100-21345

I

NYO-3046

PROCEEDINGS OF THE ROCHESTER CONFERENCE ON MESON PHYSICS

January 11-12, 1952

by

A.M.L. Messiah and H.P. Noyes

Dept. of Physics, University of Rochester
Rochester, New York

AT (30-1) - 875

36
4

Individual copies will be supplied upon
request as long as the supply lasts.

This document is
PUBLICLY RELEASABLE

H. Kinn
Authorizing Official

Date: 10/20/29

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

II

Foreword

A small informal conference on Meson Physics was held at the University of Rochester on January 11-12, 1952 (this being the second of a series made possible by the support of a group of Rochester industries). The first day of the conference was devoted to π meson interactions with nuclei and the second to the new unstable particles. Although no formal papers were presented, it seemed worthwhile to make the conference deliberations available to a wider audience. In their account of the proceedings, Mr. A.M.L. Messiah and Dr. H.P. Noyes have attempted to combine haste, brevity and accuracy while at the same time retaining some of the flavor of the original discussions.

R. E. Marshak

III

TABLE OF CONTENTS

page

Interaction of π Mesons with Complex Nuclei

10:00 A.M. Friday, January 11, 1952. Prof. Enrico Fermi Presiding.

Lederman: Cloud Chamber Experiment made at the Nevis cyclotron	1
Steinberger: Absorption of 60 Mev π mesons in carbon	3
Bernardini: π meson reactions in photographic plates	5
Ficcion: Preliminary total cross sections in C and CH_2 for an average π energy of 10^9 ev.	7
Salvini: Cloud chamber study of meson reactions in C and Pb	8
Alvarez: π^- backward scattering in Al, Cu and Pb	9
Anderson: π meson reaction cross sections in Be, C, Al, Cu, Zn, Cd, and Pb	10
Theoretical interpretation: A general discussion started by Bethe	11

Interaction of π mesons with hydrogen and deuterium

2:00 P.M. Friday, January 11, 1952. Prof. Enrico Fermi presiding.

Anderson: Absorption of π^+ and π^- mesons in hydrogen and deuterium	19
Fermi: Discussion of these results	24
Brueckner: Theoretical Interpretation of meson scattering and photomesic production	26
Messiah: On the experimental support of the charge independence hypothesis	39
Wentzel: "Orthodox" strong coupling theory	41
Fermi: Electron contamination of the Chicago meson beam	45
Cocconi: Photoproduction of neutral mesons	47

Megalomorphs (V, ν , K, $\bar{K}$)

9:30 A.M. Saturday, January 12, 1952. Prof. J. Robert Oppenheimer Presiding

Oppenheimer: Introductory remarks	50
Fretter: Data on V particles	52
Report on Leighton's data	56
George: Report on K meson production in high energy nuclear events observed by Perkins, et. al.	58
Ritson: Note on relativistic increase of ionization	62
Peierls: Report of Bristol data on K and $\bar{K}$ mesons	66
Greisen: Evidence against the copious production of K mesons at high energies from the underground data	66

2:00 P.M. Saturday, January 12, 1952. Prof. J. Robert Oppenheimer Presiding

Fretter: Further report on Leighton's experiments	69
Abstract of V particle data from Manchester	69
Thompson: V particles	73
Rossi: Report on the work of Bridge and Annis	79
Lord: "V particles" produced by the Chicago cyclotron	82
Oppenheimer: Introduction to theoretical discussion of the heavy particles	85
Pais: An ordering principle for megalomorphian zoology	87
Marshak: "To be or not to be (astonished), that is the question."	93

Appendix I: List of Conferees

Appendix II: Abstracts of papers not presented at conference

Appendix III: Extract from letter of Fermi to Feynman

Appendix IV: Summary of Proceedings (Some People Don't Know Where to Stop"
by Arthur Roberts)

INTERACTION OF π MESONS WITH COMPLEX NUCLEI

10:00 A.M. Friday, January 11, 1952. Professor E. Fermi presiding.

In the first place a survey of the experimental situation is given. An attempt to dig out the experimental results: what is the relative importance of the various events which can take place (for example, the relative importance of shadow scattering and nonshadow scattering), the importance of interference effects, and so on.

Lederman. Cloud Chamber Experiment Made at the Nevis Cyclotron.

A cloud chamber in a magnetic field containing a carbon plate has been exposed to the π meson beam of 62 ± 10 Mev produced in the Nevis cyclotron. The experiment is performed with mesons of both charges. A similar experiment has been performed with the Cornell synchrotron by Shapiro, with a meson beam of 48 ± 15 Mev. Shapiro's results are in essential agreement with the results of Lederman and collaborators, and they are indicated in the table below. The Columbia workers analyze their data in the following fashions: they call elastic scattering any scattering event in which the energy loss of the meson is less than 15 Mev; all other scattering events are called inelastic scattering and any event in which no outgoing meson is observed is called a "star". In particular, 15 % of the π^+ stars and 20 % of the π^- stars are "zero prong stars". It must be noted that the charge exchange events are here automatically counted as "stars", and also, that, due to the finite thickness of the plate ($2g/cm^2$) some of the inelastic scattering events are seen as stars in this experiment. The angular distribution for

scattering of mesons of both charges is shown on Graph I which follows.

The main feature of these two curves is the very strong forward scattering and also a slight increase of the scattering cross section in the backward direction for the π^- mesons. The very large charge dependence of the elastic scattering must also be noted; for instance at 20° , one obtains 100 mb/sterad. and 15 mb/sterad. for π^- and for π^+ respectively. (Noted in graph).

Results concerning the total cross sections are given in Table I.

Table I
(cross sections in mb)

	Elastic scattering		Inelastic scattering $\Delta E > 15 \text{ Mev}$	Stars			Total Incoherent
	$20^\circ - 180^\circ$	$65^\circ - 180^\circ$		Protons	40 Mev	Total	
				0	1	2	
π^-	165 ± 15 (95 ± 34)	63	46 ± 10	110	34	4	148 ± 18 (240 ± 54)
π^+	89 ± 11 (78 ± 23)	38	15 ± 8	34	77	42	153 ± 22 (215 ± 37)

the first column concerns the elastic cross section integrated from 20° to 180° ; column two gives the total cross section for inelastic scattering and column three the total cross section for "star" production; the sum of the last two, namely the total absorption cross section is reported in column four; the numbers between parenthesis are the results of Shapiro's experiment at 48 Mev.

The absorption of π^+ mesons exhibits an interesting feature. In $12 \pm 4\%$ of the observed stars, two fast protons emerge, both with energy ≥ 60 Mev and, within 10° , in opposite directions, consistent with the reaction $\pi^+ + d \rightarrow p + p$.

Fermi noted that the total cross section which is reported by this experiment and various others seems quite close to geometrical, a fact rather puzzling as one would expect perhaps $2\pi R^2$ in order to leave some room for the diffraction scattering. Bethe gave the following explanation: light elements like carbon are partly transparent, and the total cross section which is observed, namely about 350 millibarns, is just about the geometrical cross section. As far as the heavier elements are concerned, for example, silver, the diffraction scattering goes into such small angles that, with the geometries used, it could not be seen; more precisely, it is impossible to distinguish between diffraction scattering and multiple scattering because both regions have the same width in silver, for example.

Steinberger. Absorption of 60 Mev π Mesons in Carbon.

In connection with this point, Steinberger referred to

an absorption experiment on 60 Mev π mesons in carbon, which has been performed at Columbia. It is a transmission experiment arranged in the following manner: the incident beam is defined by two $2\frac{1}{2}$ inch crystals ten feet apart, the second crystal being 18 inches from a $4\frac{1}{2}$ inch crystal. Absorbers are placed in the 18 inch gap, their centers subtending a half-angle of 50° at the $4\frac{1}{2}$ inch crystal. Without the absorbers, 95% of the beam is detected in the final crystal. It is clear that the diffraction scattering is completely missed by this experiment. One finds a cross section of 237 ± 20 millibarns, and if one allows 45 millibarns for elastic scattering (Lederman's result), one is left with 192 millibarns for the inelastic and star production cross section; this is much less than the geometrical cross section, namely 1000 millibarns, which would be obtained if the nucleus were completely black. It must be noted that in his calculations of the geometrical cross section, Steinberger adds to the radius of the nucleus the wavelength of the incoming meson. Bethe asked to what extent it is possible to measure experimentally the reaction cross section, that is the cross section for any event except shadow scattering, and the answer is that the measurement should be done in two steps: first, to determine the total absorption by an attenuation measurement, then to measure the part taken by the backward elastic scattering which must be subtracted. This has been done for carbon only, up to now. In heavier elements presumably the backward scattering would be much less; to be more precise, the backward scattering could be greater in absolute value but much less compared with other events.

Bernadini's π Meson Reactions in Photographic Plates.

Photographic plates have been exposed to the beam of mesons coming out of the Nevis cyclotron. Mesons of either charge are considered and the energy of the meson beam may range from 30-100 Mev. One calculates the total cross section for capture and inelastic scattering; one calls "inelastic" scattering events those where the energy loss of the meson is greater than 10 % of its original energy; the results are collected in the following table.

150 Events. Capture and Inelastic Scattering of π Mesons in Photographic Emulsion

The cross sections σ are given in barns, the mean free paths λ in cm.

Energy	35-50 Mev		70-80 Mev		~ 100	
	λ	σ	λ	σ	λ	σ
π^+	35 ± 4	0.38 barns	25.5 ± 3	0.67 barns		
π^-	30 ± 4	0.69 barns	21 ± 3	0.95 barns	22.7 ± 2	0.92 barns

The statistical accuracy is about 10% . These cross sections are average cross sections over the elements composing the emulsion, more precisely they are an average by atoms. They should be compared with an average geometrical cross section, namely the average area covered by the different nuclei, which in this case is 0.830 barns (75% of this area is contributed by the heavy nuclei and 25% by the light nuclei in the emulsion.) In such experiments, meson reactions with hydrogen are easy

to detect, and only two out of 400 have been seen, despite the relative abundance of hydrogen in the emulsion. (The relative abundance of hydrogen, silver and carbon in the emulsion goes as 5.6, 1.7 and 2.25). One must note also that some of the mesons which were actually inelastically scattered may have been counted as elastic scattering and, therefore, may have been lost in the computation of the cross section; however, the error cannot be too large, since the elastic scattering is very probably concentrated in the forward direction and since the average energy loss in the inelastic events is found ^{to be} surprisingly large. The total elastic scattering cross sections at angles $> 35^\circ$ were found to be in this specific experiment .17, .19, .15, .17, and .19, that is, almost independent of energy, and rather small. At 100 Mev, the cross section is about the geometrical one, presumably slightly higher, which is accounted for if one considers that the meson has a finite size. At lower energies, the energy dependence should be compared to some extent with the excitation function for meson-deuterium capture. The details of the inelastic scattering events at 100 Mev confirm the previous ones at lower energy: they constitute more than 20% of the incoherent processes (40 sure inelastic scatterings out of 188 "stars" + stops + inelastic scattering); the same peculiar angular distribution and the same large average energy loss (about 60 Mev) is found. Bernardini proposes to explain the difference in the reaction cross section for π^- and π^+ mesons as the Coulomb barrier effect. According to the classical formula the ratio is given by:

$$\gamma = \frac{\sigma_{\pi^-}}{\sigma_{\pi^+}} \approx \frac{1 + V/E}{1 - V/E}$$

where V is the barrier height and E the meson energy.

One finds:

$\frac{E}{\sim 40 \text{ Mev}}$	$\frac{\gamma \text{ exp.}}{1.8}$	$\frac{V \text{ exp.}}{10 \text{ Mev}}$
$\sim 70 \text{ Mev}$	1.4	9.6 Mev

This estimate of the barrier height of $V \sim 10 \text{ Mev}$ should be compared with the conventional barrier for heavy elements in the emulsion ^{of} $\sim 11 \text{ Mev}$, and that for light ones ^{of} $\sim 3 \text{ Mev}$ (The relative rates of heavy and light nuclear interactions are about 80% and 20%). It must be noted that the classical formula above is only valid when $V/E \ll 1$.

Piccioni. Preliminary Total Cross Sections in C and CH_2 for an Average π Meson Energy of 10^9 ev .

This is a cosmic ray experiment using π mesons created in penetrating showers. The experimental arrangement is the following: the π mesons originate in a block of lead containing counters imbedded in the lead to form a penetrating shower detector. Below this detector is a piece of magnetized iron and below this the absorber in which π meson reactions are studied, both surrounded by hodoscopic counters that define the deflection of the incident particles in the iron to 2° . One can in this way obtain: a) the ratio of the number of positive to negative particles in the shower, which is found to be $1/5$; therefore, the positive excess due to protons is no more than 20% of the particles. Other experiments have shown that μ mesons are not produced in such an arrangement. b) The energy spectrum of the particles. The spectrum starts at 200 Mev and 75% of the particles have energies of more than 300 Mev. The spectrum has a maximum at 500 Mev and above this falls off according to a power law. Since the average meson wavelength is 10^{-14} cm , the shadow scattering occurs at angles less than 20° and has a cross section ^{of} ~ 0.2 geometrical.

The cross section for inelastic events and for scattering at angles $> 20^\circ$ in carbon is found to be 230 millibarns. This cross section has been corrected for the errors due to loss by ionization in the carbon plate and for ^{the} errors due to the existence of μ meson showers (a 10% effect). The charge exchange events have also been looked for and the cross section appears to be extremely small, too small in fact to be measured with good accuracy. One finds 40 ± 80 milli-

barns. This result seems to be in contradiction with the previous result of cloud chamber experiments indicating that practically the full geometrical cross section of carbon gives rise to charge exchange. Concerning the total cross section for events in carbon given above, one must note that shadow scattering is expected to be within 20° and should not be included in this cross section. Very preliminary results concerning the total cross section for inelastic events and scattering above 20° for hydrogen lead to 20 ± 15 millibarns. No difference in cross section between π^+ and π^- has been detected. Errors due to $\pi \rightarrow \mu \rightarrow e$ decay are less than the ionization correction.

Salvini. Cloud Chamber Study of Meson Reactions in Carbon and in Lead.

The experimental arrangement consists of carbon or lead plates in a cloud chamber. 70 - 80% of the incident particles are in the relativistic energy range. The experimental arrangement permits one to detect the electromagnetic component and, by the same token, to detect possible cases of charge exchange. The meson energy investigated is the same energy range as Piccioni used. The charge exchange events are found to be extremely small. In carbon, out of 67 events, five were accompanied by electromagnetic radiation; in lead, out of 73 events, nine were accompanied by electromagnetic radiation. The events accompanied by emission of electromagnetic radiation are then analyzed to see if they can be due to charge exchange. It is concluded that two out of the five events in carbon and five out of the nine events in lead could possibly be charge exchange; however, it is not proved at all that they are charge exchange. Combining the results of these two experiments one finds that out of

100 charged mesons, ⁴³ will undergo scattering (usually/with a very scattering large energy loss), 20 events will be accompanied by electromagnetic radiation out of which not more than 10 could be charge exchange, and 40 events will be observed without electromagnetic radiation nor any outgoing mesons.

Alvarez. π^- Backward Scattering in Aluminum, Copper and Lead.

The experiments were carried out by Harry Heckman in Barkas' group. A beam of π^- mesons of 50 - 70 Mev is obtained from the Berkeley cyclotron and is sent ^{into} ~~on~~ the material under study in which the photographic plates have been imbedded; the π^- meson is identified by the star produced in the photographic plate. Meson reactions in the surrounding material may be analyzed in the following manner. If there were little scattering, the ratio of forward to backward mesons stopping in the plates would have a sharp maximum at the plate corresponding to their range in the material under study. If, however, there is appreciable elastic scattering this ratio will be constant up to this plate. If one makes the extremely questionable assumption that the back scattering is chiefly elastic scattering and that the elastic scattering forward is equal to the elastic scattering backward, one obtains the following results for the total elastic scattering in various materials (i.e. two times the measured back scattering). In copper, $\sigma_{Cu} = 480 \pm 120$ millibarns, that is 1/2 of the nuclear area; in lead, $\sigma_{Pb} = 1000 \pm 300$ millibarns, that is 1/2 of the nuclear area; in aluminum, $\sigma_{Al} = 100 \pm 30$ millibarns, that is 1/6 of the nuclear area. As was remarked by Oppenheimer, the measurements reported here are a rough measurement of the back scattering with no particular effort to discriminate

between elastic and inelastic scattering. One must note however, that one advantage of this type of experiment over the experiment in plates (like Bernardini's experiment) is that there ^{one} gets the effect on all the elements which compose the photographic emulsion.

Alvarez mentioned also experiments in photographic emulsion which are of the same type as Bernardini's and which have been performed by Bradner and Rankin in Berkeley. They will not however, be reported at this conference because their results are given in a different fashion from Bernardini's and consequently the comparison with Bernardini's results is rather difficult to make for the moment.

Anderson. π Meson Reaction Cross Sections in Beryllium, Carbon, Aluminum, Copper, Zinc, Cadmium, and Lead.

These are straight absorption experiments and the experimental arrangement is just the same as the one used by Steinberger in the similar experiment that he performed at the Nevis cyclotron. The beam of mesons passes through the scintillation counters 1 and 2, then through the absorbing material, behind which are placed the scintillation counters 3 and 4. Counter 3 subtends a cone with apex at the middle of the absorbing material of half-angle 50° ; the corresponding cone for counter 4 has half-angle 25° . Experiments are conducted with and without the absorber. Coincidences 1, 2, 3, are recorded; then coincidences 1, 2, 4 permit correcting for shadow scattering (this correction is calculated by assuming the nuclei to be black and considering the apparent increase in the absorption cross section when one passes from the first coincidence arrangement to the second one, an increase which turns out to be 15% for carbon and 7% for lead.) The experiment

has been conducted with π^- mesons only, in two energy bands, namely 109 ± 10 Mev and 133 ± 10 Mev. Measurements have been made with the following absorbers: beryllium, carbon, aluminum, copper, zinc, cadmium and lead. One finds reaction cross sections (that is, the cross section for any event except diffraction scattering) just about the geometrical cross section (namely $\pi r_0^2 A^{2/3}$, where $r_0 = 1.4 \times 10^{-13}$ cm) with an accuracy of about 15%. The results for carbon and copper are recorded in the following table.

π Meson Reaction Cross Sections

	E(Mev)	σ C	σ_{Cu}
π^- Chicago	133 ± 10	406 ± 27 mb	1014 ± 65
Chicago	109 ± 10	385 ± 41	1005 ± 66
Columbia	85	344 ± 13	990
Columbia	60	237 ± 10	940
Columbia	42	195 ± 10	960
π^+ Columbia	60	229 ± 20	
π^+ Rochester	38	250 ± 50 (preliminary)	

The cross sections reported in this table are not corrected for shadow scattering. The results obtained with ~~the~~ meson beams of lower energy in the similar experiment of Steinberger at Columbia are reported also in this table for purposes of comparison ^{as is} ~~as is~~ a very preliminary result obtained by Barnes at Rochester.

Theoretical Interpretation

According to Bethe, three important results may be obtained from Lederman's experiment at Columbia:

- a) The determination of the mean free path of the meson in nuclear matter.
- b) The definite existence of interference between Coulomb scattering and diffraction scattering.
- c) The observation of pairs of high energy protons coming out of the nucleus with approximately opposite directions.

The mean free path ℓ_Λ of mesons in nuclear matter can be obtained from experiments on partly transparent nuclei like carbon. This mean free path turns out to be: with 60 Mev π^- at Columbia, $\ell_\Lambda \approx 7 \times 10^{-13}$ cm., with 40 Mev π^- at Cornell, $\ell_\Lambda \approx 4 \times 10^{-13}$ cm. (Steinberger would prefer to give 9.5×10^{-13} for the ^{first} figure). The difference between the two numbers should be found rather in the analysis than in the experimental results themselves.

From the existence of interference between ^{Coulomb} scattering and diffraction scattering, that has been observed in Lederman's experiment, one can conclude that the π^- meson feels a 12 Mev/^{deep} attractive potential, in the carbon nucleus. The previous very rough measurements of this potential made at Cornell agree with this number. If one tries to interpret this number in terms of an average scattering amplitude for the scattering of mesons by an average nucleon, one finds that this scattering amplitude is far smaller than the well established scattering amplitude of π mesons by protons. From this, one has to conclude that the scattering potential of π mesons by protons and by neutrons have opposite signs, i.e. $V(P + \pi) \approx -V(N + \pi)$.

Weisskopf remarked that one could as well conclude that the meson-nucleon potential is completely different in nuclear matter from that in free space. This view was supported by Oppenheimer, who made a comparison of this phenomenon with the phenomenon of capture in nuclei. In fact, so much goes on that one could not expect to be able to build it up from what is observed in the elementary process. One could ask the question, for instance, whether a big modification to the situation in free space could come from the fact that (low momenta) recoils of the nucleon are excluded. Lederman's and Bethe's answer to this is that this recoil effect has been calculated for the forward scattering and is small.

In connection with this discussion of the diffraction scattering, Serber proposed the following interpretation which could explain the rise of the elastic scattering cross section in the backward direction. The diffraction scattering occurs inside an angle determined by the ratio

λ/R where λ is the wavelength of the π meson and R the radius of the nucleus. Another effect which comes in is the correlation scattering between closely correlated nuclear particles which gives angles determined by the ratio λ/d , where d is the distance between the two nucleons, rather by the previous ratio λ/R , which means angles greater by an amount about $2R/d$; therefore, one may think the rise in the backward direction may be due to correlation scattering. A calculation of such correlation effects would of course depend very strongly on the model. But its main qualitative feature would be to present some wiggles at big angles, and the rise in the backward direction may be thought of as one such wiggle.

The last item discussed by Bethe is the observation of a pair of protons coming out of the nucleus with high energy and about opposite directions in the absorption of positive π mesons. This observation gives support to the conjecture, whereby the positive π is captured by a "deuteron" in the nucleus:

THIS CROSS SECTION IS

Λ to be compared with the cross section for capture of π^+ mesons by free deuterium, which has been measured experimentally; one can in this way deduce the number of "deuterons" present in the nucleus and one finds 5Z. This should be compared with the interpretation given by Levinger of the photoelectric effects in heavy nuclei; he is lead to a number of "deuterons" ^{equal} to $\Lambda \approx 1.6A$, and one must consider the agreement as quite good in view of the uncertainties of such theories. This number should be useful to interpret other experiments in nuclei where the internuclear interaction plays an important role.

In connection with the problem of capture of mesons by nuclei, Rossi mentions the study conducted at MIT of the capture of negative π mesons in He^4 made in a cloud chamber. The result is that the capture process leads chiefly to protons; tritium has been seen in only one event? One must note that there is a possibility of having missed some low energy deuterons in this experiment.

According to Marshak, the question arises whether in nuclei it is the "deuterons" which do the job of absorbing, or whether the pro-

cess is undertaken by larger ^{clusters of} particles. In fact, in the absorption of slow π^- mesons, the deuteron model does not work well and predicts a much too large number of high energy protons coming out. It is certainly consistent to take the deuteron model for this particular experiment we are speaking about, but it is not sure at all that the multinuclear model should be excluded. Bethe's answer to this is that ^{here} the deuteron model really stares you in the face, because ^avery large fraction of the stars that you see are really two fast outgoing fast protons coming in almost opposite directions. Steinberger's view is that there is no need to speak about deuterons in the nucleus since the only way of getting the absorption of positive π mesons is precisely to have two protons coming out as seen; and, in fact, the same Fourier transform

which was proposed by Chew and Goldberger, would fit the experimental result very nicely. Oppenheimer explained that to speak of ^adeuteron model or any other model is nothing else than a way to describe a number of types of momentum transfer between nucleons that may occur when the absorption process takes place. As an argument against the deuteron model, Bernardini quotes an experiment of capture in flight of positive π mesons by heavy nuclei. In 10% of the cases, one gets a very high energy proton which could not be obtained by a deuteron model. Serber remarked that the occurrence of the correlated high energy protons is indeed remarkable, as it implies a high correlation between neutron and proton in the nucleus at a separation of 5×10^{-14} cm. Bethe wanted to draw the attention again to Levinger's calculation, because he actually took the two body forces and calculated how much

correlation there should be to explain the γ ray absorption. Breit asked if this result was consistent with α particle structure in the nucleus. Bethe said yes, since these correlations could also occur inside α particles.

At this point, Heisskopf asked for a more systematic discussion, as he had not understood what either Oppenheimer or Bethe had said, and did not think he was alone. Oppenheimer tried to clarify the matter in the following way: we were used to think^{ing} of the nucleus as a homogeneous structureless affair for low energy nucleons, though we know that very strong interactions do set in when they are tried out alone in free space. If you add the last neutron or the last proton to a nucleus, you do not find that it acts as if it were in a very stormy sea, but rather in a very smooth potential. However, when sufficient energy is available, the storm turns on. The inconsistency between the nucleon scattering experiments and the success of the shell model, in explaining nuclear structures, has been considered as an indication that strong nonlinearities of some kind exist in the nuclear body, such that in the nucleus you lose the binary interaction that you detected in the scattering. Now, in so far as those numbers fit, it seems more correct to say that the shell model has really to do with ^{the} exclusion principle and not with the washing out of the nuclear forces. Chew suggests the following interpretation: when two nucleons are close together in the nucleus $(n) + (p)$, the potential dominates their wave function to a certain extent, but the shape of the wave function is about the same as in deuterium; the difference is only the normalization.

Then to get the normalization, it would be a fairly good guess to take the ratio between the average density in the nucleus and the average density in the deuteron. The factor of 5 should not then be too surprising. Then, Bethe, explained that one must take in the deuteron only its inner part, that part which has very high momenta; and, to talk about the number of effective deuterons is just to talk about the probability of getting high momenta. All that is done is to join the wave function of the deuteron at distances smaller than 10^{-13} cm. to the general wave function, and even the n-p scattering should be contained already in this inner part of the deuteron wave function. Marshak proposed the following test of Bethe's view: namely to see how the capture

cross section of positive mesons ~~with~~^{by} C^{12} and N^{14} compare, since the difference between the two nuclei is in the extra deuteron which exists in N^{14} . According to Bethe's guess, the 5 Z law should hold, therefore a ratio 6/7 should be found. The experiment is now being tried at the Rochester laboratory. The energy dependence, according to this view, should be given by the energy dependence of the deuteron, but it is hard to calculate because here you must really know the forces at small distances. Roberts remarked that in an old experiment the production of two fast protons in oxygen was found to be quite small - only one or two millibarns - which seems to be in disagreement with these results. Although these experiments were at lower energy, the discrepancy appears real as most of the energy comes from the

rest mass of the π . Foldy wondered if these results were incompatible with absorption taking place at the surface of the nucleus, that is

whether they are a strong argument against non-linearity. Bethe countered with the question of how such non-linear effects would affect the meson wave function entering the nucleus, which according to the diffraction experiments suffers little change. Bernardini commented that the stars in photographic emulsions are in agreement with the Goldberger model of absorption by two fast nucleons, using the mean free path of 7×10^{-13} cm. for the meson. Oppenheimer would not question the existence of non-linear effects, but thought that surface absorption would be much more likely to give a single fast nucleon, with the rest of the energy going to the nucleus as a whole, rather than two fast protons coming out in nearly opposite directions.

Cocconi raised the question of whether there could not be some general agreement of what is meant by "geometrical cross section". Fermi suggested $1.4 \times 10^{-13} \text{ cm}^2$ as a nice round number, but was ready to accept $1/\mu$ instead. Bethe objected that the $1.47 \times 10^{-13} \text{ cm}^2$ obtained from isobar energies in β decay, is probably the most accurate value for the nuclear radius and is not in agreement with this. Fermi countered that the notion of nuclear radius is probably intrinsically inaccurate, namely "that if you were crossing the radius you probably would not notice it".

Marshak asked how strong the evidence is for opposite sign for the interaction between $\pi^+ p$ and $\pi^- n$. Bethe thinks it is well established. Marshak went on to point out that there is an ambiguous way in which one could interpret the results of the experiment. He said that the results of the experiment are not yet clear, and that the results of the experiment are not yet clear.

2:00 p.m. Friday, January 11, 1952 Prof. E. Fermi presiding

Interaction of π Mesons with Hydrogen

Anderson. Scattering of π^+ and π^- Mesons in Hydrogen.

These recent experiments have been conducted with meson beams of energy ranging from 50-220 Mev. The meson beam produced in the Chicago cyclotron is bent in the fringing field of the cyclotron, then passes through a channel in a steel wall, is bent in a 45° magnet to remove every particle that does not have the same magnetic rigidity as the mesons which will be considered in the experiment, then is sent into the observation arrangement. The energy measurement is made by a stretched wire. No background counts are measured when the deflecting magnet is turned off; it selects an energy band of ± 4 Mev. The first experiments have been made with π^- mesons and they are a standard transmission measurement. The experimental arrangement is as follows: the meson beam is defined by passing through the two crystal scintillation counters 1 and 2. Then is placed the absorber, which is a tank of liquid hydrogen, then at least two liquid scintillation counters 3 and 4. Recording the quadruple and double coincidences, with and without the hydrogen in the tank, permits one to determine the absorption cross section. One must note that the geometry in the experiment is rather good: assuming an isotropic distribution of the scattering, it is found that only 2% of the scattering events are recorded in 3 and 4. The coulomb scattering is very small (less than 1%), and corrections for it are made, for example, by inserting an aluminum scatterer that gives the same coulomb scattering. Many corrections are made, in particular, a correction for π - μ decay in flight. An advantage of using a liquid hydrogen target is that, compared with the CH_2 target, the energy loss is considerably less, and, therefore, the beam energy is

better defined. (Also the decay in flight is a function of the velocity,

which gives a larger ^{correction} in a C - CH₂ experiment) The meson beam is

contaminated with electrons and negative muons which have the same momentum

as the negative pions. This contamination is measured by an absorption

experiment in aluminum. Above 100 Mev one finds about 6 % negative

muons, and 1 % or less electrons. Below 100 Mev the number of electrons

increases enormously and the beam is about 70 % electrons at 60 Mev.

This contamination has been taken into account in the calculation of

the total absorption cross section. The experimental results are

recorded in the accompanying table(I). These results are also in the

accompanying graph(I) Cross sections should be compared with the

"geometrical" cross section, namely 61 millibarns. One notes the

continuous increase in cross section with energy, until it reaches

at about 170 Mev, the "geometrical" cross section. The next series

of experiments attempted to measure the relative importance of the

various reactions of negative pions with hydrogen which could take place.

This was made with a meson beam of 112±6 Mev because it was the beam which had

Table I

Energy band (Mev)	$\sigma (\pi^- + p)$ in mb	$\sigma (\pi^+ + p)$	Laboratory
55 $\pm$ 5	(3 $\pm$ 2)		(Brookhaven: pure scattering)
56 $\pm$ 8		20 $\pm$ 10	Chicago
60 $\pm$ 20	19.6 $\pm$ 3	28 $\pm$ 3	Columbia
82 $\pm$ 7		50 $\pm$ 13	Chicago
85 $\pm$ 15	21 $\pm$ 3		Columbia
89 $\pm$ 8	21 $\pm$ 8		Chicago
112 $\pm$ 6	31 $\pm$ 9		"
118 $\pm$ 6		91 $\pm$ 6	"
135 $\pm$ 6	52 $\pm$ 6	152 $\pm$ 14	"
176 $\pm$ 6	66 $\pm$ 6		"
217 $\pm$ 6	60 $\pm$ 6		"

22

the largest intensity. The cross section for photoabsorption of pions by hydrogen may be obtained from the inverse process; using a detailed balance argument; one gets 3 millibarns, a rather small number. All the rest of these events are divided between direct scattering and charge-exchange scattering. The relative importance is estimated by conducting direct scattering experiments placing the two final counters opposite the target at 90° to the beam. The γ ray from the π^0 decay can be observed in the two counters at 90° if one interposes a lead converter. Quadruple coincidences are recorded with and without the lead converter, with and without hydrogen in the tank. One gets an estimate of the cross section for charge exchange and ^{the} cross section for direct scattering, by making some assumption about the angular distribution of those reactions. The result is not too sensitive to the angular distribution assumed.

If one assumes isotropy, one finds:

$$\sigma(\pi^-, \pi^0) \simeq 25 \text{ mb} \pm ?$$

$$\sigma(\pi^-, \pi^+) \simeq 13 \text{ mb} \pm ?$$

which add ^{roughly} up _A to 31 mb as they should. It is very clear that these measurements are very rough. However, it is absolutely certain that charge exchange scattering dominates the other. Note that if the π^0 meson would decay into electron pairs also, rather than decay only by emitting two γ rays as has been assumed, this would make the percentage of charge exchange even greater.

Experiments with positive pions have also been conducted. One can get positive pions in the same range of energy, but very much lower in intensity, by reversing the proton current in the cyclotron (and the current in the deflecting magnet), thus selecting mesons coming backward from the cyclotron target. The positive pion beam is very low

less contaminated than the negative pion beam. At 60 Mev, one found 40% positrons, and this contamination was going down very rapidly with increasing energy, so that it was completely negligible above 100 Mev. The cross section is reported on the table and on the graph given above. One notes the steep increase of this cross section with energy, and also that this cross section is very much larger than the similar cross section for π^- mesons, reaching a factor of 3 around 135 $\pm$ 6 Mev. The ratio 3 at this energy has been rechecked, by making two measurements where the experimental arrangement was exactly identical except for reversing the sense of the field in the magnets.

To the Chicago points must be added several other experimental points which have been obtained in other laboratories. They are indicated in the table and in the graph. Firstly, there are points measured at Columbia by Steinberger and collaborators. These are transmission experiments, and the experimental arrangement is the same as in the Chicago experiment, except that polyethylene rather than liquid hydrogen is used as an absorber. One must mention also the cross section at Brookhaven, obtained by sending the beam of 50 Mev negative pions in a diffusion cloud chamber and recording the number of scattering events found in a given length of track. The cross section, which is therefore the cross section for pure scattering: $\sigma(\pi^-, \pi^-) = 3 \pm 2$ mb; Lederman added that the π^+ cross section was about twice the π^- cross section. Tracks have also been observed which merely stopped in the gas of the chamber, but it is impossible to say at the moment if these stops are charge exchange events, or if the track is fading out because the saturated vapor has been exhausted. Very preliminary results are reported by Lord concerning the analysis of photographic emulsion exposed to a beam of 135 Mev negative pions. A few scatterings of negative pions by protons in the emulsion are isolated

by observing the angles of the recoil proton and of the scattered meson with the incident track and showing these correspond to the correct angles. The method is checked by counting also all $p - p$ collisions of the 400 Mev protons giving a total cross section for 22 events of 25 mb, which agrees with Berkeley. Since therefore, all $p - p$ events are seen, it seems likely that all $\pi^- - p$ scatterings are also seen. Seven events have been observed and lead to a cross section for pure scattering of 4 ± 2 mb. Finally, one must report the cross section reported by Piccioni in the morning session, of 20 ± 15 mb, which is an average cross section for pions of both signs; according to Piccioni, although those results were very preliminary, it seems that the difference between π^+ and π^- is wiped out at this energy.

Another series of experiments concerns the measurement of absorption cross sections of mesons of both signs in deuterium. Such measurements have been made both at Columbia and Chicago. They consist of a standard transmission measurement; the cross section is obtained by comparing the attenuation beam when one encounters heavy water or ordinary water. The results are recorded in Table II. The sum of the

cross sections for π^- and π^+ absorption in hydrogen is also given.

One sees that the assumption of charge symmetry (not to be confused with charge independence), which requires that the absorption cross section in deuterium of negative and positive mesons be equal, is consistent with the experimental results. On the other hand, one remarks

Table II

E (Mev)	$\sigma_{\pi\pi}^{\pm\pm}$ (mb)		$\left(\sigma_{\pi^-}^H + \sigma_{\pi^+}^H \right)$ (mb)	Laboratory
	π^-	π^+		
39 $\pm$ 25		12 $\pm$ 14		Chicago
60	33 $\pm$ 4	36 $\pm$ 4	(44)	Columbia
72 $\pm$ 17		60 $\pm$ 12	(70)	Chicago
79 $\pm$ 10	51 $\pm$ 14	74 $\pm$ 17		Chicago
85	54 $\pm$ 5			Columbia
104 $\pm$ 16	103 $\pm$ 9			Chicago
115 $\pm$ 9	120 $\pm$ 26			"
122 $\pm$ 16		120 $\pm$ 16	(122)	"
127 $\pm$ 14	124 $\pm$ 9			"
133 $\pm$ 8	117 $\pm$ 14		(204)	"
209 $\pm$ 14	172 $\pm$ 25			"

26

that the sum of the absorption cross sections

of
mesons

of both signs in hydrogen, $\sigma_{\pi^+} + \sigma_{\pi^-}$ seems to be always greater than the cross section for absorption of mesons of any one ~~sign~~ ^{sign} in deuterium, not too much greater at lower energy but significantly greater at high energy, around 150 Mev, where the former is about twice the latter. Steinberger remarked that in the cross section for absorption in deuterium have been included the events whereby the meson is merely captured. At 60 Mev, for example, the cross section for this process alone, is about 7 mb. This would make the unbalance even greater.

Fermi. Discussion of These Results.

The discussion of the theoretical interpretation of the experiments that have just been reported, was opened by Fermi, who commented on the Chicago experiments on meson scattering in hydrogen. According to Fermi, the measurements at energies below 100 Mev are not too reliable, and one should focus on the higher range of energy from 90 Mev up to 230 Mev, where the cross section becomes very large and, therefore, the experimental results are more accurate.

Then, one is lead to consider the three following cross sections:

$\sigma(\pi^+, \pi^+)$, the cross section for scattering of positive pions

$\sigma(\pi^-, \pi^-)$, the cross section for pure scattering of negative pions

$\sigma(\pi^-, \pi^0)$, the cross section for charge-exchange scattering of negative pions

A well established fact, is that, in the energy band considered,

27

the first is sensibly higher than the sum of the two others and to put it in quantitative form,

$$\frac{\sigma(\pi^+, \pi^+)}{\sigma(\pi^-, \pi^-) + \sigma(\pi^-, \pi^0)} \approx 3$$

Another fact, which is however not so clearly established is, that the charge exchange scattering of π^- mesons dominate the pure scattering, leading to a ratio that one would like to see equal ^{to} 2:

$$\frac{\sigma(\pi^-, \pi^0)}{\sigma(\pi^-, \pi^-)} \approx 2$$

for reasons which will become clear later, ^{all} though the experimental errors are so large, that the only thing that can be said is that the number 2 is not inconsistent with the experimental result. (Fermi: "It is well known that errors are non-measurable things"). It must also be kept in mind that all the measurements made are transmission measurements, except the direct scattering measurement made at "90°" with 112 Mev negative pions; and, up to now, the latter measurement, a very rough one indeed, constitutes the only look that one has got, about what really are the reactions which take place. With all these qualifications, one can state that the cross-sections $\sigma(\pi^+, \pi^+)$, $\sigma(\pi^-, \pi^0)$, $\sigma(\pi^-, \pi^-)$ go in decreasing order and their relative magnitudes are not incompatible with the numbers 9 ; 2 : 1.

Another very striking effect is the very steep increase of the total cross sections with energy. Then arises the question about ^{the} evidence or lack

of evidence of a resonance in the band 100-200 Mev. To know the answer, it is at least necessary to see if the cross section really starts dropping at higher energy. For the moment, one just has a look at the top of the hill and one does not really know what is beyond.

If one assumes charge independence, i.e. ^{that} the isotopic spin is a good quantum number, the two possible isotopic spins, namely $I = 3/2$ and $I = 1/2$ scatter independently. If, moreover, one assumes that the isotopic spin $I = 1/2$ does not scatter at all, one gets just the ratio 9:2:1 which has been considered above; on the other hand, to assume that the $I = 3/2$ does not scatter at all, would lead to the ratio 0:1:2. This conclusion is independent of angular momentum, spin correlation, or anything else. One can therefore interpret the experimental results by postulating the existence of a broad resonance level $I = 3/2$ in the band of energy 100-200 Mev, with the consequence that practically all the scattering comes through $I = 3/2$ in this energy region. The above interpretation is due to Brueckner, who was invited to explain his work in more detail.

Brueckner. Theoretical Interpretation.

Firstly, Brueckner refers to the situation encountered in the photo-production of π^0 mesons by protons, where, as was pointed out by Oppenheimer, strong non-linear effects do show up. The point was actually investigated

by Case and himself and also by Miyazawa in Japan. And it could be in fact understood, if one assumes that strong coupling phenomena and isobaric formation were present, with a resonance at about 170 Mev and with isotopic spin $3/2$. Similarly, it is possible to set up an analysis of the scattering experiments in a phenomenological way, where the existence of isobaric states is postulated. The first point is to assume that the isotopic spin is a good quantum number, which leads one to consider just two scattering states, namely scattering states with isotopic spin $I = 3/2$ and $I = 1/2$. Secondly, practically all the meson experiments, in particular the scattering experiments at low energy, suggest that the meson interacts in states of unit angular momentum (p -states). At this point of the discussion, Fermi wondered however, to what extent this last statement is supported by the experiments. At low energy, the scattering cross section shows a tendency to stay up, indicating the contribution from S -states. Brueckner does not deny the contribution from other states and he gives the example of the radiative absorption at low energy with a cross section of about 3 millibarns. At this stage, came the following historical statement. Brueckner: "When you make a phenomenological analysis -----". Fermi: " ----- you have to know the phenomena, of course". Brueckner continued. The principle of the analysis is to make approximations which make the description as simple as possible. Therefore, one assumes that the scattering takes place through p -states only. This prevalence of p -states is, in fact, one of the dominant features of the

30

pseudoscalar theory, and also of the experiments at low energy. Then one is left with two isotopic states ($3/2, 1/2$) and two angular momentum states ($J = 3/2, J = 1/2$), which gives four scattering states in all, and the cross section may be expressed in terms of four phase shifts. Then, using the Breit-Wigner resonance formula, one can write down the energy dependence of the various phase shifts, which depend on the parameters, the reduced width and the resonance energy itself. This leads to eight parameters in the theory. Now, the strong coupling theory predicts a resonance scattering only in one state, namely, $I = 3/2, J = 3/2$. The other states are not resonant. Taking the resonance energy given by the strong coupling theory, this disposes of four of the parameters. To determine the other four, one requires that, at low energy, the isobar, if it is present, can be excited only very weakly because the meson in a p -state interacts so weakly when it is moving slowly. This is a feature that shows up when one looks at the strong coupling theory, at low energy it goes over into the weak coupling result. This last statement provoked ~~large~~ reactions from the whole audience, and a sophisticated remark of Ventzel's barely found its way up to the microphone. Marshak drew the attention again to the definite evidence for s -coupling at low energy, so that one should certainly not take completely without qualification, the hypothesis that only p -coupling governs the interactions of slow negative pions with hydrocarbons.

31

about the behavior of the strong coupling theory in the limit of low energy, Brueckner fixes the remaining parameters by assuming that in low energy limit, the ratios of the three cross sections and their angular dependence is the same as given by the weak coupling theory (Oppenheimer calls quite incredible this prediction of the weak coupling theory). One is left then with two parameters, namely, the $(3/2, 3/2)$ resonance energy, and something which may be called the coupling strength. These two are chosen in such a way as to fit the best the experimental data. The predictions of this theory are given in the accompanying table.

Theoretical Ratios Predicted by Brueckner

Energy Mev	60	85	110	140
$\frac{\sigma(\pi^- \pi^0)}{\sigma(\pi^- \pi^-)}$	1.26	1.59	1.83	2.16
$\frac{\sigma(\pi^+ \pi^+)}{\sigma(\pi^- \pi^-) + \sigma(\pi^0 \pi^0)}$	1.41	1.86	2.6	2.8
(experimental)	(1.75)	(2.5)	-	(3.0)

The resonance energy corresponds to 137 Mev kinetic energy for the meson in the center of the mass system (that is, about 200 Mev in the laboratory). At the peak, about 60% of the scattering is resonant scattering, 40% corresponds to the nonexcited states. The prediction of the total absorp-

32

tion cross section are as good as they can be, namely the theoretical curve passes through the "experimental points". As far as the percentage of charge exchange in negative pion scattering is concerned, the comparison between the theory and the experiment is not very significant in view of the inaccuracy of the experimental points. [However, combining Lord's result of 4 ± 2 mb for direct (π^-, π^-) scattering at 135 Mev with Anderson et al.'s total π^- cross section of 52 ± 6 mb (and subtracting 3 mb for radiative absorption) leads to at least six times more charge exchange than direct scattering, which is in rather bad disagreement with Brueckner's theory. But Lord's results are very preliminary.]

Then Brueckner analyzes the deuterium scattering. Firstly, if charge symmetry holds (not to be confused with charge independence), the cross section should be the same for mesons of both signs; this happens to be the case within the limits of the experimental errors. One must note that this constitutes a rather sensitive test of the charge symmetry hypothesis, in view of the big difference between π^+ and π^- in the scattering by protons. Secondly, one would like to compare the cross section σ_D for scattering of π^- , say, by ^{the} Λ deuteron, with the sum of the scattering cross sections of π^- by ^a Λ free proton and ^a Λ free neutron, i.e. if charge symmetry holds, with the sum $\sigma_p + \sigma_n$ ^{the} of scattering cross sections (including charge exchange) of mesons of both signs by free protons. The calculations have been carried out at two energies by Watson

33

and Chew, and give the following results:

E =	60 Mev	85 Mev
$\frac{\sigma(D)}{\sigma_{\pi^+} + \sigma_{\pi^-}}$	= 0.874	1.020

(The experimental number at 60 Mev is around 0.8 which exhibits the interference effects). The question arises to know what happens at higher energy where the experiments exhibit a definite fall of this ratio down to a value ^{of} about 0.6 at 135 Mev. Chew proposed the following tentative explanation: if the resonance were very sharp, one could understand it since the internal motion of the deuteron would throw you off the resonance; a meson coming with just the resonance energy for the proton at rest, would find itself out of the resonance for the proton moving in the deuteron. It was answered by Fermi and Marshak, that this resonance can be anything but sharp, if it exists at all.

According to Fermi, one can look at the excitation curve of the cross section $\sigma(\pi^+, \pi^+)$ say, in the following fashion. Its initial steep rise with energy is well explained by the predominance of p - states which requires roughly an E^2 dependence. Then, even if the postulated decrease would be real, it could be understood without speaking of resonance at all, so long as one asserts that the interaction goes through p - waves only, an assertion which, in fact, has no clear justification, but which is implied

34

by the explanation proposed above; this decrease is imposed by the upper limit $12 \pi \lambda^2$ of the p - contribution to the scattering cross section, that is a $1/E$ dependence. One would therefore expect a curve like the one shown in the diagram below.

It would not be correct then to speak of resonance, although it might be thought at first to be a resonance.

According to Brueckner's analysis, the resonance energy should be $E_R = 137$ Mev. As for the level width, (30-70 Mev), it does not make sense to speak of it, since it is extremely energy dependent, and one must rather speak in terms of reduced width. The effective coupling constant is about 0.3.

Fermi concluded that, if there is any resonance at all, it must anyhow be very broad. Oppenheimer explained that it has to be broad since it would not make sense at all to have in this region a level whose life time would not be very short.

According to Brueckner, the life time of the level that he uses is of the order of 10^{-23} seconds. Breit remarked that, then, to speak of the

resonance does not mean ver. Weisskopf criticized the use of the Breit-Wigner formula. In fact, the Breit-Wigner formula is applicable firstly, if the phase shift goes across 90° , secondly, if the energy dependence of the phase shift is linear over a certain range of energy. Bethe noted that, insofar as one needs to explain the experiment in terms of large phase shift, this could not certainly be obtained with the help of the weak coupling theory. Fermi came again to the argument of the upper limit to the cross section, in order to point out that the scattering cannot go through only one level, more precisely through only one p-level. Take the most favorable case, namely $I = 3/2$, $J = 3/2$; then the scattering cross section for positive mesons should be less $8\pi\lambda^2$, and the scattering of the negative mesons should be less than $\frac{8\pi}{3}\lambda^2$; in both cases, the experimental points corresponding to the highest energy measured at Chicago falls beyond this upper limit. Fermi thinks that d-states, in particular, should be considered also. On the other hand, it is clear that this upper limit argument is no disproof of Brueckner's interpretation, where only 60% of the scattering is accounted for by the resonant level and 40% comes from the other states. Concerning the meaning of the postulated resonance, Breit says that it is not possible, in fact, to distinguish between real resonance due to a compound state coming from an intimate interaction of a complicated type, and the simple potential resonance like the one coming from the existence of a centrifugal barrier, and both views would ~~amount~~^{lead} to the same results. According to Oppenheimer, one could

think of the resonance even without picturing the meson-nucleon interaction as a phenomenological potential existing between them, but, rather consider that the meson production or absorption by a nucleon is the primary process. Marshak takes the view that Brueckner's explanation is far too specific; in fact, the introduction of a resonance level is not necessary to understand the photoproduction of mesons; it could be explained in another way (anomalous magnetic moments); and as far as the meson scattering is concerned, the above discussion shows that the very meaning of a resonance is very much open to doubt, and the relative ratio between the cross sections can be understood just by postulating that the scattering goes almost uniquely through the isotopic spin $3/2$. To try to understand it in terms of a strong coupling picture, is very much open to doubt because all strong coupling predictions are wrong up to now. In answer, Oppenheimer agreed that all predictions of the strong coupling theory are wrong, but if one starts from the Yukawa equations, the strong coupling treatment is the only one which would lead you to an idea like this of isobaric states, and permits one to understand why the scattering goes chiefly through one state; in this respect, the strong coupling theory contains a certain amount of truth in that its predictions seem to be qualitatively correct, although it is completely wrong quantitatively (in the strong coupling theory the resonance should be very sharp and it is not).

37

Brueckner then gave a more detailed account of the situation with respect to photoproduction of mesons, namely with respect to the reactions:

Concerning the charged meson production (reaction 2), the (PS, PV) weak coupling theory predicts a cross section reaching a value of about $\pi (\hbar/\mu c)^2 (g^2/\hbar c) (e^2/\hbar c)$ for 100 Mev mesons, i.e. $\sigma \simeq 10^{-28} \text{ cm.}^2$ if one takes $g^2/\hbar c = 1/3$. The strong coupling theory gives about the same result. The excitation functions, together with the angular distribution predicted by the weak coupling theory, are not in too bad agreement with experiment, as shown in the graphs below.

Turning to the neutral photoproduction, it turns out that

38

the conventional weak coupling calculations would predict neither the very steep rise in the excitation function, nor the rather roughly isotropic distribution, nor the right order of magnitude unless one gives to the coupling constant $(g_p^2 / \hbar c)$ a quite unreasonable value. A possible way to get around this difficulty is, as Kaplon did, to take into account the anomalous magnetic moment; this gives an excitation function in excellent agreement with the experiment and an angular distribution close to isotropic (it is in fact too isotropic, and Silverman's experiment at Cornell indicates more anisotropy than this treatment leads to); on the other hand, $(g_p^2 / \hbar c)$ must be given a value about twice the value required by the symmetric theory.

Another way to get around the difficulty is to postulate the existence of a resonance for isotopic spin $3/2$ and spin $3/2$ as is suggested by the strong coupling theory. Then, one obtains an additional contribution, the "isobaric contribution", which fills the gap between the weak coupling prediction and the experimental result, without abandoning charge independence. Were this resonance alone coming into play, the ratio of photoproduction cross section of neutral to charged mesons would be exactly 2. The ratio actually predicted is about 0.7 to compare with the experimental ratio of 0.8. The neutral photo meson production cross section exhibits the required steep rise and, agreement with the experimental excitation function is obtained if the energy level of this isobaric state is fitted with a kinetic energy of the

39

meson of about 137 Mev, ⁱⁿ ~~a~~ surprising agreement with the level required to fit the scattering experiment. (The following remarks were brought out by a discussion by Fermi, Oppenheimer, Watson and Brueckner). It must be noted that the assumption of charge independence leads to a unique prediction, although the total isotopic spin is not conserved in such reactions as these in which the electromagnetic field comes into play, in the same way as the weight of the elements of a multiplet may affect the transition probability even though the angular momentum is not conserved in the transition. Essentially, one assumes that the transition (or at least the "isobaric" part of it) goes through the isobaric state, and the cross section ^{is} ~~A~~ derived from the probability of the formation of this state (related to its photowidth) and its probability of decay into a nucleon and a meson; in fact, the classical equation merely describes this two step process. Chew remarked that the shape of the excitation function does not require the resonance at all, simply the factor of 2. He wondered whether this was really much to worry about, since one was an electric dipole transition through an S - state and the other a magnetic dipole involving a p - state, and the theories are not much good to begin with.

Fermi recalled that, up to now the scattering experiments do not point at all toward the existence of a resonance. The only things that one can say are: a) that the scattering goes chiefly through the

40

isotopic spin $3/2$. No evidence shows up, however, that there is only one spin and one angular momentum that contributes. b, That p-transitions predominate on the low energy part of the excitation curve, as is exhibited by the E^2 rise, which has nothing to do with the resonance, but with the fact that, at low energy, P - waves have a very small amplitude at close distance.

Oppenheimer, however, asserted that it is the first time that there is any smell at all of ~~these~~ phenomena which have been on the books for ten years, namely, the existence of some loosely bound systems of isotopic spin $3/2$ and spin $3/2$; and this very fact is worth some attention.

Steinberger raised the question of whether such an isobaric state could have some relevance with the steep rise with the energy obtained in the reaction $p + p \longrightarrow d + \pi^+$. According to a calculation by him and collaborators, the phenomenological interaction $(\sigma \cdot q) e^{i q \cdot r}$ (q , meson momentum) suggested by the weak coupling theory could not fully account for this rise. Marshak and others questioned the value of this calculation which depends strongly on the shape of the nucleon - nucleon potential for large momentum transfers and therefore, is marred with uncertainties.

In answer to a question of Weisskopf, to obtain a clear explanation why the nucleons are given an isotopic spin of $1/2$ whereas free mesons are given an isotopic spin 1, Fermi gave the following exp-

41

lagnation, after having noted that it is so low brow that he gets into trouble. One should think in terms of the Dirac hole theory. Then, whereas the proton is a positive particle, the antiproton must be thought of as a hole, that is, a missing proton of positive charge. On the other hand, mesons are not holes, a point which is made clear by the Pauli-Weisskopf picture. Brueckner mentioned predictions for the production of mesons in nucleon - nucleon collisions, which derive from the assumption of charge independence and of the predominance of interaction in p - states, and which provide a powerful test for this theory. (See Watson and Brueckner P. R. of this summer). These predictions are in agreement with ~~the~~ experiment; however, the experimental errors are so large that it is not very significant.

Messiah. On the Experimental Support of the Charge Independence Hypothesis.

In fact, one may ask whether the experiments of scattering of π^- mesons by protons may provide a very severe test of the hypothesis of charge independence. Under this hypothesis, the three cross sections $\sigma(\pi^+, \pi^+)$, $\sigma(\pi^-, \pi^-)$, $\sigma(\pi^-, \pi^0)$ are expressed as functions of the two scattering amplitudes corresponding to the two possible values of the isotopic spin, more precisely as functions of their magnitude and their relative phase. The limitations that this imposes are best shown in the

42

diagram $\frac{\sigma(\pi^-, \pi^0)}{\sigma_-}$ vs $\frac{\sigma_-}{\sigma_- + \sigma_+}$ (Here: $\sigma_- = \sigma(\pi^-, \pi^-) + \sigma(\pi^-, \pi^0)$ and $\sigma_+ = \sigma(\pi^+, \pi^+)$) drawn below, where the allowed points should fall in

the unshaded area; the Chicago "point" at (112) Mev has also been

plotted.

When π^+ scatters three times more than π^- , exactly $2/3$ of the π^- scattering ought to be charge exchange, which gives the proportions 9:2:1 that Fermi indicated already. However, as soon as the unbalance π^+/π^- lessens (which means that some $I = 1/2$ scattering comes in), the range of values that are denied to $\frac{\sigma(\pi^-, \pi^0)}{\sigma_-}$

for charge independence to hold, quickly becomes so small, that the test of this hypothesis ceases to be severe. (Fermi: however

$$\frac{\sigma_-}{\sigma_- + \sigma_+} > 1/4).$$

In connection with this, Messiah indicated the interest of studying the meson production in $p + d$ collisions, and in particular:

An immediate consequence of the charge independence hypothesis is that, at any given energy and any given angle, there ought to be exactly twice as many π^+ as π^0 , i.e. $\frac{\sigma_+ (\theta, E)}{\sigma_0 (\theta, E)} = 2$. Chew remarked that this relation should hold also when the three nucleons wind up as $p + d$ in the final state. However, the interest of the particular reactions stated above lies in the fact that, not only charge independence imposes a very stringent condition on the result, but the actual experimental verification ought not to be too difficult.

Wentzel. "Orthodox" Strong Coupling Theory.

Before discussing this subject, Wentzel pointed out that there was an experimental method for finding out whether or not there is resonance, although there is probably not quite enough energy available yet. Say there is a resonance at roughly (including the mass of the meson) 280 Mev. Then one could take mesons of sufficient energy (~ 300 Mev) to give Raman scattering down into this level; then coming out one should see two mesons, one of almost constant 140 Mev kinetic energy. Now, Wentzel gave an account of the predictions of the "orthodox" strong coupling theory for the scattering of mesons. It is true that there exist numerous pieces of evidence that the coupling cannot be really very strong; however, one might still be in the region of fairly strong coupling, that is on the borderline where the strong coupling treatment could provide a better approximation than the weak coupling treatment. In this respect, it

44

is worthwhile to look into this model theory again, since some of its qualitative predictions may carry a certain measure of truth.

The strong coupling theory involves two parameters, the coupling parameter g and the source radius a , which might in principle be determined from ~~the~~ nuclear forces and the isobar energy respectively, so that the theory does not involve any more arbitrariness. Then, the Hamiltonian is written:

$$H = H_I + H_M + H_{\text{int.}}$$

H_I is the energy of the compound nucleus, ground state, and excited states, H_M the energy of the free meson and $H_{\text{int.}}$ the interaction energy, which is expanded in inverse powers of g . In this expansion, the leading term corresponds to a scattering term, bilinear in the meson amplitudes; it looks, to a certain extent, like a potential and we call it "true scattering"; it is independent of g and involves only the source radius. The higher order terms have never been really computed; they describe for example emission and absorption processes, multiple production, etc. -----.

$$H_{\text{int.}} = H_{\text{sc.}} + H_{\text{em.abs.}}$$

$$(g^0) \quad (g^{-3})$$

Outside of the resonance region, the leading term is the only one significant and gives in fact a quite small cross section for the source radii which are usually taken: $a \ll \hbar/\mu c$. At resonance,

$H_{\text{em.abs.}}$ gives however a much larger contribution despite the presence of the small factor $1/g^3$; in fact, at resonance, the value of g has a bearing on the linewidth but not on the strength of the resonance. The true scattering term is well known; on the other hand, the general behavior of $H_{\text{em.abs.}}$ is clear from the charge and ang-

45

ular momentum conservation; for example, with the pseudoscalar charge symmetric theory which is the only one referred to hereafter, it can be expressed in terms of isotopic spin and so on; but its energy dependence is not clear at all.

Let us consider first the scattering theory far below the resonance region, where the true scattering term has only to be considered. The result may be expressed as a function of the meson momentum K , the isotopic spin and spin I, J (and their z - components M, M respectively). The diagonal element of H_{sc} is therefore a function of I and J , at least in the case we are dealing with here, namely, the elastic scattering of a meson by a nucleon in its ground state. In the latter case, it automatically involves only p - waves, and I and J can, each one, take one of the two values $3/2, 1/2$ leading to four possibilities. One must then introduce the quantity $a' A_{IJ}$; a' is a rather complicated expression about equal to the source radius and A_{IJ} assumes the following values:

$$A_{3/2,3/2} = 1/2 \quad A_{3/2,1/2} = 1 \quad A_{1/2,1/2} = 0$$

Then the phase shifts for the four possible p - states are given by:

$$\tan \delta_{IJ} = \frac{\pi K^3}{\omega^2} \frac{1}{\frac{1}{a' A_{IJ}} + R}$$

Where R is a reaction term: $R = P.P. \int_0^{\text{cut-off} \approx 1/a} \frac{K^4 dK}{\omega_K^3 (\omega_K - \omega)}$

$$\omega = \sqrt{m^2 + K^2} = \text{elastic meson energy}$$

46

Note that, in the low energy limit, neither the angular distribution nor the ratio of the free cross sections discussed previously goes to the quantity predicted by the weak coupling theory, contrary to Brueckner's assertion; (however, what the experimental values of these quantities are, are not clear at all for the moment). Note also that, because of the presence of this reaction term which is not at all small, the answer depends very much on the source function. Note finally that, from the very beginning, it is assumed that p - waves only come into play because we have just taken the first term in the expansion of $H_{\text{int.}}$.

When one goes through a resonance region, the result is changed by the contribution coming from the term $H_{\text{em.abs.}}$. In the region we are interested in, it is a $(3/2, 3/2)$ resonance. Then the formula for the phase shifts are left unchanged except that $A_{3/2, 3/2} = 1/2 + \text{added terms}$, and the tangent of the phase shift $\delta_{3/2, 3/2}$ is multiplied by a factor $\frac{\omega - \epsilon_1}{\omega - \epsilon_2}$, where ω is the (relativistic) energy of the incoming meson, ϵ_1 is a certain zero point and ϵ_2 the resonant energy; this leads to an energy dependence of this phase shift like the one indicated in the following diagram.

47

Note that although the zero point E_1 is a definite feature of the strong coupling theory, it is not clear if one could test it experimentally since it is so close to the rest mass of the meson that one would find oneself in a region where the scattering cross section is immeasurably small anyway. On the other hand, if one uses one's imagination E_1 might be less than μ so that no ~~resonance~~ ^{Zero point} would occur.

Fermi. Electron Contamination of the Chicago Meson Beam.

The electron and positron contamination respectively are reported roughly on the accompanying graph. It was first observed when using a copper target 1.2 cm. wide in order to produce the mesons. Since the radiation length in copper is about 1.5 cm., it was first thought of as coming from the pair formation by the γ -rays produced in the π^0 - decay; the electrons or positrons having the same magnetic rigidity of the mesons would follow the beam all the way through. If this explanation should hold true, the electron contamination should practically disappear when one replaces the copper target by a beryllium target. This was actually done, but the electron contamination was only slightly reduced, not more than about 20%. Garwin, at Chicago has made some accurate measurements to locate the origin of these electrons and they seem to come from the target or from very close to the target. (For example, they couldn't come from decay in flight.) A possibility would be that the π^0 could decay directly into an electron pair; according to Garwin's calculation, this could account for the intensity observed, provided 10% of the π^0 - mesons decay in this way rather than in the usual mode of two γ - rays. Lederman said that at Columbia a cloud chamber experiment had shown the contaminants are definitely

electrons. In connection with this, Fretter gave an account of some of the results found at Bristol in photographic emulsions. Perkins has counted the pairs in the penetrating showers and, plotting the number of pairs found vs. the distance from the origin of the star, he found that a very large proportion of pairs are formed quite close to the star and it is concluded that about 2% of the π^0 mesons might produce pairs directly, implying a lifetime for pair production of about 10^{-15} seconds. Peierls questions the relevance of this to the above discussion for the following reason: in a photographic plate, the direct mode of decay of a π^0 - meson into two γ - rays is practically impossible to see; therefore the small fractions of π^0 's which can be detected are those which decay into one γ - ray and an electron pair. It is a higher order process, which can be calculated quite unambiguously, (cf. Dallitz P.P.S. 64, 667 (1951)), and it turns out that this mode of decay should occur in 1.2% of the cases; this calculated value is quite consistent with Perkin's data. Summarizing, Fermi thinks that the explanation of the electron contamination in terms of the possible decay of the neutral π meson into an electron pair needs to be investigated more closely; if this is true, there exists characteristic lifetimes for the two possible modes of decay

$$\pi^0 \longrightarrow 2\gamma \quad \text{and} \quad \pi^0 \longrightarrow e^+ + e^-$$

and therefore the branching ratio is independent of energy, a fact which should be recognizable in the variation of the electron contamination with energy. One must note, as was pointed out by Pais, that in the decay of the pseudoscalar meson into an electron pair, the lowest Feynman diagram gives a vanishing contribution; it is indicated in the figure below with, beside it, another higher order Feynman diagram which does give a non-vanishing contribution:

In other words, from the theoretical point of view, the decay into two electrons is of higher order; to what extent this disfavors the electron decay versus the two γ - decay is not clear, since it is a matter of detailed theory.

Then, reports were given on the latest results of the experiment on photoproduction of mesons conducted at the Cornell synchrotron.

Firstly, Wilson explained^{ed} that an experiment on photoproduction of positive π - mesons in deuterium gave the same cross section as the cross section for photoproduction by protons, showing that the photoproduction by protons is unaffected by the presence of the neutron in the deuterium. Then Cocconi spoke of the photo-production of π^0 's. Cocconi (and Silverman). Photoproduction of Neutral Mesons.

The first set of experiments was intended to measure the nuclear Compton scattering. A beam of 310 Mev γ - rays is sent ~~an~~ into a polyethylene target. One measures the outgoing γ - ray at 90° in coincidence with the outgoing proton at the angle which is required by the kinematics of the Compton scattering. The counting rate turned out to be so small that one could only set an upper limit to the Compton cross section, namely three times the Thomson cross section ($0.3 \times 10^{-30} \text{ cm}^2$). In order to get a better counting rate, in the following experiments, only the γ - rays outgoing at 90° were counted, but, putting an absorber before the γ - ray counter of con-

50

venient thickness, one required the counted γ -rays to have an energy greater than 50 Mev. Also, by requiring a more stringent condition on the γ -ray energy, one can show that the γ -ray cannot be due to scattering; for example, γ -rays of 50 Mev could not be found at 90° if they were only due to scattering. Careful measurements have been conducted with a γ -ray beam of 310 Mev, and also a γ -ray beam of 250 Mev. The ratio between the two cross sections is found to be about 13 ± 4 , in quite consistent agreement with the previous measurement of Silverman, who found 9 ± 4 in an experiment on photoproduction of neutral mesons on hydrogen. Further, the absolute cross section was of the order 10^{-28} cm.²

Measurements of the photoproduction of neutral mesons have been made with this technique, using various targets, namely ordinary water, heavy water, polyethylene and pure carbon. Those measurements have been made with a 310 Mev γ -ray beam. One can, in this way, obtain the ratios between the cross sections for neutral photoproduction in various elements; the results turn out to be the following:

$$\begin{aligned} \frac{\sigma_D}{\sigma_H} &= 1.90 \pm .24 & \frac{\sigma_C}{\sigma_H} &= 10.1 \pm 1.8 \\ \frac{\sigma_O}{\sigma_H} &= 12.7 \pm 2.5 \end{aligned}$$

Those numbers show that the role of the neutron and the role of the proton in the photoproduction process of neutral mesons are about the same. It is quite remarkable that these ratios are so high, as such high values of the ratios are not true for the photoproduction of charged mesons.

51

Steinberger reported that for hydrogen the photomeson production cross section at 260 Mev, integrated over the angular distribution measured for positives and neutrals for Beryllium, gave a π^+ to π^0 ratio of about 2. Panofsky added that in hydrogen at 90° and 135° about the same result had been obtained.

(The meeting was adjourned until the following day).

62

MEGALOMORPHS (V, v, tau, kappa)

9:30 Saturday, January 12, Professor J. Robert Oppenheimer presiding

Introduction by Oppenheimer

At Chicago Fermi said he had become bored with the name "elementary particles." So the above name has been coined suggesting something with vast structure. There is no sharp logical order in which these particles should be discussed. V, v, and τ particles have been observed in cloud chambers and the K and τ particles in photographic emulsions. They are unstable and they have lifetimes of 10^{-9} to 10^{-10} seconds. These are of a convenient length to measure in cloud chambers and not hopeless for measurement by photographic film. They are all identified by their masses, and their modes of decay. All are produced rather copiously in really high energy nuclear encounters of 10^{10} electron volts. They all tend to present the same sort of paradox as was first encountered in the case of the μ meson, namely a small interaction cross-section that is hard to reconcile in terms of their copious production, but the explanation in terms of a cold decay product of a hot meson that worked in the previous case cannot be made to work here. We hope to sharpen up the question of whether these objects are really astonishing.

The various symbols are defined as follows: $V^0 \rightarrow P + \pi^- + ?$;

$v^0 \rightarrow (?) \pi^+ + \pi^- + ?$; $K \rightarrow \mu + ?$; $\tau^+ \rightarrow \pi^+ + \pi^+ + \pi^-$; $V^+ \rightarrow \pi^+ + (?) N + ?$

These definitions should be considered as given in heavy quotation marks.

Several examples of the τ meson have been seen to decay at rest in photographic plates into three charged products of apparently equal mass. All the τ mesons seen are charged and one of the decay products identifies itself as a π^- meson.

53

Oppenheimer has also seen pictures of two such particles decaying in flight in a cloud chamber. The K meson is seen to decay at the end of its track in a photographic plate into a charged particle. An estimate of the mass has been made and the decay product is identified as a μ meson. The V^0 "meson" is believed to decay into a proton and a π^- meson and the presence of a third particle in this decay is controversial. The V^+ "meson" decays into a charged π meson, what is believed to be a neutron, and again possibly a third particle. The v^0 meson decays into a π^- and a π^+ meson, although the presence of the π^+ meson in this decay is in doubt. It is a little less copious in observation than the V^0 "meson", but this does not necessarily imply that it is less copious in production. All the V particles are observed in cloud chambers and all are more copious at high altitudes because they are produced preferentially at high energy. What we would like to learn about these various particles is (1) their disintegration schemes, (2) their lifetimes, (3) their abundance among the products of a high energy nuclear encounter, and finally ⁽⁴⁾ their masses. We would be happy to know if they are scalar or pseudo-scalar, boson or fermion.

The two τ mesons appearing in a cloud chamber consist of two stereoscopic photographs obtained by Anderson. In each case there is a high energy star in the lead above the chamber whose products are visible and among these is a charged particle whose ionization is minimum, or a little greater, but not visibly decreasing. In the gas of the chamber this particle gives rise to three tracks arranged in a regular trihedral pyramid. At least one of these six decay products identifies itself as a π meson by a nuclear encounter. A rough estimate of the mass is obtained of 900 to 1000 electron masses. It is

54

worth noting that in spite of Powell's assigned long lifetime to the τ particle, Anderson and Leighton have taken so many pictures that it is not surprising they should see two or three of these decaying in a time of the order of a tenth of the mean life. Rossi commented that Bridge also seems to have found a similar event among ~~many~~ thousand pictures. Thompson said he had also seen one or two, but it was not possible to obtain an estimate of the mass because they were at minimum ionization.

Fretter's Data on V particles

Since no magnetic field is used in this work, only the ^{angles} and some idea of the ionization can be obtained. The only advantage of this method is that it is always possible to see ^{the} original event. Therefore it is possible to measure distances accurately and obtain a better idea of the lifetime. The data were originally analysed on the basis of assuming the decay scheme $V^0 \rightarrow p + \pi^-$. If, in addition, a mass is assumed for the V^0 particle, the π meson is found almost always to come off at the larger angle. The angular distribution in the laboratory system then required that the proton came out in the backward direction most of the time in the center of mass system. This appeared unreasonable, so that this result was interpreted as indicating either that 3 particles are involved in the decay scheme or that there is more than one two-particle decay scheme. The data have now been divided into the two categories $p + \pi^-$ or $\pi^+ + \pi^-$. This is done in the following manner: Assume a mass for the V particle and calculate β_1 and β_2 for a given angle of emission in the center of mass system; ^{then} relate this angle to the angle of the observed V particle. In most cases it is then

55

possible to rule out one of the other category by the angles and the ionization estimate. In 25 cases only 3 to 5 are ambiguous. Only those cases were analyzed in which the plane of the V contained the star. Occasionally, it was possible to identify a π meson by scattering even when the V was not co-planar with the star. Out of 35 events Fretter has only 5 which are non-coplanar. In this breakdown he has 14 V's, 8 v's, and 4 events which are not certain because they are not coplanar. In general, the non-coplanar events contain one heavily ionizing track, so that these are probably all V's; occasionally the discrepancy is quite bad. There is one-half inch of Pb above the chamber to knock out electron showers, so that it is possible that these V's originate in the Pb above the chamber. Another possible explanation is that they are due to a nuclear scattering of the V^0 meson in a lead plate in the chamber, as all non-coplanar cases are separated by at least one lead plate from the original star. One case departs by 10 to 15 degrees from coplanarity; it is in the core of the shower. There are apparently too many non-coplanar cases in this data to explain them all by nuclear scattering. However, Leighton can measure angles to one or two degrees and finds many coplanar events to this accuracy. When the events are non-coplanar, they are usually spectacularly so. These experiments were carried out at sea level. These non-coplanar events are not associated with showers in the correct direction above them. It is not easy to exclude accompanying electromagnetic component because the pictures are selected on the basis of having no electron showers in them. This is done because the electron showers tend to make it hard to distinguish the V particles. In spite of this selection criterion, however, the situation

56

is not as bad as this would indicate. In the fairly clean events selected there is apparently not enough electromagnetic radiation to give a shower in the lead plates. Fretter does not think there are π^0 's present, but cannot put a quantitative limit on their production. If the assumption of two-body decay were wrong, this would probably not seriously alter the assignment into the two classes $p + \pi^-$ and $\pi^+ + \pi^-$. This is true because there is often one heavily ionizing and one lightly ionizing track. For example, if the forward particle is more heavily ionizing, then this cannot be due to a decay into two particles of equal mass. The absence of a gamma ray or a neutrino is not nearly so well-established as the absence of a π^0 meson. The five degree accuracy of these experiments does not completely rule out the possibility of a third particle, but Leighton's accuracy of one or two degrees in coplanarity would be very hard to explain in terms of 3 body decay even if a neutrino came out correlated with the π meson in direction. Leighton is convinced that no third particle is present in the coplanar cases he observed. When Fretter's data are divided into 2 categories as above, the angles of emission in the center of mass system are no longer unreasonable. The data are not strong enough to establish definitely what the two decay schemes ^{are} but they are sufficient to rule out the possibility that the data can be due to only one scheme, namely $p + \pi^-$ decay. The masses assumed in the analysis were 800 and 2300 electron masses.

The selection system for penetrating showers was loose and accepted showers down to a few BEV. It consisted of 5 counters above the chamber and two counters below the chamber separated from the chamber by one-quarter inch

57

of lead and from each other by one inch of lead. The chamber, containing 7 one-half inch lead plates, was triggered by a coincidence between one of the upper counters and both of the lower counters. In one or two pictures the two particles triggering the cloud chamber were the two particles of the V. Two other low energy tracks appear in this picture, but no penetrating shower. The mean free path of the decay products for large scatterings and other events is 300 grams/cm^2 of lead. The abundance cannot be definitely given without a knowledge of the lifetime and the angular distribution, and evaluation of the geometry is difficult. A minimum lifetime is given by the distances and the time dilation factors calculated from the angles of separation of the two decay products. This gives 1.4×10^{-10} seconds for V^0 and 1.0×10^{-10} seconds for v^0 , although the statistics are poor. The time dilation depends on the decay scheme chosen, but can only alter these results by a factor of 2 or 3. The wide angle V's tend to occur at large distances from the axis of the shower, but this correlation is not good. The non-coplanar V's tend to have an angle of 30 degrees with respect to each other, which is the average angle of all the V's. In calculating the lifetimes, the processes and masses are assumed, and from the observed angles, the time dilation is then calculated. The lifetime is given by the distance from the star divided by the time dilation times the velocity of the particle. No correction is made for geometry. The mass is estimated in the following way: too high a mass gives a poor angular distribution in the center of mass system and too low a mass gives higher ionization calculated than actually observed in the experiment. The mass of 2300 obtained in this way is higher than the Manchester mass of 2200. Six charged V's have been observed, but these may not be real. They have the same lifetime or shorter than the other particles, which may not be consistent with other observations. They all decay close to the

originating event, that is within a few centimeters. There is 5" of illuminated area, but this spills over almost to the 7" width of the lead plates. The gamma factors for the individual V's are given in the following table.

Gamma factors $1/(1 - v^2/c^2)^{1/2}$ for V particles observed by Fretter
(These results are not accurate to three figures)

$p^+ + \pi^-$	$\pi^+ + \pi^-$
1.65	2.6
2.28	2.13
1.13	1.43
4.66	1.28
2.47	1.82
1.56	3.86
1.57	2.8
7.95	1.86
1.03	
2.9	
4.65	
1.07	
2.83	

There is no significant difference between the two decay schemes. This energy distribution has not been compared with the Manchester data. In general, the small angle V's occur farther from the original event than the wide angle V's. Of course, high energy V's have a small probability of being detected.

FRETTER'S REPORT OF LEIGHTON'S DATA

Leighton has two set-ups both using magnetic fields of about 5000 gauss. One is "the famous cloud chamber of Anderson that discovers all the new particles"; the other set-up consists of two 9" by 18" cloud chambers separated by 1" of lead and with approximately 4" of lead above them. These chambers operate 24 hours a day and the second set-up contributes

most of the data. In Pasadena, this set-up was triggered by counters above the lead and six counters below the lead below the bottom of the chamber. The cloud chamber was triggered by the firing of one or more tubes above the chamber in coincidence with 3 below the chamber. The set-up on Mount Wilson probably has an air shower inhibitor. One and one half V particles have been observed per day, $2/3$ of which give a measurable Q value. Very roughly, about a quarter of these are charged V particles, but these cases have not been analyzed. Leighton does not believe strongly in the two V particle decay schemes. He believes he can measure ionization better than the British have done, or think he can do. His measurements are at least very good. One hundred to 150 V particles have been observed; the identified masses are given in the following table.

V^0 decay products identified by Leighton

	<u>Mesons</u>	<u>Protons</u> ($> 1000 m_e$)
Positive	5 (less than $1000 m_e$)	35
Negative	53	1 (may be $1000 m_e$)

Leighton questions whether all the entries in the proton column are actually protons rather than particles of mass around a thousand electron masses.

Two $\pi - \mu$ decays and ten nuclear interactions of a negative meson have been observed, so that the negative particles are very likely π mesons. The five positive mesons are not necessarily π mesons but merely have masses less than 1000 electron masses. Because these are not positively identified, Leighton bases his analysis only on the single decay scheme, $V^0 \longrightarrow p + \pi^-$. Calculating the Q values on this assumption, he obtains a histogram with 2 peaks and a deep valley in between. These peaks have values of 34 ± 3 Mev and 75 ± 5 Mev,

60

and are of about equal height. If the data are separated into 2 classes corresponding to these two peaks, the following points emerge: [These points were not clearly stated at this time and were corrected after lunch after a telephone conversation with Leighton. The results of this conversation have been included here and comments which were based on the original table given in the morning have been omitted as they were largely irrelevant.] In the 34 MEV group the negative particles are mostly heavily ionizing mesons. Some of the positive particles are heavily ionizing and are probably protons. Most of the positive particles are lightly ionizing and are not identified. In the 75 MEV group, the positive particles are heavily ionizing, of mass greater than a thousand electron masses, and probably protons. There are 2 or 3 negative heavily ionizing particles. These are probably mesons. Most of the negative particles are lightly ionizing and are not identified. The individual errors in the Q values are approximately ± 20 MEV. Oppenheimer remarked that he had seen a histogram based on the analysis into two decay schemes a couple of months ago. In this histogram the lower peak applied to the $p + \pi^-$ disintegration, while the upper peak was flat and broad, from 60 to 150 MEV, and applied to the $\pi^+ + \pi^-$ disintegration. The Manchester group obtained a Q value of 46 for $p + \pi^-$ and 120 for $\pi^+ + \pi^-$. (See below p. 69 et. seq.) All of the events included in this analysis are not spectacularly non-coplanar. The one to two degree coplanarity of many cases is believed by Leighton to rule out the possibility of three-body decay. In all cases where the coplanarity is good, the momentum balance is also good.

George's Report on K meson production in high energy nuclear events observed by Perkins et al.

In earlier work Fowler had identified the masses of the products

61

coming from a random selection of high energy showers in photographic emulsions by plotting the values of grain density versus scattering. Particles above minimum ionization are identified ^{by} falling on or near the calculated curve for π mesons or protons. In the following work showers were not randomly selected, but were required to consist of a small narrow core of shower particles and few or no short heavily ionizing tracks. Such events are interpreted as consisting of single nucleon-nucleon encounters at the edge of a nucleus or with light elements. This selection criterion should not however affect the mass spectrum of shower particles. In the following work a new batch of plates were flown at 68,000 feet and again the mass spectrum of a random selection of showers was determined, as a repeat of the work done by Fowler. Most of the particles appeared on the π meson rather than the proton curve. There is one other technical difference in this work, namely a more careful normalization of grain density. In the original paper of Fowler there were variations in grain density due to differences between plates and variations through the thickness of the plate. To avoid this difficulty, calibration in this case was carried out in terms of the high energy primary particle initiating the shower, which was possible in 20 per cent of the cases; in the other cases the normalization was made relative to high energy electron pairs or other high energy tracks occurring near the shower in question. This new data gives some evidence for a dip in the scattering versus grain density curve at 2 or 3 times the rest mass energy, as had been predicted by Fermi and others. In the same plates as used for the random selection of showers, jets of more than 10 BEV were selected. The essential result obtained is that, in addition to the shower particles lying on the proton and the π meson curves,

62

there are many shower particles lying off the proton curve corresponding to a mass of roughly 1200-1300 electron masses. Perkins and his collaborators at Bristol have concluded from this that in high energy jets an appreciable number of K mesons are produced rather than π mesons or τ mesons. The identification is made on the basis of mass but is also confirmed by the very large frequency difference in the number of K's stopping in the plates compared to the number of τ 's when the plates are examined carefully for τ 's. The observed number of K's relative to τ 's is not so strikingly different, but the efficiency for detecting K's is much lower than for detecting τ 's. In the accompanying figure

MASS SPECTRUM $2.0 > \text{GRAIN DENSITY} > 1.1$

63

it is to be noted that while for showers caused by a primary whose energy is less than 50 Bev both protons and π mesons occur, as well as K mesons, for showers whose primary energy was greater than 50 Bev only K mesons are detected. It should be noted that only particles outside the core of the shower have been measured, that is slow particles, as particles in the core cannot be separated. Fifteen per cent of all shower particles have been identified and 70 per cent of the particles outside the median angle of the core of the shower have been identified.

The Bristol group maintains that due to the presence of the dip in the ionization grain density curve, it is now possible to separate K's and protons in a region hitherto regarded as inaccessible. If data obtained by this method are included, the mass spectrum is given in the following table:

Mass spectrum of jets with $E_p > 50$ Bev using Fermi dip

π	K	P
28	10	4

This mass spectrum is also for primaries whose energy is greater than 50 Bev, but differs from that given in the figure because that included only particles whose grain density was greater than 1.1 minimum, whereas this table includes also particles identified using the dip in the ionization-grain density curve.

In response to a question from Cocconi about the theoretical basis for this relativistic increase in ionization at high energy, Ritson replied that while it is true that Cerenkov radiation will contribute a 10-15 % increase in energy loss in this range, this radiation occurs near the actual atomic frequencies of the atom and in particular the part near the K and L levels will not be absorbed in the Ag Br crystal but will escape from the crystal. This rough calculation has been extended by Schönberg in Brussels and he maintains that all the relativistic increase in the form of Cerenkov radiation

64

should actually leave the crystal. Thus Brussels claims that this relativistic increase due to Cerenkov radiation should not exist, while Bristol claim an 8% effect, and the situation is definitely still open. Ritson raised the further point that this method of calibration apparently would be sensitive to whether or not the dip was assumed to exist. However Peierls told us that this point had been discussed in some length at the Bristol conference and the arguments given were quite convincing that the dip really exists. Further, the use made of the dip would not affect the normalization of the results because the results are normalized not to the dip but to the plateau beyond the dip, where everyone agrees the grain density levels off. That is, the term plateau has replaced the term minimum ionization which was used loosely before.

[Note added by Dr. Ritson]

The position as regards the theory of the relativistic increase is rather clearer than I described it at the conference.

The following points may be regarded as based on a sound foundation

- 1) The probable ionization loss by the ionizing particle is fairly accurately described by the formulae of Halpern and Hall, modified by Schönberg. This holds irrespectively of whether a classical picture is used which assigns a single harmonic oscillator to each absorption edge in the atom or whether a quantum mechanical picture is used which would regard the absorption edge as an ensemble of oscillators.
- 2) The Brussels paper of Janssen and Huybrechts calculates correctly this probable ionization loss.
- 3) The Brussels paper does not correctly describe the absorption of the "Cerenkov" radiation. A classical single harmonic oscillator picture is used to describe the emission of the radiation and a quantum mechanical

65

absorption edge to describe the absorption. Physically this corresponds to saying that Cerenkov radiation is emitted only with frequencies below ν_0 , the frequency of the absorption edge, and hence as the absorption edge is sharp, the Cerenkov radiation associated with the ν_0 level cannot be absorbed by the ν_0 level.

A simple treatment by Aage Bohr leads directly to the result that ionization losses are confined to a radius of the order of 10^{-6} cm in silver bromide for all frequencies, as pointed out by Pickup and Vyodic.

The overall picture is thus that we should expect a relativistic increase as predicted by Halpern, Hall etc. to be observed in the photographic plate.

The attached figure shows the theoretically predicted curve for probable ionization loss calculated by the Brussels group compared with the calibration curve used by the Bristol group.

It is clear that if the above is correct, there is no plateau until energies of 100 Mc^2 are reached, the main increase occurring in the range $10 \text{ Mc}^2 - 100 \text{ Mc}^2$ and not in the range $3 \text{ Mc}^2 - 10 \text{ Mc}^2$ as ^{used} by Bristol.

Until clear evidence to the contrary is presented, I would interpret the Bristol data as showing the relativistic increase in the above range, this increase causing a low energy group of protons to appear (when calibrated against the primary high energy tracks) as π mesons.]

George continued his report of this work by mentioning the observation of a kappa particle of energy $6 \pm .9$ Bev coming from a low energy shower which after 1.5 cm of track changed suddenly to an energy of 2 ± 0.2 Bev with negligible change in direction. This could have been the bremsstrahlung of a fast electron. However a) electrons rarely come from showers and b) when they do so they always occur in pairs presumably as the result of the materialization of a γ ray from the π^0 meson, which this track definitely was not. This one event would give a mean life of 10^{-11} sec. for this kappa meson. The plates were also examined for evidence of π^0 emission inferred from the presence of electron pairs. For a random selection of 1000 showers, the ratio of neutral to charged π production was obtained as $.52 \pm .1$. A similar search in the jet events gave a ratio of neutral π production to the production of charged π and kappa mesons of $.29 \pm .08$. Assuming that the ratio of neutral to charged π mesons remains the same in these

events, it is possible to deduce the proportion of kappa mesons and obtain the result that the ratio of K to π mesons is .6, which agrees well with the mass spectrum previously given. This is a new and independent measurement of the ratio of neutral to charged π mesons in such events. When the length of track of the jet particles was sufficient, an estimate of the total energies carried by these charged particles was made. This was then divided by the total energy of the primary particle calculated from the median angle of the jet. If all the incident energy had gone into the shower particles, this ratio should have been 1 but actually the obtained ratio was $.64 \pm .12$. Therefore, 36 % of the energy of the jet has gone into neutral radiation. Assuming that the production of π^0 was in the same ratio as obtained above, this gives the following energy distribution in the jet.

Energy distribution in jets

π^+	π^0 (calc.)	p, n	K^+
30%	15%	12%	28%

Since this adds up to only 85% of the energy, it is assumed that 15% of the energy with an error of nearly 15% is available for K^0 mesons. Bethe pointed out that using the median angle of the jet to calculate the primary energy assumed isotropy of production in the center of mass system and could be 200% wrong. Kaplon confirmed this by mentioning, in particular that for the best analyzed jet at Rochester, the actual energy differed from the energy that would be estimated from the median angle of the shower by a factor of 4. Marshak added that for events of energy greater than $5 \cdot 10^{11}$ ev observed at Rochester at least 70% ± 30 of the number of the charged shower particles appear to be π^0 's. To make this a definite experimental statement, the number of neutral particles calculated from 1/2 the number of γ rays is 70 $\pm$ 30% of that of the charged particles.

68

Feigl's Report of Bristol Data on K and τ Mesons

Those K's coming to rest in the emulsion appear to have a mass of 1125 electron masses and appear to give rise to a μ meson on decay. In two cases the μ 's are observed to decay at rest into an electron. Where the mass of the secondary particle can be measured, it is close to the mass of the μ meson. Since the energy of these decay products is not constant, decay is presumably ternary. The combined mass of the neutral decay products is less than 400 electron masses and could be 0. Marshak commented that if these particles are two neutrinos then the K's would have to be produced in pairs. The total number of K's and τ 's coming to rest in the plates is 1% of the π mesons coming to rest. It is not easy to estimate the chance of these various particles coming to rest, but this figure is compatible with the K's and τ 's being produced in comparable numbers to the π 's. An estimate of lifetime of 10^{-9} secs. is obtained from this figure. It is not clear if this difference in the no. of stopped particles is due to different decay lifetimes or due to the longer range of the heavier particles. Cocconi commented that since the plates were exposed at high latitude, the production of these heavy particles must be copious even at relatively low energy. There are now six τ mesons and one of the 18 decay products identifies itself as a π meson by causing a star. Their mass is 965 electron masses. The evidence on the mass of the K meson is compatible with it being similar to the mass of the neutral ν particle. Fretter objected to this statement since the mass of the ν particle is close to 800 electron masses while the mass of the K is certainly over a 1000 electron masses.

Greisen--Evidence against the copious production of K mesons at high energies from the underground data.

If the K mesons decay into μ mesons with a lifetime less than 10^{-9}

69

secs., then at very high altitudes the number of μ 's resulting from the decay of K's should be very large compared to the number of μ 's resulting from the decay of π mesons; this is because at high energies the π mesons will interact before decaying. A very clear test of this situation is possible from the underground data. Admittedly, the vertical distribution of intensity is not sure because of uncertainty in the primary spectrum and the laws of energy loss, which affect the curve in not exactly predictable ways. However, one feature is exactly predictable. If the μ mesons result from the decay of a very short-lived parent at high energies, the no. of μ mesons in the vertical and inclined directions should be equal. If this intensity is measured underground at a certain vertical depth and in inclined direction at a smaller depth such that the thickness of matter traversed is the same both ways, then regardless of what the laws of energy loss are, and regardless of the shape of the primary energy spectrum, the intensities should be equal. On the other hand, if the μ 's come primarily from the decay of π 's, there should be more in the inclined direction than in the vertical direction. This is because the π 's coming in the inclined direction are created at a higher level in the atmosphere where the density of the air is less, and because of this lower density they have a greater probability to decay. It is not that no π 's decay, but that at high energies the no. which decay is inversely proportional to the energy. This is a very sensitive test, because even if only 5% of the mesons created were K's and the rest were π 's, 50% of all μ mesons arriving underground would come from the decay of K's and only 50% from the decay of π 's. That is, this would be true if the lifetime of the K's were shorter by a factor of a 100 than the lifetime of the π 's, but if their lifetimes were comparable very accurate measurements would be required. The Cornell experiment has been carried out at a depth of

70

1500-2000 meters of water equivalent. The minimum energy of a μ capable of reaching these depths is $5 \cdot 10^{11}$ electron volts so that the average energy is about $1 \cdot 10^{12}$ electron volts. Here the logarithmic derivative of the curve of intensity versus depth, that is $\frac{h}{I} \frac{dI}{dh}$, is equal to $3.5 - 3.6 \pm .2$. The variation with zenith angle $\frac{\cos \theta}{I} \frac{dI}{d(\cos \theta)}$ is $3.00 \pm .05$. This difference seems real and implies that the production of short lived K's cannot be more than 7% of the production of π 's at high energy. If only π mesons were produced, the two logarithmic derivatives would differ by 0.9. If, however, the lifetime of the K meson should be $> 10^{-9}$ secs. this data could be consistent with all the μ mesons arising from K mesons. The only assumption made about the interaction of K mesons with nuclear matter is that the cross section is not larger than geometrical. At least there is the possibility here that, when the lifetime of the K meson is better known, a more accurate experiment can settle this question. Furthermore, a measurement at around 300-600 m.w.e. would give a better test if the lifetime of K is as large as 10^{-9} secs.

(Meeting adjourned for lunch.)

2:00 P.M. Saturday, January 12, 1952 Professor J. Robert Oppenheimer presiding

Further Report by Fretter on Leighton's Experiments

Fretter first reported on the characteristics of the particles observed in the two Q groups. These results have already been given in the morning session where this point was discussed. (cf. p58) He also reported that Christy suggests an interpretation of the data by assuming that the decay scheme $p + \pi$ is correct, but that the groups with different Q values have different lifetimes, so that the cloud chamber will see those cases where the proton is or is not heavily ionizing with different probability for the two groups. (Pais remarked that the difference in Q value between the two groups is just the $\pi - \mu$ mass difference.) Both groups are equally coplanar. Further, in all cases where coplanarity is good, momentum balance between the initial particle and the two decay products occurs, definitely showing that these are two-body decays. In cases where the momentum of only one of the particles and the angle between them could be measured, the Q value was still calculated assuming the $p + \pi$ decay, and in these cases the Q value fell into one of the two groups as before. There is no distinction between the two groups as to the interaction of the decay product with nuclear matter. Marshak added that Leighton's interpretation is in definite contradiction to that of the Manchester group in that he sees no evidence in his data for decay into two π mesons. In those cases where a positive π meson is identified, Leighton is ready to believe that the negative particle has mass greater than a thousand electron masses and could be a negative proton. (At this point Marshak put Manchester data on the board, so that it seems appropriate at this point to include a fuller abstract of the Manchester experiments which have been published.) The essential data for the purposes of this conference come from Armenteros, Barker, Butler, and Caplan Phil Mag. 42, 1113 (1951) to which the interested reader is referred for details. The heavily ionizing secondary particles identified as protons are listed in the following table.

IDENTIFIED PROTON SECONDARIES

Momentum (10^8 ev/c)	2.42 ± 0.2	4.8 ± 0.5	3.5 ± 0.35	4.50 ± 0.45	6.0 ± 0.6
Estimated ionization	8-15	3-4	4-6	3-4	2-3
Mass range (m_e)	1550-2400	1700-2400	1450-2300	1600-2250	1450-2500
Calculated ion. for Proton	9.3	3.1	5.0	3.3	2.3

72

There are no slow positive mesons.

The identified negative mesons are listed in the following table.

IDENTIFIED NEGATIVE MESON SECONDARIES

Momentum (10^8 ev/c)	1.05 ± 0.05	0.80 ± 0.04	0.78 ± 0.14	0.74 ± 0.04
Estimated ionization	2-3	2-4	3-4	2.5-3.5
Mass range (m_e)	270-430	210-380	290-370	230-330
Calculated ion. for π	2.0	2.7	2.8	3.0

One negative secondary from a V starting just above the 7 mm. lead plate was heavily ionizing above the plate and much more heavily ionizing below it. 5 cm below the plate this track is deflected through 23° with no marked change in ionization. The momentum and ionization are consistent with this being a π - μ decay in flight. The angle of deflection is close to the most probable angle for the decay of a π with this momentum. The probability of having observed such an event is about 25%.

The momentum spectrum of positive particles contains several at minimum ionization with momenta less than 7×10^8 ev/c, where a proton would be heavily ionizing; these are identified as positive mesons in the analysis, although they could possibly be other positive particles of mass less than $1000 m_e$. Coplanarity could be checked in only two cases and in these was observed to be better than 5° . No clear evidence exists for accompanying electromagnetic radiation.

The tracks were assigned to the two proposed decay schemes

$$V_1^0 \longrightarrow P + \pi^- \quad (1)$$

$$\text{and } V_2^0 \longrightarrow \pi^+ + \pi^- \quad (2)$$

in the following manner:

Laboratory system

Rest system

For random emission in the rest system, the transverse momentum p_T (which is experimentally measured) is close to p^* , the probability of it lying between p_T and $p_T + dp_T$ being

$$\mathcal{P}(p_T)dp_T = \frac{p_T dp_T}{P^* (P^{*2} - p_T^2)^{1/2}}$$

Hence the experimental determination of this distribution can be used to check whether the emission is random. Define

$$\alpha = \frac{p_+ \cos \phi_+ - p_- \cos \phi_-}{p_+ \cos \phi_+ + p_- \cos \phi_-}$$

Then

$$\alpha = \frac{p_+^2 - p_-^2}{P^2} = \frac{m_+^2 - m_-^2}{M^2} + 2P^* \cos \theta^* \left(\frac{1}{M^2} + \frac{1}{P^2} \right)^{1/2} \equiv \alpha_0 + f(P, \cos \theta^*)$$

where $f(P, \cos \theta^*) = 0$.

Also $p_T = p_+ p_- \sin \phi / P$.

Since p_+ , p_- , and ϕ are measured, the observed value of α and p_T can be used to determine which decay scheme a given V fits. Since the five events with identified protons must satisfy (1), they are used to obtain the values $\bar{\alpha} = 0.60$, $p^* = 1.10 \pm .10 \times 10^8$ ev/c. Three events having both decay particles less massive than protons give $\bar{\alpha} = 0.08$, which is consistent with the $\bar{\alpha} = 0$ required by (2); $p^* = 1.40 \pm 0.15 \times 10^8$ ev/c for these events. Then the remaining 21 cases can be assigned to one or the other class from their measured α and p_T by first seeing which α line (0 or 0.6) they fall closest to and then seeing if $p_T (\approx p^*$ for $\alpha \approx \alpha_0$) is consistent with this assignment. All but 3 cases are unambiguously assigned. The 16 V_1^0 's give an average α of 0.65 ± 0.02 corresponding to a mass of $2250 \pm 35 m_\pi$. 12 of these could be measured accurately giving an average Q value of 46 ± 6 Mev. The 10 V_2^0 's give an average α of 0.05 ± 0.06 and for $p^* = 1.5 \times 10^8$ ev/c, a mass of about 800. 8 of these could be measured accurately and gave a Q value of 122 ± 13 Mev. The assignment into the two classes is further strengthened by the fact that the observed distribution of p_T for the two classes fits the calculated distribution (different in each case).

74

very well. The overall separation is 85% efficient if α and P_T are measured to 15%.

Finally, the observed momentum distribution of the charged decay products seems to exclude the possibility that V_1^0 and V_2^0 are the alternative modes of decay of a single parent

$$V_1^0 \longrightarrow P + \pi^- + \pi^0 \quad (3)$$

$$V_2^0 \longrightarrow N + \pi^+ + \pi^- \quad (4)$$

This distribution is

Momentum (10^8 ev/c)	0-8	8-16	16-24	24-32	32-40	>40
a) observed V_1^0 prod.	6	3	2	2	1	2
b) observed V_2^0 prod.	3.2	6.4	1.6	1.6	—	3.2
c) calculated for (4)	13	3	—	—	—	—

Note that V_1^0 contains more low momenta than V_2^0 , which is the reverse of what would be expected on the (3), (4) decay scheme; there the nucleon carries most of the momentum in the vast majority of cases, so that in (4) the π mesons should usually have low momenta. If (3) and (4) are postulated, then the mesons will have approximately the same momentum distribution in both cases, and the meson momenta in (4) should be given by twice the momentum of the negative particles in (3). This calculated value is given in line (c), and as expected is concentrated at low energies, in complete contradiction to the observed momentum distribution. The absence of low momenta mesons in V_2^0 decay is therefore a strong argument against the decay scheme (3), (4). } Marshak stressed the point that there are several cases of positive particles with momentum less than 4×10^8 ev/c whose mass was definitely less than a thousand electron masses and which, therefore, the Manchester group identified as positive π mesons. It was commented that this is not in disagreement with the Pasadena data, where five positive π mesons are also observed. Rossi reported that Blackett had definitely

told him at Copenhagen that there were cases in the Manchester data where both particles were less massive than protons. Bethe remarked that there are cases when both particles have minimum ionization and have comparable momenta. However, if the Q value of this reaction is only 75 Mev and the decay goes to one proton and one meson, then the proton must always have much more momentum than the meson when both are at minimum ionization. This is therefore again evidence for the two π decay. Rossi quoted from the paper the definite statement that there are three cases where both products are less massive than the protons. Peierls commented that the Manchester group have in addition made a complicated argument based on the angular distribution which again supports the assumption of the mode of decay into two π mesons (cf. abstract above). Oppenheimer commented that the assumption of only one mode of decay is quite special and that he was sure that we are not persuaded it is true. The only thing that is hard to reconcile between the Cal-Tech and the Manchester data is that one would expect to find a few more identifiable positive π mesons in the Cal-Tech data. But for fifty negative π mesons observed, one would expect at most only fifteen identifiable positive π mesons and five are in fact found. That the analysis of the data on the basis of the single decay scheme resulted in two peaks of Q values was not necessarily significant; this sort of thing has happened before when nuclear resonances were analyzed using bad data. The discrepancy^{cy} would be something to worry about only if it were forced by the data, which it is not.

Thompson: V particles

In 20,000 photographs, 1400 penetrating showers have been found in a magnetic cloud chamber, triggered in a manner similar to that used in the previously described experiments. In these sea level photographs, 41 V or v particles are found. Although this indicates only one neutral V particle for every thirty or thirty-five penetrating showers, the probability of missing them in this experimental arrangement is large; at least one half must decay above the chamber and another three quarters of those observed would be missed at the sides and back of the chamber. It is, however, difficult to evaluate the solid angles and make an accurate correction for the number lost. Only two particles are needed to trigger the chamber, so that pictures of very small showers can be obtained. In one large penetrating shower two V particles

76

were observed in the same photograph. A picture of this event was shown and a second slide of a case where the masses of both particles of the Υ could be measured. (This second event is number 5 in the tables given below.)

Cases where the positive particle is identified.

	<u>Momentum</u>	<u>Ionization</u>	<u>Calculated for a proton</u>	<u>Mass (m_e)</u>
1.	1.2 Bev/c	1-2	1.3	ionization not far enough from minimum
2.	0.75	2-4	2.0	2520
3.	0.38	3-6	5.1	1680
4.	>0.2	2-5	—	>500
5.	0.66	2-3	2.3	1928

Since these pictures contain many grey tracks varying almost continuously in velocity, ionization estimates were made by comparing the unknown tracks with these. Since ionization rises rapidly in this region, the measurement of the mass thus obtained is not as bad as might be thought. The mass was calculated by using the central value of the ionization in the range of values estimated by this method. The mean value of the mass of the five identified positive particles given in the table is $2000 \pm 400 m_e$, where the error is not conservatively estimated. Therefore these results do not lend any support to the presence of a positive particle whose mass is less than one thousand electron masses. It should be noted that the positive decay particle must have a long lifetime, if it is unstable, since the total track length of such particles observed in these experiments and at Manchester is very large. The mass values obtained for the negative particles given in the next table are not sufficiently accurate to distinguish between π and μ mesons.

Cases where the negative particle is identified.

	<u>Momentum</u>	<u>Ionization</u>	<u>Calculated ionization for a π meson</u>	<u>Mass (m_e)</u>
5.	65 Mev/c	3-4	4.1	250 ± 50
6.	71	2-3	2.6	270 ± 50
7.	84	2-4	2.7	275 ± 50

77

There is more information about the nature of the particles than these tables indicate. There are several cases, one of which was reported last spring, in which the positive disintegration fragment has a mass that is easily less than one thousand electron masses. In those cases, the negative particle has high momentum, and the assumption of the decay scheme $p^- + \pi^+$ results in the same calculated Q value as the previous cases of $p^+ + \pi^-$. However, further work has neither confirmed nor disproved this evidence for the presence of a negative particle of nucleonic mass. There are five cases where the positive particle is definitely much less massive than the proton and in which the assumption of a negative nucleon would give a reasonable Q value

Since cases where the heavy positive particle occurs are most frequent, Q values are given for these cases, and only for those four cases where the mass of the positive particle has been measured

Analysis of cases where p is identified.

	<u>Q</u>	<u>γ</u>	<u>θ_p in center of mass</u>
1	31 Mev $\pm$ 5	1.62	86°
2	36 $\pm$ 10	1.33	129°
3	44 $\pm$ 20	1.19	110°
5	36 $\pm$ 10	1.16	40°

If the decay were actually a two body decay, the emission of the proton should be isotropic in the center of mass system, and it is seen from the table that the average angle is indeed about 90°. This is at least evidence that there is no large anisotropy of emission in the center of mass system. Since there is a large pile of lead above the cloud chamber, and the mean free path for nuclear interaction is short, it is unusual to have a single nuclear event above the chamber. There is evidence in many pictures for at least two or three interactions. There are also pictures where no penetrating shower is seen. Therefore, when complete lack of coplanarity occurs in experiments of this type, it is not significant. However, in event number 5, it is possible to analyze for coplanarity, as even if there is more than one event above the chamber, these events all occur with their centers on a single line. Two

78

straight tracks occur in this picture which can be extrapolated back in space to give the origin of the neutral V particle. The measured values of the momentum of the π meson and the proton in this event are 58 Mev/c and 63 Mev/c respectively, and these values check the assumption of coplanarity (see figure below).

Event No. 5

In the light of the earlier discussion it seems appropriate to discuss how the calculated Q value will be affected by errors of measurement in the proton momentum in the case of a $p + \pi^-$ decay. In brief, the effect of this error is almost invariably to raise the calculated Q value. To see how this comes about note that, since the mass of the neutral V particle is not much greater than the mass of the proton, in the laboratory system the vector momentum of the proton will lie very close to the direction of motion of the V particle. Hence, a measurement of the momentum of the proton gives approximately the β of the neutral V particle. Therefore, the y component of the π^- meson momentum will not change rapidly with errors in the proton momentum because the direction of the resultant π^- meson momentum will not change. If the Lorentz transformation is carried out and the Q value calculated, it is then

found that the curve of Q value versus the x component of the proton momentum has a minimum for Q values about 20 Mev. Therefore, if Q values are measured falling in the range between 20 and 100 Mev, the errors in these values are different depending on the proton momentum, and it is not correct to take a straight numerical average of these Q values. However, in the four cases discussed in these experiments, the value of the proton momentum is close to the minimum of the curve and hence the error in the Q value is small.

[(It seems appropriate at this point to include the actual equations for this situation to see how this result comes about.)

Symbols: p = momentum of proton in laboratory system.

π = " " pion " " "

E_p = energy of proton " " "

E_π = " " pion " " "

M = mass of proton

μ = " " pion

primes indicate center of mass system

Q = disintegration energy in ctr. of mass system

x = direction of V_0

Carrying out the Lorentz transformation, the Q value is

$$Q = \gamma [E_p + E_\pi - \beta (P_x + \pi_x)C] - Mc^2 - \mu c^2 \quad (1)$$

The center of mass system is defined by

$$P'_x + \pi'_x = 0 \quad (2)$$

or

$$C(P_x + \pi_x) = \beta (E_p + E_\pi) \quad (3)$$

Substituting this value for β in equation (1) gives

$$Q = [(E_p + E_\pi)^2 - (P_x + \pi_x)^2 C^2]^{\frac{1}{2}} - Mc^2 - \mu c^2 \quad (4)$$

Since, as has been argued above, we are interested in the variation of Q with (errors in) p_x , we investigate Q as a function of P_x , holding other quantities constant.

Since

$$\frac{\partial E_p}{\partial P_x} = \frac{P_x C^2}{E_p} \quad (5)$$

we find

$$\frac{\partial Q}{\partial P_x} = \frac{C^2 [P_x E_\pi - \pi_x E_p]}{E_p [(E_p + E_\pi)^2 - (P_x + \pi_x)^2 C^2]^{\frac{1}{2}}} \quad (6)$$

and

$$\begin{aligned} \frac{\partial^2 Q}{\partial P_x^2} = & \frac{(P_x E_\pi - \pi_x E_p)^2 C^4}{E_p^2 [(E_p + E_\pi)^2 - (P_x + \pi_x)^2 C^2]^{\frac{3}{2}}} \\ & + \frac{E_\pi (M^2 C^4 + C^2 P_y^2) C^2}{E_p^3 [(E_p + E_\pi)^2 - (P_x + \pi_x)^2 C^2]^{\frac{1}{2}}} \end{aligned} \quad (7)$$

Therefore, since $\frac{\partial^2 Q}{\partial P_x^2}$ is always positive, Q as a function of P_x has a minimum at $P_x = \pi_x E_p / E_\pi$, and increases away from this value. According to Thompson, this minimum occurs for Q near 20 Mev using the values of momenta usually encountered in V^0 decays. Therefore, errors in the measurement of the (x component of the) proton momentum have the least effect on the calculated Q value in this region and cause large errors in Q outside of this region.]

If a true $p + \pi$ decay were to be misinterpreted as a decay into two meson-like particles, the actual asymmetry in momenta would require a large Q and the positive particle would have to come out predominantly in the forward direction. Such cases have been calculated and Q values in the range of 100 to 200 Mev were obtained, while the angles of the positive particle in the forward direction were indeed very, very small. The momentum diagram for event number five is given in the figure above. The agreement in y component of 58 or 63 Mev/c is within the accuracy of the method.

Rossi: Report on the work by Bridge and Annis

This work has not yet been completely analyzed, so four pictures were shown and discussed. They were obtained in a 20" by 20" cloud chamber containing lead (and in one picture also aluminum) plates, triggered by a penetrating shower detector above the chamber which selected particles from nuclear interactions of the range of about 5-10 Bev. The first picture was published last May, and contains what Rossi calls an S or stopped particle. This particle is heavily ionizing and comes to rest in a lead plate of the chamber, giving rise in this plate to a lightly ionizing particle which traverses five 1/4" lead plates without multiplying and without scattering more than two or three degrees. It is practically impossible to assume that this is an electron of less than 50 Mev, so this cannot be a case of μ -electron decay. That is, an electron of 50 Mev traversing 35 grams per square centimeter of lead would lose 42 Mev by ionization alone, while this particle shows no scattering and emerges from the last plate still at minimum ionization. As thousands of pictures of particles coming to rest in the plates have been obtained, this is a very unusual event. Since the secondary particle is not an electron, it must be a meson, and from its range, it must have an energy greater than 100 Mev, although there is no way to distinguish between a π or a μ meson. It undergoes no nuclear interactions and from the small coulomb scattering its momentum is estimated as 190 Mev/c. This particle therefore looks like a kappa one¹ as observed at Bristol, and its mass as estimated from scattering and range is 800 ± 800 ⁻⁴⁰⁰ electron masses. If an attempt were made to explain this particle by the decay scheme $S \longrightarrow \pi^+ + \pi^0$, then one should see the electron cascade produced in the lead plates from gammas from the decay of the π^0 . Since, in its own frame of reference, the S particle is seen to exist in the cloud chamber for 10^{-9} seconds, it cannot have a mean life much shorter than this figure. The Q value of the decay must be quite high, again indicating that the mass of the stopped particle is at least one thousand electron masses.

A second photograph was shown of the only known case in which both particles of a V decay produced interactions in a lead plate. Therefore neither decay product of this V particle can be a μ meson. Assuming that this is a ν particle, and that the decay is symmetric between the two π mesons, the angle of 19° between the branches of the ν gives a momentum of .9 Bev/c, which is

82

consistent with the small scattering of the secondary particles. If this particle were assumed to be a V particle, the proton must have at least .7 Bev/c so as not to be heavily ionizing; the π meson then must have 350 Mev/c, which is still consistent with the picture.

A few days ago a third picture was obtained of a very narrow V with an angle of only 4° . If the decay products are two π mesons, they must each have an energy of 4 Bev, but the decay is also interpretable as $\pi + p$. One of the secondary particles disappears in a lead plate producing a complex electron shower originating from at least three photons in the plate and (perhaps) containing no penetrating particles. The total energy of the shower is consistent with the assumption that the 4-5 Bev of energy of the initiating particle went into two π^0 mesons. If, in addition, it is attempted to ascribe two of the cores of this shower to the decay of a single π^0 meson, it is found that the angle between the cores corresponds to an energy of 1 Bev per particle rather than 2 Bev. The second particle of the V strikes one of the lead plates at a point somewhat obscured by the electron shower from the first particle, but it is believed to also cause an interaction in this lead plate. The event can be analyzed with considerable certainty as four simultaneous pictures were taken of this event. Bridge and Annis would like to interpret this as a negative proton converting into two π^0 mesons in the lead plate, but this interpretation is by no means forced by the data. For example, a high energy π could hit a proton changing the proton into a neutron and giving all its energy to two π^0 's. Fretter commented that a proton in penetrating showers can be observed to cause this kind of event. Rossi continued that the initiating particle must have at least 4 Bev to explain the shower; if it were of higher energy, the angle of the shower would be smaller. The scattering is imperceptible which also indicates an energy of 2 Bev or more. Rossi would interpret this event as a proton or π meson causing an interaction in the plate, since we have as yet no positive evidence for the existence of negative protons.

Thompson remarked that in the heavily ionizing tracks used to standardize the ionization measurements in the experiments discussed earlier this afternoon, there are a total of two hundred to three hundred proton tracks, and none of these are negative. Thirty five of these tracks were carefully measured, and gave

83

protonic mass. This negative evidence is not impressive, because it is not known how many of the grey tracks actually originate in a primary event rather than from evaporation. A few negative meson tracks were also seen, but these were easy to recognize. Rossi continued by stating that although the origin of the V is close to the plates it is definitely separated, and this is certain, not only because of the four separate pictures, but also because nearby tracks penetrating these plates actually are not separated from the plates. Rossi admitted that the probability of three gammas from two π^0 's converting in the plate was small, but countered that one of the electron pairs from the plate might have been directly produced. Furthermore, one of the tracks appeared too heavy to be a single electron, and might have contained an unresolved electron pair or another penetrating particle.

Over a year ago in the same chamber, using Gregory and Tinlot's arrangement of alternating lead and aluminum plates, a picture was obtained of a charged V particle decaying in the gas of the chamber to give a π meson passing backwards to an aluminum plate where it was backscattered and traversed 2 Pb and 2 Al plates coming to rest in the third lead plate. This secondary particle is definitely identified as a meson (not a proton) from the scattering and range. This scattering in the aluminum plate forms the only known identification of the charged decay product of the charged V particle as a π meson, although this picture, as all individual charged V particle pictures, could be interpreted as a scattering in the gas. Interpreting this as $V^+ \longrightarrow \pi^+ + \pi^+$ and assuming elastic scattering, the range of the π^+ gives a lower limit to the energy of the π^+ and hence a lower limit to the mass of the V^+ definitely greater than 2200 electron masses but consistent with 2300 electron masses. Alternatively, interpretation of this decay as $V^+ \longrightarrow \pi^0 + \pi^+$ puts a lower limit on the mass of v as 850 electron masses. Therefore, this picture is consistent with charged and neutral v particles having the same mass. If an attempt is made to identify the S, K, and charged V particles as all the same particle, then they cannot have lifetimes as much shorter than 10^{-9} seconds. However, the identification of the decay products of the kappa's as μ mesons and the identification of the decay product of this charged v particle as a π meson makes it impossible to simplify the picture to this extent. Furthermore, the mass of the v^+ going to $\pi^+ + \pi^0$ of 800 to 850 electron masses is definitely smaller than

84

the S or kappa mass. Also it is rather unlikely that gamma rays coming from the π^0 meson would have been missed in this experiment. So the only simplification possible is the identification of the S and kappa mesons ^{as the same} particle.

The Manchester group have obtained a clean picture of a charged V particle decaying; in the same picture there appears a neutral V whose point of origin apparently is the decay point of the charged V particle. Rossi has similar evidence, consisting of a slow particle not energetic enough to produce a shower coming to rest in a lead plate and a V particle appearing in the gas somewhat below this plate. Fretter commented that Manchester has a similar picture of a stopped particle and a v particle in the gas; differing in that the stopped particle has an energy of 2×10^9 ev. Rossi summarized this discussion by stating that we know that there are charged unstable particles, some decaying to give a π meson, some decaying to give a μ meson, some with masses of 2300 or 800 electron masses, and some having masses of 1100 to 1200 electron masses. Rossi raised the question whether the photographic emulsion pictures of $K \rightarrow \mu$ decay might not possibly be explicable as cases of $\pi \rightarrow \mu$ decay in flight. It is true that the μ meson has an energy of 6 Mev and is travelling backwards relative to the apparent direction of the kappa track; however, this could have happened if the π meson had been scattered in that direction just before the μ mesons ^{was} emitted. If this were the case, the identification of the kappa meson would rest solely on the accuracy of the measurement of its mass through scattering and grain density. George added that Liverpool has found another case of $K \rightarrow \mu \rightarrow e$ decay as reported to him in a postscript of a letter from Powell.

(The meeting was adjourned for tea.)

Lord (and Schein). "V Particles" Produced by the Chicago Cycotron

The experimental arrangement consisted of exposing a photographic plate imbedded between two blocks of lead in the 145 or 220 Mev π^- meson beam. These mesons have a range of about 7 centimeters in lead and would be stopped before coming to the end of the lead blocks. The plates were searched for tracks consisting of a single slow proton and a fast meson forming a V pointed in the direction of the beam. Two thousand nuclear collisions were found in the emulsion, of which quite a few could have been of this form. These could be interpreted as (1), meson stars caused by a meson coming backwards, (2),

85

neutron stars, or (3), V particles. However, events of the first or second kind are quite rare. Events of the first kind could be mistaken for V particles only if a meson travelling backward in the emulsion were to cause a one prong star. Of the two thousand events, only $1/60$ were stars of any description caused by mesons travelling backward in the emulsion, counting the presumed V particles as stars. For mesons travelling in the direction of the beam, the probability of producing one slow proton was found to be only one in thirty. The total probability for such an occurrence is therefore $1/30 \times 1/60$ or $1/1800$; therefore, only one event in the two thousand could be such a chance event resembling a V particle. One objection to this argument is that the figure $1/30$ was obtained for 145 Mev mesons going forward, while the mesons coming backwards would have energies of only 30-50 Mev. This point has not yet been investigated thoroughly, as the results of these experiments turned up only three days ago. However, Bernardini's data on one pronged star events indicates that they do not increase rapidly with energy.

Eight events of this character were found. Assuming only that they are in fact V particles decaying into a proton and a negative meson, the Q value of the decay can be calculated from grain density and multiple scattering. The direction in which the meson is travelling can only be determined in one case and this unfortunately is the case where the meson is moving backwards; this is presumably the single chance background event. The Q values for these eight particles are given in the table.

Q values for Chicago cyclotron "V particles"

21 ± 10 , 25, $4.3 \pm .1$, 42, 32, 54 ± 10 , <78, 33

They correspond to a momentum of the V particle of from 57 to 195 Mev/c. The event with Q value $4.3 \pm .1$ Mev had a slow meson which gave rise to a star in the emulsion. The ratio between nuclear collisions and V particles appearing in the emulsion should be constant. Using the usually assumed decay time for the V particles, they should have a mean free path for decay in the emulsion of $1/2$ to 1 centimeter. The data then imply that one π^- meson in 500 on striking a lead nucleus produces a V particle.

The possibility of events of the second type is a weak point in the argument. However, some plates were exposed in the meson beam before deflection by the magnet, where there were many more neutrons. Of 170 events in these plates, only one was a neutron initiated event, and this gave rise to a slow meson. As it takes a high energy neutron to produce a meson, and as the apparatus was behind six feet of iron, most of the neutrons present should be of very low energy, making this explanation appear unlikely. However, this point has not been completely settled in the minds of the experimenters. Neutrons arising from the absorption of π^- mesons should not have enough energy to reproduce π 's in secondary events with any reasonable probability. For example, fast protons are produced very rarely by π^+ and if, as was indicated yesterday, the energy is shared between two of them, the energy available is very considerably reduced; therefore, while this type of event is energetically possible, the process is extremely improbable. Marshak objected that high energy neutrons may be five or ten times more probable than high energy protons. Lord replied that the results mentioned were for π^+ absorption rather than π^- , which should remove some of the discrepancy. He continued that in three cases the π meson was identified by scattering and grain density; if the unidentified cases were fast protons rather than mesons, they would have to have energies of from 120 - 180 Mev, which seems unlikely. The plates were exposed directly in the meson beam in order to be able to observe V particles even if their lifetimes were short as 10^{-13} seconds. Plates were also exposed without the lead and a preliminary search revealed no V particles in them, but this search was not exhaustive. The factor of 1/60 does seem a little low, but it was experimentally evaluated from all stars produced by mesons travelling in the backward hemisphere. The angular distribution of all elastically scattered mesons was measured, and found to be 20% of all events. The overwhelming component of this scattering was inelastic and was spherically symmetrical, so that 10% going in the backwards direction seems quite reasonable.

Bernardini commented that for 100 Mev mesons incident, including only the inelastic scattering and neglecting elastic scatterings, 50% of the mesons were scattered backwards with energies distributed mostly around 50 Mev, which is quite a lot. For example, in 152 cases of the elastic and inelastic scattering, in three cases the meson was coming backward and produced a star and

in two cases this was a one prong star. (The direction of the meson was completely defined in two cases.) These include only interactions in flight and neglect all cases of stopped mesons. While it is true that the number of stars with one, two, and three prongs does not change very much with increase in the energy, the probability of small pronged stars increases with the decreasing energy, and around 30 - 40 Mev, 25% are one pronged stars.

Oppenheimer. Introduction to Theoretical Discussion of Heavy Unstable Particles
by Pais

We have not yet learned anything that would incline us to change the original list of decay schemes written down this morning, although a few more question marks might be desirable. All of these objects seem to be produced at fairly high energies with reasonable probability. So in these nuclear collisions, some reasonably strong interactions must be involved. We know that high masses are adverse to producing particles, yet we see that these heavy particles compete fairly well with the production of π mesons. Therefore, the question arises as to how they can last so long. Since they come out of nuclear matter, they must be associated with the proton, antiproton, neutron, anti-neutron system capable of making mesons and (as is known in the case of the neutral π meson) gamma rays as well. I do not think anyone is persuaded there are not particles of much shorter life, because the instrumental situation favors finding lifetimes in the observed range.

Three alternative explanations have been proposed which may be schematized as (1), the live parent, (2), the heavy brother, and (3) selection rules. The first turned out to be the correct explanation of the μ meson. This was the conjecture of Marshak and Bethe that there was a step after production in which the strongly interacting particle could turn into something else that did not interact strongly with nuclear matter. This explanation does not, however, work out well for the V particles. Let the hypothetical parent of the K , τ , V or v particle be called x and be strongly coupled to nucleons. If the decay of x into the lighter particles were extremely rapid, these particles could recreate x virtually, and since it is strongly coupled through nucleons to still lighter particles, it would decay preferentially to these, and the heavy V particles would not in fact be produced. If, on the other hand, the decay of x into the V particles were very slow, then x itself through its

88

interaction with nucleons could again decay into still lighter particles than the V 's. That is, since n must go to x in something of the order of 10^{-23} seconds, x must go to V with a lifetime capable of competing with this, as otherwise x would return to n . But fast and slow are not absolute terms, there are selection rules, and the whole explanation does not appeal to Oppenheimer as a possible thing. The argument does not invalidate the $\pi \rightarrow \mu$ case, because here it is impossible for the reverse reaction to occur simply on energetic grounds. What is said here holds, of course, only for the V particle and not for the lighter particles.

The second explanation assumes that a heavy mate is associated in the production of any of these unstable particles, and there is therefore not enough energy to return through this state to the unstable nucleon system. The formal classification of this scheme is left to Pais. It is true that there is little experimental evidence for the production of pairs of these particles, but the detection efficiency is not great, we do not know what x is, and it is still an open question.

The third alternative of selection rules was discussed very thoroughly in Tokyo last summer. Although in our picture of the neutral meson it has associated with it proton anti-proton pairs and hence electromagnetic currents, these currents are not terribly strong. If one assumes that there are only two quanta involved and that half of the time there is a proton anti-proton pair instead of a neutral meson, one obtains a decay rate maybe a hundred times larger than observed. So one can say that there is a tendency for electromagnetic and meson-producing currents to be weaker than one would think. This is formally called regulator theory, not a very clear idea physically, but it is still a possibility. There is another possible selection rule. Of all these objects, the only one of which there was a trace in the literature before its discovery is the V particle. That is, it is vaguely related to the isobars mentioned yesterday for example by Wentzel. If such isobars exist in the hundred Mev region, we have seen that they must be very short-lived, which is not surprising as there is nothing to hold them together. But in the very high energy collisions in which V particles are produced, there can be instantaneously very high angular momenta, and particles produced in such states might decay to stable forms of high angular momenta. This argument does not apply to the production of kappa, ν and tau and the V particles seem a little common to be

89

such specialized products. So it seems better to pursue the more likely alternative of the heavy brother hypothesis which Pais will now proceed to do.

Pais. An Ordering Principle for a Megalomorphian Zoology

The following is an attempt to decouple the production of these heavy particles from their decay, talking for the moment only of the observed species. This involves an approach not previously mentioned at this conference. An ordering is attempted by assigning to the protons, neutrons, V 's, π 's, and v 's, a "mass number" as indicated in the table.

"Elementary Particle" Families

N_0 (nucleons) ($p = N_0^+$, $n = N_0^0$)	π_0 (pions) ($\pi^0 = \pi_0^0$, $\pi^\pm = \pi_0^\pm$)	e
N_1 (heavy V particle) ($V_1^0 = N_1^0$; $V_1^\pm = N_1^\pm$)	π_1 (light v particle) ($v_2^0 = \pi_1^0$; $v^\pm = \pi_1^\pm$)	μ
$(N_2?)$ ("resonance" in π -nucleon scattering)	?	?

We begin by introducing the Yukawa interaction but avoid all details specifying the coupling. This coupling is then simply written $(N_0 N_0 \pi_0)$. This suggests a matrix of interactions of the form $(N_1 N_j \pi_k)$, with i, j , and k equal to zero or one and with the possibility of higher indices in the future. A selection rule is now introduced which does not follow from present theories, but which is not in contradiction with known facts. This rule is $(N_1 N_j \pi_k)$ can only be strong if $i + j + k$ is even. This rule singles out three interactions, which we indicate as strong by writing G before the interaction. In addition to the Yukawa interaction $G(N_0 N_0 \pi_0)$, there is $G(N_1 N_0 \pi_1)$. This second interaction requires that V and v be produced simultaneously. $G(N_1 N_1 \pi_0)$ can also be a big interaction.

90

These interactions offer enough opportunity to create V and v but if only these interactions exist, these particles would be stable. This is due to the conservation of evenness. For example, V decay in this notation would be written as $N_1 \longrightarrow N_0 + \pi_0$. But since the left hand side is odd and the right hand side is even, this can never occur through even couplings.

We will now gradually introduce the conventional interactions and ask what these imply as to instability and lifetime. The first to be introduced is electromagnetic interaction. But in this language all electromagnetic interactions are even because of gauge invariance. For example the conventional electromagnetic interaction is

$$\bar{\Psi}_0 \gamma_\mu \Psi_0 A_\mu$$

We assume that the photon has mass number 0. If there were possible an interaction of the form

$$\bar{\Psi}_1 \gamma_\mu \Psi_0 A_\mu$$

then N_1 could go to $N_0 + \gamma$. However, it is well-known that such mixed current densities are not allowed by gauge invariance, that is essentially by the conservation of charge. Therefore, the introduction of electromagnetic interactions, which are even, leaves no possibility of decay, and the particles are still stable. It is true that there might be Pauli-type terms leading to magnetic dipole interactions of the form

$$\bar{\Psi}_i \gamma_\mu \gamma_\nu \Psi_j F_{\mu\nu}$$

But although we can write such interactions down, all that are observed to occur up to the present can be derived from the elementary couplings in the manner sketched by Feynman and in this way one can never get $i = 1, j = 0$, so that the only possible ones are still even. Therefore it is not inconsistent to exclude these cases. Breit objected that this kind of interaction was just as reasonable as those already assumed. Pais agreed that there was no argument of symmetry or invariance to exclude such terms but insisted that he has the liberty to omit them without logical inconsistency. Bethe added the additional argument that terms of this form are not renormalizable.

Pais now introduced exceedingly weak $i + j + k$ odd couplings with

the order of 10^{-11} . These would be $g(N_1 N_0 \pi_0)$, $g(N_0 N_0 \pi_1)$, $g(N_1 N_1 \pi_1)$. We said all must be small and essentially of this order. It cannot be accurately estimated as roughly speaking the large and small g 's will be mixed in any higher order calculation. He added that if the interaction $(N_1 N_0 \pi_0)$ were large, it would give a resonance at the mass of the V particle, which is not observed in the Chicago experiments. Oppenheimer objected that one would also not see this if the V particle had a spin of $1/2$. Pais added that if a particle N_2 is assumed and $(N_2 N_0 \pi_0)$ is strong, as the above rules would indicate, it could give a true resonance as observed in the Chicago experiment. This point has not yet been investigated, however. It did not seem appropriate to discuss in detail the decay schemes, which will be reported in a paper. However, Pais stressed that the generalization of Furry's theorem used by Fukuda and Miyamoto to obtain selection rules was very useful in sorting out these decay schemes. (Cf. Fukuda, Hayakawa and Miyamoto, Prog. Theor. Phys. 5, 283 (1950) p. 291). He also added that if the frequency of production of N_1^0 is estimated from the frequency of the occurrence of the decay in N_1^0 going to $N_0^+ + \pi_0^-$, the production will be underestimated. This is because on general symmetry grounds one would also expect the decay N_1^0 going to $N_0^0 + \pi_0^0$, which would not be observed in the cloud chambers except as gamma rays unrelated to V events. In the decay scheme $\pi_1^0 \rightarrow \pi_0^+ + \pi_0^-$, if we accept that π mesons are pseudoscalar, then π_1^0 must be scalar or vector. Since this process is not renormalizable, only regulator results are available and the Japanese give a decay probability of 10^{19} to $10^{21} \times (g^2/\hbar c) \times (G^2/\hbar c)^2$. Hence, small g is definitely required for this process. [If I may step out of my role as note taker for a minute, I would like to add that this process is in fact renormalizable, if one introduces contact interactions of the form proposed by Salam. This introduces a new empirical constant into the theory, which can be chosen to give the observed lifetime for the v_2^0 . Furthermore, the decay lifetime into two gamma rays, which is finite and at first sight large, although unaffected in lowest order, can vanish when higher order terms are included, but only for a particular relationship between the coupling constants of π mesons and v particles with nucleons. H.P. Noyes] In Pais' scheme, the decays into $\pi_0^0 + \gamma$ or into two γ 's are smaller in the ratio e^2/G^2 and e^4/G^4 respectively, irrespective of selection rules.

Oppenheimer commented that if Lord is right, then Pais is wrong.

Wentzel asked if it would be possible to assign unit spin to the ν particles. Oppenheimer answered that this would be possible for the ν_2^0 , but for ν_1^0 this would require a neutrino in the decay scheme, which is certainly possible, but has not been observed. He added that this theory is on the one hand an extension of the old rule that the number of nucleons is conserved and on the other hand a generalization of where you would expect to find weak couplings other than in β decay. We would have not been surprised if these new heavy particles had been found to undergo something closely related to β decay, as perhaps the kappa particle does; but there are other particles which clearly do something quite different.

Pais continued by raising the question whether this scheme was capable of explaining the apparent dissymmetry between the charged and the neutral V particles. If, as the scheme in the above form essentially assumes, they are produced in comparable numbers, the question arises whether the observed dissymmetry can be due to differences in decay. Since it is difficult to find selection rules for spinors, there is apparently no possibility of explaining the dissymmetry of N_1^+ by selection rules and it turns out that the selection rules applied to π_1^+ cannot exclude various possibilities sufficiently. If we now extend the picture to include the μ meson, the decay $N_1 \longrightarrow N_0 + \mu + \nu$ becomes possible. From dimensional arguments this should lead to a lifetime of

$$\tau \sim \frac{1}{\hbar} \frac{g_F^2}{(mc)^2} \left(\frac{mc}{\hbar} \right)^4 \frac{\hbar^2}{mc^2}$$

where g_F is the Fermi coupling constant for β decay. Accepting the general order of magnitude of the Fermi constant, this decay lifetime is also of the order of 10^{-10} seconds, so that it can presumably compete with the observed form of charged V particle decay. In view of the uncertainty of the constants at the present time, it would be silly to attempt a detailed calculation of this branching ratio. A priori, three decays suggest themselves for the π_1 particle

93

However, the last two possibilities are rigorously forbidden by the following selection rule. Consider β decay of the π_1^0 particle according to the scheme indicated in the figure.

If such a neutral particle is coupled with τ_3 to the nucleons, the proton loops and neutron loops will cancel each other identically making this decay scheme strictly forbidden. But the first process might be fast, and could then explain the dissymmetry between charged and neutral ν particles. No such possibility exists for N_1^+ . Oppenheimer noted that the problem with the kappa is ^{as} to how it is produced rather than as to its decay. Marshak added that the universal Fermi interaction gives a lifetime of 10^{-9} seconds for this decay, which is in good agreement with the experiments; in addition all forms of Fermi interaction give roughly the same order of magnitude for the process going to an electron and two neutrinos instead of a μ and two neutrinos (calculation by Messiah). The possibility that some kappa's decay directly into electrons is certainly not excluded by the present data.

Pais continued by discussing pseudoscalar heavy bosons of mass sufficiently large so that they could decay into three π mesons. Consider the decay scheme

$$B^+ \longrightarrow \pi_0^+ + \pi_0^+ + \pi_0^-$$

which is apparently a rare event. This implies on general symmetry grounds the decay scheme

$$B^+ \longrightarrow \pi_0^+ + \pi_0^0 + \pi_0^0$$

94

This could appear in cloud chambers as a rare event of a charged ν particle with accompanying photons. If this charged pseudoscalar boson has a neutral analogue, this should decay according to the following three schemes

$$B^0 \longrightarrow \pi_0^0 + \pi_0^0 + \pi_0^0$$

$$\pi_0^+ + \pi_0^- + \pi_0^0$$

$$\pi_0^+ + \pi_0^- + \gamma$$

The second of these would appear as a rare event of two non-coplanar π mesons with accompanying gamma rays. However, one can easily convince oneself [?] that the first two possibilities could be forbidden by assuming that B^0 has isotopic spin three while the π mesons have isotopic spin one. Then the third alternative would be the most probable, and since it is not divergent it has been calculated. If the B^0 had a mass of 960 electron masses, the spectrum of the π momenta in the center of mass system is very much more strongly peaked than one would expect. If a $\pi^+ + \pi^-$ pair corresponding to the peak of this momentum distribution were observed in a cloud chamber, they would be interpreted as the products of a two body decay of a neutral particle of mass close to 800 electron masses. Marshak asked why, since the neutral π^0 meson decays into two gamma rays in 10^{-14} seconds, the B^0 could be expected to decay at any slower rate. Pais replied that in his schematization, this second process is forbidden by the 1-0 selection rule; that is π^0 goes by G but B^0 goes by g.

Pais then went on to the third column of the table (p. 87), which he likes even better than the others. He remarked that he would like to look at this schematization as the unfolding of an ordering in which one talks about families of elementary particles rather than elementary particles themselves. He would hope ultimately for a master equation for each group which essentially by means of a quantization process would give not only a set of mass values but also certain selective principles to go with the new quantum numbers. One might call this a weak coupling isobar theory. Thus, surely everybody would like to class the μ meson with the electron. And just as surely no one would believe that one can get a particle of 210 electron masses by using the strong

fields surrounding the electron, because there are no such strong fields. So this particle, which on some bases is the superfluous particle of physics, could be considered necessary as a weak coupling isobar.

Oppenheimer concluded this presentation of Pais' schematization of the particles by saying that even apart from the details heard today, the new particles do show one thing we were not at all prepared for, that is, very slow decays characteristic of β decay but now not in the same four spinor formalism. He is very sympathetic to this effort to take seriously the conservation of nucleons and the occurrence at hitherto unpredictable places of couplings of quite different orders of magnitude from anything that we have met in the rest of physics. This is a way of beginning to take these things seriously and beginning to codify them. He thinks that this has to be done, whether this is the right way to do it or not.

Marshak. "To be or not to be (astonished), that is the question"

Marshak attempted to point out what seemed to him difficult to understand, and what was not, among the new particles. He does not think one should lump them all together from the point of view of surprises. For example, the kappa meson can be considered as a heavier state of the spin 1/2 particles. If you say you have a universal interaction with ^{the} same coupling constant among all spin 1/2 particles, you find that for example the kappa should go into a μ meson and two neutrinos with a lifetime of about 10^{-9} seconds or ^{into} an electron and two neutrinos with about the same probability. This is in good agreement with the present data, and the existence of the alternative mode of decay could be settled by future measurements. The fact that Rossi found no gammas accompanying his S particle speaks in favor of the fact that the accompanying neutral particles are not π^0 mesons. Similarly, the tau meson can be considered as a heavy boson. Since it decays into three π mesons, it must be pseudoscalar and decay into either two π mesons or a π meson and a gamma ray is forbidden. It could of course decay into a positive (or negative) π meson, ^{a π^0 meson,} and a gamma ray, but this decay is relatively slow. If one assumes that decay into two π 's goes something like the π^0 decay into two gammas with about 10^{-14} seconds lifetime, then when the decay products are three π 's, 10^{-10} seconds is perhaps not

96

of the question. Pais remarked that since the decay into three π 's is in fact divergent one can obtain anything one wishes for this lifetime. Marshak admitted that the ν particle is hard to understand unless one accepts the explanation suggested by Noyes. (Cf. note p. 89). In particular, it is hard to understand why it does not decay into two gamma rays. The biggest surprise is undoubtedly the V particle as it is heavier than a nucleon and yet it still has a long lifetime. So it is not necessary to lump all these particles together as completely surprising. Oppenheimer added that it is still necessary to assume that κ 's are produced in pairs in order to explain their copious production, and that the situation is still worse with V particles.

(The meeting was adjourned after it was suggested that any new data which people had not had time to present be left with the recorders to be incorporated into the proceedings.)

Out-of-town guests

Alvarez, L. W., Berkeley
Anderson, H. L., Chicago
Ashkin, J., Carnegie Tech.
Bernardini, G., Illinois
Bethe, H. A., Cornell
Breit, G., Yale
Brueckner, K. A., Indiana
Case, K. M., Michigan
Chew, G. F., Illinois
Cocconi, G., Cornell
Collins, G. B., Brookhaven
Dyson, F., Cornell
Feld, B. T., M.I.T.
Fermi, E., Chicago
Feshbach, H., M.I.T.
Foldy, L. L., Case
Fretter, W. B., Berkeley
Fukuda, H., Institute
Goldberger, M., Chicago
Greisen, K., Cornell
Johnson, T. H., Brookhaven
Kerst, D. P., Illinois
Lawson, J., General Electric
Lederman, L., Columbia
Liddel, U., ONR
Lord, J., Chicago
Oppenheimer, J. R., Institute
Pais, A., Institute
Panofsky, W. K. H., Stanford
Peierls, R., Birmingham, England
Piccioni, O., Brookhaven
Frimakoff, H., Washington U.
Rabi, I. I., Columbia
Rainwater, J., Columbia
Ramsey, N. F., Harvard
Reynolds, G. T., Princeton
Richman, C., Berkeley
Rossi, B., M.I.T.
Salvini, G., Princeton
Segre, E., Illinois
Serber, R., Columbia
Steinberger, J., Columbia
Thompson, R. W., Indiana
Villars, F., M.I.T.
Watson, K. M., Indiana
Weisskopf, V. F., M.I.T.
Wentzel, G., Chicago
Wheeler, J. A., Princeton
Wick, G. C., Carnegie
Wilson, R. R., Cornell
Yang, C. N., Institute
Yukawa, H., Columbia

Local Faculty

S. Barnes
J. Bruner
M. Camac
M. Cartwright
W. Cartwright
H. Childs
K. Enslein
D. Feldman
B. French
H. Fulbright
E. George
M. Kaplon
R. Marshak
J. Platt
R. Mortenson
P. Noyes
C. Oxley
D. Ritson
A. Roberts
J. Tinlot
F. Buff, Chemistry
B. O'Brien, Optics
E. Wiig, Chemistry

Local Graduate Students

C. Angell
T. Auerbach
A. Bromley
D. Clark
P. Daitch
N. Francis
L. Goldfarb
L. Goldman
J. McCarthy
A. Messiah
J. Perry
A. Petschek
J. Rosenthal
H. Schulte
F. Tenney

Local Industry

R. E. Kruger, Roch. Gas and Electric Co.
E. A. Sanford, Pfaudler Co.
J. H. Webb, Eastman-Kodak Co.

Uhlenbeck and Chang. "Is there a neutral μ meson?"

This paper points out that the simplest way to obtain a zero value at the upper limit of the μ meson decay spectrum is to assume a finite mass for one of the neutral particles. A mass of $40 m_e$ would reduce the upper limit by only 2 Mev and hence is consistent with present data, as is the shape of the spectrum calculated using tensor interaction and $(\mu^-, \mu_0) (e^-, \nu)$ pairing of the fields. If the μ_0 were coupled to π^0 in the same way that $\mu^{+\pm}$ is coupled to $\pi^{\pm}$, it could conceivably be detected by its decay into a neutrino and two gamma rays, which would have a lifetime of about 10^{-9} seconds.

Feld, Frisch, Lebow, Osborne, and Clark. "Photomeson Production in Carbon and Hydrogen".Lebow, Feld, Frisch, and Osborne. "Photomeson Production in Deuterium".

These two papers describe a study of the energy and angular distribution of the photomesons produced in paraffin, heavy paraffin, and graphite exposed to the X-ray spectrum of 330 Mev electrons. The mesons were detected in photographic plates imbedded in Copper blocks. The number of positive mesons produced per proton in C compared to H is 0.32 ± 0.05 at 90° and 0.07 ± 0.01 at 26° . The negative-positive ratio for carbon is not strongly energy-dependent and has the average values 1.43 ± 0.13 at 90° and 1.03 ± 0.25 at 26° . The cross section for H as a function of energy at 34° and 107° is plotted in the first figure. For deuterium the experimental negative-positive ratios are 1.5 ± 0.5 at 90° and 0.87 ± 0.22 at 26° . The ratio of the D to the H cross section for producing π^+ is plotted in the second figure in comparison with theoretical curves for an interaction Hamiltonian $\vec{\sigma} \cdot \vec{K} + L$. The point at 26° is therefore evidence for a large $\vec{\sigma} \cdot \vec{K}$ (i.e., spin dependent) interaction.

PHOTOMESON PRODUCTION IN HYDROGEN

RATIO OF POSITIVE PION MESON PRODUCTION IN DEUTERIUM AND HYDROGEN

Appendix III

Extract from letter of Fermi to Feynman
January 18, 1952

Let's assume (a) that the resultant isotopic spin is a good quantum number; (b) that the scattering, at least in a certain energy interval, is due to p-waves only. In the scattering of pions of any charge by nucleons there are involved only states of isotopic spin $1/2$ and $3/2$. If we restrict ourselves to p-waves only, the true spin can have only the values $1/2$ and $3/2$. There are, therefore, only four combinations of isotopic and true spin that count, namely, $3/2-3/2$, $3/2-1/2$, $1/2-3/2$, and $1/2-1/2$. I shall abbreviate the notation by writing as indices the four combinations, $33, 31, 13, 11$. From the assumptions made it follows that at a given energy all the scattering phenomena are characterized by four real quantities, namely the four phase shifts α_{33} , α_{31} , α_{13} , and α_{11} for these four states. These four real quantities are, of course, functions of the energy. In a scattering measurement, on the other hand, it is possible, in principle, to measure for each energy the three scattering cross sections of π^+ on protons and π^- on protons, without and with exchange of charge. Furthermore, each cross section can be measured at 0° and 90° in the center-of-mass system so that this gives for each energy six measurable quantities that can be expressed in terms of four phase shifts only, whereby two verifiable conditions are left over. The formulas are a little bit complicated and, if I have made no mistake, they are the following. σ_+ , σ_- , σ_0 are the cross sections per steradian of the three processes. One finds

$$\begin{aligned}\sigma_+(0^\circ) &= K^2 \left\{ 4 \sin^2 \alpha_{33} + \sin^2 \alpha_{31} + 4 \sin \alpha_{33} \sin \alpha_{31} \cos (\alpha_{33} - \alpha_{31}) \right\} \\ \sigma_+(90^\circ) &= K^2 \left\{ \sin^2 (\alpha_{33} - \alpha_{31}) \right\}\end{aligned}$$

102

$$\sigma_{-}(0^{\circ}) = \frac{\lambda^2}{9} \left\{ 4 \sin^2 \alpha_{33} + \sin^2 \alpha_{31} + 16 \sin^2 \alpha_{13} + 4 \sin^2 \alpha_{11} + \right. \\ \left. + 4 \sin \alpha_{33} \sin \alpha_{31} \cos (\alpha_{33} - \alpha_{31}) + 16 \sin \alpha_{33} \sin \alpha_{13} \cos (\alpha_{33} - \alpha_{13}) + \right. \\ \left. + 8 \sin \alpha_{33} \sin \alpha_{11} \cos (\alpha_{33} - \alpha_{11}) + 8 \sin \alpha_{31} \sin \alpha_{13} \cos (\alpha_{31} - \alpha_{13}) + \right. \\ \left. + 4 \sin \alpha_{31} \sin \alpha_{11} \cos (\alpha_{31} - \alpha_{11}) + 16 \sin \alpha_{13} \sin \alpha_{11} \cos (\alpha_{13} - \alpha_{11}) \right\}$$

$$\sigma_{-}(90^{\circ}) = \frac{\lambda^2}{9} \left\{ \sin^2 (\alpha_{33} - \alpha_{31}) + 4 \sin^2 (\alpha_{13} - \alpha_{11}) + \right. \\ \left. + \sin (\alpha_{33} - \alpha_{31}) \sin (\alpha_{13} - \alpha_{11}) \cos (\alpha_{33} + \alpha_{31} - \alpha_{13} - \alpha_{11}) \right\}$$

$$\sigma_{0}(0^{\circ}) = \frac{2\lambda^2}{9} \left\{ 4 \sin^2 (\alpha_{33} - \alpha_{13}) + \sin^2 (\alpha_{31} - \alpha_{11}) + \right. \\ \left. + 4 \sin (\alpha_{33} - \alpha_{13}) \sin (\alpha_{31} - \alpha_{11}) \cos (\alpha_{33} + \alpha_{13} - \alpha_{31} - \alpha_{11}) \right\}$$

$$\sigma_{0}(90^{\circ}) = \frac{2\lambda^2}{9} \left\{ \sin^2 (\alpha_{33} - \alpha_{31}) + \sin^2 (\alpha_{13} - \alpha_{11}) - \right. \\ \left. - 2 \sin (\alpha_{33} - \alpha_{31}) \sin (\alpha_{13} - \alpha_{11}) \cos (\alpha_{33} + \alpha_{31} - \alpha_{13} - \alpha_{11}) \right\}$$

Concerning the possibility of checking experimentally similar formulas, I am afraid that this may prove very difficult. At low energies, as far as we know, the cross sections of the pions on hydrogen become very small and in addition the influence of the s-scattering, which is small but not negligible, is probably important. One might think, of course, to add to the previously considered phase shifts of four p-waves also the two additional phase shifts of the s-waves. At the same time the experimentally observable quantities would increase from six to nine because when s-waves also are scattered, interference between s- and p-waves would make it meaningful to measure for each event the cross section forward, backward and at 90° . Apart of the difficulties of doing this with usable accuracy, there is one theoretical difficulty that arises from the fact that the isotopic spin at low energy is certainly not too good a constant of motion because of the mass difference between the neutral and the charged pion, and also between the neutron and the proton. I have tried to see how this complication could be corrected for, and I think that it can be done, but I doubt that it is entirely unambiguous.

At higher energy, on the other hand, where the measurement would be more readily feasible, it is probable that higher angular momenta become important. Unfortunately, the energy range that is accessible to our experimentation is not adequate to decide whether and where the d-waves become important.

Summary of Proceedings

Some People Don't Know Where To Stop

Once upon a time, the world was less complex
With fewer nervous wrecks, with lots more time for sex
Electrons and protons were all we could afford
They were good enough for good old Rutherford
The positron, the neutron, and that horrible neutrino
The beginning is easy to recite for us,
The ending is nowhere in sight for us.
And though the answers will some day be nearer,
Things will get worse, before they get clearer.

We had pi-mesons
And mu-mesons,
And some folk thought it too few mesons,
Went out and discovered some new mesons,
Some people don't know where to stop.

Now a few mesons
Might do mesons
A good turn by turning to glue mesons
But how can you use twenty-two mesons?
Some people don't know where to stop.

Once we laughed at guys like Alikhanian,
And put our money on
The western way.
But now the laugh is turned upon the other side
Those mesons never died
They simply fade away.

There's no clarity
Or regularity
Such profusion's mere vulgarity
We're guided by faith, hope and parity
Some people don't know where to stop
Just ask Yukawa
Some people don't know where to stop.

105

Maybe the V-particle
Is the article

Mysterious, what-can-it-be particle
We don't understand yet the free particle
Some people don't know where to stop.

We have a weak coupling
Strong coupling

Wrong as we knew all along coupling
Each month our troubles are quadrupling
Some people don't know here to begin.

Once we thought we understood the deuteron
There's nothing cuter on
The earth.

But that was when we thought 10 Mev a lot
And theory was not
For mirth
At birth.

Now our brain we rack
In vain we tack-

le problems which even would pain Dirac,
And drive us to taking cocaine, alack!

Some people don't know where to stop
Throw in that towel, Powell.

Some people don't know where to stop
Just slack it, Blackett

Some people don't know where to stop
Pull in your neck, Caltech,
For whaddaya waitin', Leighton?
The sooner the better, Fretter

Some people don't know where to stop
Don't get saucy, Rossi
No improvisin', Greisen
Cut the holoney, Piccioni,

Some people don't know where to stop
Cut the holoney, Piccioni,

You're making me, a fool

at the end, Salant

106

(I can go on like this all night)

Some people don't know where to stop

Get away from that piano, you dope,

Some people don't know where to stop.

Arthur Roberts
January 3, 1952.