$\pi^- - p$ Interactions in the 1.0-Bev Region*

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We have examined 450 $\pi^- - p$ collisions of energy about 1 Bev. About one-third of these have been found in emulsion and the the rest in the Brookhaven hydrogen diffusion chamber. About one-half of the total cross section at this energy comes from elastic processes. The differential elastic cross section is characterized by a sharp peak in the forward direction and considerable bump in the backward hemisphere. We believe we have demonstrated that a considerable portion of the elastic cross section is produced by refraction rather than diffraction. The target radius of the nucleon at this energy seems to be $\geq 1.1 \times 10^{-13}$ cm which is essentially the same result that has been found at 1.4–1.5 Bev. The inelastic processes seem to exhibit somewhat different features at this energy from those at 1.5 Bev. The angular distributions of all products are almost isotropic. The nucleons seem to slightly prefer the backward hemisphere but not to nearly the same degree as found at 1.5 Bev. The π^- seem to lose most of their energy in the inelastic processes and this too is somewhat different from the 1.5-Bev results. The momentum change spectrum for the nucleons is nearly the same at 1.0 and 1.5 Bev.

These results are discussed in terms of the Dyson-Takeda model which introduces a pion-pion interaction. We also discuss possible isobar formation.

I. INTRODUCTION

THIS article reports a study made of $\pi^- - p$ interactions in the energy region of 0.9 to 1.0 Bev. It was in this energy region that measurements, using counters, of the total $\pi^- - p$ cross section by Shapiro, Leavitt, and Chen[1] and Cool, Madansky, and Piccioni[2] indicated a maximum at an energy of about 1 Bev. Later measurements have confirmed and expanded these results.[2–4] The purpose of this experiment has been to study the phenomena in the energy region close to the maximum of the total cross-section curve to find whether there are interactions peculiar to the 1.0-Bev region which result in an enhanced cross section. As a comparison we have available the data on $\pi^- - p$ interactions in the 1.5-Bev region.[5,6]

Both the hydrogen diffusion cloud chamber and on-track scanning in emulsion were used in the study. These techniques complement each other very well and give cross checks in places. The magnet diffusion chamber used in the experiment is the same one used by the Brookhaven group in their experiments.[6] The operating conditions were, except for the slightly lower energy of the π beam, virtually identical with those used by Eisberg *et al.*[6]

II. CROSS-SECTION MEASUREMENTS

The cross section for $\pi^- - p$ interactions giving rise to charged particles was measured in the cloud chamber by a method similar to that used by Shutt and his collaborators.[6] We have measured the total beam track-length passing through the central portion of the diffusion chamber and the number of interactions in this region. The pictures were sampled by counting tracks in every 13th picture in this same region. In addition we have estimated the scanning efficiency from the elastic scattering data. A plot of the number of elastic scatterings *versus* azimuth angle indicates that those cases in which the plane of the two tracks is perpendicular to the chamber are missed quite often. Using the lack of uniformity of this histogram we estimate a scanning efficiency of 85%. We use this same efficiency for the inelastic events as well. The average cross section determined for all the runs was 38±3 mb. This cross section is corrected for scanning inefficiency and for a μ plus e contamination of 7%.[4] This number is subtracted from the cross section measured by Cool *et al.*[4] to get the cross section for zero-prong events.

In emulsion a direct cross-section measurement is impossible because of the difficulty in distinguishing edge collisions from free hydrogen collisions.[5] Also at this energy there is a considerable contamination of fast electrons in the beam which greatly adds to the complication. Our mean free path for hydrogen-like events was 5.3 meters as compared to 4.5 meters at 1.5 Bev.[5] The $\pi^- - p$ cross section according to Cool *et al.* at 900 Mev is 47±2 mb as compared to 30±3 mb 1.5 Bev.

The elastic collisions consist of approximately equal numbers of edge and free collisions at 1.0 and 1.5 Bev.[5] We attribute this apparent discrepancy in cross section to the increased electron and μ contamination at 900 Mev. We observed several beam tracks which suddenly upon deflection become low-energy electrons, presumably through bremsstrahlung. This is direct evidence for a considerable contamination of high-energy electrons.[7]

* Supported in part by a contract with the U. S. Atomic Energy Commission and by grants from the Wisconsin Alumni Research Foundation.

[1] Shapiro, Leavitt, and Chen, Phys. Rev. **92**, 1072 (1954).
[2] Cool, Madansky, and Piccioni, Phys. Rev. **93**, 637 (1954).
[3] S. J. Lindenbaum and L. C. L. Yuan, Phys. Rev. **100**, 306 (1955).
[4] Cool, Piccioni, and Clark, Phys. Rev. **103**, 1082 (1956).
[5] W. D. Walker and J. Crussard, Phys. Rev. **98**, 1416 (1955). See this reference for reference to earlier emulsion work.
[6] Eisberg, Fowler, Lea, Shephard, Shutt, Thorndike, and Whittemore, Phys. Rev. **97**, 797 (1955).
[7] We have found only 35 cases in emulsion of what seem to be $\pi^- - n$ collisions at this energy. Assuming 50% of H collisions are edge collisions we deduce $\sigma_{\pi^- - n}/\sigma_{\pi^- - p} = 35/65$. This is to be compared to a ratio of about 1:1 found by the same method at 1.5 Bev. These results are consistent with the findings of Piccioni

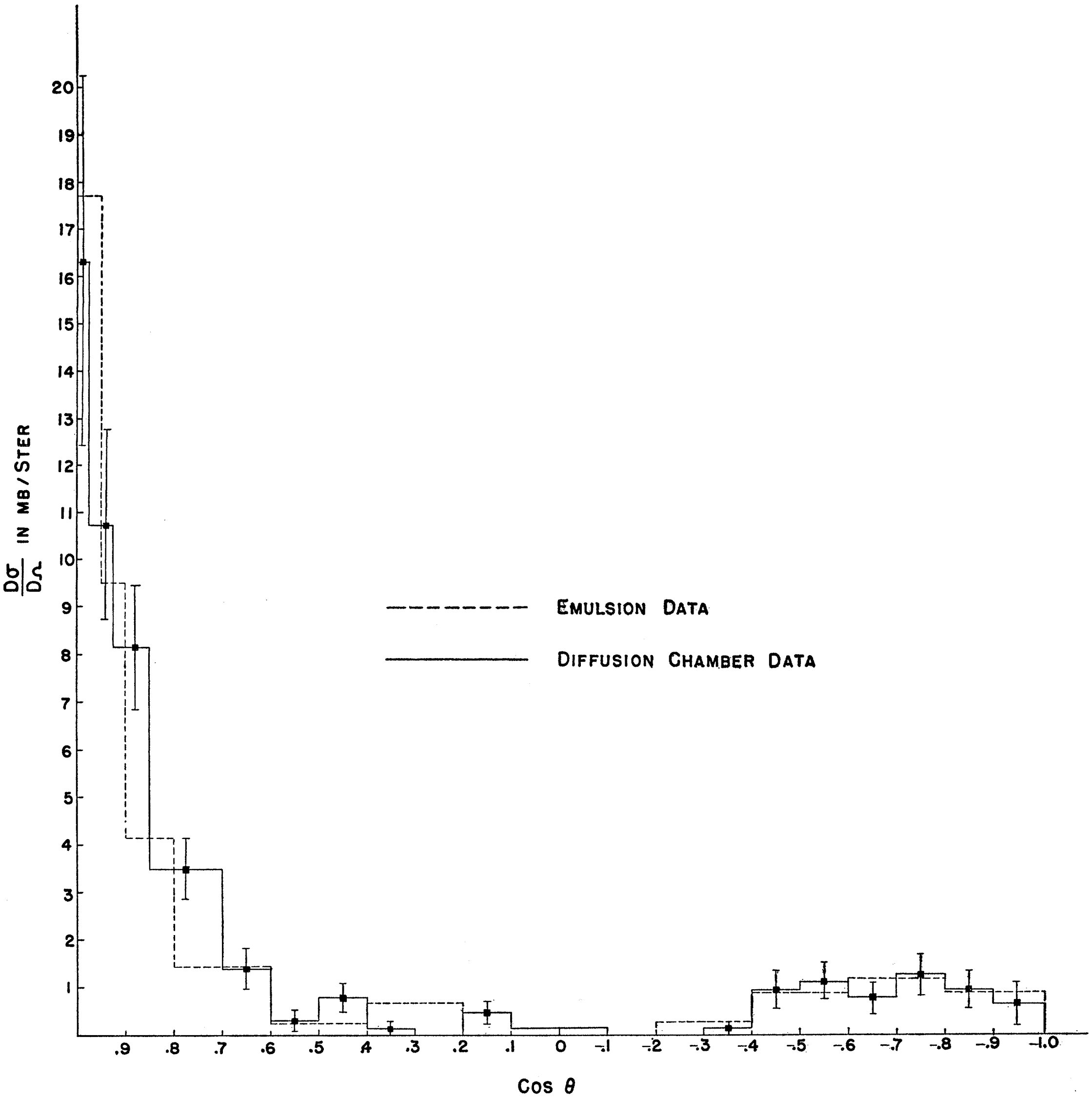

FIG. 1. Center-of-mass differential elastic cross section at about 1.0 Bev. The solid histogram is the diffusion chamber data. The dotted histogram is the emulsion data. The errors shown indicate the statistical uncertainties.

The cross section, σ_x for the various kinds of interactions, x, in emulsion are obtained by using the total cross section, σ, of Cool *et al.*[4] as follows

$$\sigma_x = (n_x/n)\sigma,$$

where n_x = number of cases of type X, and n = total number of cases. The results of this analysis for both cloud chamber and emulsion work are given in Table I.

The data in Table I are taken from the analysis of 320 interactions in the diffusion chamber and 130 events in emulsion. The errors attempt to show the effects of uncertainties due to statistics and analysis.

et al. It is interesting to note that of these cases only one example of $\pi^- + n \rightarrow 2\pi^- + p$ was found. This would seem to indicate a large proportion of elastic events at this energy among the $\pi^- - n$ cases.

Zero-prong events probably come about by the reactions listed above in Table I. From the relations given by Gell-Mann and Watson[8] one can deduce the cross section for the reaction $\pi^- + p \rightarrow \pi^0 + \pi^0 + p$ from the cross section for the other two single-meson production processes. It is approximately true that $\sigma_D = \sigma_C = \sigma_E$. The ratio of elastic to inelastic charge-exchange scattering according to the above scheme is less than as for the cases in which charged prongs are emitted.

III. ELASTIC SCATTERING

The examples of elastic scattering are usually the easiest cases to identify. The "diffraction" or small-

[8] M. Gell-Mann and K. M. Watson, *Annual Reviews of Nuclear Science* (Annual Reviews, Inc., 1954), Vol. 4.

TABLE I. Tabulation of cross section from analysis of cloud-chamber and emulsion interactions.

Type of interaction	Cloud chamber (960 Mev) in mb	Emulsion (900 Mev) in mb
A: $\pi^-+p\rightarrow\pi^-+p$	$20\ \pm3$	18.6 ± 3
B: $\pi^-+p\rightarrow\pi^0+N$; C: $\pi^-+p\rightarrow\pi^0+\pi^0+N$	$8\ \pm5$	$10\ \pm3$
D: $\pi^-+p\rightarrow\pi^-+\pi^++N$	9.5 ± 2	$7\ \pm2$
E: $\pi^-+p\rightarrow\pi^-+\pi^0+p$	6.9 ± 2	9.5 ± 3
F: $\pi^-+p\rightarrow\pi^++\pi^-+\pi^-+p$; G: $\pi^-+p\rightarrow\pi^-+2\pi^0+p$; H: $\pi^-+p\rightarrow\pi^-+\pi^++\pi^0+N$	$1_{-0.5}^{+1}$	$1_{-0.5}^{+2}$
I: $\pi^-+p\rightarrow\Lambda^0+\theta^0$; J: $\pi^-+p\rightarrow\Sigma^0+\theta^0$; K: $\pi^-+p\rightarrow\Sigma^-+K^+$	$0.8_{-0.3}^{+1}$	

angle scatterings are generally quite easy to see because the protons usually have greater than minimum ionization. The elastic scatterings in which the proton goes forward in the center-of-mass system are a little more difficult to see and identify because the proton is at minimum ionization. The uniqueness of the kinematic relationships aids one greatly in distinguishing these cases from inelastic collisions. Almost always in the cloud chamber work, whenever the proton or pion track from an apparently elastic scattering was longer than 7 centimeters, a momentum measurement was made to see whether indeed the case was elastic. No inelastic cases were observed. In the emulsion work because we accept edge collisions the discrimination between elastic and π^0 production is not perfect. Because of the accurate momentum determination on the proton, there were only one or two cases out of 15 in which there was any question.

As previously stated, our estimated average scanning efficiency in the diffusion chamber was 85%. The losses usually occur when the scattering plane is perpendicular to the plane of the chamber. The ability to see a given event depends critically on the angle of deflection. The plane angle distribution of $\pi-\mu$ decays is given in the paper of Eisberg *et al.*[6] The true distribution should be approximately flat between 0° and the maximum angle. They observed a sharp fall-off in the distribution below 1°. In this part of their experiment the angular deflections were magnified by a factor of 5. This means that they did not efficiently observe deflections less than about 4°. We have scanned some of our pictures with great care for $\pi-\mu$ decays. The efficiency for detection of the $\pi-\mu$ decays was 20%. The maximum deflection at this energy is about 2.25°.

We have tried to estimate our scanning efficiency for the detection of small-angle scatterings in the magnet chamber. To do this we have compared the data of Eisberg *et al.*[6] taken with the magnet chamber with their data from the long chamber which was scanned more efficiently because of the angular magnification. We deduce that their scanning efficiency in the angular interval 5° to 10° deflection was about 70%. This is very close to the efficiency one estimates by assuming that plane deflections of 3° and less are missed.

We have used the correction factor 1/0.7 for the lab angular interval 5° to 10°. For the angular interval 0° to 5° we have used a factor of 2. We feel that the last correction is low rather than high. This is based on our observations on $\pi-\mu$ decays. For the deflection of less than 5° we found that unless the deflection is nearly in the plane of the chamber the events are missed.

Correcting for inefficiencies we find a forward scattering cross section of about 16 mb per steradian. The results are shown in Fig. 1. We feel the maximum errors for the forward differential cross section are about 30%, at least on the low side. The cross section could be considerably higher than our quoted values since we observe only down to angles of the order of 3°.

The emulsion data are plotted as the dotted histogram in Fig. 1. In on-track scanning one detects with no particular effort deflections of 2°−3°. The differential cross section is calculated on the basis of Table I which in turn depends on the total cross section measured by Cool *et al.*[4]

There are no corrections applied to the emulsion data. There are undoubtedly some cases missed in scanning but probably more are lost as a result of the suppression of small momentum transfers in the case of edge collisions.

If one considers the two experiments together, a value of 16 to 17 mb/sterad for $d\sigma/d\Omega(0°)$ is based on 35 counts in the interval at the smallest angles. This value is in agreement with the counter measurements of Cool *et al.*[4] Recent calculations made by Sternheimer[9] and also Cool, Piccioni and Clark[4] using the dispersion relationships give a value for $d\sigma/d\Omega(0°)$ of 14 mb/sterad.

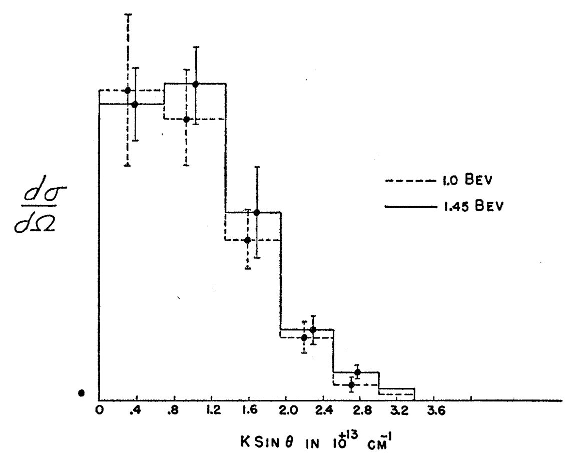

FIG. 2. Comparison of the forward peaks of the center-of-mass differential elastic cross section curves at 1.0 and 1.45 Bev. The data at 1.45 Bev are taken from the work of Eisberg *et al.*[6] and Walker and Crussard.[5] In the plot the normalized value of $d\sigma/d\Omega$ is plotted against $K\ \sin\theta$, where $K=1/\lambda$. No corrections are made to either set of data.

[9] R. S. Sternheimer, Phys. Rev. **101**, 384 (1956).

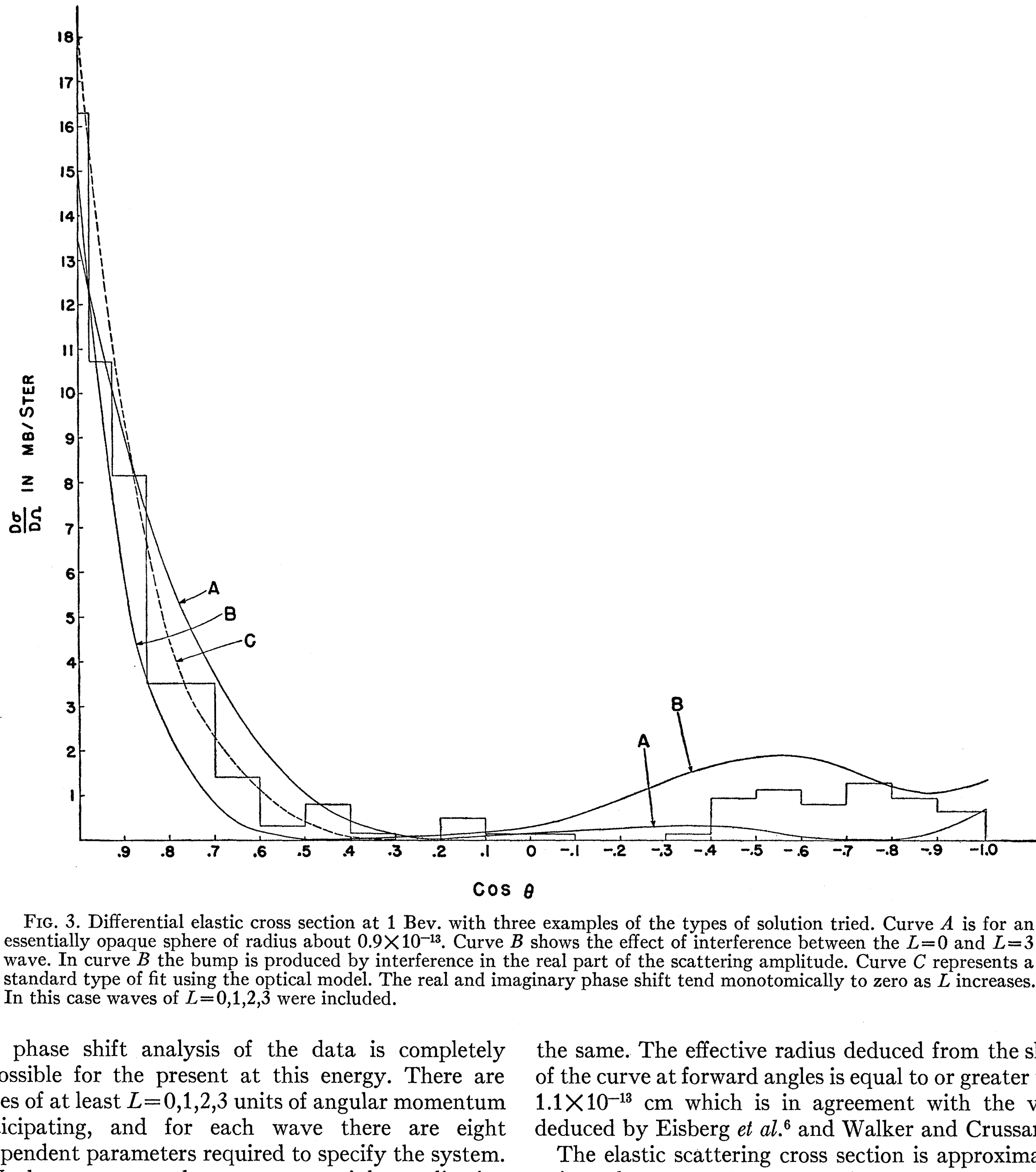

FIG. 3. Differential elastic cross section at 1 Bev. with three examples of the types of solution tried. Curve A is for an essentially opaque sphere of radius about 0.9×10^{-13}. Curve B shows the effect of interference between the $L=0$ and $L=3$ wave. In curve B the bump is produced by interference in the real part of the scattering amplitude. Curve C represents a standard type of fit using the optical model. The real and imaginary phase shift tend monotomically to zero as L increases. In this case waves of $L=0,1,2,3$ were included.

A phase shift analysis of the data is completely impossible for the present at this energy. There are waves of at least $L=0,1,2,3$ units of angular momentum participating, and for each wave there are eight independent parameters required to specify the system.

We have attempted to extract mainly qualitative information from the data. Figure 2 shows a comparison $d\sigma/d\Omega$ in the forward direction at 1.0 and 1.5 Bev. The change of wavelength has been taken into account in the plot. The curves have been normalized at 0° and neither curve has been corrected for scanning inefficiencies at the small angles. The "1.5"-Bev data were taken from the work of Eisberg *et al.*[6] and Walker and Crussard[5] so that the scanning might have been somewhat more efficient at the small angles at the higher energy. The fact that the two curves agree fairly closely indicates that the target size presented by the nucleon to the pions at the two energies is about the same. The effective radius deduced from the shape of the curve at forward angles is equal to or greater than 1.1×10^{-13} cm which is in agreement with the value deduced by Eisberg *et al.*[6] and Walker and Crussard.[5]

The elastic scattering cross section is approximately twice as large at 1.0 Bev as at 1.5 Bev. Probably most of the elastic cross section at 1.5 Bev is due to diffraction scattering. Unless the target radius is considerably smaller at 1.0 than at 1.5 Bev this cannot be the case at 1.0 Bev. The target radius would have to be the order of 0.9×10^{-13} cm at 1.0 Bev in order to have the correct elastic and inelastic cross sections if the elastic cross section was all diffraction. A differential elastic cross section curve calculated on this basis is given in Fig. 3 denoted by curve A. The fit in the forward direction is poor and the curve fails completely in the backward hemisphere. This particular prescription of the nearly opaque sphere of radius 0.9×10^{-13} cm

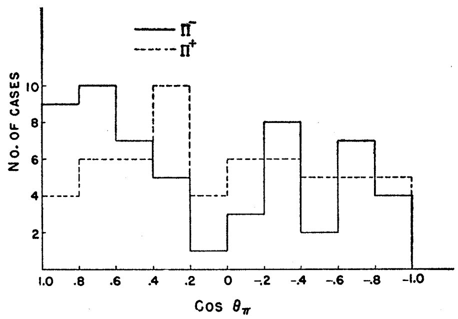

FIG. 4. Center-of-mass angular distribution of the π^+ and π^- from the reaction $\pi^-+p\rightarrow\pi^++\pi^-+n$.

also has the disadvantage that it violates charge independence, if the π^+-p cross sections of Cool *et al.* are correct.[4] Thus we are led to the conclusion that there are considerable real as well as imaginary phase shifts at 1.0 Bev.

One can attempt to fit the differential scattering curve by using at least the sense of the optical model, that is, that real and imaginary phase shifts should fall off monotonically as one goes to higher L values. One can obtain quite an accurate fit for the elastic and inelastic cross sections and the differential elastic cross section in the forward direction. A model of this type fails completely to produce the required bump in the backward hemisphere. Curve C is an example of such an attempt. The data used in synthesizing such a fit are the total elastic and inelastic cross sections, $d\sigma/d\Omega$ at 0° and the optical theorem. We have not attempted to prove any theorems about the shape of $d\sigma/d\Omega$ in the backward hemisphere. However, in all of the attempts of the optical-model type the various partial waves tend to interfere out beyond the forward peak in such a way as to produce only very small subsidiary maxima.

One could go to the other extreme and try to enhance one partial wave much more than all the others. In the limit that only one wave participates, then the differential cross section would be symmetric fore and aft, which it is obviously not. The next possibility is that one or two partial waves are required to stand out above the rest to the extent that they produce the backward bump.

There are probably many ways that this can occur. However, we have been able to find only two that seem reasonable within the framework of the analysis. We limit ourselves to $L=0,1,2,3$ waves, which corresponds to an effective radius of interaction of about 1.2×10^{-13} cm. We suppose that there is absorption of all these waves. We next suppose a phase shift of essentially 90° in the $J=\frac{3}{2}$ state of $L=2$. The spin-flip term gives a bump in the backward (and forward) hemisphere in about the right place. If there is spin flip in the $L=2$ wave, then there is automatically a large contribution of the $L=2$ wave in the imaginary part of the scattering amplitude. There is indication of a considerable amount of $P_2(\cos\theta)$ in the forward peak. The forward peak drops to a small value at point fairly close to where P_2 changes sign. This can be taken as an indication that $L=2$ is an important wave regardless of the existence of any spin flip, although we can make no claims about uniqueness.

The other possibility requires a considerable real phase shift in the $L=0$ wave and a smaller phase shift of the same sign in the $L=3$ wave. The bump is then produced by interference between these two waves in the real part of the scattering amplitude. An example of this type of fit is labeled B in Fig. 3.

Experimentally it should be possible to distinguish between these two alternatives. A single spin-flip term would enhance the cross section in the forward and backward hemispheres equally. The interference effect would not be symmetric. Thus if one could establish that

$$\frac{d\sigma}{d\Omega}(x)<\frac{d\sigma}{d\Omega}(-x),$$

then this would rule out the first possibility.

IV. INELASTIC PROCESSES

The study of the inelastic processes is quite tedious. This is so because we are always concerned with at least three-body reactions. We have looked for correlations between the various particles. One always hopes to find some sort of dramatic correlation which will give a key to the physical process. So far nothing of this sort has been recognized.

A. Experimental Details

It is necessary to bear in mind the limitations of the data produced by the experimental techniques. In the diffusion chamber ionization is extremely difficult to measure. If a track is short (<7 cm), it is sometimes difficult to establish its ionization, unless of course the ionization is greater than 3 times minimum. Also, unless the track is long the momentum measurements are inaccurate because the dipping tracks tend to be distorted. For this reason we try to identify but otherwise discard noncoplanar cases in which neither of the two outgoing tracks is greater than 5 cm in length. In almost all the cases of inelastic collisions we have measured the momentum of the incoming track

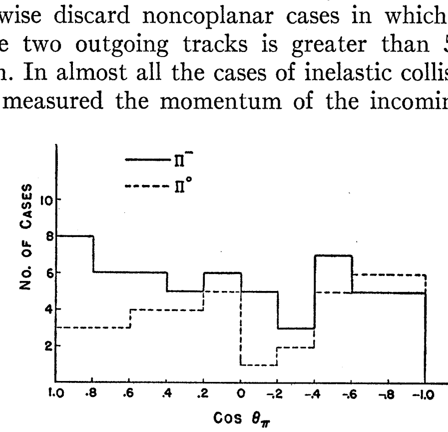

FIG. 5. Center-of-mass angular distribution of the π^- and π^0 from the $\pi^-+p\rightarrow\pi^-+\pi^0+p$ reaction.

or an adjacent parallel track. This was the momentum used in the calculation. Collisions in which the incoming momentum was more than 1.2 Bev/c were not included in the 1-Bev data.

Usually we are able to make a reasonable momentum measurement on only one of the outgoing tracks. We assume in these cases that there is only one neutral particle involved. Undoubtedly some mistakes are made because of this; however, the number is probably not great. Only three or four 4-prong interactions were observed. In fact, the number is small enough that interactions in the carbon of the alcohol give a serious background. We have in addition found a comparable number of 3-meson 2-prong events. We conclude from the small number of 4-prong events that the number of cases involving three outgoing mesons is small.

The emulsion work has a different set of difficulties. The momentum spectrum of the incoming particles is quite sharp, unlike the cloud chamber work. However, about 50% of the collisions are edge collisions, which

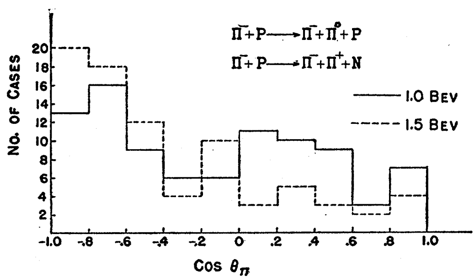

FIG. 6. Nucleon angular distribution from the two inelastic processes studied: $\pi^-+p\rightarrow\pi^-+\pi^0+p$ and $\pi^-+p\rightarrow\pi^-+\pi^++n$. There was no appreciable difference between the angular distribution of the neutrons and protons and they are consequently lumped together. The distribution may be compared with the dotted histogram from the 1.5-Bev data, which show a much larger anisotropy.

effectively broadens the spectrum. Particle identification is usually very good in emulsion for this energy region. This means that the branching ratio between the reactions

$$\pi^-+p\rightarrow\pi^-+\pi^0+p$$

and

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

should be better determined in emulsion than in the cloud chamber. There is, however, the possibility of accepting a few stars (i.e., double and triple interactions on the edge of a nucleus) which would produce some spurious events among the π^0 production cases. Walker and Crussard[5] have found perhaps a 10% contamination, which is consistent with the present results. The best estimate of the branching ratio of π^0 to π^+ production is one to one. In general we feel the π^0 production cases are more accurately determined in emulsion, and of course the π^+ production cases are much better done in the diffusion chamber.

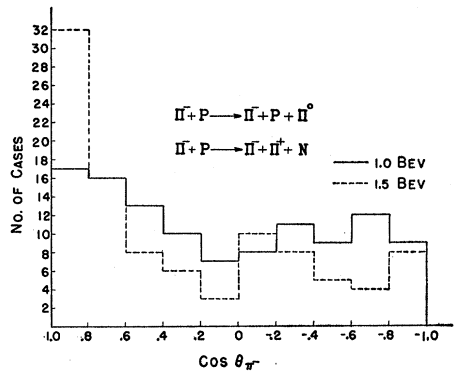

FIG. 7. Comparison of the center-of-mass angular distribution of the inelastically scattered π^- from the reactions $\pi^-+p\rightarrow\pi^-+p+\pi^0$ and $\pi^-+p\rightarrow\pi^-+\pi^++n$. At 1.0 and 1.5 Bev.

B. Angular and Momentum Distribution of the Products of the Inelastic Collisions

The angular distribution of the various products of inelastic collisions are given in Figs. 4 to 8. The distributions obtained at 1.4 to 1.5 Bev by Walker and Crussard[5] and Fowler *et al.*[6] are put in the Figs. 6, 7, and 8. The same general features are shown at 1.0 and 1.5 Bev but are much more strongly displayed at the higher energy. The nucleons seem to prefer slightly the backward hemisphere and the π^- the forward hemisphere; however the variance from isotropy is small.

It has been suggested by Dyson[10] and Takeda[11] that the bump in the cross section is due to a pion-pion interaction. Dyson proposes that the virtual pion is punched out of the nucleon field, leaving the nucleon with only slight recoil. This type of process had been suggested by Piccioni several years ago.[12]

The distribution of angles between the pions is given in Fig. 9. If the Piccioni-Dyson-Takeda process were important at this energy, one would expect an angle of about 90° between the two pions in the $\pi^- - p$ center of mass and also the nucleons would tend to go into

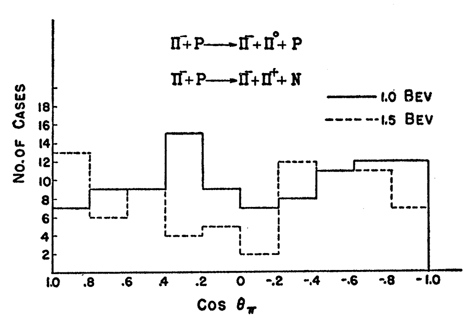

FIG. 8. Comparison of the angular distribution of the secondary pions at 1.0 and 1.5 Bev from the reactions $\pi^-+p\rightarrow\pi^-+\pi^0+p$ and $n^-+p\rightarrow\pi^-+\pi^++n$.

[10] F. J. Dyson, Phys. Rev. **99**, 1037 (1955).

[11] G. Takeda, Phys. Rev. **100**, 440 (1955).

[12] O. Piccioni—reference is made to the idea in the *Proceedings of the Rochester Conference of 1952* (University of Rochester Press, Rochester, 1952).

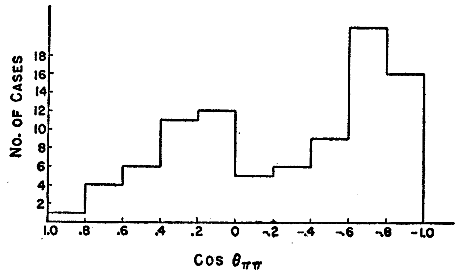

FIG. 9. Center-of-mass distribution of angle between the two pions from the inelastic scattering cases at 1.0 Bev.

the backward hemisphere. The angular distributions do not seem to show such an effect, although there are a sizeable number of cases in which the angle between the two π's is less than 90°.

The momentum distributions of the pions and nucleons are given in Figs. 10 to 14. The ratio of the momenta of the product pions is given in Fig. 15. These results seem quite reversed from the behavior at 1.5 Bev. The π^- seems to be on the average the lower energy pion in both the production of a π^+ and π^0 whereas at 1.5 Bev the reverse seems to have been the case.[5,6] In the case of the process $\pi^-+p\rightarrow\pi^-+\pi^++n$, one expects the π^- and n to be more strongly pulled into the $\frac{3}{2}$ resonance energy region than the π^+ and n. Why it is in the case of $\pi^-+p\rightarrow\pi^0+\pi^-+p$ that the π^- and p end up more correlated than π^0 and p, is not understood. We have used only the well-measured cases in

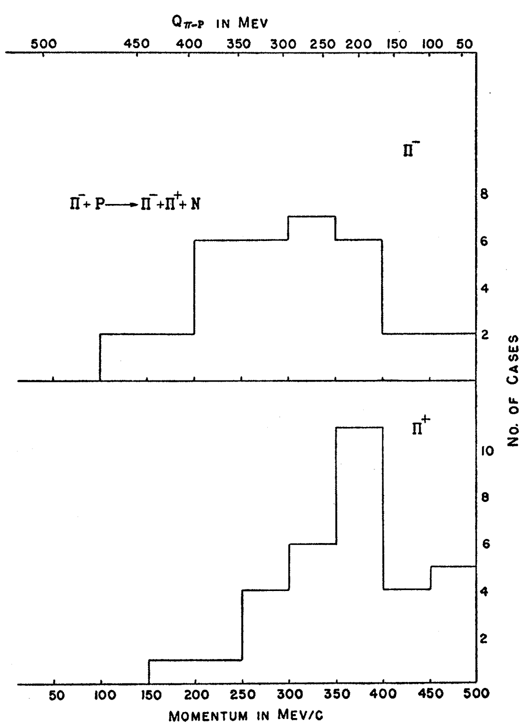

FIG. 10. Center-of-mass momentum spectrum of the π^+ and π^- from the reaction $\pi^-+p\rightarrow\pi^-+\pi^++n$. The $Q_{\pi-p}$ scale gives the relative kinetic energy of the other pion and nucleon.

compiling the spectrum, so we do not believe that the result is produced by poor measurements. In all the figures having to do with a momentum spectrum we have included a Q abscissa. The momentum of one of the three products determines the relative kinetic energy of the other two or the Q value for the pair. Interpreted literally the Dyson-Takeda suggestion would predict a bump in the nucleon spectrum corresponding to a $Q(\pi,\pi)$ of 150 Mev.

Another comparison of the data at 1.0 and 1.5 Bev can be made by looking at the momentum change of the nucleon in the course of the inelastic process. Figure

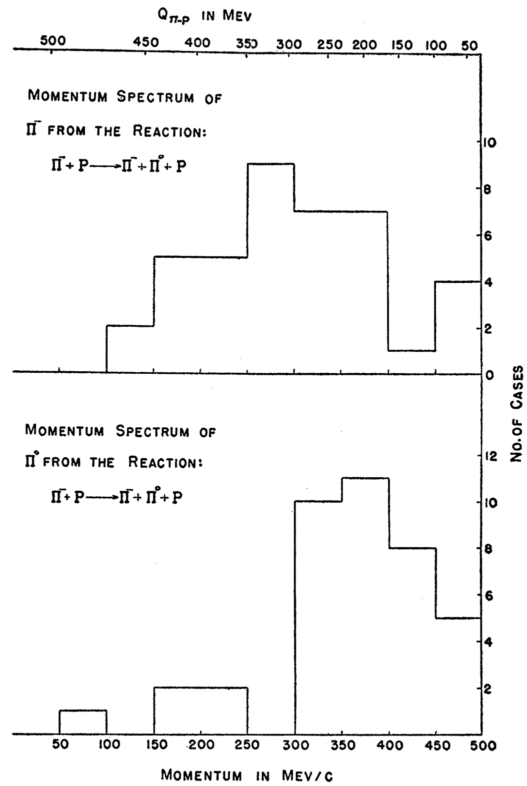

FIG. 11. Center-of-mass momentum spectrum of the π^- and π^0.

16 gives a plot of the momentum change spectrum for the nucleons at 1.0 and 1.5 Bev. The two spectra are remarkable similar. At 1.5 Bev there are a few more cases of pion production with very large and very small momentum changes. Since it is likely that many cases of pion production result from high-impact-parameter collisions, it is not surprising that low momentum transfers occur quite often. A given momentum transfer at 1.0 Bev will of course result in a larger angular deflection of the nucleon than at the higher energy. It seems remarkable that there are many elastic collisions in which sizeable ($\sim$1 Bev/c) momentum transfers occur. Intuitively one might expect such hard collisions to produce mesons.

V. DISCUSSION

It is very difficult on the basis of this experiment and the general shape of the total cross-section curve to draw any definite conclusions as to what produces the enhancement of the cross section in the 1-Bev region in the $I=\frac{1}{2}$ state. The present experiment can rule out some possibilities. It seems impossible to have the interactions go primarily through one angular momentum state. This is because of the large diffraction-like peak in the forward direction which implies the participation of several partial waves. On the other hand, it is necessary to have one or two waves behave differently from the rest in order to have the bump in the backward hemisphere. The possibilities here are spin flip in the $L=2$ wave or an interference between $L=3$ and $L=0$ waves as a result of real phase shift scattering. The latter would imply a large core scattering plus a weak high wave scattering.

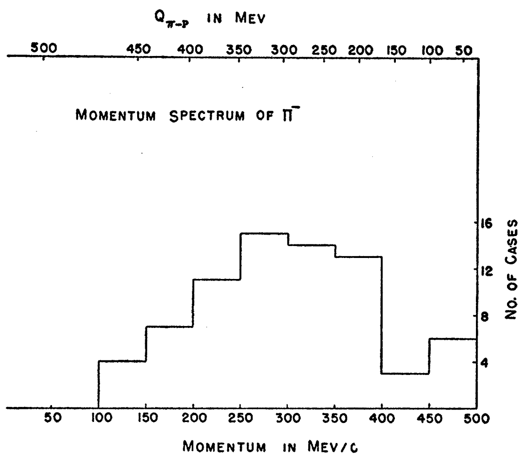

FIG. 12. Center-of-mass momentum spectrum of the inelastically scattered π^-.

One of the most appealing explanations of the enhancement is the strong $\pi-\pi$ interaction of Dyson[10] and Takeda[11] and extended by Minami and Ito and others.[13,14] It is certainly true that no strong evidence can be found to support this hypothesis from the analysis of the inelastic processes. Yet neither Dyson nor Takeda have really worked out the consequences of their hypothesis in this case. In order to do this one would have to know more about the nucleon structure. Certainly the incoming pion doesn't just punch a pion out of the nucleon's field. This possibility at least is ruled out by the present data. It should be remembered however that there is really very little phase space available for the process as proposed by Dyson. Also the wavelengths of the outgoing pions are

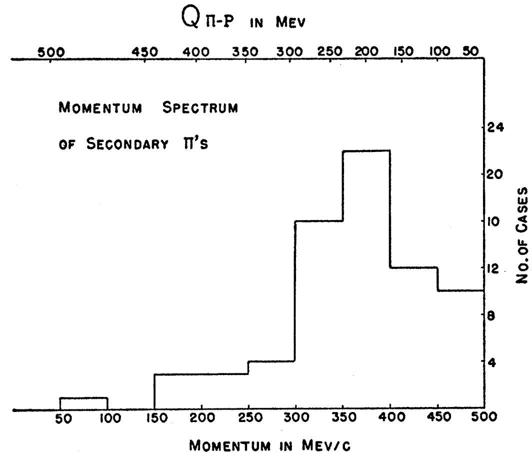

FIG. 13. Momentum spectrum of the pions produced in the inelastic collisions, i.e. π^+ and π^0.

of the order of $\frac{1}{2}$ the Compton wavelength of the pion, so that final-state interactions with the nucleon must be very important. Because the elastic processes constitute a large fraction of the total cross section, we do not believe that the strong final state interaction is the true explanation of the bump in the cross section in this energy region. It seems possible that the pion-pion interaction may give rise to elastic scattering.[15] It seems very likely from the present data that there is a considerable amount of refraction as well as diffraction around the outside of the nucleon. The general effect of a strongly momentum dependent pion-pion interaction could probably produce effects very much like what is observed. Because of the motion of the

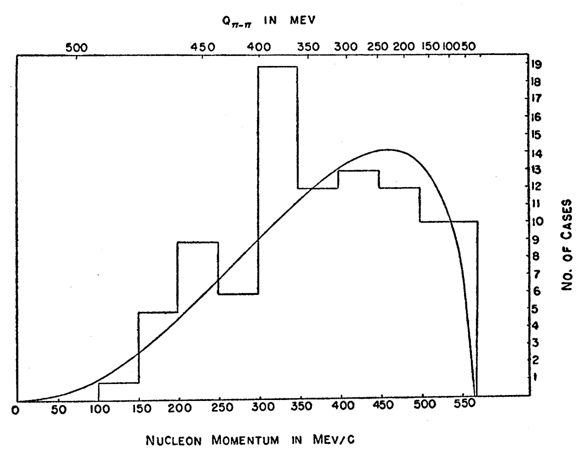

FIG. 14. Histogram giving the momentum spectrum of the nucleons from the inelastic collisions. No difference between the spectra of the neutrons and protons could be seen, and so the two are grouped together. The curve is calculated from the statistical theory. The $Q_{\pi-\pi}$ abscissa gives the relative kinetic energy of the two pions.

[13] D. Ito and S. Minami, Progr. Theoret. Phys. Japan **14**, 189 (1955).

[14] Calculations on inelastic scattering have been made by Ito, Yamayaki, and Mori, and also by T. Kotani and M. Takeda and finally by S. Minami. These authors have kindly sent prepublication information to the present authors.

[15] This sort of effect was initially proposed by A. N. Mitra and F. Dyson, Phys. Rev. **90**, 372(A) (1952). Also M. Ross, Phys. Rev. **95**, 1687 (1954) to explain some features of low energy π—nucleon scattering.

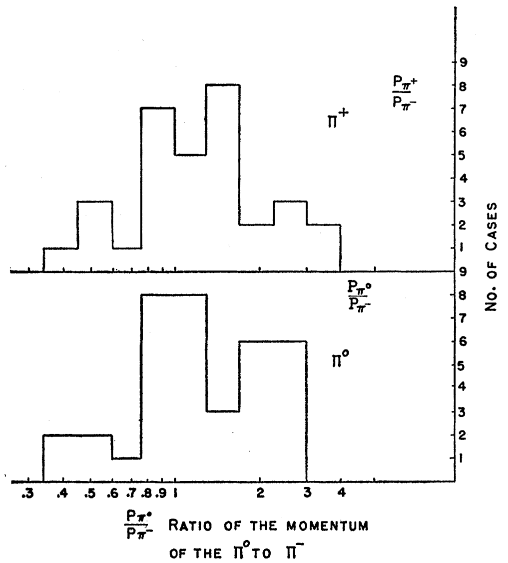

FIG. 15. Histogram showing the number of cases with a given ratio of momentum of π^+ to momentum of π^- and π^0 to π^-. This shows a little more clearly than the momentum spectrum that the secondary pion tends to have more energy than the π^-.

virtual pions the interactions would take place over a considerable range of impact parameters.[16] This means of course that several partial waves would be enhanced, which in turn means that there should be a diffraction-like peak in the elastic scattering for the whole energy region of the second maximum. Also, there might be a fairly strong J dependence. In order to obtain a J dependence from such a model one has to make assumptions about the nucleon structure. Naïvely one might assume that the meson current about the nucleon is strongly correlated with the spin direction of the nucleon. Collisions with energies below the peak in the cross section should occur preferentially with the meson current about the nucleon opposed to the incoming pion. Above the peak the collisions would be enhanced when the meson current is in the same sense as the incoming pion. Thus, for example, the $P_{1/2}$ and $D_{3/2}$ states would be important below the peak whereas above the peak $P_{3/2}$ and $D_{5/2}$ states would be important. There is also the possibility that we are encountering in the case of the 1-Bev bump a threshold effect. That is that two pions will interact strongly if their relative kinetic energy is greater than about 150 Mev. The results of the experiments at 1.5 Bev lend credulity to this sort of model.[13] The sharp decrease in the cross section above 1 Bev would be primarily the result of the damping out of the elastic processes, but why the decrease should occur so rapidly is not understood. One can apply this same type of argument to the bump in the π^+-p cross section at 1.3 Bev.[4] In this case however a different isotopic spin state of the $\pi-\pi$ system may be important, perhaps the $I=2$ state.

Another possible explanation is that the bump in the cross section is due to the excitation of an isobaric state of the nucleon. This has been discussed at some length in a paper by Cool, Piccioni, and Clark[4] in which they attribute the bump to a resonant $D_{5/2}$ state. They suppose that this occurs on top of a gradual rise in cross section due to inelastic processes. The present data cannot rule out this possibility; however, we were unable to find a quantitative fit of the differential scattering cross section for an enhanced $J=5/2$ state. The fragmentary data at 700 Mev also seem to contradict such a model.[17,18] To sum up what we consider to be the evidence which might be considered favorable to such a hypothesis, first there is some evidence from the shape of the forward peak that there is strong interaction in the $L=2$ wave. Second, the bump in the backward hemisphere might be produced by spin-flip processes coming from scattering in one of the J states of the $L=2$ wave. Finally, there is the evidence that the π^- on the average loses most of its energy in the inelastic processes. This might be indicative of isobar formation. In fact it seems likely that the π^- and nucleon end up in a $J=I=\frac{3}{2}$ state a considerable fraction of the time. As stated previously, we do not believe that the enhancement in the cross section comes from such a final state interaction.

Such a resonance would be damped by the inelastic processes, and the damping may vary with energy. Thus it would not be possible to extract the resonant from the nonresonant part of the cross section without

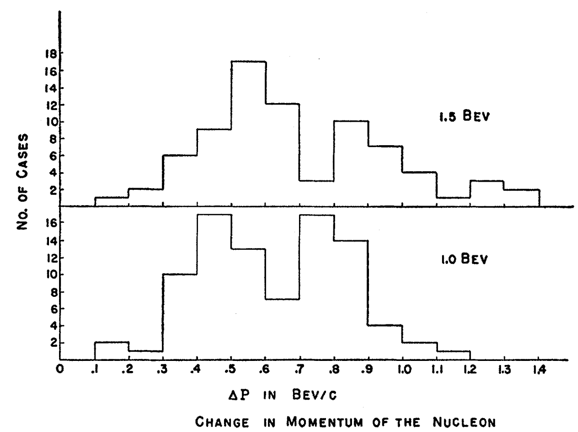

FIG. 16. Histogram showing a comparison of the nucleon momentum change spectrum at 1.0 and 1.5 Bev in the center of mass system. The maximum possible change at 1.0 Bev is about 1.2 Bev/c and at 1.5 Bev is about 1.5 Bev/c. The cases are calculated by taking the vector difference between the momentum of the incoming and outgoing nucleon. The possible importance of the momentum change of the nucleon in determining the characteristics of the reaction has been stressed by D. Ito and S. Minami, Progr. Theoret. Phys. Japan 14, 482 (1955).

[16] A proposal by B. Feld, Bull. Am. Phys. Soc. Ser. II, **1**, 72 (1956). Supposes a series of resonances in S, P, D states which may not be greatly different from the behavior proposed here.

[17] L. Alvarez, *Proceedings of the Sixth Annual Rochester Conference on High Energy Physics* (Interscience Publishers, Inc., New York, to be published).

[18] M. Blau and A. R. Oliver, Phys. Rev. **102**, 489 (1956).

detailed checks at many energies in the neighborhood of the peak.

To sum up the discussion, we have primarily considered the Dyson-Takeda suggestion of a pion-pion interaction and the one emphasized by Cool *et al.* of a D state being mainly responsible for the enhancement of the cross section in the 1-Bev region. We feel that the pion-pion interaction hypothesis has many features which would seem consistent with the results at both 1.0 and 1.5 Bev. This model does not explain why the elastic part of the cross section should be damped out so rapidly above 1 Bev, although one would expect this effect to occur at some energy.

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Scattering and Absorption of π^+ Mesons in Lead*

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The interactions of 50 ± 15-Mev π^+ mesons in lead were investigated by means of a magnet cloud chamber containing a single $\frac{1}{8}$-inch lead plate. The following cross sections were found: for elastic scattering greater than 40°, 252 ± 36 mb; for star production, 852 ± 82 mb; for charge-exchange scattering, 27 ± 19 mb. Only one of the 52 observed scatters was inelastic. The elastic scattering has a minimum near 90°. The mean free path of π^+ mesons in nuclear matter, derived from the inelastic events and large-angle scatters in this experiment, is $(9.0\pm1.5)\times10^{-13}$ cm. The results are compared with information from related experiments.

INTRODUCTION

At present, information about meson scattering and absorption in complex nuclei is still rather incomplete. Because of its fundamental nature, scattering in hydrogen has claimed the most attention. Scattering by complex nuclei has been done only in a rather exploratory fashion, but the gaps are being filled in steadily. Meson-absorption cross sections of many elements have been measured at several energies. The details of the interactions, however, have been investigated primarily for light elements. The experiment reported here furnishes data on the interactions of π^+ mesons and lead.

A cloud chamber was used because it facilitates the simultaneous investigation of several features of the meson-nuclear interactions. Of interest are: the angular distribution of the scattered mesons; the cross sections for inelastic scattering, charge-exchange scattering, and absorption; and the characteristics of the star fragments. Because these features impose conflicting requirements on the experimental arrangements, the actual experiment represents a compromise, which yields information on all these aspects with reasonable accuracy. The procedure followed was very similar to that used by Tracy[1] and is therefore described only briefly.[2]

EXPERIMENTAL PROCEDURE

The mesons were produced in a 2-inch-thick polyethylene target by the 340-Mev deflected proton beam of the 184-inch Berkeley synchrocyclotron. The meson beam[3] was deflected away from the proton beam by means of an electromagnet and passed into the cloud chamber.

The expansion-type cloud chamber[4] is 22 inches in diameter and has a sensitive region 3.5 inches deep. Across the center of the chamber was placed a $\frac{1}{8}$-inch-thick (actually 3.335 g/cm^2) lead plate covered with thin aluminum foil (4.8×10^{-3} g/cm^2) to improve the illumination. The cloud chamber was situated in a large electromagnet[4] suitable for fields up to 22 kilogauss. Fields of 5.18 and 7.33 kilogauss were used in this experiment because higher fields would have caused the radii of curvature of the meson paths to be

* Work done under the auspices of the U. S. Atomic Energy Commission.
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[1] J. F. Tracy, Phys. Rev. **91**, 960 (1953).
[2] For further details see George Saphir, University of California Radiation Laboratory Report UCRL-2833, January, 1955 (unpublished).
[3] Richman, Skinner, Merritt, and Youtz, Phys. Rev. **80**, 900 (1950).
[4] W. M. Powell, Rev. Sci. Instr. **20**, 403 (1949).