Session VI

STRANGE PARTICLE INTERACTIONS

Chairman: C. C. Butler

ALVAREZ: Introductory talk.

I will just talk about the material published in the last year, which is new, and by published I mean in preprint form. Every year at Rochester there is a compilation of the latest dope on the various strange particles, masses, life times and such things. This appears in Table 1 and takes us up to April of this year. Note that the mass is tabulated in Mev rather than in electron masses which has been the custom in the past. Table 1 is essentially self-explanatory. The starred data have not changed and come directly from the compilation of Cohen, Crowe and DuMond. Since almost everyone would agree that the mass difference of the various $K^{\pm}$ particles is so small that it will never be found by any of the methods normally associated with nuclear physics, we might as well just have one K mass and take that directly from the τ meson which involves just the Q of the reaction plus the known π-meson masses. That is what (a) in Table 1 means. The K^0 mass is the measured value of the θ_1^0 and comes from Thompson's cloud chamber work. The Σ^+, Σ^- mass difference which was first announced at the meeting last year, has held up and it seems to be here to stay. The Σ^0 was missing from the list last year, and thus was one of the holes in the Gell-Mann and Nishijima scheme which had not been filled out. It has been identified now by two different groups, the bubble chamber group at Berkeley and the Steinberger group, using different reactions, and both agree on the mass value. All of the Ξ^-'s seen so far have come from cosmic rays and none yet from the accelerators. Ξ^0 has not been seen. The bevatron conked out on us when we should have had about 1/4 of a Ξ

There are only a few comments about the lifetimes. The only change in a lifetime is of a non-strange particle, which incidentally came from work with strange particles. This is Orear's very pretty job on the limits of the lifetime of the π^0 from the decay of the $K_{\pi 2}$, in which the π^0 gives rise to a Dalitz pair. The result on the lifetime of the K^+ comes from the counter work at Berkeley of Crawford, Good, and Stevenson, and it agrees well with the previous results which we had and the more accurate results which Fitch and Motley had last year. It is based largely on the $K_{\mu 2}$'s although the τ's and $K_{\pi 2}$'s

Masses and Lifetimes of Elementary Particles

	Particle	Spin	Mass (Errors represent standard deviation) (Mev)		Mass difference (Mev)	Mean life (sec)		Decay rate (number per second)
Photons	γ	1	0.00			stable		0.0
Leptons and anti-leptons	ν, $\bar{\nu}$	1/2	0.00			stable		0.0
	e^-, e^+	1/2	0.510976	*		stable		0.0
	μ^-, μ^+	1/2	105.70 ± 0.06	*		$(2.22 \pm 0.02) \times 10^{-6}$	*	4.5×10^5
Mesons	$\pi^\pm$	0	139.63 ± 0.06	*	4.6 *	$(2.56 \pm 0.05) \times 10^{-8}$	*	0.39×10^8
	π^0	0	135.04 ± 0.16	*		$(0.0 < \tau < 0.4) \times 10^{-15}$	(O)	$> 2.5 \times 10^{-15}$
	$K^\pm$	0	494.0 ± 0.14	(a)	1 ± 5	$(1.224 \pm .013) \times 10^{-8}$	(b)	0.815×10^8
						K_1: $(0.95 \pm .08) \times 10^{-10}$	(P)	1.05×10^{10}
	K^0	0	493 ± 5	(Th)		K_2: $(3 < \tau < 100) \times 10^{-8}$	(L)(P)	$(> 0.1, < 3) \times 10^8$
Baryons†	p	1/2	938.213 ± 0.01	*		stable		0.0
	n	1/2	939.506 ± 0.01	*		$(1.04 \pm 0.13) \times 10^{+3}$	*	0.96×10^{-3}
	Λ	1/2 ?	1115.0 ± 0.16	(c)		$(2.77 \pm 0.15) \times 10^{-10}$	(d)	0.36×10^{10}
	Σ^+	1/2 ?	1189.30 ± 0.3	(W)	7.20 ± 0.1	$(0.78 \pm .074) \times 10^{-10}$	(e)	1.28×10^{10}
	Σ^-	1/2 ?	1196.50 ± 0.5	(W)	8.3^{+3}_{-2}	$(1.58 \pm .17) \times 10^{-10}$	(f)	0.64×10^{10}
	Σ^0	1/2 ?	1188.50^{+3}_{-2}	(g)		$(< 1) \times 10^{-11}$	(A)	$> 10 \times 10^{10}$
	Ξ^-	?	1321 ± 3.5	*		$(4.6 < \tau < 200) \times 10^{-10}$	(Tr)	$(> 0.005, < 0.2) \times 10^{10}$
	Ξ^0	?	?			?		

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*From compilations by Cohen, Crowe, and DuMond, Nuovo cimento 5, 541 (1957), and "Fundamental Constants of Physics," to be published by Interscience, New York, 1957. They include all data available before January 1, 1957.

†Antibaryons have the same spin, mass, and mean life as baryons.

(A) Alvarez, Bradner, Falk-Vairant, Gow, Rosenfeld, Solmitz, and Tripp, K Interactions in Hydrogen, UCRL-3775, May 1957.
(L) Lande, Booth, Impeduglia, Lederman, and Chinowsky, Phys. Rev. 103, 1901 (1956).
(O) Orear, Harris, and Taylor, Bull. Am. Phys. Soc. 1126 (1957).
(P) Plano, Samios, Schwartz, and Steinberger, Phys. Rev. (to be published) 1957.
(Th) Thompson, Burwell, and Huggett, Supplemento 3 Nuovo cimento 4, 286 (1956).
(Tr) G.H. Trilling and G. Neugebauer, Phys. Rev. 104, 1688 (1956).
(W) R. S. White, compilation of all emulsion data available from all laboratories, prepared for 7th Rochester Conference (private communication).

(a) $M_{K^\pm} = 3M_{\pi^\pm} + Q_\tau$, where Q_τ is the weighted average from Heckman, Smith, and Barkas, Nuovo cimento 4, 51 (56); from Roy Haddock, Nuovo cimento 4, 240 (56); and from Bacchella, Berthelot, et al., Nuovo cimento 4, 1529 (56). We have assumed that the K^- is the antiparticle of the K^+ and shares the same mass and lifetime. The present experimental mass of the K^- is consistent with this assumption, namely 493.4 ± 0.5 Mev (White, 1957).

(b) Weighted average of
1.227 ± 0.015 (Alvarez, Crawford, Good, and Stevenson, Phys. Rev. (to be published)).
1.211 ±0.026 (V. Fitch and R. Motley, Phys. Rev. 101, 496 (1956); Phys. Rev. 105, 265 (1957); and private communication.) The quoted errors are statistical only.

(c) Weighted average of
1114.82 ± 0.18 *
1115.74 ± 0.4 (R. Armenteros, report at 7th Rochester Conference, private communication).

(d) Weighted average of
1.9 ± 0.4 (Graves, Brown, Glaser, and Perl, Bull. Am. Phys. Soc. 2, 221 (1957)).
2.77 ± 0.2 (Eisler, Plano, Samios, Steinberger, and Schwartz, Bull. Am. Phys. Soc. 2, 221 (1957)).
3.1 ± 0.5 (A)
3.25 ± 0.33 *

(e) Weighted average of
0.95 ± 0.30 (Graves, Brown, Glaser, and Perl, Bull. Am. Phys. Soc. 2, 221 (1957)).
0.69 ± 0.1 (A)
0.89 ± 0.12 (compilation of all emulsion data available from all laboratories, prepared for 7th Rochester Conference by G. Snow (private communication)).

(f) Weighted average of
1.5 ± 0.35 (Eisler, Plano, Samios, Steinberger, and Schwartz, Bull. Am. Phys. Soc. 2, 221 (1957)).
1.6 ± 0.2 (A)

(g) Combined result from Alvarez et al., K^- Interactions in Hydrogen, UCRL-3583, Nov. 1956, and a private communication from M. Schwartz and R. Plano giving Q=73.5±3.5 for $\Sigma^0 \rightarrow \Lambda + \gamma + Q$. We have assumed that the K^- is the antiparticle of the K^+ and shares the same mean life. The present experimental mean life is consistent with this assumption, namely τ_{K^-} = 1.25 ± 0.11 (W. H. Barkas, Seventh Rochester Conference).

are in as well. The K_1 lifetime has come down a bit according to the work of the Steinberger bubble chamber group. The K_2 particle is pinned down this year for the first time by Lande, and his cloud chamber group at Brookhaven. Everyone now believes that there is a longlived anomalously decaying θ which is identified with the θ_2 of the Gell-Mann scheme. The lower limit on the K_2 lifetime comes from the fact that in the propane bubble chamber of Steinberger and Company no anomalous decays were seen, which means that the lifetime should be greater than some number which turns out to be about twice the lifetime of the positive K. The upper limit comes from the Brookhaven work where they did see these particles in a cloud chamber and if the lifetime were too long they wouldn't have seen any. The Λ lifetime hasn't changed appreciably. It is based on a compilation of data from our bubble chamber group at Berkeley and Steinberger's bubble chamber group. The Σ^0 lifetime is sort of a ridiculous thing to show because it certainly is 10^{10} times smaller than the cited value, but this is the limit you can set experimentally. So, all of the spaces in the Gell-Mann, Nishijima table have been filled except for the Ξ^0 In the past year the Σ^0 was identified, $\bar{\theta}_0$ was seen by charge exchange from K^- in hydrogen, the θ_2 was identified and the τ^0 has also been seen by Lederman and perhaps by others. Also, all the reasonable modes of decay of the charged K have been seen except the K_{e2} ($K \rightarrow e + \nu$) but that mode is also missing in the π decay. So, although it is not understood why it is missing there, it is also missing for probably the same reason in the K decay. And the decay mode $K^+ \longrightarrow \pi^+ + \gamma$ is also missing which indicates that the spin of the K is 0, since $0 \longrightarrow 0$ transitions are forbidden.

Now I am going to speak about K scattering, and first comes K^+ scattering on protons. Most of this data comes from the emulsion work done in the last few months, and also the propane bubble chamber of the Michigan group of Glaser, Meyer and Perl at Brookhaven. Fig. 1 shows the total K^+ kinetic energy. The point at 200 Mev is due to Kerth at Berkeley using counters and carbon CH_2 difference. Most of the rest of the data comes from emulsion work which has been compiled by the Goldbabers at Berkeley. I want to thank them for their slides, which include some of their own data which will not formally be reported until the Washington APS meeting next week. There is no strong indication of a variation in cross section with momentum and the cross section is about 15 mb, which is 1/4 of what is called geometric for a proton. Fig. 2 shows the angular distribution. There is not too much agreement on what the angular distribution is but it seems to be getting a little better with time. I don't

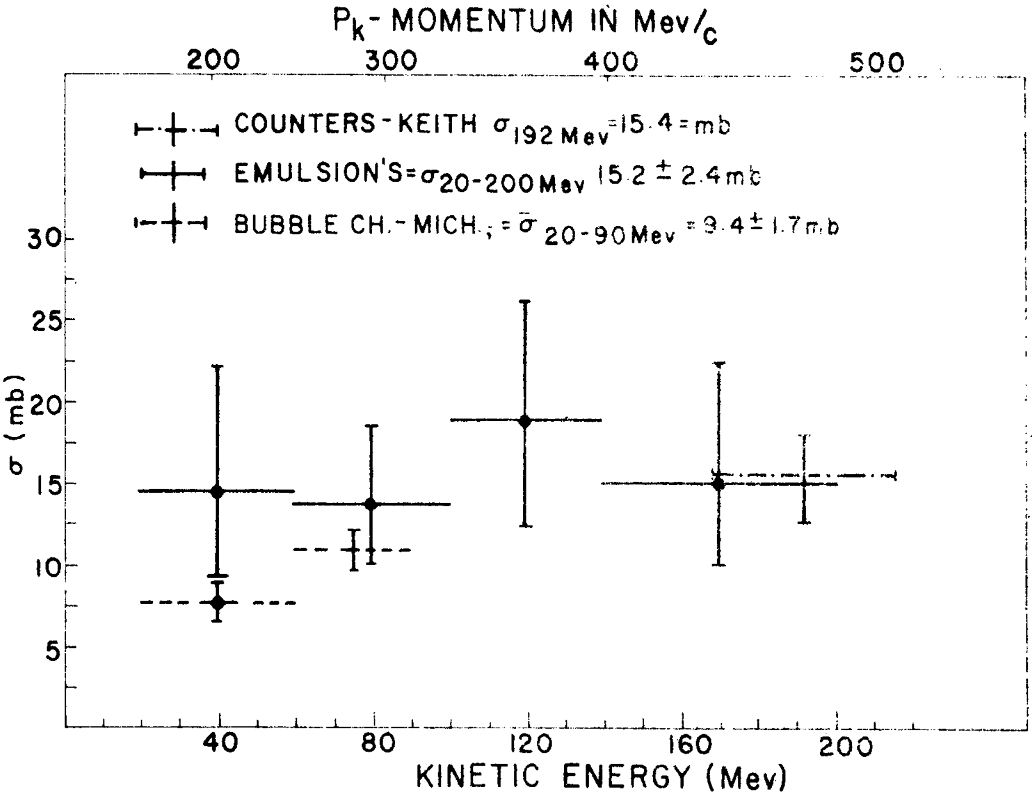
P_k - MOMENTUM IN Mev/c
200
300
400
500
COUNTERS - KEITH σ192 Mev = 15.4 = mb
EMULSION'S = σ20-200 Mev 15.2 ± 2.4 mb
BUBBLE CH. - MICH. ; = σ̄ 20-90 Mev = 9.4 ± 1.7 mb
σ (mb)
30
25
20
15
10
5
40
80
120
160
200
KINETIC ENERGY (Mev)

Fig. 1

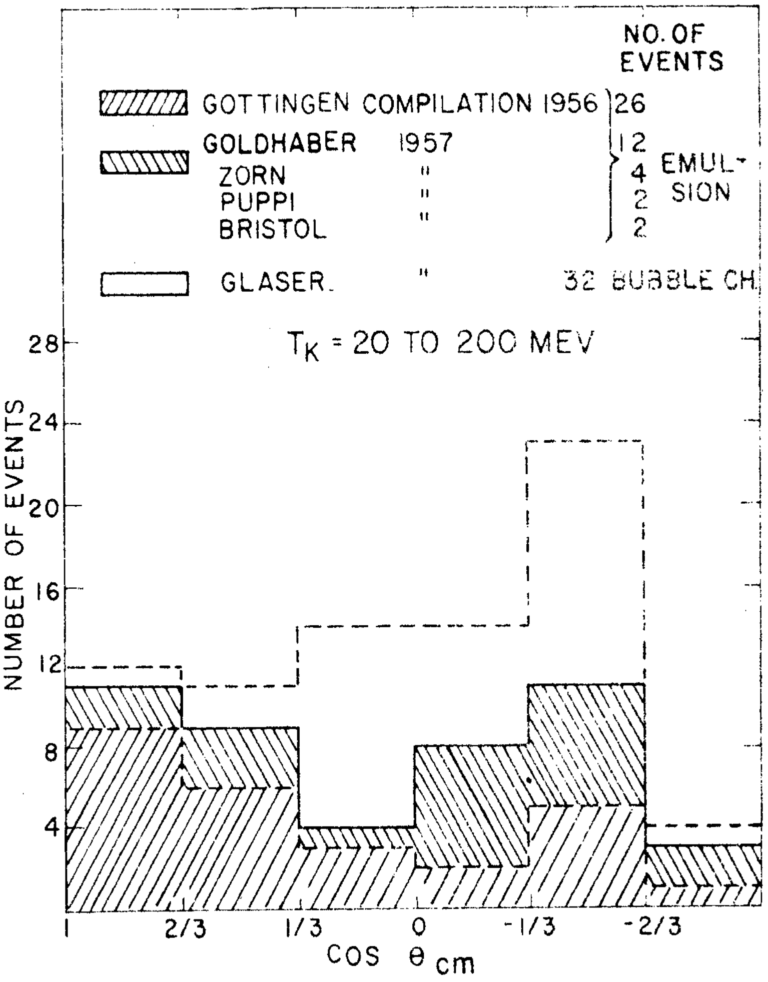
NO. OF EVENTS
▨ GOTTINGEN COMPILATION 1956 26
▧ GOLDHABER 1957 12
ZORN " 4
PUPPI " 2
BRISTOL " 2
EMULSION
☐ GLASER " 32 BUBBLE CH.
T_K = 20 TO 200 MEV
NUMBER OF EVENTS
28
24
20
16
12
8
4
1
2/3
1/3
0
-1/3
-2/3
COS θ cm

Fig. 2

think we can say too much about the angular distribution but the original emulsion data appears to be peaked forward. Glaser had it peaked a little in the backward direction, but I think at the moment it looks moderately flat. Fig. 3 is the cross section for the interaction of K^+ with all of the nuclei in emulsion. The K^+ nuclear cross section seems to rise with energy. In order to get an average cross section per nucleon, Puppi (see later) has made a calculation taking into account the Pauli principle and other effects. He gets roughly 10 mb. for the average K^+ cross section per nucleon. One of the most important things about the K^+ nuclear scattering is that one can, in principle, determine the sign of the interaction and last year Osborne presented some information on some data which favored an attractive potential between K's and nucleons. This year the fashion

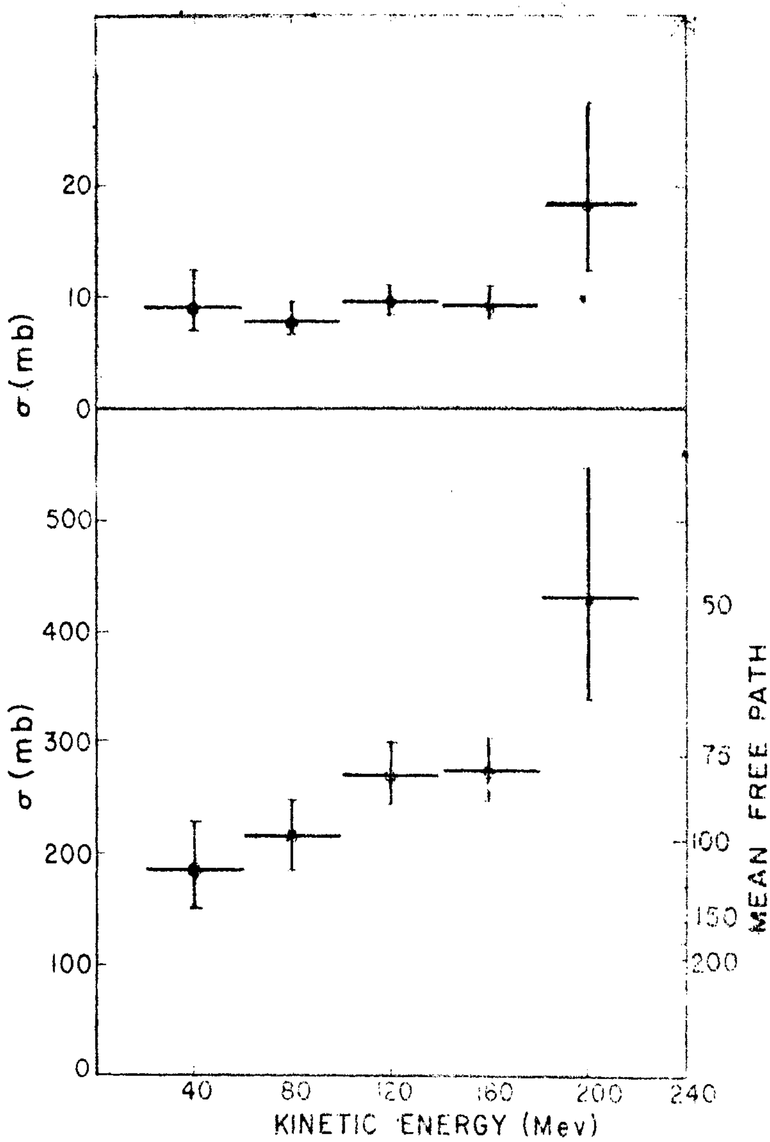

Fig. 3

is to have a repulsive one, and Puppi, I believe, will say why he believes that the potential is repulsive. I heard just yesterday that there is an event at M. I. T. which looks like a super hyperfragment with a bound K particle which may turn the thing back again to an attractive potential but we will hear more about that later. As of the moment the repulsive potential seems to be the favored one and this can give some information about the K-meson hyperon interaction. Dr. Gell-Mann has pointed out to me that if the K-meson is scalar, you can calculate uniquely that the potential should be attractive. If it is pseudoscalar you really can't tell very much. Thus if the potential between K^+ and nucleon is repulsive, one might infer that the K-meson is pseudoscalar. (Ed. note: The potential for a scalar K is attractive if one believes that perturbation theory is applicable to a scalar interaction.) From the scattering of K^+ on nuclei, one can get some information about the isotopic spin state in which the interaction is taking place. $K^+ + p$ is in a pure I = 1 state, whereas K^++n can be in both I = 1, 0 and you can have both ordinary and charge exchange scattering. The relative Clebsch-Gordon coefficients are shown in Table 2. The ratio of exchange to ordinary (for equal numbers of protons and neutrons) is also shown in Table 2. Experimental results taken from the

Table 2

	I = 1	I = 0
K^+ + p (ord)	4	0
K^+ + n (ord)	1	1
K^+ + n (exch)	1	1
$\frac{\text{(exch)}}{\text{(ord)}}$	1/5	1/1

Goldhabers' report at the Washington meeting gave (in the range 20 to 100 Mev) the ratio to be 0.16 ± .06. From 100 to 200 Mev it is 0.24 ± 0.04. Now this would make people happy with the idea that all the interaction was in the I = 1 state but I believe Dr. Puppi has reasons for doubting this and I will let him bring these up later.

For the K^- interactions the situation is more complicated because the K^- having strangeness -1 can produce all sorts of hyperons which the K^+ cannot do. There are a number of sources of information on elastic scattering of K^- on hydrogen. There are the emulsion groups of Gilbert, Violet and White at Livermore, the Goldhabers and the Barkas group at Berkeley and our work in the hydrogen bubble chamber at Berkeley. The track length scanned by the emulsion workers are: by the Goldhaber group-30 meters; Gilbert, Violet and White-30 meters; and Barkas-50 meters. The density of hydrogen in a bubble chamber is about the same as in emulsion, and the Berkeley bubble chamber photographs account for 26 meters of K^- path. The results are given in Table 3, where the cross sections are expressed in mb. The big discrepancy is the cross section for $\Sigma^+ + \Sigma^-$ production. It can be seen that below 200 Mev/c the bubble chamber and emulsion results do not agree.

Table 3

Cross Section for Interaction of K^- on protons.

Momentum of K^- (Mev/c)	Elastic Scattering	$\Sigma^+ + \Sigma^-$ Production	Total
50 -200 (bubble chamber)	42 ± 22	92 ± 31	
100-175 (emulsion)	53 ± 22	18 ± 10	
170-415 (emulsion)	$48 {}^{+15}_{-11}$	$11.4 {}^{+9}_{-5}$	
900 (antiproton group)	--	--	52 ± 9

The antiproton group consists of Piccioni, Cook, Wenzel and Lambertson. Their result was obtained using a hydrogen target. Now there is no analysis of the K^- scattering, elastic and inelastic, comparable to what we have for the K^+ just because things are too complicated. Also I might remind you that there is no simple isotopic spin connection between the K^-, nucleon and the K^+, nucleon scattering because K^- and K^+ are anti-particles. The simple relationships would hold for K^+, anti-nucleon if you knew them for K^-, nucleon.

Next comes hyperon production in $K^- + p$ interactions. All of the hyperons that were made in flight are listed in the exchange scattering in Table 3. So, let us turn to $K^- + p$ interactions at rest. Most of the results come from the hydrogen bubble chamber. Last year, based on 137 K^- going through the chamber, the production ratios for Σ^- : Σ^0 : Σ^+ : Λ^0 were 4: 2: 2: 1. This is old. Now we have more than doubled our data and the ratios now read 4: 2: 2: 1/2.

Now if we look for the isotopic spin dependence in the Σ-production, the Clebsch-Gordon coefficients give for the $\Sigma^- : \Sigma^0 : \Sigma^+$ in the I = 1 state the ratios 1: 0: 1 and for the I = 0 state the ratios 1: 1: 1. Thus the production is in a mixture of states. Based on the same assumptions we made last year you can get a value for the ratios of the matrix elements. We write

$$\frac{M_{I=1}}{M_{I=0}} = r\,e^{i\varphi}$$

and assume all K's are captured from s-states. This gives $r = .8$ and $\varphi = \pm 70^{o}$. Now this seems to bother our theoretical friends. They said this is much too big a phase angle and you can get out of this very easily by just saying that the K is captured in an s or p-state, and then the analysis is no good. So we can't say anything except that you don't have to believe this result if you don't want to.

Next, the spins of the hyperons. Treiman showed that if the spin of the hyperon is greater than 1/2, the Σ (in a reaction such as $K^- + p \rightarrow \Sigma^- + \pi^+$) would be polarized pretty much at right angles to its direction of flight. So when the Σ decays, you get more decays in the polar region than you do at the equator. And when we analyzed our first data we found, indeed, this was the case. It wasn't too believable by itself, but Fry wrote that he had exactly the same distribution from about the same number of events in emulsion and so each of us got a little extra confidence from the other's work and we said we thought that the chances were good that the spin of the Σ was greater than 1/2. Now we have each doubled our data and the second time around the distribution is quite flat and so as far as the experimental data are concerned nobody has to worry about the spin of the Σ being greater than 1/2. In fact it looks as though the spins of all of the fermions are 1/2 and of the bosons, 0.

Parity doublets could lead to a distribution which was not symmetrical when folded. We looked for that and didn't find it. However, parity doubling does not necessarily lead to an asymmetrical distribution. The absence of two Σ lifetimes also casts doubt on parity doubling.

Next, I want to say a few words about the selection rule $\Delta I = \pm 1/2$ in weak decays. This was talked about sometime ago and was originally proposed to account for the fact that the charged K decays 400 times more slowly than the neutral K. This rule predicts

$$\alpha_{\theta_1} \equiv \frac{\text{rate of } \theta_1 \rightarrow 2\pi^0}{\text{rate of } \theta_1 \rightarrow \pi^+ + \pi^-} = \frac{1}{3}$$

Experimentally (from Steinberger et al) $\alpha_{\theta_1} = 0.14 \pm .06$ which is not consistent with 1/3. In order to fix it up you have to add in not only $\Delta I = \pm 3/2$ but also some $\Delta I = \pm 5/2$ and then it gets sort of ridiculous as a rule. For the Λ, the prediction is $\alpha_\Lambda = 1/3$ which is also the measured value. Also in the case of the Σ hyperon, you can connect the lifetime ratio $\tau_{\Sigma^-}/\tau_{\Sigma^+}$ to the branching ratio $(\Sigma^+ \rightarrow \pi^+ + n)/(\Sigma^+ \rightarrow \pi^0 + p)$ if the Σ has a well defined spin and parity. But again the results are inconsistent. You can try to fix it up by saying that parity is not a good quantum number.

Now let's talk about the Pais-Piccioni phenomena. This has to do with the θ's as particle mixtures. When they interact they behave like θ_0 and $\bar{\theta}_0$. When they decay they behave as θ_1's or θ_2's. Each type can be thought of as consisting of two of the other kind with proper phase relations. Last year there was only one bit of information which was not very strong. But, in the past year the work has been done in several places, both in bubble chambers and in emulsions. The bubble chamber work is by Fowler, Lander and Powell, at Berkeley, and they have seen 10 Λ's and 11 θ_1's. The emulsion work was done at NRL by Glasser and Seeman, at Wisconsin by Fry, Schneps and Swami, and also at Padua and Milan. There they see only the charged particles coming from stars produced presumably by the $\bar{\theta}_0$ component of θ_2. At NRL they have seen one Σ^+ and one hyperfragment. At Wisconsin they have seen 4 cases unspecified to me, and Padua and Milan have seen 8 Σ's, both plus and minus and one K^-. Two other groups have also seen τ's. I believe that the group at the Fermi institute has seen 3 τ's. So the Pais-Piccioni phenomena seem to be in good shape. The Gell-Mann, Pais particle mixture seems to be well confirmed. There was a while when there was a big flap in the business a few months ago when parity and charge conjugation seemed to be on their way out. It looked as though the particle mixture theory was not going to be true but it does seem to be almost true in the way it was originally stated.

I want to say one thing about hyperfragments, in that they give a value for the spin of the Λ. You will remember that last year Karplus and Ruderman showed results of an analysis in which they deduced that the spin of the Λ was either 1/2 or 3/2. What they actually work with is the intrinsic orbital angular momentum ℓ of the π^-, p products in the Λ rest system, and they said this could be either 0 to 1. In their analysis they were influenced by the experiments out at Brookhaven which showed that there was a strong angular correlation between the production planes and the decay planes of the Λ. What Karplus and Ruderman did was to look at the ratio of the mesonic to the non-mesonic decays of hyperfragments using a kind of internal conversion theory, and since they were trying to see how high a spin would be consistent with the data, every time they came to an experimental point or theoretical point they shaded it in such a direction as to raise the spin. Now that we don't believe in these high angular correlations, one can do the analysis in a more relaxed way and just say what is the most probable value to put in the theory or the experiment. The results one gets for Q (the ratio of non-mesonic to the mesonic decays) for helium hyper-fragments, for $\ell = 0$ is 1 and for $\ell = 1$, Q should be 18. The experimental value for Q is approximately 1.5 to 2. So the spin of the Λ seems to be 1/2 and everything is getting more reasonable in the spin department.

DISCUSSION

LEWIS: In connection with your point about the lifetime of the Σ^0 being as small as 10^{-21} sec, I should like to point out that we are coming near to measuring this lifetime, since the uncertainty principle tells us that the uncertainty in the Σ^0 mass will give us the Σ^0 lifetime. For this lifetime, the mass uncertainty will be of the order of Mev.

ALVAREZ: That's a good thing to point out and also since the π^0 lifetime is getting smaller, we might hope to measure it by finding the uncertainty in its mass.

PANOFSKY: I'd like to point out that the angular correlation of the 2 γ's in the π^0 decay has been looked at and there is no uncertainty principle effect.

RITSON: Osborne at M. I. T. has looked at the inverse reaction $\gamma + \gamma \longrightarrow \pi^0$ and can put a lower limit of 10^{-19} sec on the lifetime.

TELEGDI: I want to make a comment about the ratio of non-mesonic to mesonic decays in hyperfragment decays. There is not much well established data on non-mesonic decays since they are difficult to pin down. (Ed. note: See Telegdi's talk in the Thursday P. M. session as to why only limited reliable information can be extracted from non-mesonic decays.) We feel that in view of the inhomogeneous character of the reported data on non-mesonic decays an estimate of the non-mesonic to mesonic branching ratio does not appear to be profitable.

KARPLUS: The evidence from the heavier hyperfragments also seems to bear out the $\ell = 0$ orbital state in the Λ -decay.

GATTO: I wish to point out that because of parity non-conservation you would expect some contribution from the $\ell = 1$ state.

BARKAS: K^- interactions in flight.

The results which I'll discuss come from quite a number of laboratories and there are really an enormous number of people involved. The bulk of the work is from the K-stack collaboration in Europe, Göttingen, Rochester, Naval Research Laboratory, Livermore and Berkeley. Most of this work resulted from a single bevatron experiment last fall and Fig. 4 shows the set-up in obtaining the K^- mesons. The 4" quadrupole focuses the beam upon a degrader which reduces the momentum

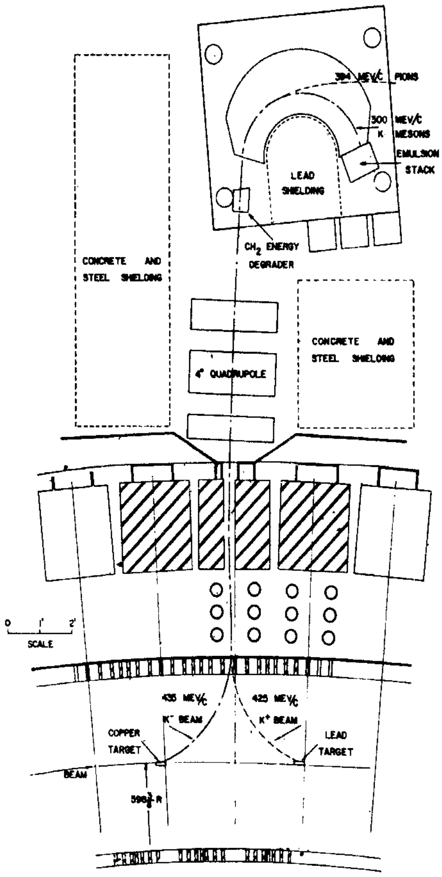

Fig. 4

of both the π's and K's but the K's by a greater amount. Then bending the beam through 180° by means of a very powerful magnet we catch the K's in the emulsion but not the π's. The momentum of the K's is (300 + 10 or 20) Mev/c. With this arrangement, about 10,000 K meson tracks have been followed.

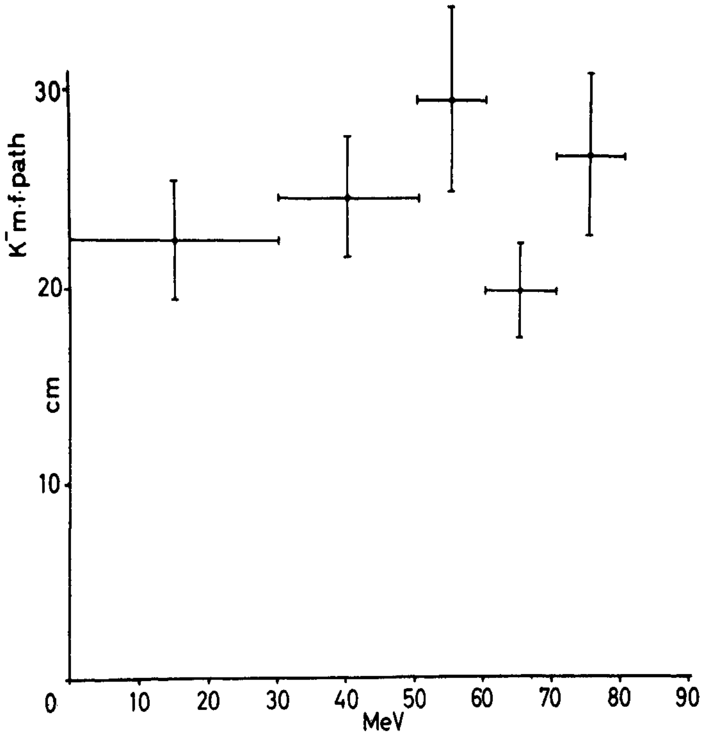

Fig. 5

Fig. 5 shows how the mean free path for interaction varies with energy. (This comes from Göttingen.) You may recall that the geometrical mean free path in emulsion is about 27 cm.

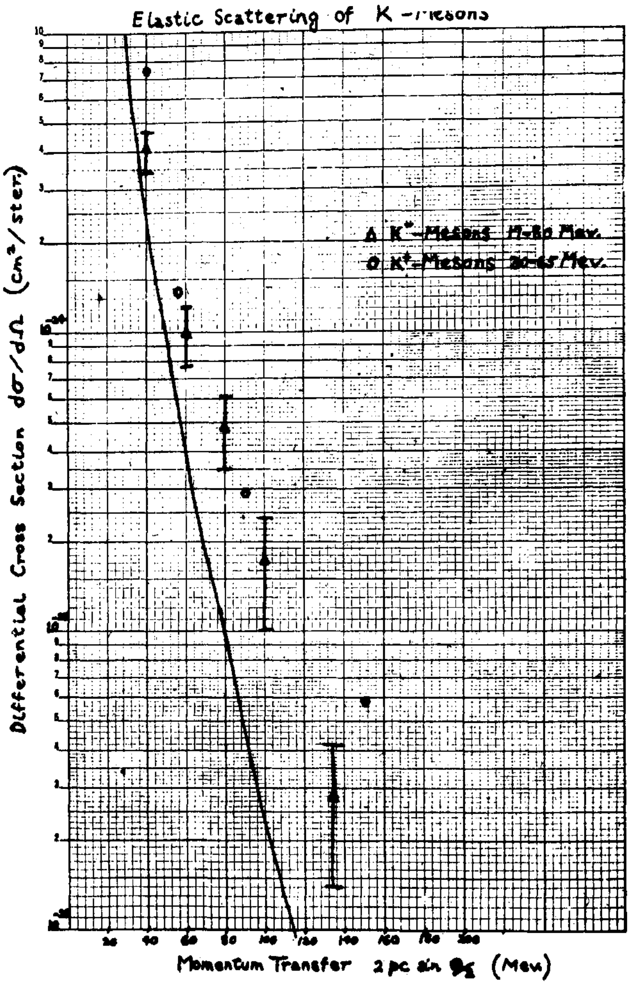

Fig. 6

Fig. 6 shows the elastic scattering of the K^- as they penetrate the emulsion. For comparison some K^+ data are included and the curve is Coulomb scattering from a nucleus of finite size.

Fig. 7 shows the K⁻ inelastic scattering which occurs in about 5% of the cases. Δ E is the energy loss of the K⁻ and notice that when the K⁻ enters the nucleus it loses quite a bit of energy.

One interesting point is that in the 10,000 events seen we get about one capture on free hydrogen per 350 captures at rest.

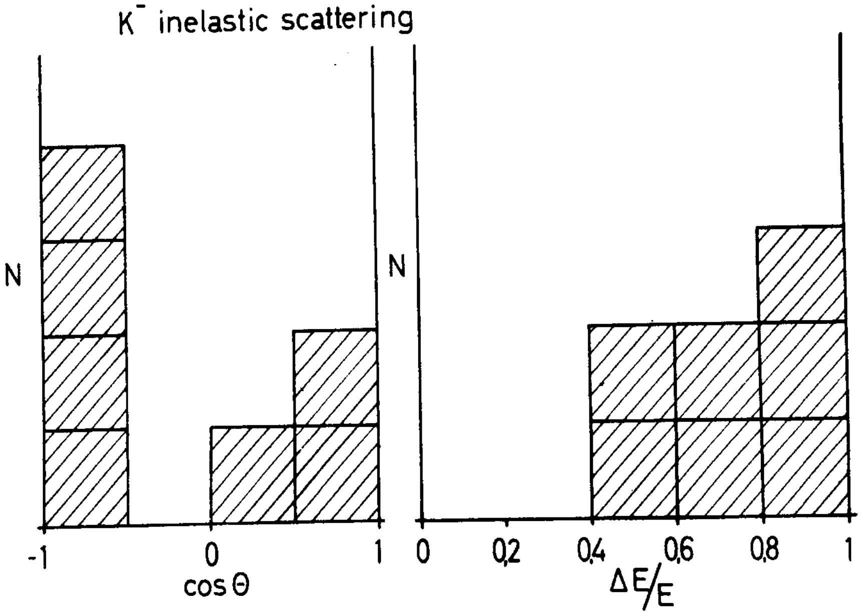

Fig. 7

Table 4 gives the mean free path in emulsion as determined in Berkeley.

Table 4

Energy in Mev	Mean Free Path in Cm
30 - 52	23.5 ± 2.5
52 - 69	22.4 ± 2.3
69 - 83	19.5 ± 2.1

These results seem to indicate a rather large cross section.

CECCARELLI: K^- interactions on free protons.

I will summarize the data on the interaction in flight of K^- mesons on free protons which was collected by the groups mentioned by Dr. Barkas. These events are separated into the two classes, elastic scattering $K^- + p \longrightarrow K^- + p$ and capture, $K^- + p \longrightarrow \pi^\pm + \Sigma^\mp$. Of course, in emulsion, we cannot detect the reactions leading to neutral particles.

Fig. 8 shows the results for these reactions as a function of energy. Reasonable estimates for the reactions leading to Σ^0 or Λ^0 would perhaps double the capture cross section. These results are in bad disagreement with the bubble chamber results presented by Alvarez. At the higher energies the ratio of elastic scattering to capture is about 5 to 1 or perhaps 5 to 2 if we include an estimate for the Σ^0 and Λ^0 production. Fig. 9 shows the angular distributions for these reactions averaged over energy. They seem to be flat.

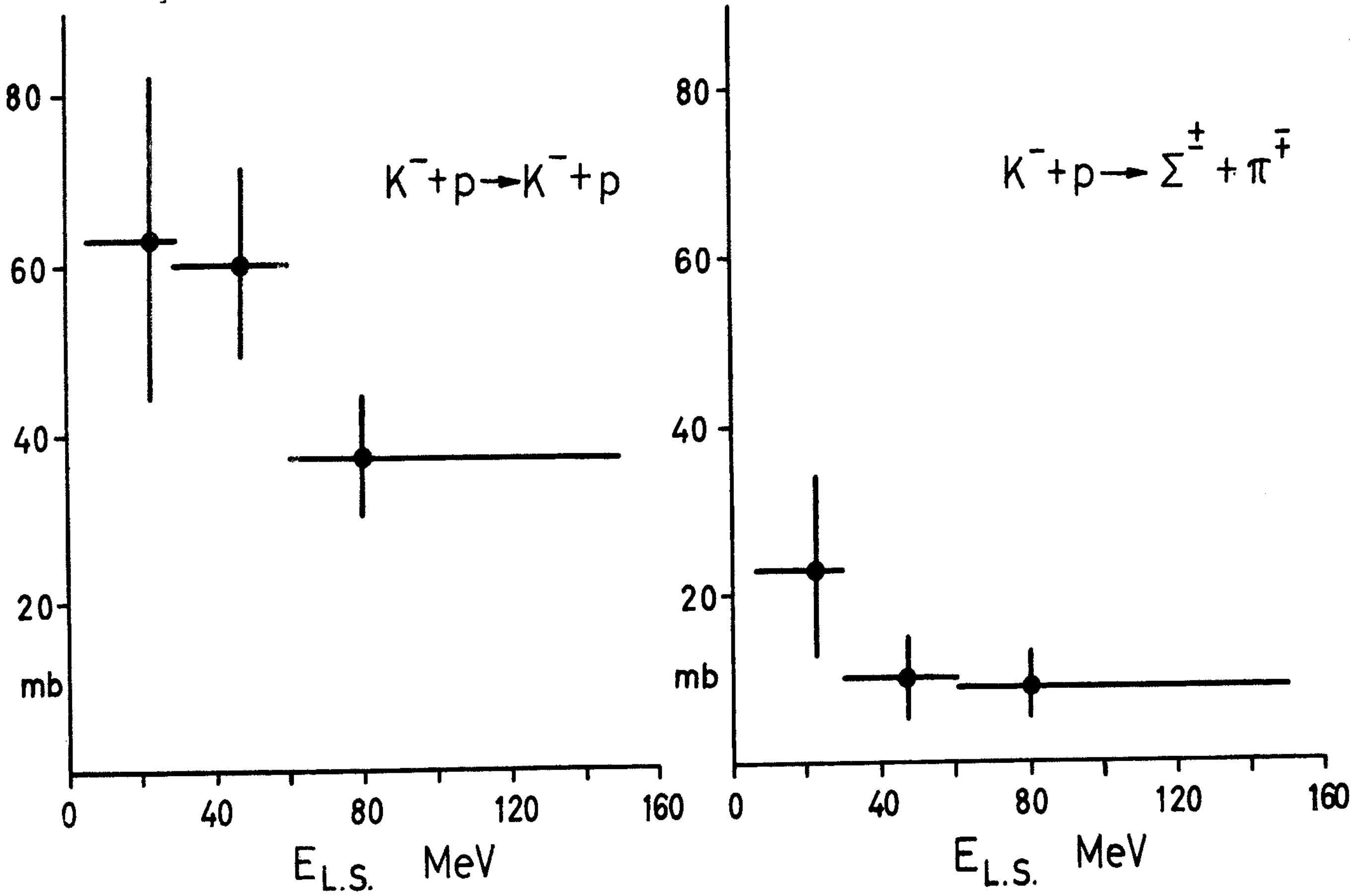

Fig. 8

Brookhaven 2 events
Berkeley (Barkas) 13 events
Berkeley (Goldhaber) 2 events
Europe Collab. 12 events

Göttingen group 22 events
Livermore group 11 events
Rochester group 7 events

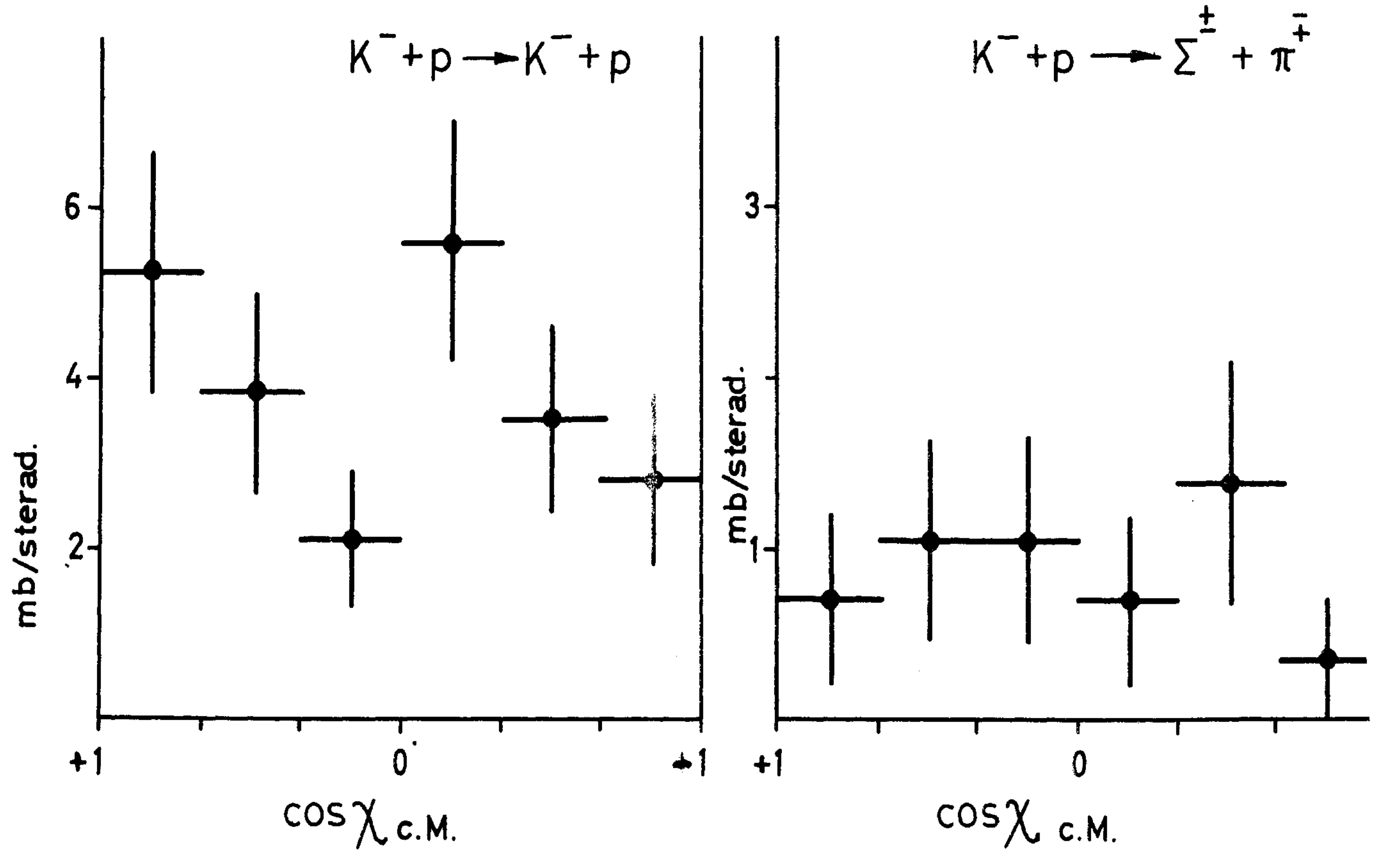

Fig. 9

I would also like to make a few remarks about the ratio of scattering to capture in complex nuclei. The following arguments were developed at Göttingen. Whereas, on free protons the ratio of scattering to capture was about 5 to 2, on complex nuclei the ratio is enormously different -- about 4 to 100. Of course, in nuclear emulsion, charge exchange on complex nuclei would be included in the capture cross sections. We tried to estimate the charge exchange scattering on free protons by looking at tracks disappearing in flight and producing no visible prongs. We also looked at the frequencies of 1, 2 and 3-pronged stars at rest and in flight in order to get an estimate of an upper limit for charge exchange, Σ^0 and Λ production. In this way, we estimate a value of about 1 for the ratio of elastic $K^- + p$ scattering to the rest of the processes. We then proceeded to carry out a Monte Carlo calculation for K^- interactions on complex nuclei, using various values for the above ratio. We also assumed isotropic angular distributions in the center of mass system. We treated the strength of the K^- nucleon potential as a parameter and obtained the results shown in Fig. 10. The intersection of the shaded area with the curves gives the potential required. This potential appears to be definitely negative.

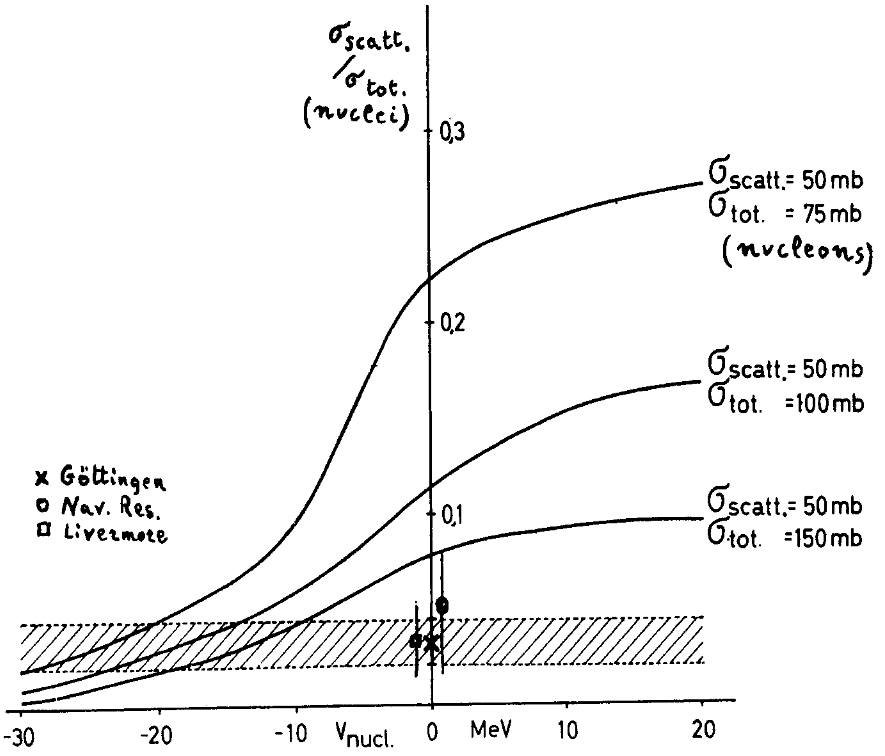

Fig. 10

<u>WHITE:</u> K^- interactions with bound protons.

I am going to talk about the analysis by the Göttingen and Livermore groups of the two reactions $K^- + p \longrightarrow \Sigma^+ + \pi^-$ and $K^- + p \longrightarrow \Sigma^- + \pi^+$ where the proton is bound, and the K^- is captured at rest.

In this study only those captures are included in which a charged π -meson and one additional charged particle are emitted. Fig. 11 shows the energy distribution for the Σ^+ hyperons as obtained by the Livermore group. The Göttingen group have a similar distribution but peaked at around 25 to 30 Mev. The curve in Fig. 11 is based on a model we have used. The external energies of the π 's and Σ 's will, of course, be modified from the values for K^- capture on free protons by the internal proton momenta and the Coulomb and nuclear potentials. If one assumes the Σ 's have a wavelength inside the nucleus which is small compared to the nuclear potential then

$$T_{I\Sigma} = T_{O\Sigma} + V_C + V_N \quad ,$$

where $T_{I\Sigma}$ is the Σ kinetic energy inside the nucleus, $T_{0\Sigma}$, is its value outside, V_C, V_N are the Coulomb and nuclear potentials respectively. In our model we assumed a Gaussian distribution for the proton momenta, a Σ potential of 25 Mev (this is not sacred, anything between 0 and 30 would work) and a pion potential of 40 Mev and isotropy for the reaction in the center of mass system. The Göttingen analysis assumed a Σ potential of 0 and a Fermi rather than a Gaussian distribution. The Σ^- energy distribution is shown in Fig. 12. We may note that the sign of V_N will be the same for both Σ^+ and Σ^-, whereas for V_C the sign will be opposite and it is this which causes the shift in the energy distribution. This shift can be accounted for by a V_C = 10 Mev. (The Göttingen

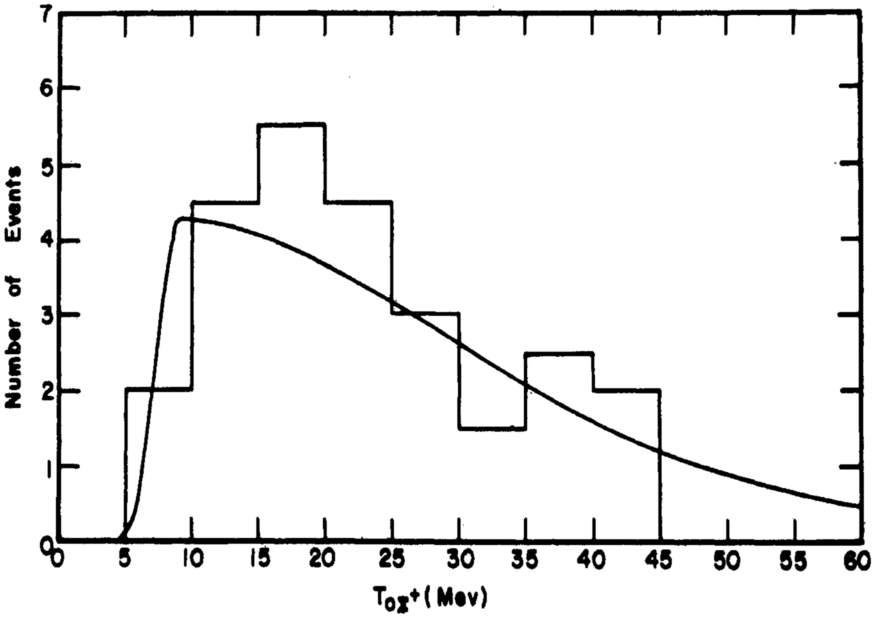

Fig. 11

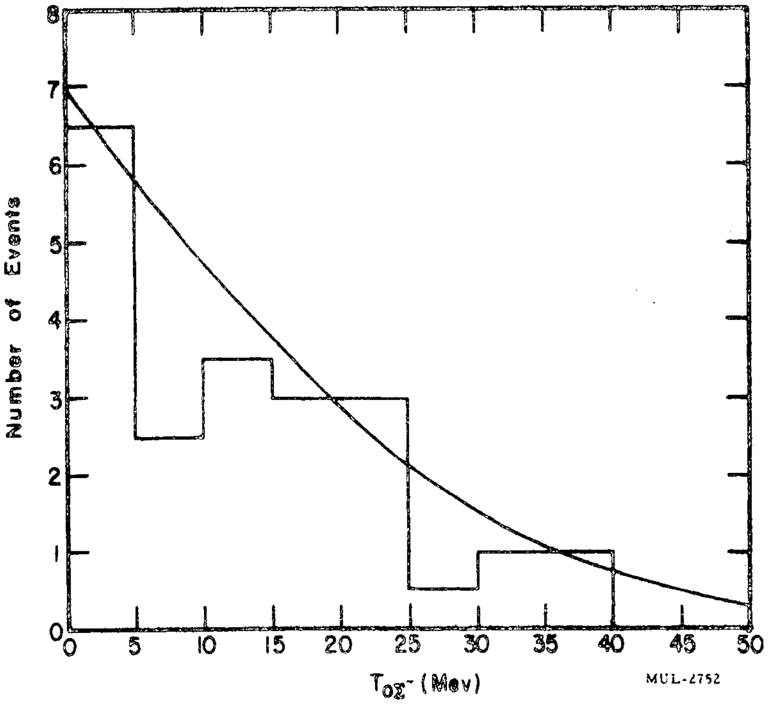

Fig. 12

group get a value of about 6 Mev.) It is this potential, then, which keeps more Σ^- inside the nucleus and so lowers the Σ^-/Σ^+ ratio from that obtained for free protons. For free protons the ratio is 2, for protons bound in emulsion nuclei it is 0.83 ± 0.25.

I'd like to say a few words about the identification of Σ^-. There is a divergence of opinion amongst experimenters on how to detect Σ^- hyperons. The difficulty is due to the fact that when a Σ^- is captured in a nucleus, a Λ + neutron can be produced and then escape leaving a 0-pronged star. There are various ways of trying to detect these Σ^- which of course look like protons. I will mention 2 methods, one used by the Göttingen group and one by us at Livermore. The method used by the Göttingen group is pictured in Fig. 13. One sees that for the identified events, the angular distribution is peaked near 180°. The lower figure gives the cases where a Σ was not identified and the distribution is fairly flat with a peaking towards 180° By subtracting the uniform background, the Göttingen group has been able to get the number of Σ^- that make 0-pronged stars. The method we use at Livermore is to make use of conservation of charge and energy. In the event producing the Σ we make sure that the π-meson is positive and that energy is balanced correctly.

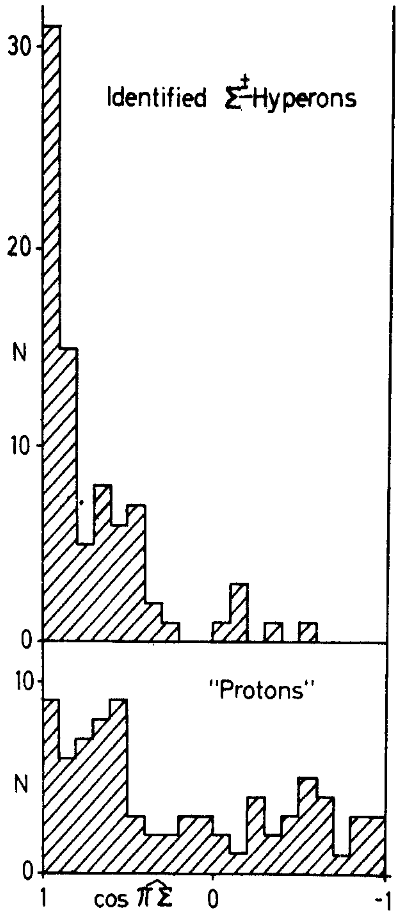

Fig. 13

DILWORTH: K^- interactions at rest

The results given here include preliminary data on about

2700 K stars at rest from the K-stack collaboration, (see Appendix for names), the Brussels-Milan-Saclay group, and the N. R. L. Washington group.

The frequency of occurrence of the various types of K^- - star observed is shown in Fig. 14 (prong distribution) and Table 5. These refer to a sample of 1798 K^- at rest from the K-stack group, those of the other two groups are equivalent.

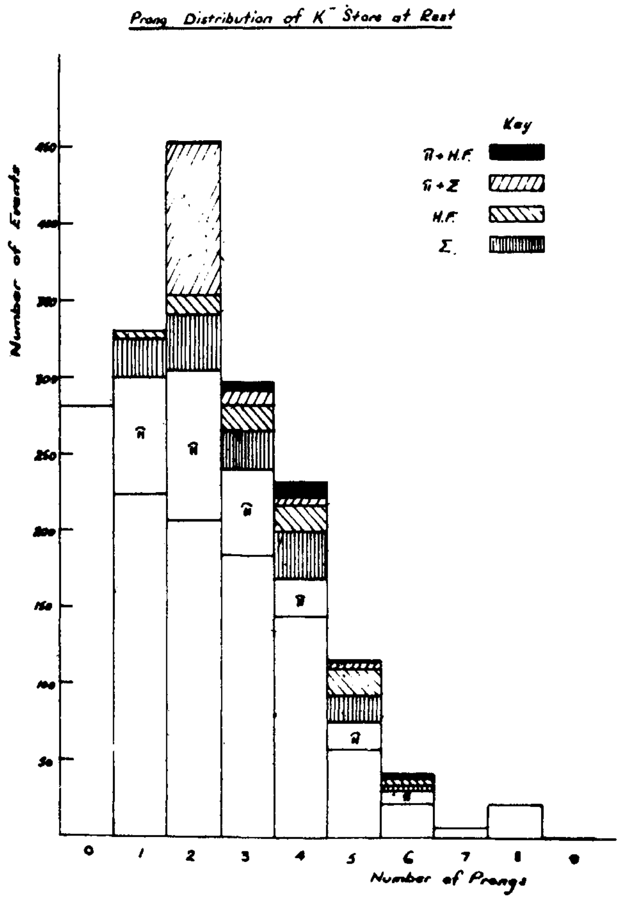

Fig. 14

Table 5

Evaporation		π		Σ		$\pi+\Sigma$		HF oo GOK	HF + π	2 fast baryons
K_ρ	K_σ	alone	with evaporation	alone	with evaporation	alone	with evaporation			
281	867	77	206	25	112	99	20	74	22	18

The number of Σ -hyperons given here includes those coming to rest which give a visible star or large blob. A survey of the ends of protons has shown that whereas in our plates, a blob is a good indication of the presence of an interacting particle, the number of spurious Auger electrons is of the same order as the number of

Σ^- and cannot be used therefore for identification. Only those 1-prong Σ^--stars which are clearly not scatterings have been included.

The ratio of $\Sigma^- : \Sigma^+$ among the hyperon decays in flight can be deduced from the number of $\Sigma^+ \longrightarrow p$ in flight, taking the branching ratio ($\Sigma^+ \longrightarrow p + \pi^0$)/($\Sigma^+ \longrightarrow n + \pi^+$) = 1. From the ratio of all $\Sigma^- : \Sigma^+$ in stars from which are emitted both Σ and π, we can, knowing the same ratio in the hydrogen bubble chamber, estimate the number of Σ^- lost due to their giving a zero prong star, or, as pointed out by Dr. White, to their being emitted in low energy states, and hence derive the $\Sigma^- : \Sigma^+$ ratio for all stars (See Table 6).

Table 6

(a) Σ^- decays in flight

$\Sigma^+ \to p$ in flight	Estimated $\Sigma^+ \to \pi^+$ in flight	Total No. $\Sigma^\pm \to \pi^\pm$ flight	Estimated $\Sigma^- \to \pi^-$ in flight
28	28	54	26

(b) Missing Σ^- in $\Sigma + \pi$ stars

Σ^+ observed			Σ^- observed			Expected	Missing
Rest	Flight	Total	Rest	Flight	Total		
35	24	59	30	12	42	118	76

(c) Estimated $\Sigma^- : \Sigma^+$ ratio in all stars

Σ^+ observed	Σ^- observed	Missing Σ^-	$\Sigma^- : \Sigma^+$	Expected
124	141	255	3:1	2·6:1

The fraction of high energy hyperons and protons observed can give us an estimate of the frequency of interaction of the K^- with 2 nucleons. ($K^- + 2N \longrightarrow N + Y$). The energy spectrum of the Σ-hyperons shows 19 Σ with energy greater than 60 Mev out of a total of 265, the BMS group gives 6 fast Σ out of 59, both with equal numbers of fast positive and negative. The ideogram (Fig. 15) demonstrates that this group is unaccompanied by π-mesons. Taking into account the missing Σ^-, this indicates that about 4% of all hyperons are produced in 2N interactions. From the proton energy spectrum (Fig. 16) we find that about 9% of all K^- stars contain a fast proton. Of these a part will arise from π absorption and knock-on. The number of stars in which two fast baryons is emitted is 1% of the total.

An attempt may then be made to attribute the bulk of the stars to the single nucleon interactions (see Fig. 17). The bubble chamber results on K-interactions in hydrogen give as the ratio

$$\Sigma^- : \Sigma^+ : \Sigma^0 : \Lambda$$

= 4: 2: 2: 1/2. It might be hoped to obtain from the nuclear emulsion work the ratio of K^-+N: K^-+

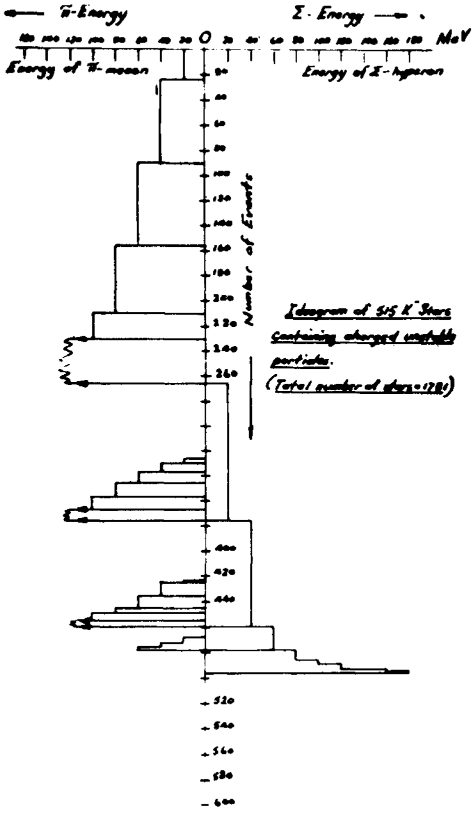

Fig. 15

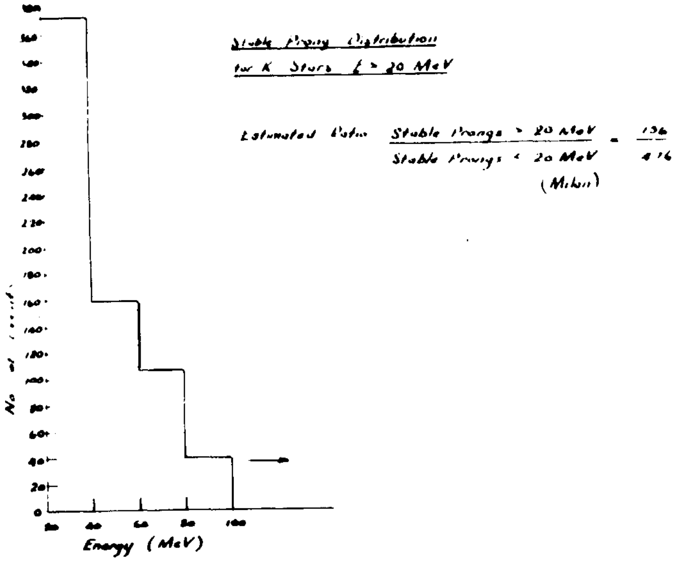

Fig. 16

and the ratio Σ^- : ($\Lambda^0 + \Sigma^0$) from interactions with neutrons. The problem is complicated by the presence of nuclear absorption and charge exchange of the interaction products. An estimate can be obtained by making the simplifying assumptions:

(1) that π^- and π^+ absorption is equal

(2) that charge exchange effects are symmetrical between the charges.

Since the Σ^+ is produced only in interaction (1), the absorption of the π -mesons is given by the ratio of the number of Σ^+ hyperons unaccompanied by a meson to the total number of Σ^+, correction being made for the number of Σ^+ from 2N interactions:

			Energy of	
			Y	π (MeV)
(1)	$K^- + P \longrightarrow \Sigma^+ + \pi^-$	+ 102 MeV	14	88
(2)	$K + P \longrightarrow \Sigma^0 + \pi^0$	+ 100 MeV	14	86
(3)	$K^- + P \longrightarrow \Sigma^- + \pi^+$	+ 90 MeV	12	78
(4)	$K^- + N \longrightarrow \Sigma^0 + \pi^-$	+ 100 MeV	14	86
(5)	$K^- + N \longrightarrow \Sigma^- + \pi^0$	+ 95 MeV	13	82
(6)	$K^- + P \longrightarrow \Lambda^0 + \pi^0$	+ 181 MeV	28	153
(7)	$K^- + N \longrightarrow \Lambda^0 + \pi^-$	+ 181 MeV	28	153
(8)	$K^- + (P \text{ or } N) \longrightarrow \Lambda^0 + \pi + \pi$	+ 41 MeV		
(9)	$K^- + (2 \text{ Nucleons}) \longrightarrow \Sigma + \text{Nucleon}$	+ 240 MeV	106	134
(10)	$K^- + (2 \text{ Nucleons}) \longrightarrow \Lambda^0 + \text{Nucleon}$	+ 320 MeV	142	178

Fig. 17

$$\frac{\pi^- \text{ absorbed}}{\pi^- \text{ emitted}} = \frac{\Sigma^+ \text{ alone} - 10}{\Sigma^+ + \pi} = \frac{65 - 10}{59} \simeq .93 \sim 1.$$

Applying this figure to the π^+ -mesons accompanying the Σ^- -hyperon, the ratio

$$\frac{K^- + N \longrightarrow \Sigma^- + \pi^0}{K^- + P \longrightarrow \Sigma^- + \pi^+} = \frac{99 - 10 - 42}{42 + 42} = \frac{47}{84} \sim 0.6. \qquad \text{(A)}$$

The total number of charged π -mesons seen, after correction for scanning loss, is 565. Hence the number of charged π 's produced is 1130 and the number of neutral π's is 580. The neutral π's are produced in interactions 2, 5 and 6, whose intensities are now all known as fractions of N_1, the number of $\Sigma^- + \pi^+$ (hence $N_1 = 470$) and N_2, the number of $\Sigma^+ + \pi^-$ ($N_2 = 235$). Since the number of Σ^+ seen is 124 this means that Σ^+ absorption is 111/235 i.e. about 50%. The charged π's arising from interactions 4 and 7 are then 1130- (470 + 235) = 425, which gives the ratio

$$\frac{\Sigma^- + \pi^0}{(\Sigma^0 + \pi^-) + (\Lambda^0 + \pi^-)} = \frac{0.6\,N_1}{\frac{425}{470}\,N_1} \sim 0.7 \quad \text{(B)}$$

Ratios (A) and (B) can be compared with those to be expected from the bubble chamber data on $K^- + P$ interactions, assuming charge independence. (see Table 7)

Table 7

	Predicted	Found
$\dfrac{K^- + N \rightarrow \Sigma^- + \pi^0}{K^- + P \rightarrow \Sigma^- + \pi^+}$	0.6	0.6
$\dfrac{K^- + N \rightarrow \Sigma^- + \pi^0}{(K^- + N \rightarrow \Sigma^0 + \pi^-) + (K^- + N \rightarrow \Lambda^0 + \pi^-)}$	0.67	0.7

The agreement is good, although the uncertainty in the experimental values is quite large as a glance at the actual numbers involved will show.

On the other hand, the experimental π^- / π^+ ratio is very different from what one should expect.

Table 8

Total π^- / π^+	π^- / π^+ for $E < 40$ Mev	for $E > 40$ Mev	Predicted value
$\frac{119}{23} = 5.2$	$\frac{83}{15} = 5.5$	$\frac{36}{8} = 4.5$	1.5

It should however be pointed out, that this ratio is heavily biased if there is, as Dr. White suggests, an assymetry in the energy spectra of π^+ and π^- , since the higher energy π -mesons are more difficult to follow and more likely to leave the stack before being stopped. Thus of the 142 π - mesons followed, only 3 have energy greater than 70 Mev. The true π^-/π^+ ratio can only be found when all π 's emitted under given geometrical conditions have been followed, to their end, irrespective of their initial energy.

A small contribution to the π^- / π^+ ratio at low energies may arise from the presence of what we call 'cryptofragments'. There is evidence that in some cases the Λ^o remains trapped in the nucleus and decays or interacts there. Four of the Σ^- interactions at rest release a visible energy greater than the mass difference between Σ^- and Λ^o . Among the K^- stars there are some in which a π -meson and more than 200 Mev visible energy is seen, indicating that the hyperon does not escape. The range distribution of normal hyperfragments and GOKs rises very steeply towards very short ranges, a large fraction being less than 2 μ long, i.e., they appear as double centered stars or DOKs. It is tempting to extrapolate to zero range.

DISCUSSION

PUPPI: (Showed several pictures to indicate that the π^- 's come out of a nucleus with much less energy than π^+ 's and so would have a shorter range in the emulsion.)

WHITE: Concerning the high π^- / π^+ ratio, I should like to make a comment on a preliminary investigation which looks at one pronged events. We measure the energies of the π^- and π^+ and the π 's which don't stop in the emulsion. One expects the π^- 's to come from $\pi^- + \Lambda^o$ and $\pi^- + \Sigma^o$ production, with the energies of the π 's peaking at about 130 Mev and 70 Mev respectively. We find the π distribution to peak at about 100 Mev. This can be explained in terms of the model I presented in which some of the Σ^+ and many of the Σ^- are trapped inside the nucleus. The π^+ which come out will then have a higher energy around 100 Mev.

PERL: K^+ scattering on hydrogen in a bubble chamber.

This was the work carried out by Meyer, Glaser and myself.

The energy of the K^+ was 20 to 90 Mev and the average energy was about 65 Mev. We had 32 events. I want to just say a few words about the angular distribution which was probably not evident from the figure (Fig. 2) in Professor Alvarez's talk. In all of our events we see both the K recoil and the proton recoil and so the event is over-determined kinematically which means good identification of a hydrogen event. Fig. 18 shows our angular distribution in the center of mass system. In the first section we do not have very many events because at this small angle we cannot separate hydrogen from carbon events. So simply consider our data from $\cos\theta = 2/3$ to -1. The first point to make is that these angles are sufficiently large that you do not expect any Coulomb interference. Therefore it is not possible from our data to say anything about the sign of the phase shifts. Secondly, if you then look at the possibility of fitting the data with an s-wave then you get an enormously small X^2 probability, about .1%. We do not know of any bias in our distribution. Thus, the distribution is fairly strongly non-isotropic, and so we are inclined, on the basis of our data alone, to consider that p-waves are present in this energy range. To do the analysis seriously you should put in some d-waves. Of course we can't do this because the statistics are much too small. Therefore we feel that it is somewhat premature to take K^+ scattering on hydrogen at this energy range as being purely s-wave, and to use that as a model. We would prefer to keep an open mind and would strongly emphasize the great interest in doing further scattering in this range to see the extent of the p-wave interactions.

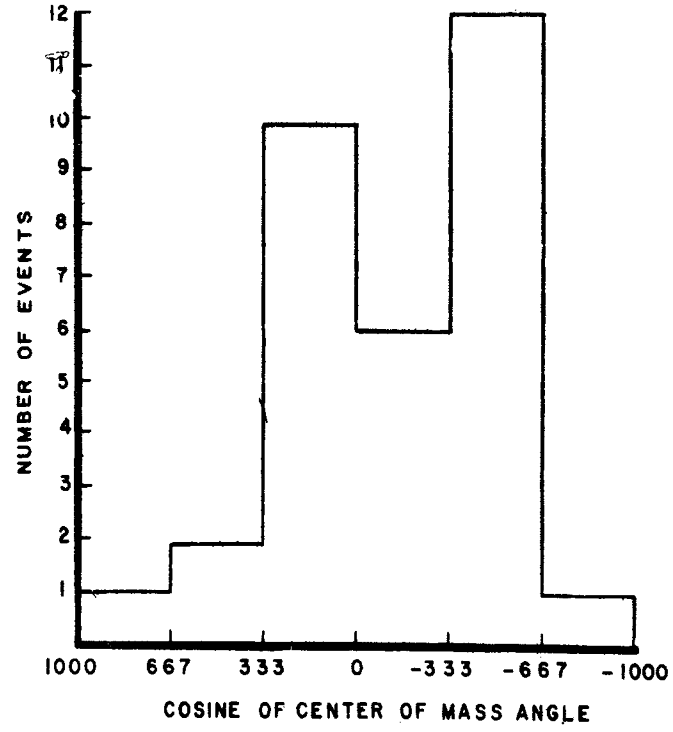

Fig. 18

PUPPI: K^+ interactions in nuclear emulsions.

The laboratories involved in the work on K^+ interactions in nuclear emulsions are Berkeley, Bologna, Bristol, Brookhaven, Dublin, Göttingen, Harvard, M.I.T. and Padua (see Appendix). There are roughly 1000 inelastic collisions observed in the emulsions.

Table 9 shows the experimental mean free path, λ , for all inelastic processes.

Table 9

Energy of K^+(Mev)	λ(Meters)	σ(per nucleon) in mb.	$\frac{\text{charge exchange}}{\text{inelastic}}$	
30 - 90	1.22	9	.1	(16)
90 - 160	0.89	10	.2	(53)
160 - 210	0.61	12	.25	(35)

From the value of λ one can roughly infer the elementary K^+ -nucleon cross section. To do this one must take into account the Coulomb effect and the Pauli principle and use the formula of Fernbach, Serber and Taylor to take into account the shadow effect. This leads to the results in column 3 of Table 9. Another piece of information is the ratio of charge exchange to inelastic scattering (i.e. the ratio of cases when the K^+ is not seen to emerge over the cases when it is) and this is shown in column 4 of Table 9. The figures in parenthesis give the number of events on which the result is based.

What can we learn from these figures? Not very much if we restrict ourselves to the total cross section. Professor Alvarez told us that the elementary cross section for K^+ + P is about 15 mb and independent of energy. Now, an emulsion nucleon is about .45 of a proton. Thus the proton part contributes about 7 mb to the result in column 3 and so the neutron must contribute between 2 and 5 mb. Well, if the interaction is pure T = 1, then the neutron cross section will be precisely 1/2 that of the proton i.e. about 3.5 mb and this certainly lies between 2 and 5 mb. But, you get no knowledge of the relative importance in the T = 0 and 1 states.

Now consider the numbers in column 4. If there is only T = 1 interaction, the ratio should be about .2 and you expect this to be constant in energy if the elementary cross section is constant in energy and angle. However, if you believe the figures in column 4 then you must have some T = 0 interaction. Another point is that it is hard to understand the substantial inelastic scattering in the backward hemisphere if the elementary cross section is really isotropic.

DALLAPORTA: The sign of the K^+ nuclear potential.

K^+ - nucleus scattering has generally been interpreted by making use of the optical model and dividing the events into elastic and inelastic. The elastic part is assumed to be due to scattering from both the Coulomb and nuclear potential. The conclusions obtained by practically all of the laboratories quoted by Puppi are that the nuclear potential is repulsive. This is based on both the elastic and inelastic events.

The elastic evidence requires looking at small angle scattering to see whether one has constructive or destructive interference with the Coulomb potential. Fig. 19 shows the results. The upper curve gives constructive interference, i.e., a repulsive nuclear potential of about 15 Mev.

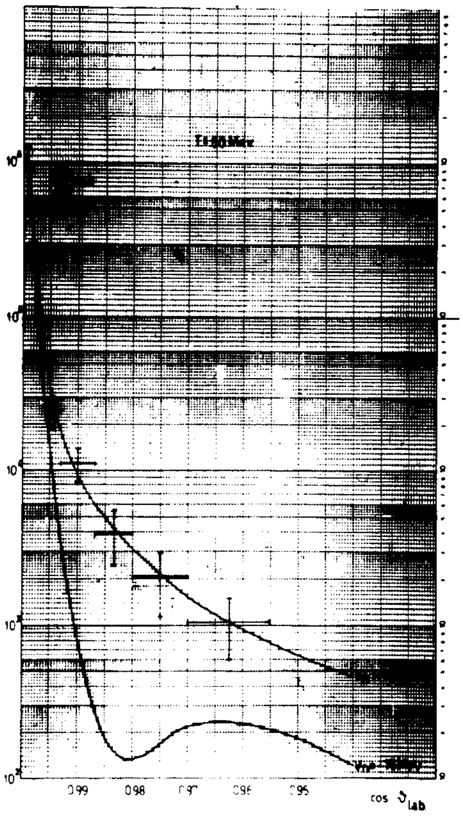

Fig. 19

The second piece of evidence for the sign makes use of the inelastic events. We interpret inelastic events as the scattering of the K^+ by a single nucleon in the nucleus. If the nucleon were free then the fractional energy loss of the K meson would have a definite relation to the angle of scatter. This is the curve shown in Fig. 20. The experimental points fall below this curve which implies that the incident K is experiencing a potential energy in the nucleus. Again, in Fig. 21 we show the mean value of the energy loss as a vunction of the incident K^+ energy. The curves are calculated for various values of the potential, and you see that a repulsive $V_C + V_N$ of about 20 to 30 Mev fits the experimental results. We deduce that V_N is repulsive and about 10 to 20 Mev.

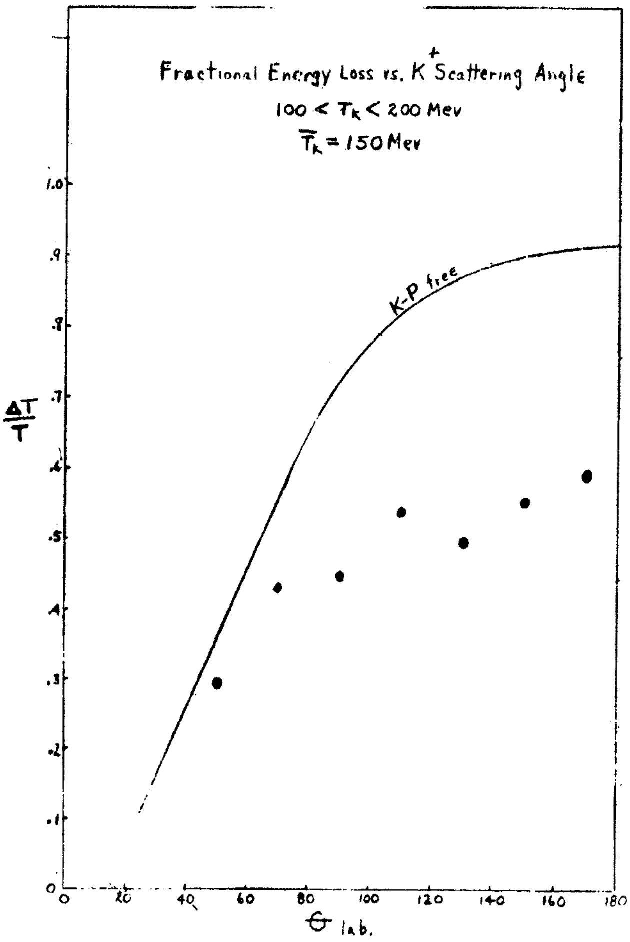

Fig. 20

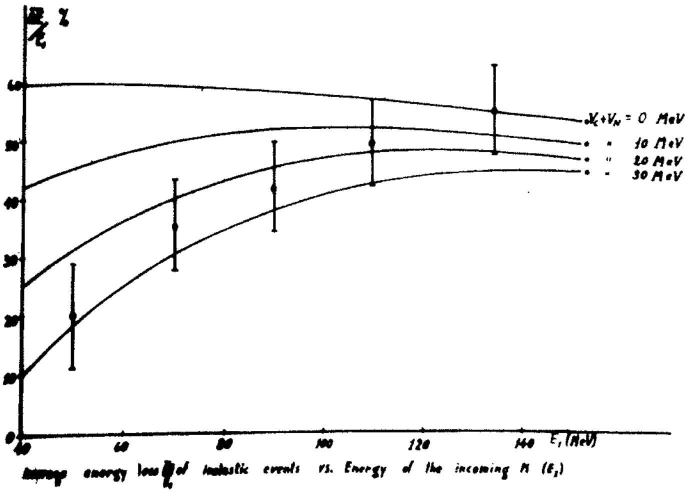

Fig. 21

I would like to mention, also, the direct attenuation experiment performed by Kerth, Kycia and Van Rossum on K^+ scattering in C, Al, Cu, Ag and Pb, also in hydrogen using the CH_2, C difference. The results were also analysed in terms of the optical model and are consistent with those obtained in emulsion, i.e. a V_N of about 20 Mev. The K^+ nucleon cross section per nucleon was about 10 mb which is consistent with the result given by Dr. Puppi.

HOANG: K^+ interaction in the energy interval 30-65 Mev.

The Rochester data on K^+ - scattering were obtained by analyzing all K^+ scatters having a projected angle on the emulsion plane $\geq 2^o$. Fig. 22 shows the differential cross section for the elastic scattering. The ratio of the experimental cross section to that of Coulomb scattering increases monotonically with scattering angle: the interference between the nuclear and the Coulomb scattering is constructive.

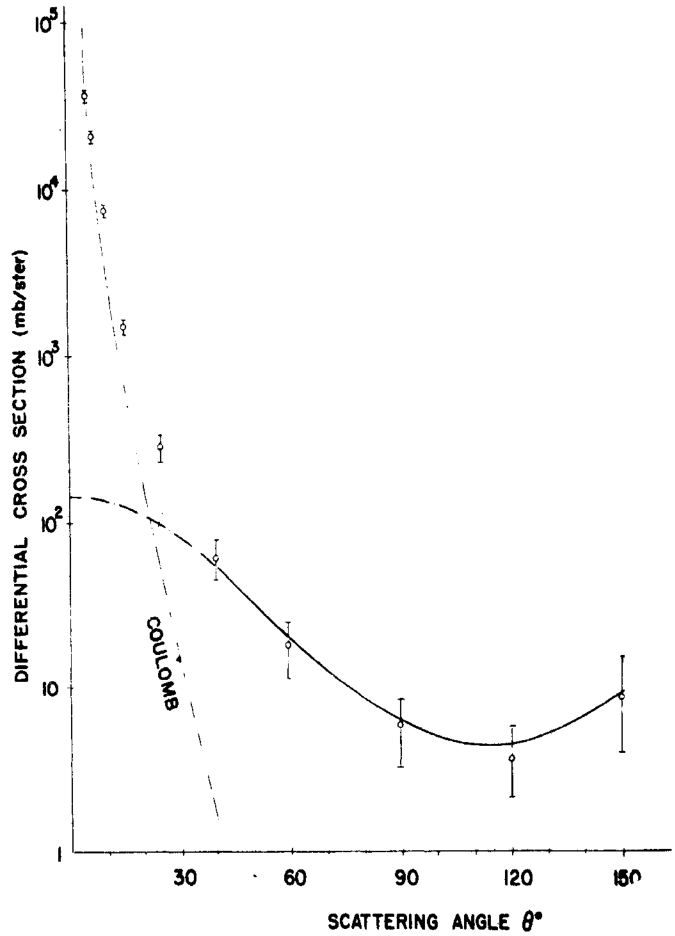

Fig. 22

An attempt was made to determine the real part V_r of the nuclear potential felt by the K^+ - meson inside the nucleus using the experimental cross sections at $7\ 1/2^o$, 10^o, 15^o and 25^o. The best fit corresponds to $V_r \simeq 15$ Mev; this gives an average K^+ -nucleon cross section about 8 mb, from which we deduce an average cross section (assumed isotropic) per free nucleon $(m_p/m_p + m_K)^2 \times 8 \simeq 4$ mb which is significantly lower than the K-p cross section. The factor $(m_p/m_p + m_K)^2$ is to take into account the binding effect: i.e. the nucleon involved in the elastic scattering is fixed in the nucleus.

The mean free path for inelastic scattering is 63.7 ± 6.5 cm, which corresponds to an average cross section $\sim$ 7mb per nucleon and to an imaginary part of the K-nucleus potential $V_{im} \simeq 3.6$ Mev. The energy loss involved in the inelastic scattering is found to be small in contrast with the observed large momentum transfer ; actually about 70% of the inelastic scatterings have a $\Delta E/E_0 < 10\%$.

The charge exchange cross section is found to be very small in comparison with that of inelastic scattering: $\sigma_{ch}\,\text{exch}/\sigma_{inel.} < 1/10$. This implies that in the energy region 30-65 Mev the scattering amplitudes in the Iso-spin states T = 0 and T = 1 must be of the same order of magnitude.

These characteristic features observed in the incoherent scatterings of K^+ - meson, together with the fact that the proportion of multiply charged prongs in the K^+ -star is exceptionally high , $\sim$ 80%, seems to indicate that the K^+ interaction in the energy region 30-65 Mev is mostly with a cluster of nucleons rather than with a single nucleon.

CALDWELL: An unusual event with a large energy release.

(This work was done with Boldt, Bridge and Pal)

An unusual event has been found among the pictures taken with a large multiplate cloud chamber at the Brookhaven Cosmotron. A drawing is given in Fig. 23. A 1.8-Bev π^- (track 1), after traversing 13 plates, interacts and produces one track of near-minimum ionization (track 2), an energetic Λ^0 (1 Bev/c, tracks 4 & 5), and a heavy track (track 3). The heavy track traverses 1.5 gm/cm^2 of the following iron plate before giving rise to two heavily-ionizing, upward-going tracks (tracks 8 and 9)

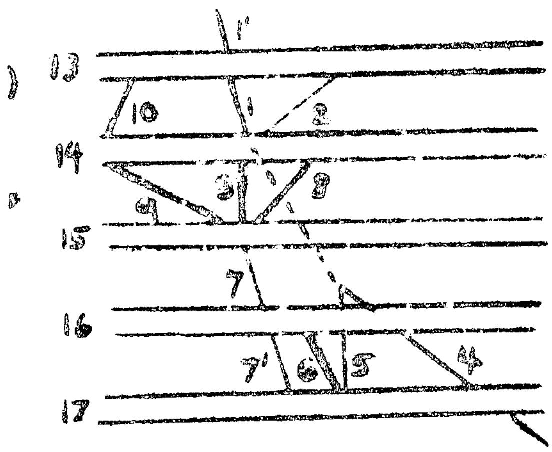

Fig. 23

and one lightly-ionizing one (track 7), going downwards. The latter, which is most probably a π , is still near minimum ionization after traversing 22.6 gm/cm^2 of iron, and probably interacts before stopping. The three tracks are not coplanar by 28^{o} , and they represent a minimum energy release of about 400 Mev. If they are decay products, the parent particle, which cannot be a τ meson, lived about 10^{-9} seconds, if the decay was in flight. Also, from energy and momentum considerations and photometric ionization measurements, the "parent" almost surely cannot have a charge larger than one.

Thus we seem to have a singly-charged particle (or group of particles) which is produced in association with a Λ^{0} , lives a relatively long time, and decays or interacts, giving an unusually large energy release, despite its not being a K^- or hyperon, if the idea of associated production is correct. The probability that this is a chance coincidence is about 10^{-5} . Any trivial explanations for this event which we have been able to think of also have probabilities of this order. So far, the only explanation we have which is at all consistent with the empirical evidence and does not invoke a new particle is that this event is an example of a K^+ particle bound to two nucleons, even though this explanation would be in conflict with some widely-held views concerning the potential between K^+ mesons and nucleons.

RAVENHALL: K^+ scattering in emulsion.

This is a report of an analysis carried out by Igo, Ravenhall, Thaler and Tiemann based on experimental work of G. Goldhaber, S. Goldhaber and Lannutti. I would like to give a preliminary report of an optical model calculation. One uses a real and imaginary nuclear potential with nuclear shapes given by the electron scattering data. The imaginary potential is determined by the total inelastic cross section but it also depends to some extent on the real part of the potential. Now we don't have any final results to report but it does seem that the various stages of the analysis of the elastic scattering are significantly altered by putting in the imaginary part to the potential. One factor, for instance, is that although the imaginary potential is so small that the nuclei are by no means opaque, it turns out from the optical model calculation that the variation with atomic number of the inelastic cross section varies with atomic number like $A^{2/3}$ rather than A. The reason for this is that the repulsive Coulomb interaction deflects the trajectories of the incident particles. This sort of effect does alter the apportioning of the total inelastic cross section of the various elements in emulsion and can make quite an appreciable effect on the mean free path in nuclear matter. Fig. 24 shows our results for elastic scattering. I think you should notice the difference from the previous Fig. 19. Although we feel that our results will not change the qualitative conclusions of the previous workers, they may change the quantitative conclusions.

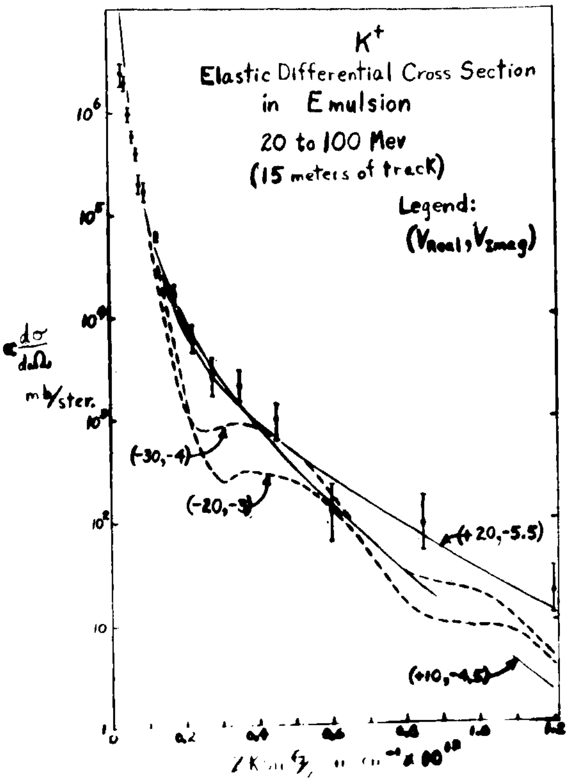

Fig. 24

BARKAS: Σ^- interactions

As a by product of the K⁻ work we have obtained certain scraps of information on Σ interactions. The most important material is obtained from Σ^- coming to rest and making stars in the emulsion. If one were to engage in a though experiment he would try to think just what would happen in a medium like emulsion which consists on the one hand of hydrogen and the C, N, 0 group of elements and the Ag, Br group of elements. The Σ^- can interact with a proton of the emulsion in the following way: $\Sigma^- + p \longrightarrow \Lambda^0 + n + 80$ Mev for a free proton. I am not going to discuss the reaction $\Sigma^- + p \longrightarrow \Sigma^0 + n$ because in a bound proton the energy is extremely marginal and probably this reaction doesn't go at all. In a real nucleus, we will have something like this: $\Sigma^- + Z^A \longrightarrow (Z-1)^{*(A-1)} + n + \Lambda^0$. Now if Z^A is a light element, and the neutron and the Λ^0 escape, the residual nucleus will in general disintegrate. In the case of a heavy element the tendency would be, first, that it be less likely that they both escape and secondly, the excitation would have to be rather large before anything becomes visible. However if the Λ^0 is trapped, then in a light element we will see a hyperfragment. Most of the hyperfragments are found to have very short ranges and in fact I think the ranges are too short to come out of a heavy element. The great majority of them cannot come out of heavy elements, and I personally do not believe that the hyperfragments generally come from heavy elements. In the case of the heavy element, though, the Λ^0 can also be trapped. And in that case we would expect the energy of a pion to show up somehow and generally in the form of something that looks like a π^- star. Well, with that background we looked at the stars produced by Σ^- hyperons and the results of my own group and of the Livermore group gave energies in the stars which were generally under 50 Mev of visible energy, whereas from the heavy elements you might expect more than that. Thus, we have a real disagreement between our work and that of the K-stack because they have a number of cases where there is quite a lot of energy evident. I should say also that in the light elements hyperfragments came out in 1/4 of the cases, both our results and those of Livermore indicating about the same thing. Fig. 25 shows a typical

Capture of K^- Meson producing Σ^- hyperon which in turn is captured to produce a ${}_{\Lambda}Li^9$ hyperfragment

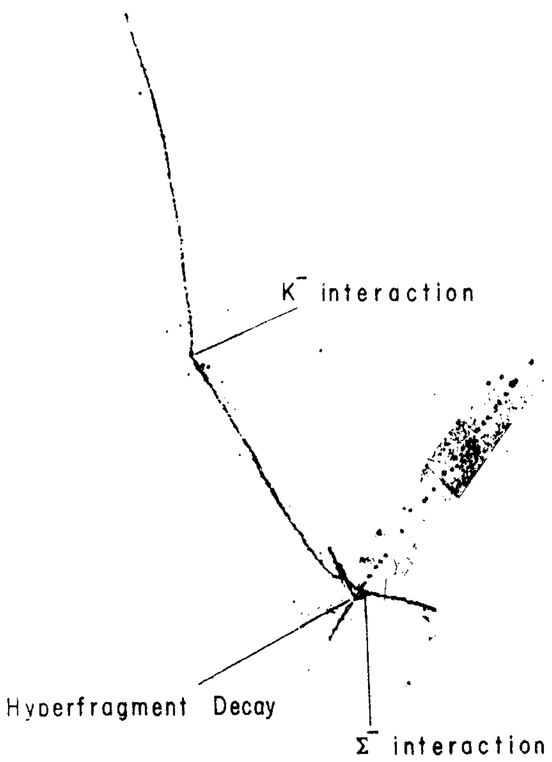

Fig. 25

event. Fig. 26 gives the results found in Wisconsin. The 44 is based on the presence of Auger electrons. Fig. 27 shows our results. The 0-pronged stars were recorded if we saw a blob at the end of the Σ^- -range. Fig. 28 shows our distribution of energy. Light nuclei are identified when there are prongs present which could not come from a heavy nucleus. The visible energy is the kinetic energy of the prong plus the binding energy. Notice that in the unidentifiable nuclei there are none with more than 50 Mev visible energy. Fig 29 is from the K-stack collaboration. They did not separate into light and heavy, but notice they get many events with energies greater than 50 Mev.

Characteristics of Σ^- endings

Prong No.	No. of events
0	22 + ($\sim$ 44)
1	30
2	13
3	5
4	1
	71 + ($\sim$ 44)

Fig. 26

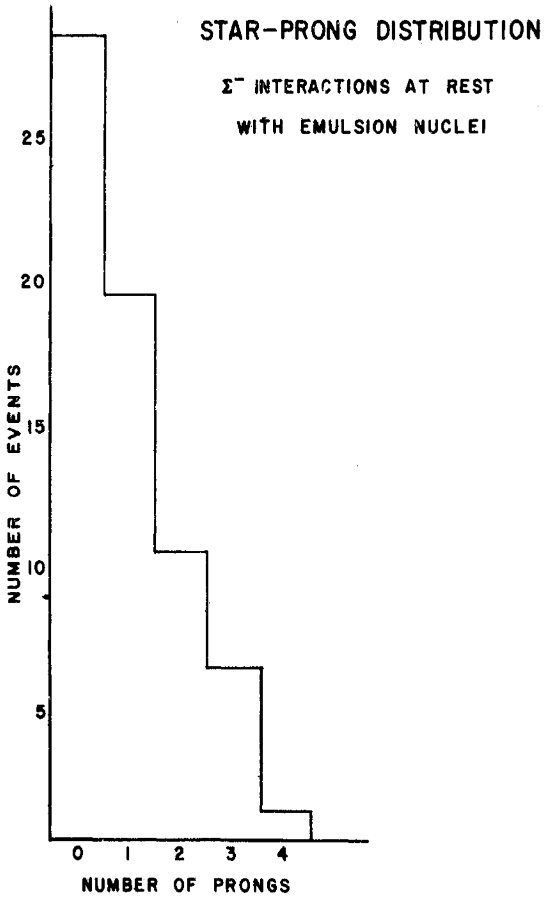

Fig. 27

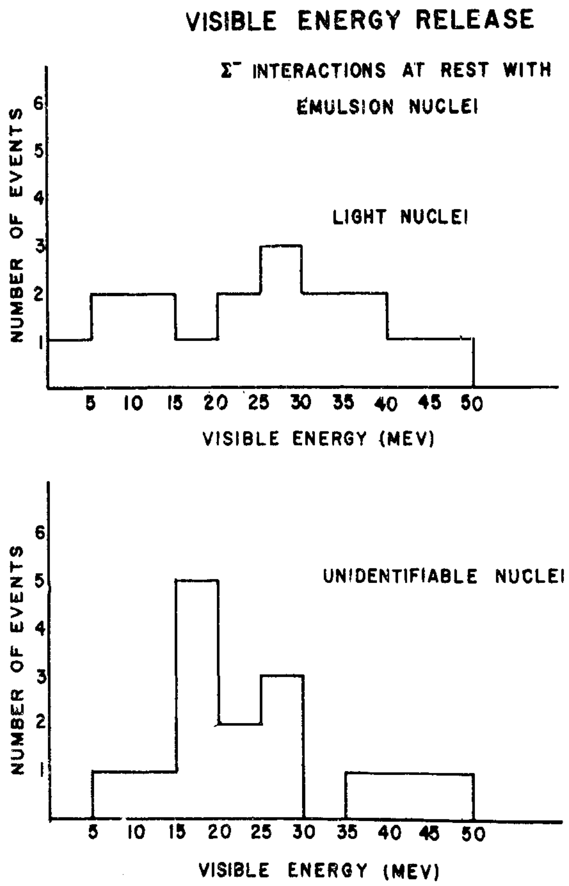
VISIBLE ENERGY RELEASE
Σ⁻ INTERACTIONS AT REST WITH EMULSION NUCLEI
LIGHT NUCLEI
NUMBER OF EVENTS
1
2
3
4
5
6
5 10 15 20 25 30 35 40 45 50
VISIBLE ENERGY (MEV)
UNIDENTIFIABLE NUCLEI
NUMBER OF EVENTS
1
2
3
4
5
6
5 10 15 20 25 30 35 40 45 50
VISIBLE ENERGY (MEV)

Fig. 28

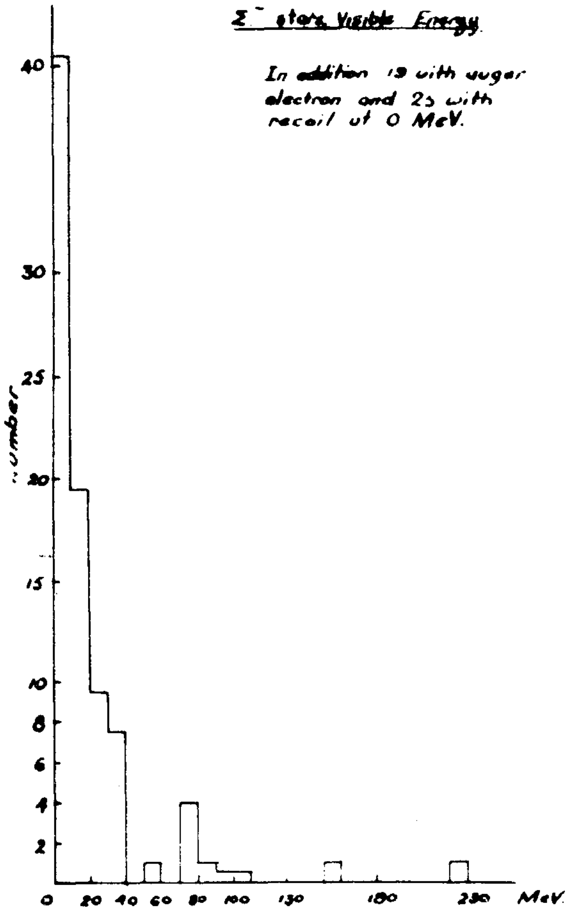
Σ⁻ stars Visible Energy
In addition 19 with auger electron and 25 with recoil at 0 MeV.
number
2
4
6
8
10
15
20
25
30
40
0 20 40 60 80 100 130 180 230 MeV

Fig. 29

LEVI SETTI: Interactions of neutral K particles.

I will summarize two similar experiments carried out, respectively, by the Milan-Padova group (Baldo-Ceolin, Dilworth, Fry, Greening, Huzita, Limentani, and Sichirollo) and the Chicago EFINS group (Ammar, Friedman, Levi Setti, and Telegdi). In the Milan-Padova experiment, an emulsion stack was exposed to a neutral beam at 90° to the 6.2 Bev proton beam at a distance of 2.6 m from a Cu target which got 8×10^{12} protons. In the other experiment, a neutral beam at 45° was used at a distance of 6 m; the Be target used received 3×10^{12} protons. Strange particle decays, captures and connected stars were looked for using area scanning. The events found at Milan-Padova, in a volume of 15 cm^3, were as follows:

9 Σ^+
6 Σ^- (in 6 cases an associated $\pi^{\pm}$)
4 K^-

12 GOKs (God only knows)

The events found at Chicago (in a volume of 10 cm^3) were:

3 τ's
2 K^+ (positive strangeness)

1 K^- (negative strangeness)

1 Σ^+
4 GOKs

A common feature of all these events is that they originate from parent stars in the stack. The parent stars are very small, with an average visible excitation energy of about 20-30 Mev. These events (the stars) are interpreted as the nuclear interactions of neutral, long lived K-mesons. There are a number of arguments supporting this conclusion. In two of the sigma-production events of Milan-Padova one can actually estimate the mass of the incoming particle. The interactions are interpreted as

$$\bar{\theta}_0 + n \longrightarrow \Sigma^- + \pi^+ \; ; \; \bar{\theta}_0 + n \longrightarrow \Sigma^+ + \pi^-$$

where the two final particles are the only visible prongs. The mass of the $\bar{\theta}_0$ is found to be $(1000^{+30}_{-180})m_e$ in one case, and $(995^{+75}_{-270})m_e$

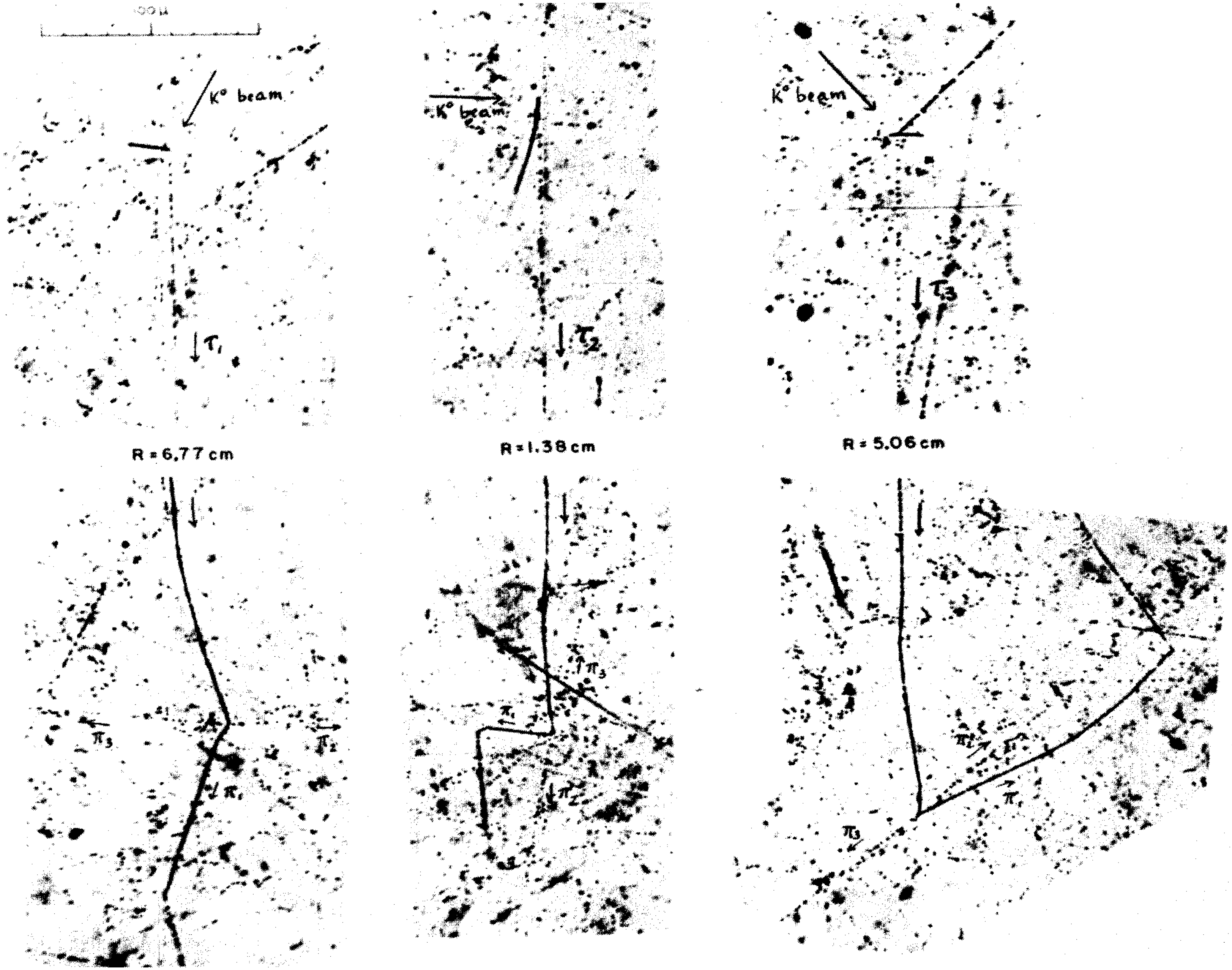

Fig. 30: Three tau events

in the other. The errors quoted take into account the Fermi momentum of the target nucleons.

In the cases where sigma's and pi's were observed, the total visible energy (including pi rest-mass and excess sigma mass) was about 530 Mev, with a spread of 40 Mev. The average pion energy was about 93 Mev. Also those cases in which a pion is not visible are consistent with the production, by a θ^0, of a Σ^+ and a π^0. Another piece of evidence comes from the charge-exchange processes observed at Chicago.

The top half of Fig. 31 is self-explanatory; the bottom half shows the kinetic energy, in the laboratory, of the observed $K^\pm$ as function of the angle of emission with respect to the incident beam. The solid curve is calculated assuming a process $\theta^0(\bar{\theta}^0)+N\rightarrow K^\pm+N$ for an incident θ^0 beam of 140 Mev. The dotted curves are possible limits if one assumes a Fermi energy of 20 Mev for the target nucleons.

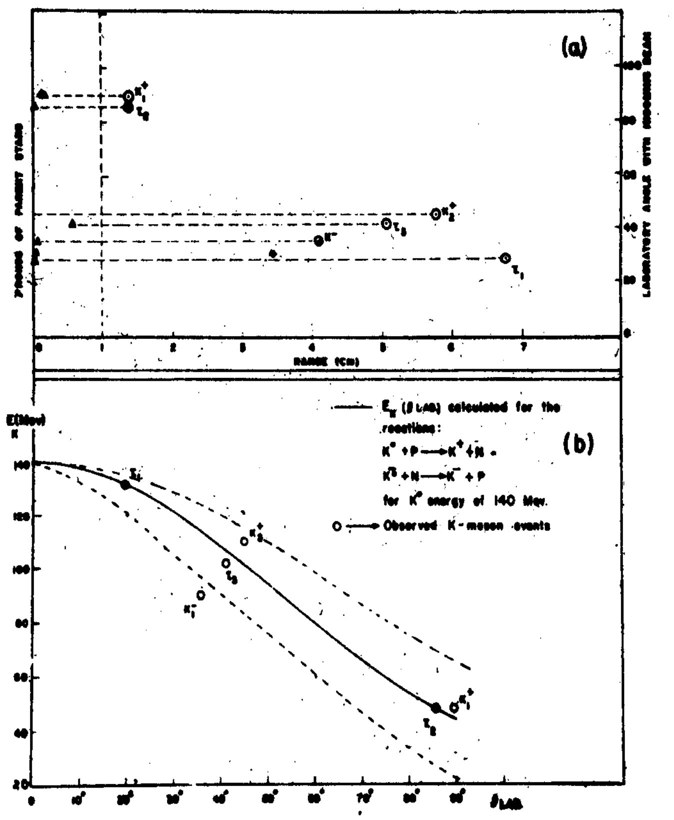

Fig. 31

As for the possibility of these events being produced by high energy neutrons, an estimate of the neutron flux with energy above threshold for strange particle production has been made for both experiments. Criteria based on the observation of stars with total prong number greater than the cut-off corresponding to E = 1.2 Bev have been used, as well as criteria based on shower particle production. The final conclusion is that neutrons could account for only 1/10 of the observed events.

Thus we conclude that we have seen the Θ_2 component of the Pais-Gell-Mann scheme, and the elementary interactions observed were

$$\Theta_0 + p \longrightarrow K^+ + n$$

$$\bar{\Theta}_0 + n \longrightarrow K^- + p$$

$$\bar{\Theta}_0 + n \longrightarrow \Sigma^\pm + \pi^\mp$$

and probably $\bar{\Theta}_0 + p \rightarrow \Sigma^+ + \pi^0$

Assuming some of the GOKs are hyperfragments we have seen the production of Λ by a $\bar{\Theta}_0$.

I would also like to mention that a similar experiment has been done by the M.I.T., Harvard and Johns Hopkins group using the 3 Bev Brookhaven beam. They looked for Λ 's in their emulsion and found about 7, indicating that the Λ 's may have been produced in their emulsion by a long lived Θ_0.

APPENDIX

1) The members of the K-stack collaboration are, from
Bristol: Bhownik, Evans, Falla, Hassan, Kamal, Nagpaul and Prowse,
Brussels: René
Dublin Institute: Alexander, Johnston and O'Ceallaigh
University College, Dublin: Keefe
University College, London: Burhop, Davies, Kumar, Lasich, Shaukat, Stannard
Milan: Bacchella, Bonetti, Dilworth, Scarsi
Padua: Grilli, Guerriero, Von Lindern, Merlin, Saladin.

2) The members of the groups participating in the work on K^+ interactions in emulsions:

Berkeley: Chupp, G. Goldhaber, S. Goldhaber, Lannutti.
Bologna: Giambuzzi, Marchi, Quareni, Vignudelli, Wataghin.
Bristol: Bhowmik, Evans, Nilsson, Prowse.
Brookhaven: B. Sechi-Zorn, G. T. Zorn.
Dublin: Anderson, Keefe, Kernan, Losty.
Göttingen: Biswas, Ceccarelli-Fabbrichesi, Ceccarelli, Gottstein, Warshneya, Waloschek.
Padova: Grilli, Guerriero, Merlin, Saladin.

3) THE SMALL ANGLE SCATTERING OF K^- -MESONS FROM EMULSION NUCLEI, B. Bhowmik, D. Evans, G. N. Fowler and D. J. Prowse, University of Bristol.

The small angle scattering of charged particles from nuclei affords a method of determining the sign and magnitude of the potential operating on them in nuclear matter. The present experiment obtains information on the nuclear potential experienced by negative K-mesons in nuclear matter by the study of the small angle scattering from emulsion nuclei of K-mesons in the energy range 30-70 Mev.

A stack of stripped emulsions was exposed to the momentum analyzed K^- -beam from the Bevatron. Tracks having the characteristic grain density expected for the K-meson beam were picked up 3 mm. from the emulsion edge and followed to the end of their range, those due to K-mesons being identified by the ionization-range method. All deflections of greater than 2^o in the horizontal plane were recorded and the space angle of the deflection was measured if the event occurred more than 3 mm. from the end of the K-meson range. The angle of deflection projected in the plane of emulsion was measured to $\pm$ 0.5^o with an ocular protractor and the dip of the track to $\pm$ 0.5^o over a horizontal distance of 100 μ under x45 objectives and x15 eyepieces.

165 scattering events were found between the energy limits 30-70 Mev on 23 metres of meson track length. Only events on tracks identified by being followed to rest have been included to eliminate the possibility of introducing distortion in the differential cross-section by the presence of protons. The differential cross-section is shown in Fig. 32. plotted in barns per steradian with curves calculated for different potentials.

The curves shown in Fig. 32 have been calculated for a mean energy of 53 Mev on the basis of the optical model using an extended charge for the nucleus and phase shift analysis in W. K. B. approximation. The difficulty is to know what value of 'W' (imaginary part of potential) to take. It can be seen that the experimental points fit the theoretical curves reasonably well for $V_{total} = (-15 + i\ 10)$ Mev, although below 10^o the theoretical curves are insensitive.

There is an indication based on very poor statistics that there is a peak in the K-P elastic scattering cross-section at $\sim$ 35 Mev; should the same be true for elastic scattering from nuclei, the mean energy taken here (53 Mev) would not be correct; the effect of lowering the energy would be to raise all the curves, bringing in fact the repulsive potential curve nearer the experimental points. Plotting our results as a function of energy does not, however, indicate within the statistics, a peak at $\sim$ 35 Mev.

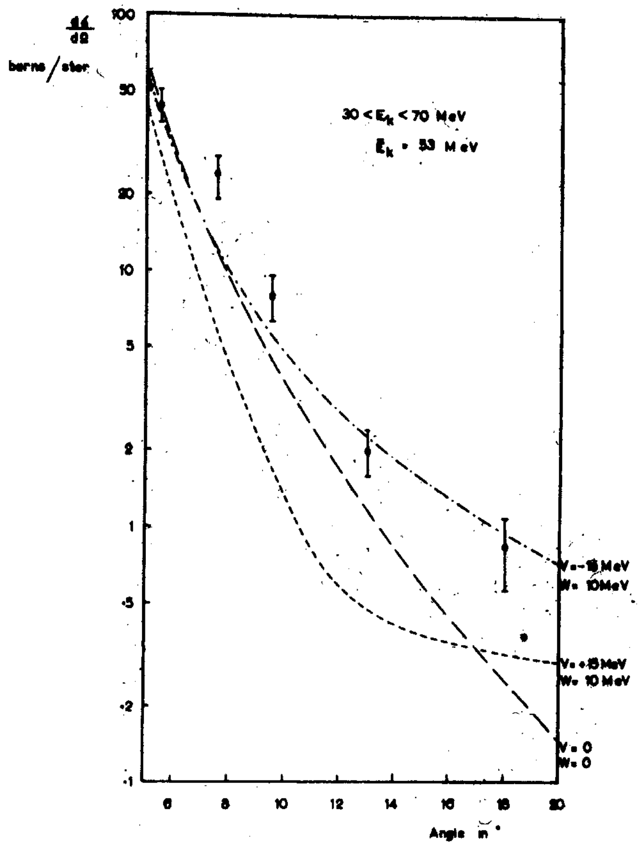

Fig. 32

4) REMARK ON THE MECHANISM OF PRODUCTION OF Σ^+ IN THE K^- CAPTURE AT REST BY NUCLEI IN PHOTOEMULSION,

by T. F. Hoang.

In a systematic investigation on Σ^+ (definitely identified by their decay to $p + \pi^0$) emitted by K^- capture at rest it has been found that about (65 ± 8) % of these Σ 's are associated with a π^- emitted in the opposite hemisphere of the hyperon, and that in these cases no other evaporation prong (including recoil) was emitted. This indicates that the mean free path of absorption of π^- inside the nucleus is on the average $\sim 9.7^{+4.1}_{-2.8}$ fermi assuming the π emitted inside the nucleus.

An attempt was made to determine the energy of the associated π^- by tracing its track to the end; our results together with those of the Livermore group (private communication from Dr. White) are shown in the Fig. 33. The average of $E_\Sigma + E_{\pi^-}$ is 74.2 Mev, while the Q value of the reaction $K^- + P_{\text{bound}}$ is 95.4 Mev. It is to be noted that 50% of these cases have an energy loss $Q - (E_\Sigma + E_\pi) < 14$ Mev and that this energy loss, which seems too small to be regarded as due to π^- scattering, is most likely due to excitation of the residual nucleus.

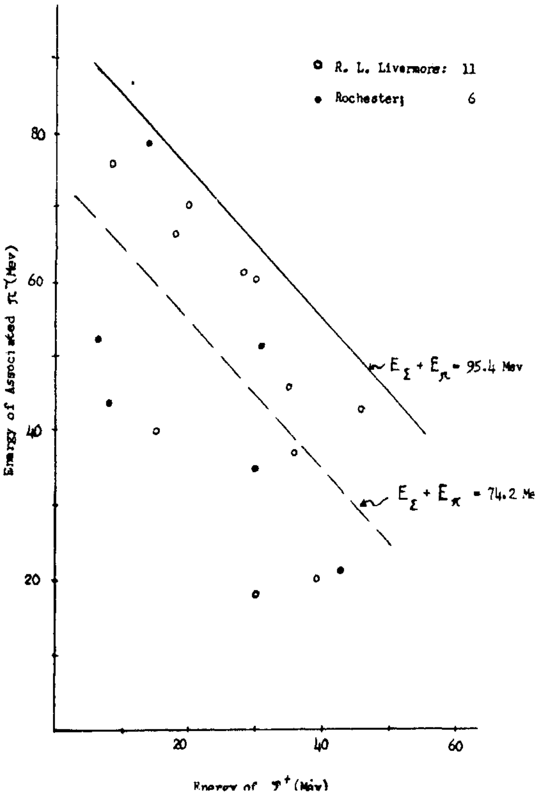

Fig. 33

5) THE INTERACTIONS OF POSITIVE K-MESONS WITH NUCLEI IN PHOTOGRAPHIC EMULSION AT ENERGIES BETWEEN 0 - 130 Mev., B. Bhowmik, D. Evans, S. Nilsson, D. J. Prowse; H. H. Wills Laboratory, University of Bristol. F. Anderson, D. Keefe, A. Kernan and J. Losty; University College, Dublin.

148 Metres of K^+-meson track in the energy range 0 - 130 Mev have been scanned in an unbiased way.

Analysis of the results in elastic and inelastic scattering events indicate that:

(1) K^+ -interactions are consistent with the current schemes for the classification of heavy unstable particles.

(2) the cross-section for scattering from neutrons is 6 ± 3 mb.,

(3) the average emulsion nucleus behaves as a repulsive potential well of ~ 20 Mev. (This comes from the

Coulomb interference in elastic scattering.)

and

(4) that the differential cross-section for the scattering of K-mesons from nucleons within the nucleus is peaked towards backward angles. This is done by analysing the inelastic events assuming the statistical model of the nucleus and a maximum Fermi momentum of 215 Mev/c.

6) LOW ENERGY K-N AND $\bar{K}$-N INTERACTIONS, D. Amati, University of Naples and B. Vitale, University of Catania.

The low energy K-N and $\bar{K}$-N interactions have been studied using the Salam interaction Hamiltonian for the nucleon-heavy meson-hyperon system. We have not taken into account effects due to recoil of baryons, virtual baryon-antibaryon pairs and pion-baryon interactions. We have besides disregarded, in the analysis of the K-N and $\bar{K}$-N scattering states, virtual intermediate states containing more than two heavy mesons at the same time. This can be obtained in a consistent way disregarding $\bar{K}$ contributions when studying K-N interaction, and K contributions when studying $\bar{K}$-N interactions. Our model is then very similar, apart for the presence of isobaric spin indices and matrices, to that already used by T. D. Lee (P.R. 95, 1329 (54)).

In this approximation, the integral equations for the $\bar{K}$-N scattering states can be exactly solved and the phase shifts can be obtained for the two isobaric spin scattering eigenstates with $T = 0$ and $T = 1$ respectively, where T stands for the total isobaric spin of the $\bar{K}$-N system. The integral equations for the K-N scattering states can be solved by the Fredholm method; we have done this using its first approximation. We shall have to deal, also in this case, with two isobaric spin eigenstates with $T = 0$ and $T = 1$, respectively.

A cut-off energy η is introduced, in order to avoid "ghost" difficulties as in the Lee case; for kinetic energies of the K meson up to about 200 Mev results are rather insensitive to the numerical value of η ; they will be given in the following for two different values of η , namely $\eta = 2$ Bev and $\eta = 3$ Bev.

We have assumed the K to have parity equal to the relative parity of nucleon and hyperon; assuming the source function to be spherically symmetric this will give, together with our previous assumptions, nucleon-heavy meson interaction only in S-states.

1) K-N interaction.

If we put $G^2_\Lambda/4\pi = G^2_\Sigma/4\pi = 0.3$ we obtain:

Table 10

$\eta = 2$ BeV;	$E_K = 100$ MeV:	$\eta_0 = -8°$	$\sigma_0 \sim 1$ mb	$\eta_1 = +27°$	$\sigma_1 = 9$ mb
	200 MeV:	$\eta_0 = -11°$	$\sigma_0 \sim 1$ mb	$\eta_1 = +32°$	$\sigma_1 = 6$ mb
$\eta = 3$ BeV;	$E_K = 100$ MeV:	$\eta_0 = -8°$	$\sigma_0 \sim 1$ mb	$\eta_1 = +32°$	$\sigma_1 = 13$ mb
	200 MeV:	$\eta_0 = -10°$	$\sigma_0 \sim 1$ mb	$\eta_1 = +38°$	$\sigma_1 = 9$ mb

The qualitative aspect of these results is not modified in a significant way by small variations for the numerical value of $G^2_\Lambda/4\pi$; the $T = 0$ phase shift is always small and negative, the $T = 1$ phase shift results positive.

There is no value for G^2_Λ that can give the correct $T = 1$ cross section at 100 MeV and at the same time a negligible $T = 0$ interaction if we put $G^2_\Sigma = 0$; the same holds if we put $G^2_\Lambda = 0$. To get negative values for the $T = 1$ phase shifts, we have to use rather higher values of the coupling constants and work in a region with much higher sensitivity to small variations of their numerical values. With $G^2_\Sigma/4\pi = 0.8$ and $G^2_\Lambda/4\pi = 0.4$, for instance, we get:

$\eta \doteq 3$ BeV; $E_K = 100$ MeV: $\eta_0 = -9°$, $\sigma_0 \sim 1$ mb, $\eta_1 = -21°$, $\sigma_1 = 6$ mb.
and the $T = 1$ phase shift is negative to zero kinetic energy.

We conclude therefore that the present model can at least give a good account of the observed enhancement of the $T = 1$ scattering amplitude at low energy over the $T = 0$ amplitude; but that conclusions concerning the sign of the relative phase shifts are of a rather less conclusive nature.

2) $\bar{K}$-N Interaction

It is easy to see that, in our model, only Λ^0 intermediate states contribute to the T = 0 scattering and only Σ intermediate states contribute to T = 1 scattering. The integral equations can be exactly solved.

Using η = 3 BeV we obtain the following table:

$G_\Lambda^2/4\pi$	$G_\Sigma^2/4\pi$	E_K(Mev)	η_0	η_1	σ_0(mb)	σ_1	σ $(K^-+p)_{el.}$	σ $(K^-+p)_{ch.ex.}$
0.3	0.3	30	-12°	-14°	7	9	8	0.1
0.3	0.3	100	-20°	-24°	5	7	6	0.1
0.4	0.8	30	-15°	-23°	10	23	16	1.0
		100	-24°	-40°	7	18	12	1.0

The phase shifts are negative for both values of the isobaric spin.