beam
	1.21 ± 0.11	Fitch *et al*	Counters - Brookhaven K-Beam
K^+_L	$0.7 {+0.15 \atop -0.10}$	Harris *et al*	Emulsion - Brookhaven K-Beam

Fig. 3

Note here that there are no lifetime measurements for $K^+_{\beta 3}$ and $K^+_{\mu 3}$. These are very difficult to measure with counters. However, one can get some idea of their lifetime by comparing the fractions of $K^+_{\beta 3}$ and $K^+_{\mu 3}$ to other K^+'s found in experiments which observe K^+'s at different times of flight. For example, one can compare these ratios in an experiment in the K^+ Berkeley beam in which the time of flight is $\sim 1.5 \times 10^{-8}$ sec and in the Ecole Polytechnique stack exposed directly to the proton beam where the K's had a time of flight of 5×10^{-10} sec. The proportions are about the same in the two experiments, hence $K^+_{\beta 3}$ and $K^+_{\mu 3}$ cannot differ greatly in lifetime from other K^+'s. Bon.

The following is a brief summary of some additional observations on heavy mesons. For the τ^+ we note the following points:

(a) $\tau^+ \rightarrow \pi^+ + \pi^- + \pi^+ + Q$ (= 75.0 ± 0.2 (1.5))

The Q value is Amaldi's given at Pisa.

(b) Bombay has seen 1 τ which requires a 32 Mev γ-ray to balance energy and momentum. In some 96 τ's, Bristol has seen two non-coplanar cases. These suggest the possibility of internal bremsstrahlung.

(c) From the Dalitz analysis spin and parity are 0^-.

(d) The frequency of $\tau'^+ \rightarrow \pi^+ + 2\pi^0$ is about 20 per cent of τ^+.

(e) For the $\left.\begin{array}{l}\tau^0 \rightarrow \pi^+ + \pi^- + \pi^0 \\ \quad \rightarrow 3\pi^0\end{array}\right\}$ there is no definite proof that it exists.

However, some anomalous V^0 have Q values consistent with τ^0.

For the $K^+_{\mu 2}$ and $K^+_{\pi 2}$ there is essentially nothing in addition to the mass and lifetime measurements already given. Abundance at production will be reported at a later time in this conference. It can be pointed out that recently Dublin and the Ecole Polytechnique have observed the π^0 from $K^+_{\pi 2}$ to decay into $2e + \gamma$.

At present about 30 cases of $\mathcal{K}^+(K^+_{\mu 3})$ have been found. The results now favor the $K^+_{\mu 3} \rightarrow \mu + \pi^0 + \nu$ decay scheme, where the maximum energy of the μ is 130 Mev. Some cases of high energy μ secondaries have now been found ($\sim$90 and 110 Mev) and in Rochester the π^0 in the $K_{\mu 3}$ decay has been inferred from the observation of high energy electron pairs presumably arising from the alternate decay mode of the π^0. These observations make the above decay scheme appear quite certain. (See Crussard's discussion later.)

There are now about 25 cases of K^+_β. The observed maximum secondary energy is around 260 Mev. If the decay scheme is $K^+_{\beta 3} \rightarrow e + \pi^0 + \nu$ the maximum electron energy is 230 Mev. Attention should be called to possible biases in the K_β data since low energy and high energy secondaries are easily missed. Crussard will discuss this in more detail later. Note that not a single example of K_β has been recognized in cloud chambers. This most likely is because of their relative scarcity.

For the θ^0 we note the following points:

(a) $\theta^0 \rightarrow \pi^+ + \pi^- + Q$ (= 214 $\pm$ 5 Mev. Thompson et al).

(b) Ecole Polytechnique now has one case in which both secondaries interact in the multiplate chamber. This confirms Thompson's statistical evidence that both secondaries are π-mesons.

(c) Lifetime $\approx 1.7 \begin{smallmatrix} + 0.6 \\ - 0.4 \end{smallmatrix} \times 10^{-10}$ sec (Gayther).

(d) Spin-parity both odd or both even.

(e) Alternate mode of decay: $\theta^0 \rightarrow \pi^0 + \pi^0$ (see Osher and Moyer results later). If it exists it rules out odd spin for θ^0.

Essentially the characteristics and decay schemes discussed above were for K^+ or K^0 mesons. For the K^- mesons the situation is less clear even with respect to a knowledge of the decay modes. This arises because most K-particles observed in emulsions stop and are abosrbed in a nucleus rather than decay. While in cloud chambers it has been found that V^- events are of higher energy when observed in the cosmic radiation and it is thus more difficult to identify decay schemes. The $\tau^- \rightarrow \pi^- + \pi^+ + \pi^-$ has been observed in cloud chambers at Cal. Tech., Manchester, Paris and Fretter's group at Berkeley. This identification is positive and unambiguous. Princeton may have a τ'^-, but this case is based on knowledge of p*, the π^- momentum in the center of mass coordinates, and is not an absolute proof. As for the existence of the $K^-_{\mu 2}$ and $\chi^-(K^-_{\pi 2})$ there have been indications again from p* values that one or both modes exist but again the proof is not complete. Paris observed a single case of a probable $K^-_{\pi 2}$ in which the charged secondary interacted, was therefore a π^- and two electron showers were seen, most likely from the π^0. This interpretation was completely consistent but was of such high energy that in fact it could have been a $K^+_{\pi 2}$ within an error of two standard deviations. Recently Ekspong and G. Goldhaber at Berkeley have seen two K-decays in flight in emulsion. One has been found to be a $K^-_{\pi 2}$, the other a $K^-_{\beta 3}$. The $K^-_{\pi 2}$ identification depends on a mass measurement of the π secondary which left the stack.

Now we summarize the properties of hyperons.

The $\Lambda^o \rightarrow \gamma + \pi + Q(= 37 \pm 1$ Mev) has a lifetime $\tau = 3.7 {+0.6 \atop -0.5} \times 10^{-10}$ sec. Additional data on the Q value, published by Fretter's group at Berkeley, the Princeton group, and Bristol (reported later in this meeting by Friedlander) have only confirmed this without changing the Q value. An experiment of Osher and Moyer, reported later, will bear on the question of the alternate mode $\Lambda^o \rightarrow n + \pi^o$. Λ^o is not only found produced in association with K mesons, but apparently also occurs as a decay product of at least two other hyperons, namely

$$\Sigma^o \rightarrow \Lambda^o + \gamma$$
$$\Xi^- \rightarrow \Lambda^o + \pi^-.$$

The Σ^+ has two decay modes,

$$\Sigma^+ \rightarrow \pi^+ + n + Q_1 \; (= 110 \pm 5 \text{ Mev})$$
$$\Sigma^+ \rightarrow p + \pi^o + Q_2 \; (= 115 \pm 5 \text{ Mev})$$

Q's measured in emulsion

with a branching ratio of approximately unity. The second Q has been well measured since the range of the proton is only 1680μ and usually stops in the emulsion. There is some evidence for the neutron from the double cloud chamber of Paris. Interactions in the multiplate chamber were seen to occur along the predicted lines of flight of the neutrons. No evidence exists for the π^o in the other decay mode. Several measurements of lifetimes of $\Sigma^{\pm}$ have been made. These are

Rome	$5 \times 10^{-11} < \tau < 3 \times 10^{-10}$	For decays in flight only.
Bristol	$3.5 {+1.5 \atop -1.1} \times 10^{-11}$	
Fry	$3.4 {+1.4 \atop -0.8} \times 10^{-11}$	
Fry	$1.41 {+.19 \atop -.27} \times 10^{-10}$	Including $\Sigma^{\pm}$ at rest.

The last value of Fry takes into account particles decaying at rest and the discrepancy might be explained if the Σ^- had a longer lifetime than Σ^+ and Σ^+ decayed predominantly in flight. (See Fry's discussion later. Also Steinberger's direct Σ^- lifetime measurement.)

The Σ^- has previously been identified in the Brookhaven diffusion chamber, Fetter's cloud chamber and in emulsions. Recently, 3 Σ^- (really Y^- as they are identified only roughly as to mass) have been seen to stop and give rise to hyperfragments. These were observed by the Padua, Chicago and Lausanne groups. Considerable new information about the Σ^- will be given during this conference (see S. Goldhaber as well as others).

The evidence for the Σ^0 rests on the work of the Brookhaven cloud chamber group and Walker et al on associated production of $\theta^0 + \Lambda^0$. In some cases energy and momentum does not balance in an apparent $\pi^- + p \rightarrow \theta^0 + \Lambda^0$ reaction and suggests a Σ^0 was produced which decayed immediately to $\Lambda^0 + \gamma$ (see Fowler later in this conference). As yet the γ has not been observed.

The Ξ^- hyperon is now well known even though there are only about 10 known cases. The decay is $\Xi^- \rightarrow \Lambda^0 + \pi^- + Q$ ($= 65 \pm 4$ Mev). It is known that the charged secondary is a π^- since it has been observed

(Paris group) to interact in a cloud chamber plate. The mean life is unknown, but it seems short. Gell-Mann, Pais and others predict a neutral Ξ^o. However, this will be difficult to detect since it presumably decays into $\Lambda^o + \pi^o$. A few Ξ^- have been observed in emulsions, at least their Q values seem about correct. Cal. Tech. has seen the production of $\Xi^- + \theta^o + \theta^o$, a process predicted by Gell-Mann, Pais, and others.

There are a few "freak" cases which are difficult to explain. For example, there is the Eisenberg event in which a Y (measured mass $\sim$3220 $\pm$ 700 m_e) seems to decay into a K (measured mass $\sim$ 850 m_e) which later produces a super σ star and is thus negative. The Q value is about 5 Mev for a two-body decay. Fry has observed a K^- meson of 43 Mev being ejected from the secondary star produced by a hyperfragment. In this case the total energy in the star is greater than 550 Mev. Fry also has reported two hyperfragments decaying with energy releases larger than that associated with a bound Λ^o. Another hyperfragment with an anomalous Q has been found by the Rome group.

Perhaps a few comments should be made with respect to the $V^{\pm}$ events seen in cloud chambers in the cosmic radiation. For the V^+, the major portion appear to be slow and p* analysis indicates that a large fraction of slow V^+ are $K^+_{\mu 2}$ and $K^+_{\pi 2}$. This is well confirmed by the Cal. Tech., Indiana, Princeton, Berkeley and Paris groups. Further, most V^+ are K^+, but a relatively small fraction could be Y^+. The mean life appears long ($\sim 10^{-8}$ sec), except for one observation by the Princeton group on K^+

particles which gave a lifetime $\sim 5 \times 10^{-10}$ sec. This is the only indication of a short lifetime component. The situation with V^- is less clear. First the number of V^- is comparable to the number of V^+, but they are considerably more energetic than V^+ and appear to have a shorter lifetime. Most secondaries of V^- interact and are thus π-mesons most likely. Since Ξ^-, τ'^- seem rare, perhaps the V^- are predominantly Σ^- or $K^-_{\pi 2}$. This, however, is far from proved.

The last point is the anomalous V^o. This is a neutral decay which fits neither the Λ^o or θ^o Q values. Q values based on decay into 2π mesons range in more or less continuous fashion from low values $\sim$ few tens of Mev up to the Q of the θ^o (214 Mev). Some will fit with $\tau^o \rightarrow \pi^+ + \pi^- + \pi^o$ for example. Others will not. Block et al, Cowan, Harmon have given evidence that one type of anomalous V^o has an electron as one decay product. Other possible decay schemes for anomalous V^o events are

$$K^o \rightarrow \pi + \mu + \nu + Q(= 248 \text{ Mev})$$
$$K^o \rightarrow \pi + \pi + \gamma + Q(= 212 \text{ Mev})$$
$$K^o \rightarrow e + \pi + \nu + Q(= 354 \text{ Mev}).$$

Also one should not forget that electron pairs from $\pi^o \rightarrow e^+ + e^- + \gamma$ can simulate V^o (see Peyrou later in this report). The question of the neutral decay schemes is open and merits considerable work.

GOTTSTEIN was elected by those who had contributions on the τ-meson to combine the results into a single talk. The following people contributed:

K. Gottstein, Max-Planck Institut für Physik, Göttingen, Germany

A. Berthelot, Saclay, Gif-sur-Yvette, France

J. Crussard, Ecole Polytechnique, Paris, France

N. Dallaporta, Universita di Padova, Padova, Italy

M. W. Friedlander, University of Bristol, Bristol, England

R. Haddock, University of California, Berkeley

G. G. Harris, Columbia University, New York

C. O'Ceallaigh, Dublin Institute for Advanced Studies, Dublin, Ireland

Gottstein pointed out that this summary would not be as welldone as he would have liked it to be since he had had too short a time to organize the material. The first information presented was on the relative abundance of τ, τ' and K mesons. These were the combined results of Berkeley and M.I.T. shown in the left side of Table I and of Padova on the right.

	Berkeley and M.I.T.	Göttingen	Padova	Dublin
τ/K_{all}	0.0581 ± 0.0041	0.050 ± 0.007		0.065 ± 0.0061
τ'/K_{all}	0.0193 ± 0.0036			0.0217 ± 0.006
τ'/τ	0.332 ± 0.067		0.19 ± 0.07	0.312 ± 0.086
Number of τ used	202	56	53	112
Number of τ' used	65		10	13

Table I

Next, Gottstein reported a careful investigation of the τ Q value by the emulsion groups at Milano, Brussels, Genova, and Saclay. (Ed. note: we insert here a summary of this work prepared by A. Berthelot which amplifies slightly Gottstein's remarks.)

"We have measured the Q value of τ decay at rest in photographic emulsions by a method designed to be independent of the choice of any particular range-energy relation.

"After carefully testing that the three branches are coplanar, we measure the three angles α_1, α_2, α_3 between the branches. Choosing an arbitrary value for Q, it is possible to calculate from energy and momentum conservation the kinetic energies E_1, E_2, E_3 of the three π's. The measurement of the corresponding ranges gives three points of a range-energy relation for pions. It is possible then by the measurement of a sufficient number of τ's to determine a range-energy relation which is dependent of the value chosen for Q.

"In the same stack, the range of μ from π decay at rest is measured and converted to a π range by use of the ratio m_π/m_μ. Then Q is chosen so that the range energy curve fits this point.

"The present measurements have been made on a part of the K1 stack irradiated in the K^+ meson beam at the Bevatron. At the present stage the range-energy relation is determined in the interval 4.5 to 56 Mev by 81 points on the assumption that it is linear in log E, log R coordinates. The best Q value deduced from them is:

$$Q = (0.547_0 \pm 0.003)\ m_\pi$$

$$= (76.4_3 \pm 0.4_2)\ \text{Mev}$$

"The quoted error is the one which results from the estimated experimental errors. It does not include that which results from the uncertainty on the m_π/m_μ ratio. A change of $\pm$ 0.001 from the accepted 1.321 value will result in a $\pm 2.7 \times 10^{-3}$ m_π or $\pm$ 0.37 Mev."

Gottstein continued with a discussion of methods of finding information on the spin and parity of the τ. These are:

1. the triangle plot of Dalitz;
2. the Fabri calculation of the probability that the π^- has smallest energy, the middle energy or the largest energy among the three decay π's (Fabri has calculated these probabilities for different spin and parities of the τ);
3. the angular distributions of Costa and Taffara at Padova (these are the angular distributions to be expected of the angles between the π mesons);
4. the Dalitz cos θ distribution, where θ is the angle between the direction of the π^- meson and the directions of the $2\pi^+$ mesons in their own C.M.;
5. the π^- energy distribution of Dalitz;
6. the polarization test suggested by Thirring.

It is, of course, obvious that biases in scanning could seriously affect conclusions drawn from the above tests which are statistical in nature. When comparing data, then one must be very careful of biases. In particular along the track scanning is preferred to area scanning. Table II shows some scanning information.

Laboratory	Number of 's	Type of Scanning	Is the identification independent of energy?
Berkeley	100	?	?
Bristol	93	Area	Almost
Columbia	72	70% Track 30% Area	Almost
Göttingen	106	Track	Yes
Padova	190	Area	Yes

Table II

Fig. 4 shows a Dalitz plot. It does not contain all events listed above but shows fairly clearly the uniform distribution of points which is typical of the spin 0^- particle. The solid curve was calculated with non-relativistic kinematics and the dashed curve, relativistic. Fig. 5 shows for comparison a hypothetical distribution for spin 1^- and for 1^+. (Note: These figures were from G. G. Harris, Columbia University.)

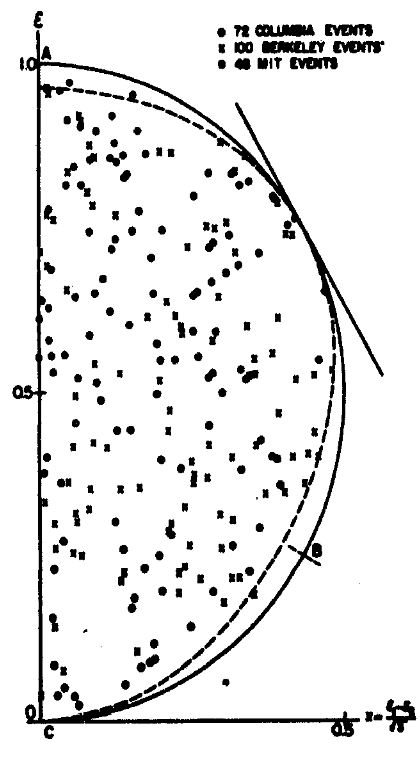


Fig. 4

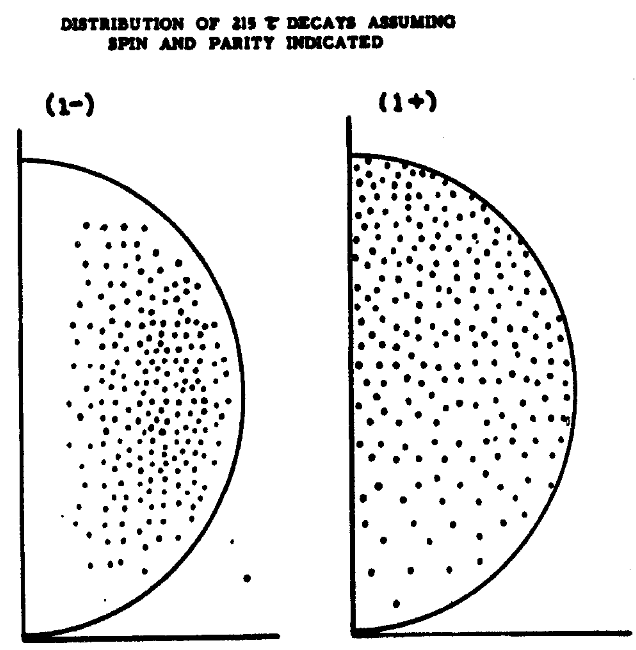


Fig. 5

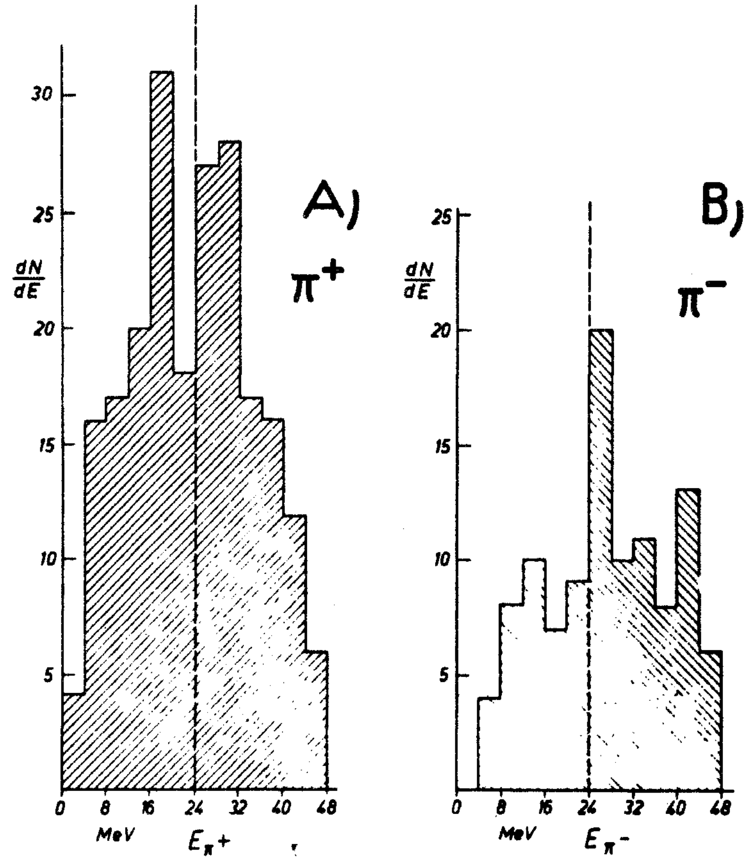


Fig. 6

Fig. 6 shows the π energy distributions from the Göttingen data. We see the symmetry of the π^+ energy about 24 Mev. Note that the π^- energy is not exactly symmetrical, being weighted a little on the higher side. The Columbia data shows this same behavior for the π^- energy. Gottstein commented that he had received from Berkeley an energy distribution of π's from the τ', and this distribution appeared uniform.

In Fig. 7 the data of Fig. 6B have been divided by the phase space factors. Also included are the theoretical curves for various spins and parities calculated by the M.I.T. group. For the case 0^- one would thus expect a uniform distribution. This, of course, assumes (a) that the

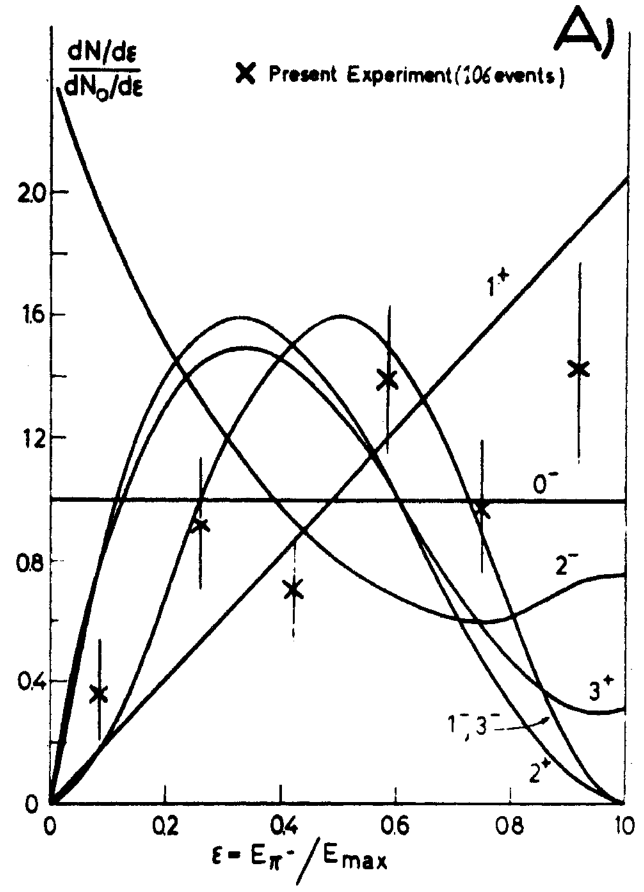
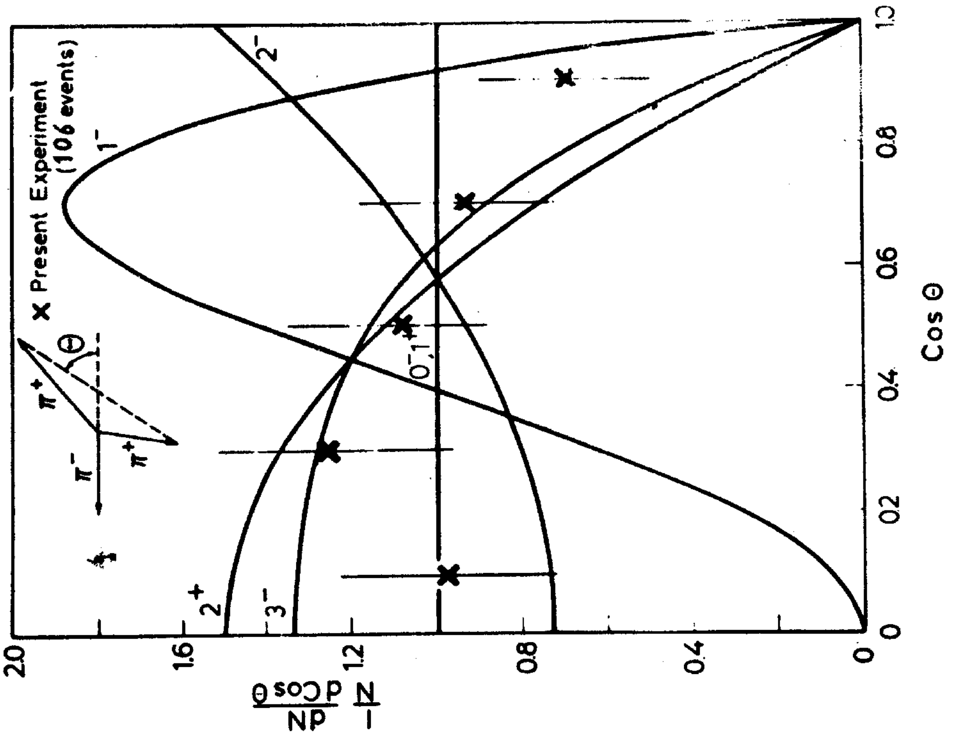


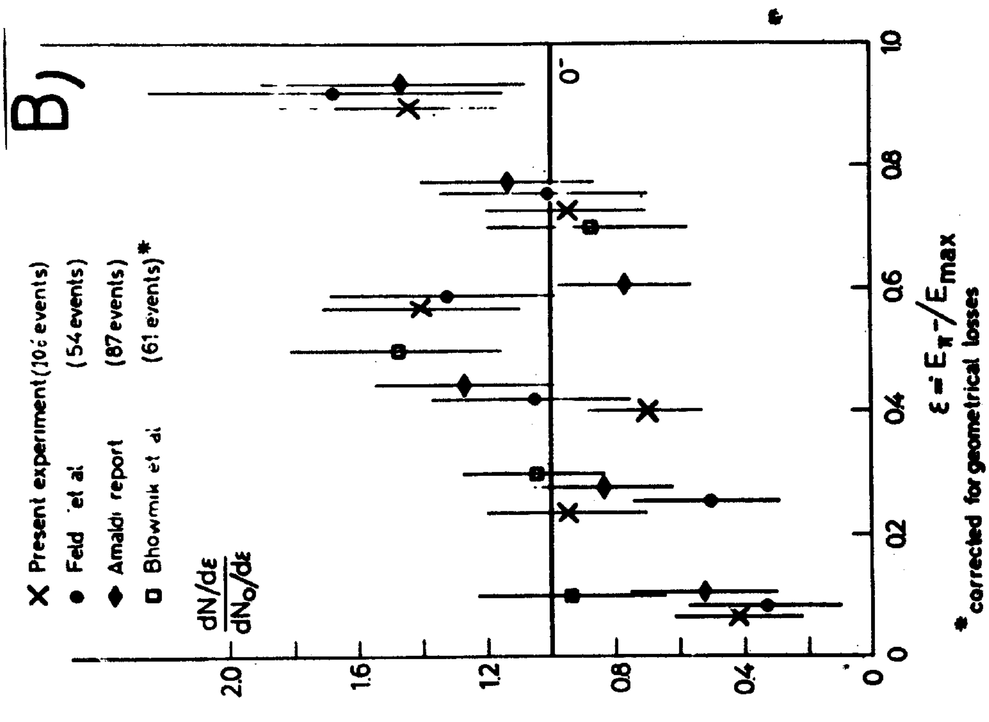
Fig. 7

matrix element is energy independent and (b) the outgoing π mesons do not interact. Note that the experimental points seem compatible with 0^- and 1^+. Fig. 8 shows a plot of more experimental data including the Göttingen data, M.I.T. data, the data from Cosmic Rays contained in Amaldi's Pisa report and Bristol data. If you draw a straight line through the points, the best line would seem not to have zero slope (0^-) or slope = 1 (1^+) but somewhere in between. Some additional results from Copenhagen show this trend also. Fig. 9 shows the cos θ test of Dalitz. The Göttingen data are plotted and are compatible with 0^- or 1^+, even perhaps with 2^- or higher spin. Those spins and parities which appear excluded are 1^-, 2^+ and 5. However, if the τ has spin



× Present Experiment (106 events)
Cos Θ
dN/dCos θ
N

Fig. 9



B)
× Present experiment (106 events)
● Feld et al (54 events)
◆ Amaldi report (87 events)
□ Bhowmik et al (61 events)*
dN/dε / dN₀/dε
ε = E_π−/E_max
* corrected for geometrical losses

Fig. 8

greater than 1, then it might be polarized. Thirring has suggested that the τ should have a high probability of maintaining this even if it is slowed down in dense material. However, all groups consistently find no correlation effects in the angle between the plane of decay and the incoming direction of the τ. This test was proposed by Teucher, Thirring and Winzeler. Fig. 10 gives experimental results on this angular distribution for τ mesons and K_L mesons. The dotted line corresponds to uniform distribution per unit solid angle. This test shows isotropy both for τ's and K_L-mesons.

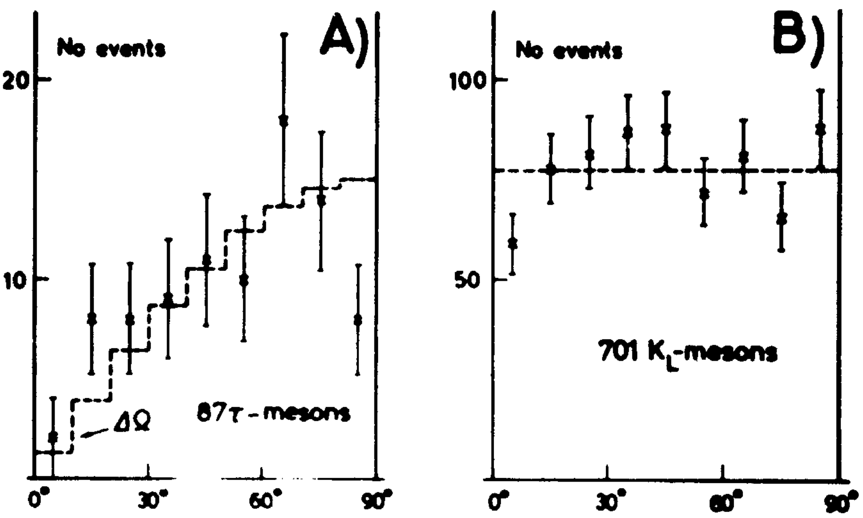


Fig. 10

Gottstein noted that either 0^-, and 1^+ taken alone did not fit the data well; however, a mixture of two kinds of τ mesons, one being 0^- and one being 1^+, would. He noted that this idea had already been discussed. Another, and simpler possibility was that the phase space distributions have after all been altered by such effects as $\pi - \pi$ interactions, etc.

Discussion

Harris commented that when all the data was taken together, then one saw that there were more π^- mesons of energy greater than 24 Mev (one-half of total possible) than less than 24 Mev. This is only a slight asymmetry. Furthermore, the total evidence favored 0^- over 1^+. 2^- cannot be distinguished from 0^-.

Ed. Note: The new extensive τ data from the Padua group (about 30% of the total τ data) is summarized below.

190 tau^+ mesons from two large stacks exposed at 90^o to the K^+ beam from the Berkeley Bevatron are in good agreement with the Dalitz, Fabri and Costa-Taffara distributions for zero spin and negative parity, while the probabilities for the combination 1+, 1-, 2+ and 3- are all very small. Particular evidence for even spin and odd parity comes from the low end of the pi^- energy spectrum.

51 events were found by scanning along the tracks; the remainder by area scanning. The acceptance criteria were (a) at least two pions end in the emulsion, so permitting identification of the negative pion, (b) coplanarity within the experimental errors, and (c) a Q-value of 75 ± 4 MeV, derived from the pion ranges and momentum balance. The decay planes appear to be oriented at random both with respect to the emulsion and to the K^+ beam: this is taken to mean that the sample is free from bias.

CRUSSARD presented a paper on $K_{\mu 3}$, $K_{\beta 3}$ spectra combining data from Dublin, Bristol, Berkeley, Rochester and Ecole Polytechnique.

The K_β are found by measuring flat secondaries of a certain length, usually 2 cm length or more. There is a bias against finding very slow ones and against very fast ones which leave the emulsion stacks too soon. Fig. 11 is the secondary energy spectrum for 26 cases. This includes

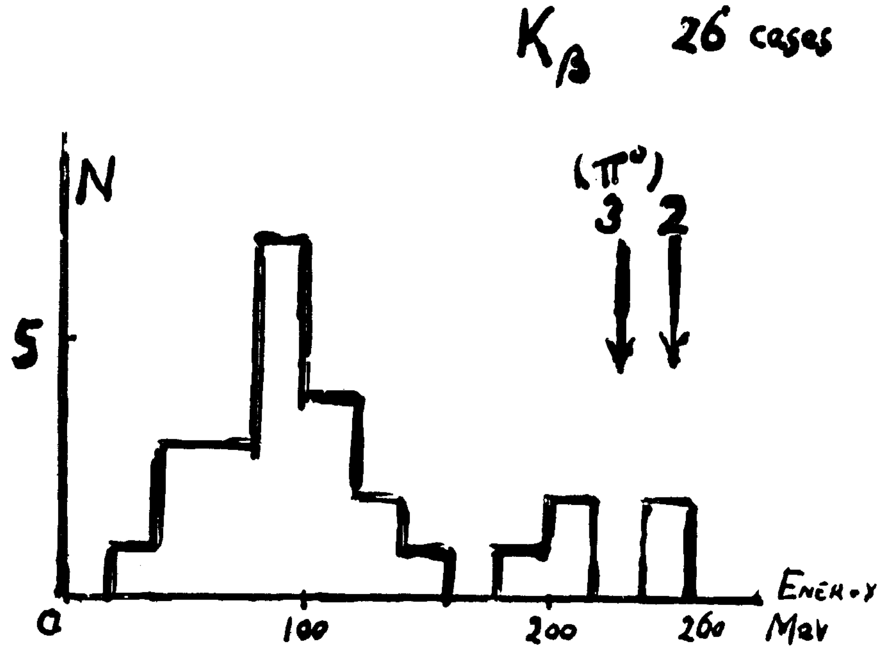


Fig. 11

5 old cases, G-Stack 5 cases, Dublin 6 cases, Ecole Polytechnique 5 cases, Richman's group at Berkeley 2 cases, Rochester 2 cases, the M.I.T.-Berkeley-Brookhaven collaboration 1 case. The energy values are not corrected for bremsstrahlung loss. If this correction is added it would shift the energies higher slightly. The shape is not yet well defined, but there are a few cases near the upper limit of energy. The arrow (2) indicates the energy of an electron from the decay

$$K_{\beta 2} \rightarrow e + \nu \quad \text{(neutrino)}$$

where the mass of $K_{\beta 2}$ = 495 Mev. The arrow (3) indicates the maximum energy the electron may have if it comes from the decay

$$K_{\beta 3} \rightarrow e + \pi^0 + \nu$$

where $K_{\beta 3}$ has the mass = 495 Mev. The cases near the upper limit may be a slight indication for the $K_{\beta 2}$ mode. It is premature to say more.

For the $K_{\mu 3}$, the data was broken down into an unbiased group, and a second group less systematically selected. Dublin contributed 12 cases, the G-stack 4 and the Ecole Polytechnique 3 to the unbiased sample of 19 cases. These are unbiased in the sense that the events are selected for secondary potential range and have measurements on at least 4 cm path length. Fig. 12 shows these 19 cases together with a rough phase space curve for the decay

$$K_{\mu 3} = \mathcal{K} = \mu + \nu + \pi^0.$$

The two cases indicated with the crosses are from Dublin and they are still in process of analysis and should be considered at this moment as tentative. The data fits reasonably well with the $K_{\mu 3} \rightarrow \mu + \nu + \pi^0$ decay, but does not fit with either

$$K_{\mu 3} \rightarrow \mu + \nu + 2\pi^0$$

or

$$K_{\mu 3} \rightarrow \mu + 2\,\nu.$$

Fig. 13 corresponds to the less-well selected group. The contributions to this curve are as follows:

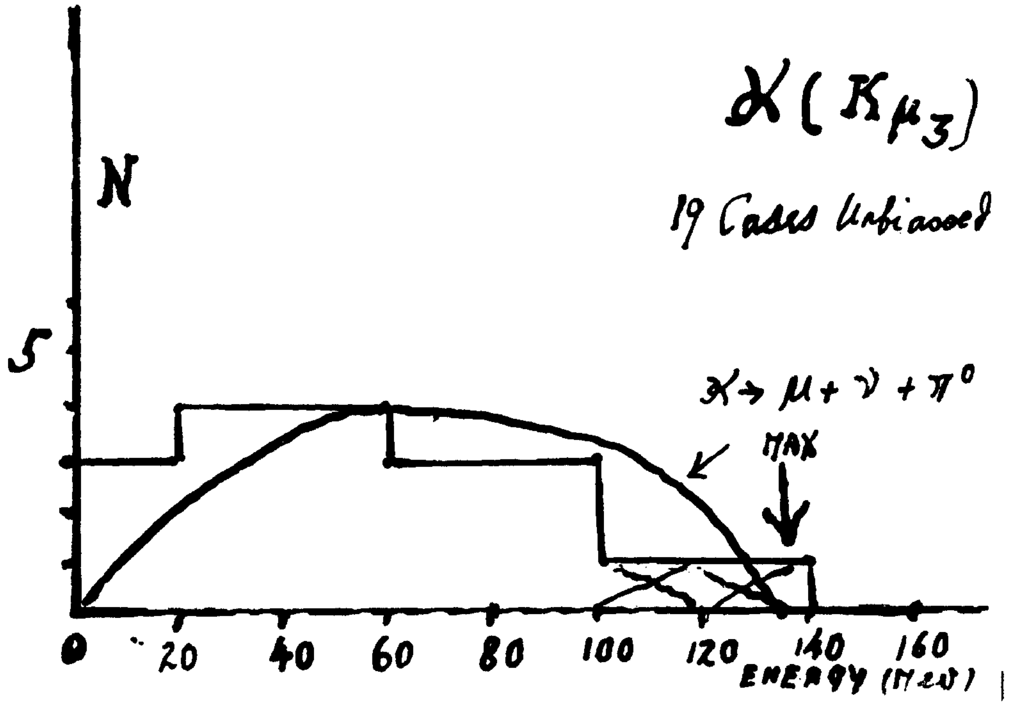

$\mathcal{X}(K_{\mu_3})$
N
19 Cases Unbiased
5
$\mathcal{X} \to \mu + \nu + \pi^0$
MAX
0
20
40
60
80
100
120
140
160
ENERGY (MeV)

Fig. 12

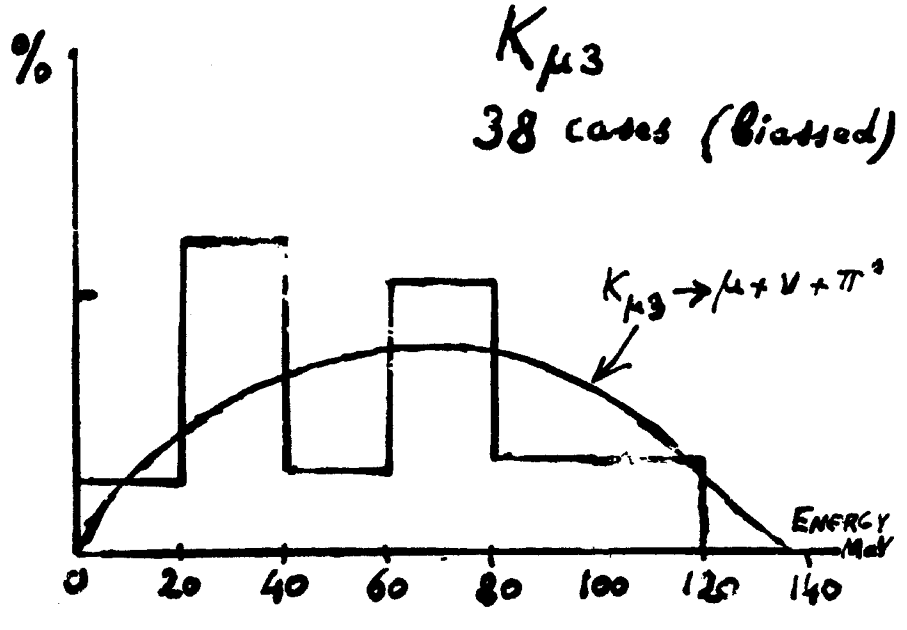

$K_{\mu 3}$
38 cases (biassed)
%
$K_{\mu 3} \to \mu + \nu + \pi^0$
ENERGY MeV
0
20
40
60
80
100
120
140

Fig. 13

Group	Cases
Richman's (Berkeley)	15
Rochester	7
M.I.T.	7
Ecole Polytechnique	6
Barkas' (Berkeley)	3
	38

In this group there is a large bias toward finding low energy secondaries. However, a correction has been applied to fill in the spectrum, by calculating percentage of $K_{\mu 3}$ among all K's rather than adding numbers of cases. Following Stork's approach of the problem, we have divided up the data into three categories: (1) $K_{\mu 3}$ found in direct scanning; (2) secondary not measured very extensively, mostly by grain count; (3) secondary measured extensively; and corrected them accordingly. One sees again that this group also fits well with the $K_{\mu 3} \rightarrow \mu + \nu + \pi^0$ decay.

Discussion

Markov asked if there was a possibility that a decay of the type

$$K^+ \rightarrow \mu^0 + \nu + \pi^+$$

which would be the symmetrical charge analog of

$$K^+ \rightarrow \mu^+ + \nu + \pi^0$$

had been observed. This reaction seems to be the only possibility for detecting μ_0 if it exists. Kaplon answered that at least in the Rochester cases of $K_{\mu 3}$ decay, the μ^0 was not possible. Markov then asked if, from the upper end of the $K_{\beta 3}$ decay spectrum, one could exclude the following decay:

$$K_{\beta 3} = e + \nu + \nu' + \nu''.$$

This is in a certain sense like $\mu \rightarrow e + \nu + \nu'$.

O'Ceallaigh suggested that there was no clear evidence on this point. Markov commented that the following schemes exist experimentally:

$$\begin{aligned} K &\rightarrow \mu + \nu \\ &\rightarrow \mu + \nu + \pi \\ &\rightarrow e + \nu + \pi^0 \end{aligned}$$

Theoretically, then, it is hard to see why the others should not exist also (for example; $K \rightarrow e + \nu$).

KAPLON described a $K_{\mu 3}$ event which throws light on the neutral decay particles (see Hoang et al, Phys. Rev. 101, 1834 (1956) for complete details). Fig. 14 shows the event which was found in an emulsion exposed to the K^+ beam of the cosmotron. A K^+ decays into an identified μ meson and an electron pair. That the light secondary is a μ follows from ionization and scattering measurements and the ability to rule out all

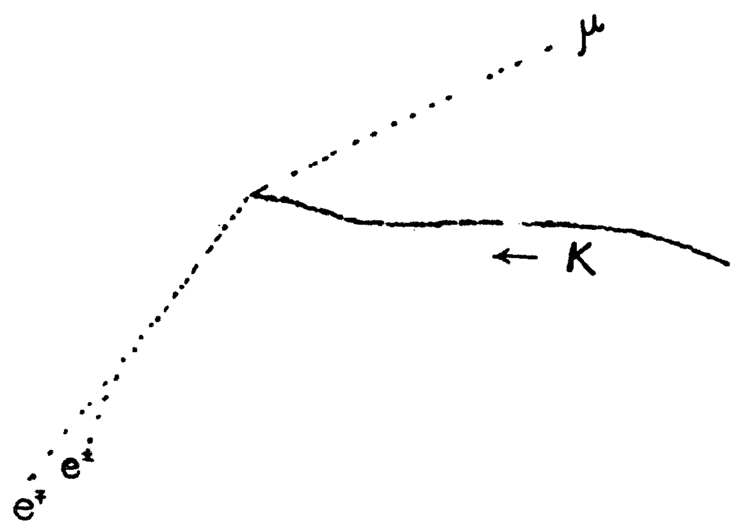


Fig. 14

decay schemes in which the light secondary could be a π meson. Fig. 15 shows the ionization discrimination for the secondaries of $K_{\mu 2}$, K_{e3}, $K_{\pi 2}$. For this event the light secondary has ionization in the trough. From dynamical arguments, the $K_{\mu 2}$ decay, the $K_{\mu 2}$ radiative decay, the $K_{\pi 2}$, the $K_{\pi 2}$ radiative decay, the τ' decay can be ruled out. Also, the light secondary cannot be an electron; hence $K_{\beta 3}$ is ruled out. The only consistent explanation is that the light secondary is a μ-meson of 110 $\pm$ 10 Mev kinetic energy. Assuming it is a μ-meson and from the measured electron energies one can determine the upper limit on the neutral mass in the scheme

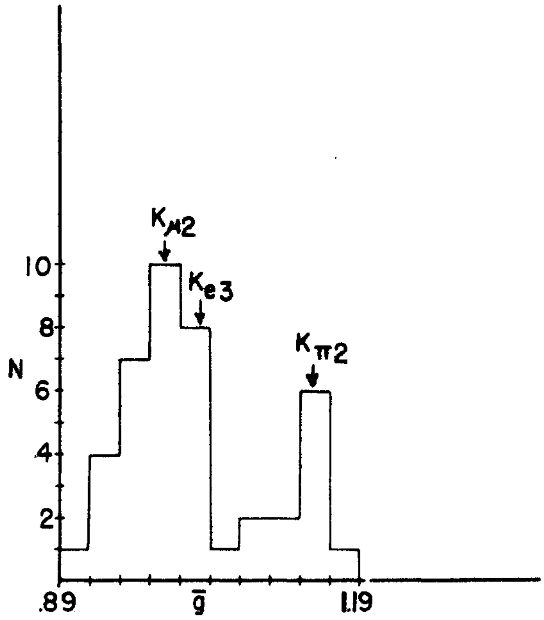


Fig. 15

$$K^+_{\mu 3} \rightarrow \mu^+ + \pi^o + X^o$$

where X^o is the unknown neutral. This upper limit is 75 Mev for this event. For this event the neutral could not be a μ^o.

If we divide the phase space for the $K^+_{\mu 3} \rightarrow \mu^+ + \pi^o + \nu$ into two regions, (1) below 75 Mev, kinetic energy of the μ, and (2) above 75 Mev, and then compare the experimentally observed numbers in these two regions, corrected for biases, it was found that the experimental numbers agreed with the phase space prediction.

S. GOLDHABER gave the most recent results on K^+, K^- masses, the

$\Sigma^- - \Sigma^+$ mass difference, and K^- lifetime. These results come from the following sources:

K^+ - mass	Birge <u>et</u> <u>al</u>, Berkeley
K^- - mass	Webb, <u>et</u> <u>al</u>, Berkeley
K^- - lifetime	Iloff, <u>et</u> <u>al</u>, Berkeley, M.I.T. and Harvard
$\Sigma^- - \Sigma^+$ mass difference	Chupp <u>et</u> <u>al</u>, Berkeley

Fig. 16 shows the mass measurements by the Richman group. All mass measurements were done on particles from a momentum selected K^+ beam. Scanning was done along the track, and therefore unbiased. The first column gives the mass as measured on the track of the decaying K meson. The second column gives the mass as determined from the range of the decay products and assuming a decay scheme. Note how consistent these two sets of values are, indicating no significant difference in mass as measured in these two ways. There is no evidence here to support the Lee-Orear cascade decay hypothesis.

MEASURED MASSES AND STANDARD DEVIATIONS*

	PRIMARY MASS	SECONDARY MASS
τ	966.6 ± 1.9	966.1 ± 0.7
$K_{\mu 2}$	967.2 ± 2.2	964.8 ± 2.8
$K_{\pi 2}$	966.7 ± 2.0	964.2 ± 2.0
$K_{\mu 3}$	968 ± 6	
$K_{\beta 3}$	963 ± 10	

Fig. 16

For the K^- mass to K^+-mass ratio, the value is

$$\frac{K^- \text{ mass}}{K^+ \text{ mass}} = 0.998 \pm 0.013.$$

Thus K^- mass = 964 m_e, for K^+ = 966.5 m_e. The method was to compare K^-, K^+ ranges under the same geometry and in identically selected momentum beams. In order to take into account small asymmetries π^-, π^+ ranges were also measured (see Webb et al, Phys. Rev. 101, 1212 (1956) for complete details of this experiment). In addition to this method, there are four determinations of K^- mass from scattering on protons, namely

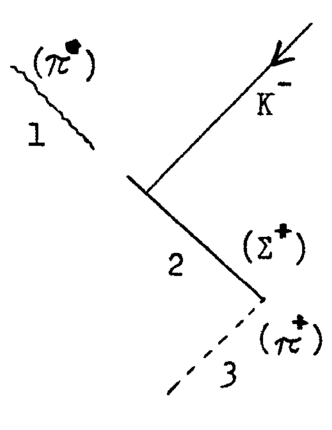
$$K^- + p \rightarrow K^- + p.$$

The following mass values were obtained:

White et al, Livermore	1008 ± 26 m_e
	980 ± 220 m_e
	993 ± 11 m_e
Bern group	979 ± 11 m_e

They seem to agree fairly well with the other determination. It would appear, therefore, that the K^- has the same mass as the K^+.

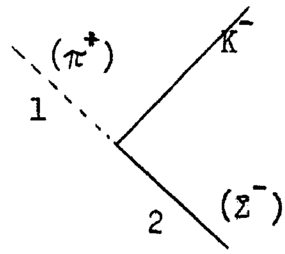
Last year at Berkeley the following event was seen, in which the particles 1 and 2 were accurately collinear. The event was interpreted as a K^- capture by a proton, namely



$$K^- + p \rightarrow \Sigma^+ + \pi^-$$
$$\Sigma^+ \rightarrow \pi^+ + n$$

Particles 1, 3 escaped from the emulsion. Now, by assuming the K^- mass, one can find the mass of particle 2 or vice versa.

Another event, similar but not exactly the same, was seen. Again 1 and 2 are collinear, but 2 does not decay and has a somewhat smaller range than the first case. The interpretation suggested was



$$K^- + p \rightarrow \Sigma^- + \pi^+.$$

M.I.T. also has one of each kind. Fig. 17 shows a table of these four cases. Now you can assume that the Σ^+, Σ^- masses are the same and then can calculate K^- mass. The second particle, K_{MH1}, may have been a decay in flight, hence the indication that the K^- mass is a lower limit. It is better to take the K^- mass as shown, since that now seems well measured, and calculate the Σ^+, Σ^- masses. These are shown in the last two columns of Fig. 17. Thus the mass difference between Σ^- and Σ^+ is about 14 m_e. A similar mass difference has been found in Lausanne.

1. K^- and (or) Σ^- masses from reaction $K^- + H \rightarrow \Sigma^{\pm} + \pi^{\pm}$

Event	Particle Emitted	Range $\Sigma^{\pm}$	Assume $M_{\Sigma^-} = M_{\Sigma^+} = 2327 \pm 3m_e$	Assume $M_{K^-} = M_{\tau} = 965.5 \pm 0.7$	
			Case A: M_{K^-} in m_e	Case B: M_{Σ^+}	M_{Σ^-}
K^-_{20}	Σ^+	$809 \pm 40\mu$	$\geqslant 966 \pm 6$	$\leqslant 2324 \pm 4$	
K_{MH1}	$\Sigma^{\pm}$	$> 579 \pm 25\mu$	$> 935 \pm 5$	$< 2355 \pm 4$	
K^-_2	Σ^-	$695 \pm 25\mu$	952 ± 5		2338 ± 4
K^-_{MH2}	Σ^-	$691 \pm 45\mu$	951 ± 7		2338 ± 6

2. K^- mass by a range-momentum method (compared to M_{K^+})

$M_{K^-} = 963 \pm 12m_e$ (if $M_{K^+} = M_{\tau}$)

3. K^- mass from K^-_{MH2} decay in flight

$M_{K^-} = 957 \pm 40m_e$

Fig. 17

The K^- lifetime has been determined by following along K^- tracks and observing decays in flight. Fig. 18 shows the data from three different

Table I

Results of determinations of mean lifetime of τ_{K^-} mesons

Group	Total proper time	Number of decays in flight n	Mean lifetime τ_{K^-}
Berkeley	3.96×10^{-8} sec	4	0.99×10^{-8} sec
Livermore	2.63×10^{-8} sec	3	0.88×10^{-8} sec
M.I.T.-Harvard	5.78×10^{-8} sec	6	0.96×10^{-8} sec
Total	12.37×10^{-8} sec		$\tau_{K^-} = 0.95^{+0.36}_{-0.25} \times 10^{-8}$ sec

groups. The first column is the total proper time, the second is the number of decays in flight, and the last column is the mean lifetime from each group. The totals and averages are shown in the last row. We see that the K^- has the same lifetime as the K^+. Fig. 19 shows a summary of all K particle lifetime measurements. It is clear that all measurements, in their present rough state, for various components of the $K^+(K_{\mu 2}, K_{\pi 2},\quad)$ and K^- are consistent with a unique value of the lifetime. References for this figure are given in Phys. Rev. 102, 927 (1956).

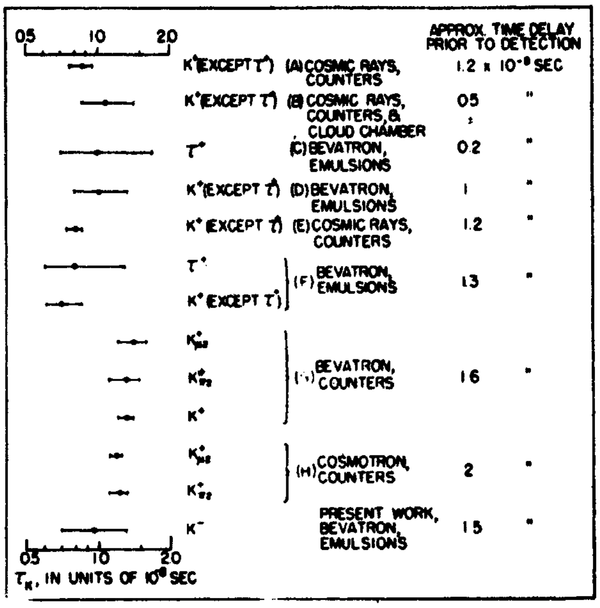


Fig. 19

ALVAREZ reported on a search for the Lee-Orear γ-ray(s) which would result from their suggested cascade decay of the τ to the θ meson. This suggestion was made to explain why all of the properties of the τ and θ, i.e., mass, lifetime, production, and scattering, are closely the same, yet the Dalitz analysis of the τ indicates that they cannot have the same spin and parity, at least if we restrict ourselves to spins below 2. The Lee-Orear idea to circumvent this trouble was that the τ should decay into the θ with emission of γ-ray(s) and the θ then would decay very much faster than the τ, say 10^{-10} sec; hence the lifetimes measured would always be the same, namely that of the τ. The θ could also be produced directly and decay with its own shorter lifetime. The process could, of course, be $\theta \rightarrow \tau + \gamma\ (+\ \gamma)$; however, in this experiment, because the detector detected $K_{\pi 2}$ decays, only the process $\tau \to \theta + \gamma\ (+\gamma)$ could be observed. The Lee-Orear scheme, of course, was based upon the experimental situation of a year ago when there appeared to be a $(\tau - K_{\pi 2})$ mass difference of 5 - 10 Mev. However, it is to be noted that now the $(\tau - K_{\pi 2})$ mass difference has been squeezed down to the order of 1 or 2 Mev; hence, there is not much room for the Lee-Orear γ-ray(s).

Fig. 20 shows the detector used in this experiment. It has previously been used for measuring $K_{\mu 2}$, $K_{\pi 2}$, τ lifetimes. K mesons enter and stop in counter C. For example, to detect $K_{\pi 2}$, γ's from π^0 decay must pass through B without converting to electrons, then convert in the copper and lead and trigger A. The counter demand for $K_{\pi 2}$ would then be pulses from CDA and no pulse from B. Now, for the Lee-Orear γ-ray counter, B was surrounded by a scintillation guard counter, and it was demanded that, in addition to the $K_{\pi 2}$ signature, counter B be triggered by a small γ-ray pulse but that the guard counter did not count. Events with large pulses in B, of course, were rejected since the γ-rays expected are only of the order of 1 Mev.

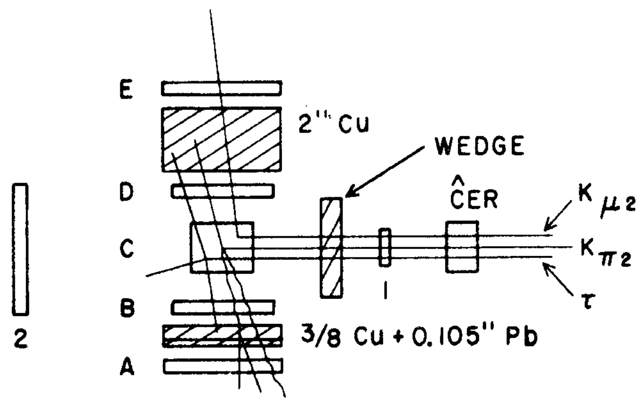


Fig. 20

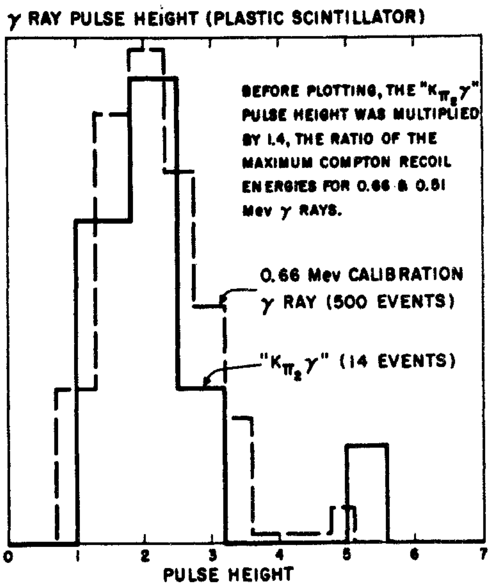
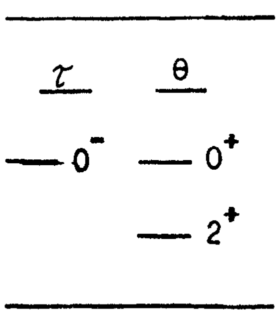


Fig. 21

Fig. 21 gives the γ-ray pulse height distribution seen in coincidence with $K_{\pi 2}$ events. One γ-ray pulse is seen in B for about ten $K_{\pi 2}$ events. Only one per cent of $K_{\mu 2}$ events are so accompanied, which is about the expected accidental background rate. Two checks were made. First, the pulse height distribution was looked at and found to be identical with an annihilation radiation spectrum, as can be seen in Fig. 21. The second check was to put an absorber between counters C and B, and it was found that the counting rate did not change. This indicated that positrons resulting from the shower in the copper and lead absorber between A and B were annihilating and giving γ-rays which produced the pulses in B. A simple Monte Carlo calculation showed that the expected number of such γ-rays was indeed about 10 per cent of $K_{\pi 2}$ counts. Therefore, no Lee-Orear γ-rays were seen with pulses of the order of 0.5 Mev or greater. The detection of the annihilation radiation was good evidence that the detector could indeed see 0.5 Mev γ-rays.

An experiment by Osher and Moyer, to be described later, shows the θ must have even spin. We have the following situation for spin and parity for the τ and θ. A $0^- \rightarrow 0^+$ transition requires two γ-rays and, in order



for it to proceed rapidly, would require a mass difference of 2or 3 Mev. The $0^- - 2^+$ transition also requires a mass difference of 2 or 3 Mev. Either of these transitions would thus produce γ-rays easily seen in this experiment. Therefore, this experiment, together with the Osher-Moyer experiment, shows that the τ does not decay via a γ-ray to the θ. The reverse, namely $\theta \rightarrow \tau + \gamma$, has not been checked but seems less likely from other considerations.

Discussion

Lee suggested the spin of the τ could also be 1^+ or 2^-. Alvarez commented that it would be simplest to have τ and θ the same particle, perhaps something like Marshak's suggestion that both are 2^+. They would shortly look for polarization by double scattering at Berkeley, and if they get a left-right asymmetry they will, of course, forget about this present τ, θ difficulty.

BLOCK discussed two events which appear unusual. One involves the decay of a positive particle, with some indication that the mass of the primary is about 1500 electron masses. The second event involves a photograph containing two nearby V's, one charged and one neutral. The plane formed by the V^- contains the vertex of the V^0, suggesting that the V^0 is the neutral decay product of the charged V, i.e., the charged V undergoes cascade decay into a π^- and V^0. The plane of the V^0 does not contain the vertex of the V^-, indicating that if the above interpretation is correct, the V^0 undergoes 3-body decay. The V^0 is compatible with an alternate decay made of a K meson. Under this assumption the V^- mass is $\sim 1500\ m_e$. The probability that the V^o and the V^- are not related, but are produced separately, is $\sim 5 \times 10^{-4}$. Alternate interpretations of the event as associated production in the chamber floor are ruled out from kinematics.

ALVAREZ reported on the work of Osher and Moyer (at the Bevatron) who have investigated the π^o Modes of Heavy Meson and Hyperon Decay. This experiment is essentially a refinement of the experiment by Collins at the cosmotron, which was reported here last year. Fig. 22 shows the experimental setup. The apparatus is essentially a very well collimated γ-ray telescope which can move upstream or downstream from the target. Fig. 23 shows data taken with a 1/8-inch copper target for best space resolution of the decay slope of the $\theta^o \rightarrow \pi^o + \pi^o$ decay mode. The dotted line shows the normalized π^o contribution directly from the target, determined by a run at the reduced energy of 0.8-1.0 Bev. The observed γ-intensity as a function of distance from the target is shown for proton energies of 5.7 - 6.0 Bev. Fig. 24 shows a similar curve but taken with

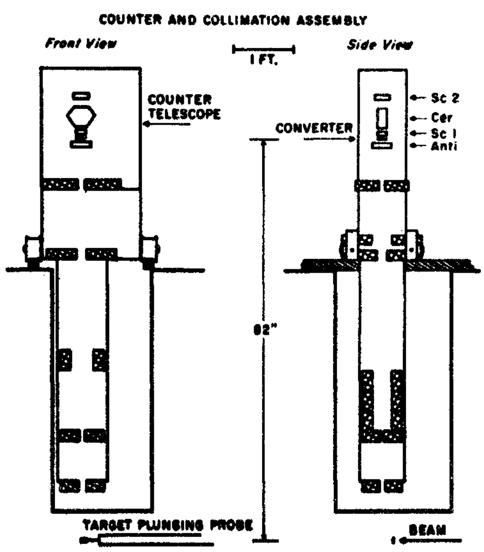


Fig. 22

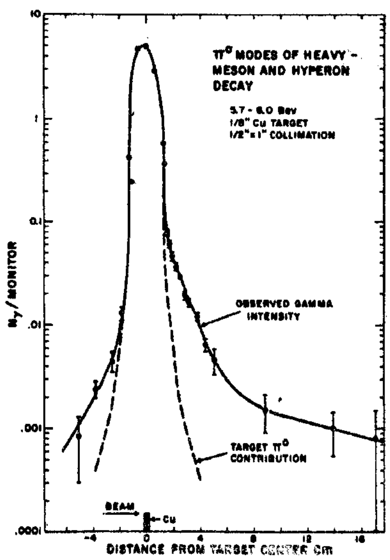


Fig. 23

a 1/2-inch copper target. This shows the downstream side to contain two well resolved components, probably from θ^o and Λ^o decay. At these energies only θ^o can go upstream; hence, the single component there indicates the presence of θ^o. Fig. 25 shows the excitation curve for the γ-intensity at proton energies of 5.7 - 6.0 Bev, 4.8 - 5.3 Bev, 3.2 - 3.6 Bev, and 1.7 - 2.0 Bev. Note the disappearance of the upstream θ^o contribution near 3.0 Bev and the fading out of the Λ^o contribution on the downstream side. The early analysis of the upstream and short-lived downstream radiation yield a lifetime near 1.5×10^{-10} sec. This

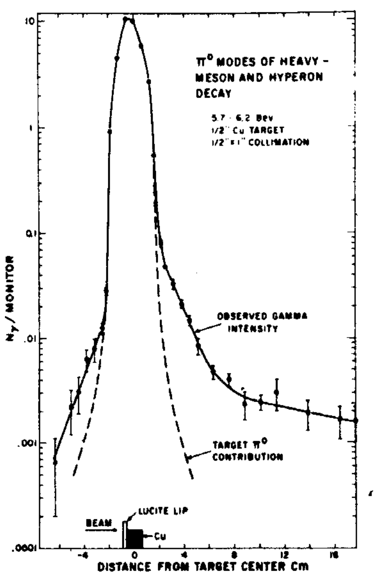


Fig. 24

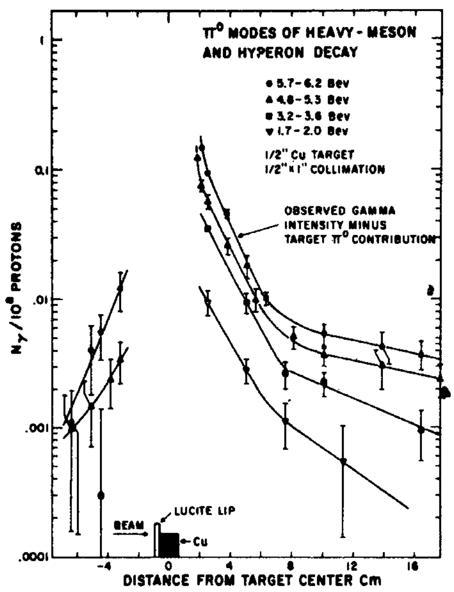


Fig. 25

suggests the $\theta^o \rightarrow \pi^o + \pi^o$. The branching ratio appears to be of the order of unity. Likewise the long lived tail is consistent with the $\Lambda^o \rightarrow \pi^o + n$ decay, though mixed with θ^+ and θ^o decay. The analysis has taken into account: incident proton energy dispersion, Fermi internal momentum distribution, and three-body phase space distribution in the associated production act as well as assumptions of angular distribution. The subsequent θ^0 decay was taken as isotropic. It should be noted that the collimation geometry and calibrated counter efficiency also enter into the observed decay rate.

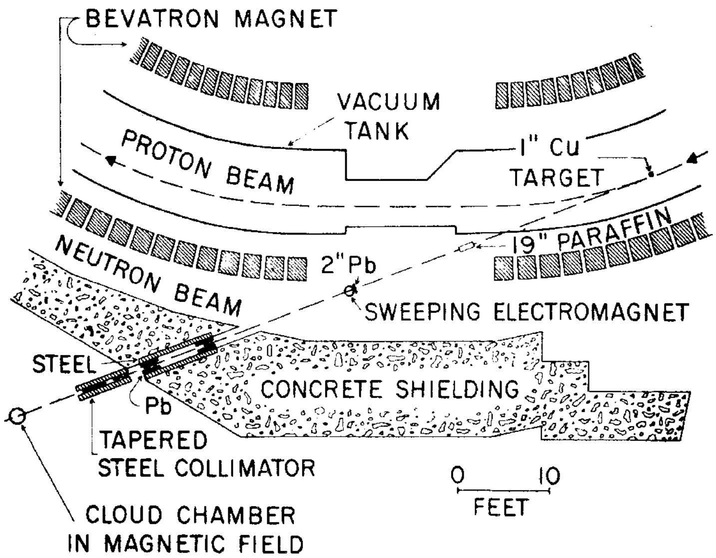


Fig. 26

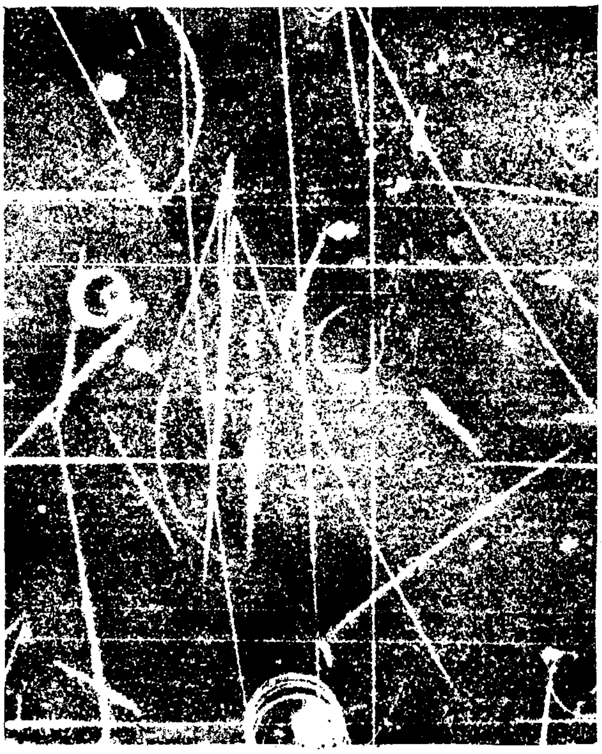


Fig. 27

FOWLER presented a single event which was good evidence for the $\Sigma^0 \rightarrow \Lambda^0 + e^+ + e^- + Q$. The event was obtained by exposing the Berkeley 35 atmosphere hydrogen diffusion chamber to the high energy neutron beam at the Bevatron. Fig. 26 shows the experimental arrangement. A 0^0 neutron beam was used. Fig. 27 shows the event found in the diffusion chamber. The n-p collision shows three charged outgoing prongs and a Λ^0 that decays 1.6 cm from the collision. One of the charged prongs is an identified negative electron.

A positive prong has essentially the same space angle (within 2^o) and is assumed to be a positive electron. The third particle is very fast and unidentified. Fig. 28 shows a summary of the measurements made on the event. The Λ^o is well identified since the proton has a large momentum and hence, for calculation purposes, corrected momentum values have been found for 4 and 5 using momentum balance and a 37 Mev Q. These are noted in Fig. 28.

Track	Charge	Measured Momentum Mev/c	Momentum Required for V^o to be Λ^o	Estimated Ionization (a)	Particle
1	+	214^{+86}_{-49}		1.0	e^+
2	-	41 ± 1		1.0	e^-
3	+	1620^{+470}_{-290}		1.0	π^+ K^+ P
4	+	642^{+174}_{-91}	800	1.5	Proton
5	-	268 ± 14	260	1.0	π^-

(a) Since the direction of the Λ^o is known and one of the decay particles is well measured there exists only one consistent set of momenta that fits 37 Mev for the Λ^o Q value and the observed angles.

Fig. 28

Fig. 29 shows a summary of various possible reaction schemes and a comparison of the mass of the Σ^o computed from this case with $\Sigma^{\pm}$ masses measured by others. Note that, on the interpretation of the associated production of Σ^o and K, the Σ^o mass is calculated to be $1235^{+37}_{-24}\, m_e$. In rather good agreement with $\Sigma^{\pm}$ masses. It should, however, be pointed out that the reaction

$$n + p \rightarrow \Lambda^o + K^+ + n + \pi^o$$
$$\rightarrow \Lambda^o + p + \theta^o + \pi^o$$

where $\pi^o \rightarrow e^+ + e^- + \gamma$ are also allowed.

Summary of calculations.

$$n + p \rightarrow \Sigma^o + \pi^+ + n + \theta^o$$
$$\rightarrow \Sigma^o + K^+ + n$$
$$\rightarrow \Sigma^o + p + \theta^o$$

where $\Sigma^o \rightarrow \Lambda^o + e^+ + e^- + \left(Q = 120^{+37}_{-24}\right)$

$$n + p \rightarrow \Lambda^o + K^+ + n + \pi^o$$
$$\rightarrow \Lambda^o + p + \theta^o + \pi^o$$

where $\pi^o \rightarrow e^+ + e^- + \gamma$

Mass comparison.

This case	1235^{+37}_{-24}
Σ^+ from decays	1186 ± 4 1190 ± 2 (1)
Σ^- from K^- capture	1196 ± 3 (1)
Σ^o from associated production in H^2	1193 ± 30(2)

(1) Pisa Conference Report, 1955.
(2) W. Walker, Phys. Rev. 98, 1407 (1955).

Fig. 29

FRY reported on the $\Sigma^{\pm}$ and on hyperfragments. A good part of the charged hyperons resulted from the absorption of K^--mesons. Some also were found in high energy states. There are 12 cases of $\Sigma^+ \rightarrow p + \pi^0$ found in 3 emulsion stacks. All were calibrated in the sense that the range energy relation has been established for each and normalized to Barkas' curves. π-μ decay calibration was used. The mean proton range from the above decay is

$$\bar{R}_p = 1669 \pm 8 \text{ microns}$$

and $$\bar{E}_p = 18.84 \pm 0.1 \text{ Mev}$$

and $$Q = 116.1 \pm 0.5 \text{ Mev}$$

$$M_{\Sigma^+} = 2327.4 \pm 1\ m_e.$$

In the error is included the straggling as experimentally determined and the uncertainty in the π^0 mass.

Then taking the K^- stars and following all resulting tracks, the branching ratio

$$R = \frac{\Sigma^+ \rightarrow p + \pi^0}{\Sigma^+ \rightarrow n + \pi^+}$$

was found and is unbiased. This value is

$$R = \frac{6}{6} = 1.$$

Fry reported that in twelve K^- absorptions, tracks were produced which, at their ending, produced one-prong stars in eleven cases and a two-prong star in one case. These are presumably tracks of Σ^- which are then captured by nuclei in the emulsion when they come to rest. $\Sigma^{\pm}$ have been observed to decay in flight. In all cases these $\Sigma^{\pm}$ were produced by K^- absorption. There were four examples of $\Sigma^+ \rightarrow p + \pi^0$ in flight and five $\Sigma^{\pm} \rightarrow \pi^{\pm} + n$ in flight. From these data estimates of lifetimes have been obtained. Considering all those cases which decay in flight gives a lifetime by the maximum likelihood method of Bartlett of

$$\tau_{\Sigma^{\pm}} = 3.4 {}^{+1.4}_{-0.8} \times 10^{-11} \text{ sec.}$$

The lifetime can also be obtained by evaluating the probability that the Σ hyperons come to rest as well as those that decay in flight. Again considering both Σ^{+} and Σ^{-}, the value is

$$1.41 {}^{+0.19}_{-0.27} \times 10^{-10} \text{ sec.}$$

This seems inconsistent with the value above. It however is possible that this value is large because the lifetime of the Σ^{-} may be long compared to the Σ^{+} and consequently only Σ^{+} decay in flight. Therefore, to obtain a clear group of Σ^{+}, we can take only those which decay in flight and only those identified Σ^{+} which stop and decay and again calculate a lifetime. This value is

$$0.76 {}^{+.2}_{-.15} \times 10^{-10} \text{ sec.}$$

and is in better agreement with the value obtained for those decaying in flight. This may point to the Σ^{-} as having a lifetime longer than the Σ^{+}.

FRY next discussed hyperfragments resulting either from high energy interactions or the absorption of K^{-}-mesons. One hundred eighty cases have been observed, of which half are clearly disintegrations of nuclear fragments. About twenty are clearly disintegrations of bound Λ^{0} in nuclear fragments, and four cases which are definitely nuclear fragments but are not bound Λ^{0}. Table III tabulates these cases.

Fragment	No. of Cases	Mesonic	Non-Mesonic
H	6 + 1 (?)	6	1 (?)
He	9 + 1 (?)	5	4 + 1 (?)
Li	18	1	17
Z > 3	~ 140	2 {1 is Be^9; 1 is C or N}	

(?) Could be Σ hyperon and not a hyperfragment.

Table III

In Table IV is tabulated the values of binding energies.

Fragment	No. of Cases	Binding Energy (Mev)
$_\Lambda H^3$	3	0.5 ± 0.6, - 0.5 ± 0.6, 0.4 ± 0.7
$_\Lambda H^4$	2	1.9 ± 2.0, 1.7 ± 0.6
$_\Lambda He^4$	3 (all mesonic)	3.9 ± 1*, 0.0 ± 2.0, 1.8 ± 0.6
$_\Lambda He^4$ or $_\Lambda He^5$	1	3.5 ± 0.8
$_\Lambda He^5$	1 (mesonic)	2.0 ± 0.6
$_\Lambda Li^7$ or $_\Lambda Li^8$	1 (mesonic)	5.4 ± 0.6
$_\Lambda Li^6$ or $_\Lambda Li^7$	1 (non-mesonic)	4.9 ± 2.5, 4.7 ± 2.5
$_\Lambda Be^7$	1 (non-mesonic)	5.9 ± 8
$_\Lambda Be^8$	1 (non-mesonic)	3.7 ± 3
$_\Lambda Be^9$	1 (mesonic)	6.5 ± 0.6
$_\Lambda C^{11}$	1 (non-mesonic)	13 ± 6

* This case is interpreted as a mesonic decay into a π^0.

Table IV

The four cases where Λ^o does not fit as the bound particle are as follows. There are two cases which look like fragments and give rise to K mesons. Another case gives rise to a 40 Mev π, probably a Li fragment and has a $Q \sim 100$ Mev. Another has a proton of about 180 Mev with two other tracks, giving a total energy about 200 Mev.

CRUSSARD presented some cases of light hyperfragments, with their binding energies. These data as shown in Fig. 30. Note the long range of the last hyperfragment $_{\Lambda}H^4$ in this table, 22.5 mm.

HYPERFRAGMENTS with MESONIC DECAY

	Hyperfragment			Secondaries			Interpretation	Binding energy of the Λ^0 Mev
	Origin	Z	Range μ	Nature	Range μ	Energy Mev		
F_3	16+2p	1	740	π^- p recoil	18 450 127 <1	33.5 ± 1.1 4.2 0.1	$_{\Lambda}H^2 \to H^1 + p + \pi^-$ $_{\Lambda}H^3 \to H^2 + p + \pi^-$ $_{\Lambda}H^4 \to H^3 + p + \pi^-$	~1.0 ± 1.2
F_4	2n+0p	2 or 3	144	π^- p recoil	8 850 ~445 1 to 2	21.7 ± 0.8 8.8 (0.6 He) (0.3 Li)	$_{\Lambda}He^4 \to He^3 + p + \pi^-$ $_{\Lambda}He^5 \to He^4 + p + \pi^-$ $_{\Lambda}Li^7 \to Li^6 + p + \pi^-$ $_{\Lambda}Li^8 \to Li^7 + p + \pi^-$	5.7 ± 0.9 (He) 6.1 ± 0.9 (Li)
F_6	0+0n	1	384	π α	>34 000 8.7 ± 0.2	54.5 ± 2.4 2.6 ± 0.2	$_{\Lambda}H^4 \to He^4 + \pi^-$	0.4 ± 2.4
F_7	10+2p	1	36	π^- p α	13 350 139 13.4 ± 1	27.6 ± 1 4.4 ± 0.1 3.0 ± 0.2	$_{\Lambda}He^5 \to He^4 + p + \pi^-$	1.3 ± 1.0
F_{14}	12+2p	1	22 500	π^- α	39 450 9.4 ± 0.6	53.6 ± 0.9 2.5	$_{\Lambda}H^4 \to He^4 + \pi^-$	1.4 ± 0.9

$\Lambda^0 \to p + \pi^- + 36.9 \pm 0.2$ Mev

Range energy relation : Baroni et al.

Fig. 30

Discussion

S. Goldhaber asked Fry what percentage of K^- stars give rise to hyperfragments. Fry answered 1/20. Salant asked how the two K mesons were identified which came from fragments. Fry replied that he had used all possible methods. Both K-mesons had the same energy, ~42 Mev. S. Goldhaber asked what minimum length was required before accepting an event as a hyperfragment. For hyperfragments with $Z > 3$, for example, the track is usually very short. Fry answered that this was true and that they had only two cases with $Z \sim 6$ where the track length was long enough to allow a determination of Z. Breit asked how long $_{\Lambda}He^5$ lived. Fry answered: of the order of 5×10^{-12} sec or longer. It can have a long life since it is not true He^5, but He^4 plus a Λ^o.

Thompson commented that the apparent difference in Σ^+, Σ^- lifetime could be a possible explanation of the apparent lifetime differences for V^+, V^- in cloud chambers. One difficulty with this, however, was that the Ecole Polytechnique group had looked for the neutrons interactions from $\Sigma^- \rightarrow \pi^- + n$ decay in a multiplate chamber and had found only one. Leprince-Ringuet noted that 7.5 neutron stars should have been seen if all V^- were indeed Σ^-, and if we suppose that all neutron interactions would have been observed in the 1/2-inch copper plates.

FRIEDLANDER reported on a re-evaluation of the Λ^0 Q value as measured in plates, using the presently accepted range-energy relations. The value remained the same, namely

$$36.9 \pm 0.2 \text{ Mev}$$

Either the Barkas or Baroni range-energy curve can be used without appreciable difference in this energy region.

A $_\Lambda H^3$ hyperfragment, analyzed by Brisbant and Iredale, decays in flight to $p + \pi^- + ?$. The unknown is a p or d with equally good momentum balance. The poor geometry of the event precludes a binding energy calculation. The proper time of flight was 1.3×10^{-10} sec.

DALITZ discussed the nature of the Λ^0-nucleon force as deduced by the binding energies of Λ^0 in light nuclei. The mean values of the binding energies for published events are:

$$_\Lambda H^3 = 0.3 \pm 0.2 \text{ Mev}$$
$$_\Lambda H^4 = 1.4 \pm 0.4 \text{ Mev}$$
$$_\Lambda He^4 = 1.3 \pm 0.2 \text{ Mev}$$
$$_\Lambda He^5 = 2.4 \pm 0.4 \text{ Mev}$$

In this discussion the assumption is made that the ΛP and ΛN interactions are equal. This is required for charge independence, and it is verified by comparing the binding energies of $_\Lambda H^4$ and $_\Lambda He^4$. Charge independence implies also that the Λ-nucleon force is not due to the exchange of a single π-meson but to several π-mesons or perhaps to the exchange of K-mesons and is thus short ranged. Consider now $_\Lambda He^5 = \alpha + \Lambda^0$ and write the interaction seen by the Λ^0 in the form

$$\int V(x - x') \rho (x')dx' \sim \rho(x)U,$$

where x is the position coordinate of Λ^0, and ρ is the nucleon density in the α-particle. From electron-scattering experiments, ρ has an rms radius of 1.6×10^{-13} cm, which is much larger than the expected range of the Λ-nucleon force. Therefore, the integral above can be approximated by the right-hand side, where U is the volume integral of the interaction potential V. One can calculate U, using the experimental shape and range of ρ, and obtains

$$U_{\alpha\text{-particle}} = 690 \text{ (Mev} \times 10^{-39} \text{ cm}^3).$$

The same calculation is repeated for $_\Lambda He^4$, in which ρ for the triton is taken to be the same shape (Gaussian) as for the α-particle with an rms radius chosen to give the observed coulomb energy difference between H_3 and He_3 nuclei. One then obtains

$$U_{triton} = 730.$$

Now the pair of coupled protons in H^3 should have an interaction with Λ^0 equal to half that for the α-particle. The interaction between Λ^0 and the odd nucleon in H^3 is thus given by

$$U_{\text{odd nucleon}} = U_{\text{triton}} - \frac{1}{2} U_{\alpha\text{-particle}} = 380.$$

On the other hand, the mean Λ^o-nucleon interaction, averaged over spin orientation, is just $\frac{1}{4} U_{\alpha\text{-particle}}$, since the α-particle represents a spin-saturated configuration:

$$\overline{U} = \frac{1}{4} U_{\alpha\text{-particle}} = 168.$$

Comparing this with $U_{\text{odd-nucleon}}$, one concludes that the Λ^o-nucleon force has a rather strong spin dependence. To exhibit this fact, one can write

$$\overline{U} = \frac{S + 1}{2S + 1} U_p + \frac{S}{2S + 1} U_a$$

where S is the spin of Λ^o, and U_p, U_a are respectively the interactions for spin parallel and anti-parallel states of the Λ^o-nucleon system. The separate magnitudes of U_p and U_a can be deduced when it is known which spin orientation gives the strongest attraction (which is, of course, equal to $U_{\text{odd nucleon}}$ above): Consideration of the ${}_\Lambda H^4$ - ${}_\Lambda He^4$ doublet will give us information on this point (see below).

As a check on the conclusions reached above, one considers next hyper-tritium, ${}_\Lambda H^3 = H^2 + \Lambda^o$. The situation here is more delicate because of the possible distortion of H^2 by Λ^o. A calculation with Hulthén wave functions for the deuteron gives

$$U_{\text{deuteron}} = 640 \text{ (without distortion)}$$

which is reduced by distortion effects to the value

$$U_{\text{deuteron}} = 580 \text{ (with distortion).}$$

However, the experimental radius for the deuteron is larger than that given by Hulthén wave functions, which did not take into account the repulsive core between the nucleons. This means the deuteron radius used in this calculation is too small, and a better calculation may yet increase $U_{deuteron}$ to bring it into agreement with 2 $U_{odd-nucleon}$ (as we would like). The thing to be emphasized in this preliminary work is that in each case one is led to the conclusion of a strongly spin dependent Λ^0-nucleon force.

The next clue for the Λ^0-nucleon force comes from the disintegration ${}_\Lambda H^4 \rightarrow \pi^- + \alpha$. The spin parity possibilities for the (${}_\Lambda H^4$, ${}_\Lambda He^4$) doublet are 0^-, 1^+, 2^-, etc. If we could determine the spin of the ${}_\Lambda H^4$ state we would know the Λ parity. Conversely, if we assume a certain spin-parity for Λ then the spin-parity for the ${}_\Lambda H^4$ system can be deduced. As an illustration, assume that Λ^0 has the spin-parity $(1/2)^+$; then ${}_\Lambda H^4$ would be 1^+. This would mean that in ${}_\Lambda H^4$, the spin of the odd nucleon is parallel to that of Λ^0, i.e., $U_p = U_{odd-nucleon} = 380$. One then finds, from the expression for $\overline{U}$, $U_a = -480$, i.e., $U_p \gg U_a$. One also concludes that the spin-parity for ${}_\Lambda H^3$ is $(3/2)^+$. In this manner, the spin-parity for ${}_\Lambda H^4$ and ${}_\Lambda H^3$ is determined for each assignment of the spin-parity of Λ^0. Therefore, an indirect test for the validity of any spin-parity assignment of Λ^0 is furnished by such reactions as

$$K^- + He^4 \rightarrow {}_\Lambda H^4 + \pi^0,$$

through a measurement of the correlation between the decay of ${}_\Lambda H^4$ with the direction of its production.

KARPLUS reported an investigation of Ruderman and Karplus on the spin of Λ^o. This is similar to considerations made by Primakoff which follows. Karplus and Rudermann consider the competition of the two schemes of decay

$$\underline{A} \qquad \Lambda^o \rightarrow p + \pi$$
$$\underline{B} \qquad p + \Lambda^o \rightarrow p + n$$

The second process can be considered as a two step process, namely

$$p + \Lambda^o \rightarrow p + p + (\pi) \text{ virtual} \rightarrow p + n.$$

Suppose in A that the π-meson carries away an angular momentum ℓ. Then the dependence of the decay rate on ℓ is given by $q^{2\ell}$ where q is the meson momentum. In B p + n must also be in a state of relative angular momentum ℓ; hence the ℓ-dependence of the rate of this reaction is given by $k^{2\ell}$ where k is the relative momentum of the nucleons. Thus the ratio, R of the rates B to A is

$$R = \frac{\text{Rate B}}{\text{Rate A}} = C\left(\frac{k}{q}\right)^{2\ell}.$$

Now $(k/q) \sim 4$; hence $(k/q)^{2\ell} \sim 17^{\ell}$, which is fairly large. The constant C above does not depend upon the Λ^o interaction constant, since it appears as a factor in both A and B. It does, however, depend upon the interaction of the π-meson with the proton, for which the Chew non-relativistic pseudoscalar theory was used. It also depends upon the density of protons which are available for capturing the pion. Furthermore, the binding energy of the Λ^o (for H and He) is small; hence the Λ^o spends an appreciable time outside the nucleus. This reduces further the probability of the virtual process. Taking all these points into account C was calculated, and the following Table V was constructed, where E_b is the binding energy in Mev. Now E_b in H and He is about 1 Mev, and the ratio R is about 1 in He (see results of Fry). This suggests $\ell = 0$; however, $\ell = 1$ cannot be excluded since the evaluation of C was not sufficiently precise. Thus the conclusion is that $\ell = 0, 1$ are allowed and the Λ^o can have $(1/2)^-$ or $(1/2)^+$, $(3/2)^+$ as spin and parity. One important assumption involved in the evaluation is that the radius of the Λ^o is small compared to the distance over which the angular momentum barrier extends. The Λ^o must have a radius larger than 2 or 3×10^{-13} cm to invalidate the assumption. This work has appeared in Phys. Rev. 102, 247 (1956). This evidence, together with that presented by Primakoff (see following report), makes $(1/2)^-$ most likely for the spin and parity of Λ^o.

	R
0	$0.4\ E_b^{-1/2}$
1	$6.8\ E_b^{-1/2}$
2	$120\ E_b^{-1/2}$
3	$2000\ E_b^{-1/2}$

Table V

PRIMAKOFF next presented his work on the ratio of the mesonic and non-mesonic decay rates of hyperfragments. He is mainly interested in the dependence of this ratio R^{-1}, in the same notation as that used in the previous paper by Karplus, on the mass number A and atomic number Z of the hyperfragment. Let τ_A be the mean life of a bound hyperon for mesonic decay, and τ_B the corresponding mean life for non-mesonic decay. Then

$$R = \frac{1/\tau_B}{1/\tau_A}\,\frac{1}{\rho}$$

where $\mathcal{P}$ is the probability for a real pion, upon emission by the Λ^0, actually emerging from the fragment. In the range $3 \leq A \lesssim 20$, $\mathcal{P}$ is approximately unity. Earlier work by Cheston and Primakoff (Phys. Rev. 92, 1537 (1953)) has shown that

$$1/\tau_B = A\ K(A,Z)\ (1/\tau_0)$$

where τ_0 is the mean life for the mesonic decay of a free Λ^0, and $K(A,Z)$ is a function which increases rapidly with A in the region $3 < A \leqq 7$ and then remains approximately constant. In fact, from $A = 3$ to $A > 6$, $K(A,Z)$ increases by a factor of about 5. In the work of Cheston and Primakoff, the assumption was made that $1/\tau_A \approx 1/\tau_0$, with the result that R increases with A essentially like A K(A,Z). Recent experimental results show, however, that R increases with A much more rapidly than that. A re-examination of the earlier work shows that the assumption $1/\tau_A \approx 1/\tau_0$ is unwarranted. In fact, one can see that $1/\tau_A$ should decrease with increasing A, due to the inhibition of the Pauli exclusion principle against emission into the residual nucleus of the relatively low momentum protons arising from bound-$\Lambda^0 \rightarrow p + \pi^-$. The Pauli inhibition factor I(A,Z) is introduced by writing

$$1/\tau_A \doteq I(A,Z)\ (1/\tau_0).$$

Consequently,

$$R = \frac{A\ K(A,Z)}{I(A,Z)}.$$

It is clear that I(A,Z) decreases rapidly with A, and a rough calculation fitted to the experimental binding energies of the hyperfragments, yields the result that

$$I \approx 1 \text{ for } A = 3 \text{ or } 4,\ Z = 1,$$

$$I \approx 0.05 \text{ for heavier hyperfragments.}$$

On this basis, one can expect R to increase by a factor of some 200-400 between A = 3, Z = 1 and, say, A - 12, Z = 6, and further one can expect that the mean life, $\tau = (1/\tau_B + 1/\tau_A)^{-1}$, of the hyperfragments should be roughly independent of A, Z. A similar inhibition effect due to the Pauli principle also occurs in the capture of negative mesons by nuclei, i.e., $\mu^- + p \rightarrow n + \nu$. Details are in press in Nuovo Cimento.