REVIEW OF INELASTIC TWO BODY REACTIONS

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INTRODUCTION AND DESCRIPTION OF CONTENTS

Two body reactions of the type

\[ A + B \rightarrow C + D \]  

(1)

can be divided into 3 types (1) elastic, which will not be discussed here (2) simple inelastic two body reactions such as charge exchange or strangeness exchange reactions (e.g. \( \pi^+ p \rightarrow \Sigma^+ K^+ \)) (3) quasi two body reactions in which there are more than two particles in the final state, but in which there is an intermediate two body state due to resonance production, e.g. \( \pi^+ p \rightarrow N^0 \omega \rightarrow p \pi^+ \pi^+ \pi^0 \). In this paper we discuss the reactions of types (2) and (3).

In Chapter I, the problem of the percentage of quasi two body reactions out of all inelastic reactions is discussed. It is shown that while this percentage falls to about 10\(^0\)/o near 10 GeV/c incident momentum, there are certain channels where the percentage is high, about 50\(^0\)/o.

In Chapter II, the peripheral nature of quasi two body reactions and the tendency of resonances to have the same differential cross section distributions as the non-resonant background, are illustrated.

In Chapter III, the two body reactions are shown to be peripheral, with slopes of the \( \text{d} \sigma / \text{d} t \) distributions comparable to that of the non-resonant background. Results are reported to show that these slopes are related to the radii of the interacting particles. The values of the slope are found to increase with energy, i.e. the diffraction peak shrinks. The absorption model predictions for the \( \text{d} \sigma / \text{d} t \) distributions are in reasonable agreement with experiment for pion exchange reactions, but are in serious disagreement for reactions which require the exchange of a vector meson. However, calculations using the Regge Pole model give agreement for both pion and vector-meson exchange.

Though slopes are all of the same order of magnitude some have about half and some about twice the slope of elastic scattering. The systematics of the variations of the slopes for different reactions is

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not understood. The results are inconsistent with the coherent Droplet Model of Byers and Yang \(^{(1)}\).

In Chapter IV, the correlations between the decay angular distributions of resonances are reported to be about the same at different incident momenta. Also, the angular correlations are about the same in the reaction \( \pi^+ p \rightarrow \Xi^0 p \) and \( K^+ p \rightarrow \Sigma^+ \Lambda \), where the same particle is assumed to be exchanged. In general, reasonable to fair agreement is obtained with the predictions of the absorption model as regards angular correlations.

In Chapter V, evidence for backwards scattering or anti-peripheral for quasi two body reactions is described. That the backward peak could be caused by baryon exchange is discussed. When negative hyperons \( (\Sigma^-, \Xi^-, \Lambda^-) \) are produced, it is found that there is no forward peak at high energy.

In Chapter VI, the variation of the cross section, \( \sigma \), with incident momentum, \( p_{\text{in}} \), is discussed \(^{(2)}\). It is found that the results fit the relation \( \sigma = \text{constant} \cdot (p_{\text{in}})^{-n} \). The values of the exponent, \( n \), are found to be about 0 for "diffraction-like" reactions, about 1.5 for reactions proceeding by exchange of a non-strange meson, about 2.0 for reactions with exchange of a strange meson and about 4.0 for baryon exchange reactions. It is shown that these results can be interpreted in terms of the Regge Pole model.

In Chapter VII, an explanation of the constant cross section for certain quasi two body reactions is given \(^{(3)}\), in terms of a diffraction scatter at one vertex followed by a final state interaction. Other reactions in which constant cross sections may be expected are discussed.
I. FRACTION OF INELASTIC PROCESSES THAT ARE TWO-BODY

The question of what percentage of inelastic reactions can be described as two body is of interest, but only recently has some information become available. In the statistical model one would expect the percentage to fall to near zero at very high energy, but in some other models the percentage of two-body inelastic reactions is assumed to be large. Here we consider first $K^+ - p$ interactions up to 5 GeV/c, and pion reactions up to 11 GeV/c, and then individual reaction channels. A paradoxical conclusion is reached.

In Fig. 1 is shown the variation with energy of the total inelastic cross section and of certain two body cross sections for $K^+ - p$ interactions. It can be seen that the fraction of these two body interactions decreases with increasing energy, being about 25% for 5 GeV/c $K^+$. However, these reactions (giving $K^+N$, $KN^+$ or $K^+N^+$ final states) come only from three and four particle reactions (here particle does NOT mean resonance) and, as can be seen in Fig. 2, the fraction of 3 and 4 particle reactions is decreasing with energy because of the rising production of 5, 6, 7... particle final states, while the total cross section is constant. Thus we should consider the figure of 25% of quasi two body productions as a lower limit since there could be other quasi two body reactions.

In the interactions of 8 GeV/c $\pi^+$ (unless specifically stated the interactions are with a proton), the total of known quasi two body cross sections was found to be 1.7 mb or 8% of the total inelastic cross section, while for 11 GeV/c $\pi^-$ interactions it was found to be about 1.1 mb or 5% (6). Thus, at first sight, it would seem that the fraction of quasi two body reactions is small at high energies. However, if we consider certain reaction channels, the situation can be different.
For example, in the reaction

\[ \pi^+ p \rightarrow p \pi^+ \pi^- \tag{1.1} \]

frequent production of \( N^{++} \) and \( p \)-mesons has been reported\(^7\). This was shown in the triangular plot of the \((p\pi^+)\) effective mass against the \((\pi^+\pi^-)\) effective mass. Since there are two positive pions each event should be plotted twice thus giving a large background. However making the assumption of maximum peripherality, that is assuming that the combination with the smallest squared four momentum transfer, \( t \), is the correct one\(^8\), then each event is plotted only once and this was done in Fig. 3 for 8 GeV/c \( \pi^+ \) interactions by the Aachen - Berlin - CERN collaboration. It can be seen that the reactions

\[ \pi^+ p \rightarrow N^{*+} p^0 \tag{1.2} \]

and

\[ \pi^+ p \rightarrow N^{*0} p^+ \tag{1.3} \]

dominate. In this channel there are in addition the reactions

\[ \pi^+ p \rightarrow pA_1 \tag{1.4} \]

and

\[ \pi^+ p \rightarrow pA_2 \tag{1.5} \]

so that 45\(^\circ\)/o of reaction (1.1) can be ascribed to the quasi two body reactions (1.2), (1.3), (1.4) and (1.5). Similarly in the reaction

\[ \pi^+ p \rightarrow p \pi^+ \pi^0 \]

the quasi two body reactions \( \pi^+ p \rightarrow p\pi, \pi^+ p \rightarrow N^* \pi \)

have been shown\(^5\) to account for 50\(^\circ\)/o of the reaction channel at

8 GeV/c, and there may still be two other quasi two body reactions\(^9\).

Also in the reaction \( pp \rightarrow pp\pi^+\pi^- \) at 5.7 GeV/c, the quasi two body reactions

\( pp \rightarrow N^{*+} N^- \) and \( pp \rightarrow N^{*0} N^+ \) (1588) + charge conjugate, were shown\(^10\) to account for over 60\(^\circ\)/o of the reaction channel (unless otherwise stated, \( N^* \) refers to the 1238 MeV isobar).

Thus we have the situation that a few reaction channels have a large percentage of resolved quasi two body reactions, and others very little. It is probable that this is an experimental bias due to resonances not being recognised. For example, the isobars with isotopic spin \( T = 1/2 \), are frequently not resolved, and hence are not counted.
Also as new resonances are discovered, the fraction of quasi two body reactions increases, and indeed if one were to make a graph plotting this fraction against the year, the graph would show a rising curve.

In conclusion, it would at first sight appear that the percentage of inelastic two body reactions decreases with energy to less than 10\%o, but as in certain reaction channels the fraction of two body reactions so far identified is high (\approx 50\%o), the final answer cannot be considered to be known yet.

II. THE PERIPHERAL NATURE OF TWO BODY REACTIONS

By peripheral we mean that instead of the t-distribution of particles or groups of particles being distributed according to phase space, there is a tendency for them to have small t-values, where t is the square of the four-momentum transfer. That inelastic two body reactions have forward diffraction-like peaks, (i.e. have peaks near t = 0) is well known. The situation in quasi two body reactions may be illustrated by considering the Chew-Low plot of Fig. 4 obtained by the Aachen – Berlin – CERN collaboration for the reaction \( \pi^+ p \rightarrow N^+ \pi^+ \pi^- \).

It can be seen that almost all events have a small value of |t|, that there are no events in the middle of the Chew-Low plot and that there are a few events near the maximum value of |t| for the given (\( \pi^+ \pi^- \)) mass - that is these events have \( u \approx 0 \) where \( u \) is the square of the crossed four-momentum transfer. These latter events with \( u \approx 0 \) are sometimes called anti-peripheral. Another important feature to be observed in Fig. 4 is that the t-distribution near the \( \rho \) and \( f_0 \) masses is the same as that of the non-resonant background.

Other quasi two body reactions have similarly been shown to be peripheral and tend to have the same differential cross section distribution as the non-resonant background.
III. SLOPE OF DIFFERENTIAL CROSS SECTIONS

It is found in general (11) that the two body reactions exhibit a forward diffraction-like peak*, that is, it is found that for small values of $|t|$ the $d\sigma/dt$ distribution can be reasonably fitted by the formula

$$d\sigma/dt = \text{constant} \cdot e^{At} \quad (3.1)$$

where $A$ is called the slope since the logarithm of $d\sigma/dt$ is usually plotted against a linear scale in $t$. The more elaborate formulation

$$d\sigma/dt = e^{a + bt + ct^2} \quad (3.2)$$

first found to be needed by Brandt et al. (12), gives a better fit to the data and extends over a larger range of $t$-values. However the simpler formula (3.1) is usually preferred, particularly since the slope $A$ can be related to the optical model radius, $R$. In the simple black disc optical model,

$$d\sigma/dt = \text{constant} \cdot e^{(\frac{R}{2})^2 t} \quad (3.3)$$

so that $A = (R/2)^2$.

That this idea has some reality can be seen from the results shown in Fig. 5 obtained by groups (13) using heavy liquid bubble chambers. Here the $d\sigma/dt$ distribution is given for the production of 3 pions by an incident pion. In each case, the distribution could be interpreted as the sum of two distributions with different slopes. The slope for small $|t|$ - values gave a radius which corresponds to that expected for the heavy nucleus, while the slope for large $|t|$ - values is about the same as for elastic scattering on a single nucleon. The results were then interpreted by assuming that the 3 pion system could be produced either coherently on the entire nucleus or incoherently on a single nucleon in the nucleus. Similarly, when three pions were produced in deuterium (14), the slope for small $|t|$ - values was found to be larger.

(*)By forward peak we mean here that the incoming particle keeps its direction. For example, in the interaction of a meson on a target proton, the meson generally goes forwards in the c.m., or to express it otherwise, by forwards we mean $t = 0$ and by backwards we mean $u = 0$. PS/5579/ak
with a value corresponding to the radius of the deuteron.

We next consider the variation of the slope with incident momentum and ask the question whether there is a shrinking of the diffraction-like peak with increasing energy. For the reaction \( \bar{p}p \rightarrow N^\ast N^\ast \), the values of the slope \( A \), are given in Table I for three different incident momenta. It may be seen that the slope increases as the incident momentum increases. The results of the CERN - Brussels group \(^{(4)}\) for several \( \bar{K}^+p \) interactions at 3.0, 3.5 and 5.0 GeV/c are shown in Fig. 6, where again it can be noted that the slope increases as the incident momentum increases. Similarly, in reactions with incident pions, the slope is found to increase with incident momentum.

Thus it may be concluded that for intermediate momenta (3 to 8 GeV/c), the slope increases with incidenta momenta, that is, there is a shrinking of the diffraction-like peak in quasi two-body reactions. It is, however, not clear to us whether this result is important or has a trivial explanation which is:

At very low momenta, near threshold, the situation is confused and one cannot generally speak of diffraction-like peaks due to (1) forward and backward "peaks" overlap (2) there is a large amount of background (3) the inelastic reaction can often be considered as passing by an intermediate state, e.g. \( \bar{K}^- + p \rightarrow \Ypsilon \rightarrow \text{hyperon + meson} \), so that the \( t \)-distribution is determined mainly by the decay angular distributions of the intermediate state. The consequence is that near threshold the "slope" is generally very small, \( \approx 0 \). At very high energies, the slope is of the order of elastic scattering, i.e. \( \approx 10 \). Clearly there must be an intermediate momentum range in which slope rises from \( \approx 0 \) to \( \approx 10 \).

We now compare the experimental distributions of the differential cross section with the predictions of the Absorption and Regge Pole Models. The Absorption Model is essentially a one-meson exchange calculation in \( PS/579/nk \).
which one considers also the interaction between the initial particles and between the final particles. It has been shown to work rather well at low momentum of a few GeV/c\(^{(15)}\) and might be expected to work even better at high energies where the absorption is less. The Aachen - Berlin - CERN collaboration\(^{(11)}\) have tested the Absorption model in \(\pi^+ p\) interactions at the higher momentum of 8 GeV/c. As shown in Fig. 7, the predictions of the Absorption model were found to be in reasonable agreement for the reactions \(\pi^+ p \rightarrow p p\) and \(\pi^+ p \rightarrow \Lambda^0\) which can proceed by pion exchange. However, the results shown in Fig. 8 for the reactions \(\pi^+ p \rightarrow N^+\pi^-\), \(\pi^+ p \rightarrow p A_2\) and \(\pi^+ p \rightarrow N^\ast\) which all require vector meson exchange, were found to disagree with the Absorption model predictions. Integrating over all \(t\)-values, the total cross sections for the latter 3 reactions was an order of magnitude greater than predicted. It was concluded that the Absorption Model in its present form is unsatisfactory.

Recently, some calculations by Barrawi\(^{(16)}\), Roy\(^{(17)}\) and Thews\(^{(18)}\) have been made for quasi two body reactions on the basis of the Regge Pole Model, using the parameters found from elastic and charge exchange scattering. In Fig.9 the calculations of Thews are compared with the experimental differential cross sections for the reactions \(\pi^+ p \rightarrow N^*\) and \(K^+ p \rightarrow N^*K^0\) which both require vector meson exchange. It can be seen that good agreement was obtained.

In fitting the experimental data for a large number of reactions, the Regge Pole theory appears to be using rather few parameters. However, since inelastic reactions have roughly the same types of diffraction peaks as elastic and charge exchange reactions, the number of parameters required to fit the differential cross sections is less than might be expected. Therefore the striking agreement of Fig. 9 compared with Fig. 8, must be taken with caution.
We now return to consider the differential cross sections of two body reactions in general. The results\(^4\) found for incident \(K^+\) mesons of 3.0, 3.5 and 5.0 GeV/c have been given in Fig. 6. In Fig. 10 are given the results\(^1\) for elastic scattering and for eight quasi two body reactions of 8 GeV/c \(\pi^+\). The most general feature found from these two figures is that the quasi two body reactions have a forward diffraction peak which has a slope of the same order as that for elastic scattering. However, there are two important deviations from this:

1) the reactions \(\pi^+ p \rightarrow n^\pi\) and \(\pi^+ p \rightarrow n^\omega\) have maxima near \(|t| = 0.2 (\text{GeV/c})^2\). This is similar to the maximum observed for the reaction \(\pi^- p \rightarrow n\pi^+\) which is generally interpreted as being due to a large spin-flip contribution.

2) The slopes of inelastic two body reactions are not all equal to that of elastic scattering, but vary from about half to twice the elastic value (here we ignore effects such as \(1\) above and anomalous behaviour of the reaction \(pn \rightarrow np\) near \(t = 0\)). In fact the slopes tend to fall, very roughly, into 3 groups as shown in Table II. The values of the slopes are to be compared with the value of 9 to 10 \((\text{GeV/c})^2\) obtained for elastic scattering. The most important point about Table II is that there is no theory at present which explains the slopes for the different reactions!

Of the two reactions \(\pi^+ p \rightarrow n^\pi\) and \(\pi^+ p \rightarrow p\pi\) which have slopes about that of elastic scattering, one proceeds by vector meson exchange and the other by pion exchange. It may be noted the double resonance production reactions \(\pi^+ p \rightarrow n^\nu\), \(\pi^+ p \rightarrow n^\nu\) and \(K^+ p \rightarrow n^\nu\), all have slopes appreciably greater than that of elastic scattering. However, as shown in Table I, the reaction \(\bar{p}p \rightarrow n^\nu\) has a slope much smaller than that of elastic scattering, which is surprising as one would have expected that the large absorption cross section of anti-particles in the initial and final states would depress the differential cross section at large \(t\)-values (close collisions), and hence make the slope

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large. Also the Coherent Droplet Model of Byers and Yang\(^{(1)}\) appears to be in contradiction with these results.

Evidence has been found in several reactions for the existence of a second peak in differential cross section distributions. This is demonstrated in Fig. 11 for the charge exchange reaction \(^{(19)}\)

\[
\pi^- p \rightarrow \pi^0 n
\]  

(3.4)

It is not clear whether this is a second maximum which occurs in all inelastic reactions or whether one should consider it only as a secondary consequence of the dip observed near \(|t| = 0.6 \text{ (GeV/c)}^2\), which is predicted \(^{(20)}\) on the Regge Pole Model. At present reaction (3.4) is one of the few inelastic two-body reactions which has been studied with good statistical accuracy at \(|t| = \text{values of about } 1 \text{ (GeV/c)}^2\) and above. It is interesting to note that the slope of reaction (3.4) taken over the \(|t|\) interval 0.1 to 0.5 is greater than that of the other charge exchange reactions perhaps due to the dip. Clearly much more experimental data is required on this subject.

IV. ANGULAR CORRELATIONS IN RESONANCE DECAY

In the decay of resonances produced in quasi two body reactions, correlations have been found to exist between the angles of the particles emitted. As shown in Table III, the density matrix elements for the reaction \(\pi^+ p \rightarrow N^+ p\) at 8 GeV/c, were found by the ABC Collaboration \(^{(21)}\) to be about the same as those found by the ABBEHLM collaboration \(^{(22)}\) with 4 GeV/c incident pions. Further it can be seen that the density matrix elements found by the CERN - Brussels collaboration \(^{(4)}\) for the reaction \(K^+ p \rightarrow N^+ K^0\) are the same as for the reaction \(\pi^+ p \rightarrow N^+ p\) which also proceeds by pion exchange. This may indicate that the nature of the incident particle may not be very important. This fact has been noted independently by Biafas and Kotanski \(^{(23)}\) who discuss it more fully.
At low energies the Absorption model has been found to describe the observed angular correlations in some detail\(^{(15)}\). With 8 GeV/c \(\pi^+\), the Aachen - Berlin - CERN Collaboration found fair to good agreement\(^{(21)}\). Table III is an example of this good agreement. The Regge Pole model cannot at present predict angular correlations. Hence, overall, it would seem that there is a need for a theory which can predict angular correlations as the Absorption Model does, and differential cross sections as the Regge Pole Model does. Up to the present, attempts to join these two models have been unsuccessful.

V. BACKWARDS SCATTERING AND BARYON EXCHANGE

In this chapter, the evidence reported for backward peaks in \(\pi\)-p and \(K\)-p interactions is presented and the interpretation of this backward peaking in terms of baryon exchange is discussed.

At the 1964 Dubna conference, results were presented indicating that in \(\pi\)-p elastic scattering there was a backward peak. Results presented by bubble chamber groups\(^{(22)}\) using 4 and 6 GeV/c \(\pi^+\) are shown in Fig. 12. It may be seen that there is a small backward peak, near 180\(^\circ\) (cos \(\Theta = -1\)). Since 1964, counter groups have investigated in some detail the backward elastic peaks. Here evidence is presented from bubble chamber data for backward peaks in quasi elastic two body reactions.

In the Chew-Low plot of Fig. 13, obtained by the Aachen - Berlin - CERN collaboration for the reaction \(\pi^+ p \rightarrow p \pi^+\pi^0\), some anti-peripheral events may be noted. To show how an angular distribution may be obtained from a Chew-Low plot, the line corresponding to cos \(\Theta = -0.8\) for different \((\pi^+\pi^0)\) masses has been drawn. Evidence for backward peaks was obtained by this collaboration at 8 GeV/c from the reactions \(\pi^+ p \rightarrow p p^+\) and \(\pi^+ p \rightarrow K^0 p\) and is shown in Fig. 14. The evidence
obtained by the ABBBHHLM collaboration (25) in 4 GeV/c π⁺ - p interactions is shown in Fig. 15. Thus it can be seen that there is reasonable evidence for the existence of backward peaks in quasi two body reactions and also that the differential cross section should be plotted against both |t| and cos θ.

Other evidence for backward peaks comes from the studies of K⁻ p interactions, especially at 3.0 GeV/c by the Ecole Polytechnique, Saclay, Amsterdam collaboration (26) and at 3.5 GeV/c by the Birmingham, Glasgow, London (I.C.), Oxford and Rutherford Lab. collaboration (27). These collaborations have tested the hypothesis that backward peaks may be explained in terms of Feynmann diagrams with baryon exchange. L. Lyons (28) has discussed this subject fully. In Fig. 16 is shown the differential cross sections calculated from the results obtained by the two collaborations for reactions of the type

\[ K^- + p \rightarrow \text{hyperon} + \text{meson} \]

where the hyperon has positive or neutral charge. It can be noted that there is a large forward peak and also a tendency for there to be a backward peak (which sometimes appears as a plateau), near cos θ = 180° (which lies at about -t = 5.0 (GeV/c)² with a value of (dσ/dt)_{180°} of 10 to 30 μb/(GeV/c)². An exception is the reaction \( K^- p \rightarrow \Lambda \phi \) which has no backward peak. This is illustrated in Fig. 17 where the Ecole Polytechnique, Saclay, Amsterdam collaboration have compared the cos θ distributions for the reactions \( K^- p \rightarrow \Lambda \omega \) and \( K^- p \rightarrow \Lambda \phi \). If baryon exchange is assumed then, as can be seen from the Feynmann diagram in Fig. 17, the ppφ - coupling constant must be appreciably smaller than the ppω - coupling constant and this is consistent with SU₃ and the value of the φ - ω mixing angle. This must be considered evidence in favour of the hypothesis that backward peaks are due to a baryon exchange mechanism.
In Fig. 18, the Birmingham, Glasgow, London (I.C.), Oxford and Rutherford Laboratory collaboration have compared the cos θ distributions for the reactions \( K^- p \rightarrow E^+ \pi^- \) and \( K^- p \rightarrow E^- \pi^+ \). It can be seen that in the latter reaction the forward peak is absent. This striking result has been simply explained by consideration of the Feynmann diagram for a forward peak in \( E^- \) production which would require the exchange of a meson of charge two and no such meson is yet known. This feature that there is no forward peak in reactions of the type \( K^- + p \rightarrow \text{hyperon} + \) meson when the hyperon is negatively charged is indicated by the other results of the two collaborations shown in Fig. 19. In all these reactions the value of \( (d\sigma/dt)_{180^\circ} \) is about 10 to 30 \( \mu \)b/(GeV/c)\(^2\) again. Or, expressed in another way, the cross section for the backward peak is found to be about 10 to 30 \( \mu \)b. It has been noted by the collaborations that the cross section is the same whether the negative hyperon has strangeness -1 or -2, that is the cross section is about the same whether the baryon assumed to be exchanged has strangeness 0 or -1.

It is possible to further test the relationship between backward peaks and baryon exchange if we assume that there are no baryons of positive strangeness which contribute. Then in elastic or charge exchange scattering of \( K^- \) mesons on protons no backward peak would be expected - however there are so far no experimental data yet available. Similarly in the reaction \( K^- p \rightarrow p K^\pi^- \) one would expect no backward peak.

The Brookhaven group\(^{(29)}\) have studied this reaction at 4.5 GeV/c and find no backward event whereas if one event had occurred it would have corresponded to a cross section of 1/2 \( \mu \)b. This cross section should be compared with the cross section of 5 to 15 \( \mu \)b that can be calculated by extrapolation from the lower energy data for reactions that do have backward peaks.

Further predictions may be made using crossing symmetry as has been described by Biłeński and Czyżewski\(^{(30)}\). Thus if there is no back-
ward peak in the reaction \( K^- p \rightarrow p K^- \), then from crossing symmetry in the annihilation reaction \( \bar{p} p \rightarrow K^- K^+ \), one would expect the \( K^- \) to be produced in the same direction in the c.m. as the \( p \), but not in the direction as the proton. However there is insufficient experimental evidence available to test this prediction. The annihilation into two pions, \( \bar{p} p \rightarrow \pi^- \pi^+ \) can be related by crossing symmetry to either \( \pi^+ p \) backward scattering or \( \pi^- p \) backward scattering. It might be expected that \( \pi^- p \) backward scattering should have a very low cross section, as it requires exchange of two units of charge, but it is possible to exchange \( N^{++} \) (the only established particle with two units of charge, among all particles with baryon number 0 or 1). In antiproton annihilations, in general, the negative pion tends to follow the direction of the (negatively charged) antiproton and this appears to hold also for the reaction \( \bar{p} p \rightarrow \pi^- \pi^+ \), although the statistical significance of the results\(^{31}\) is poor. This would be consistent with the evidence that the \( \pi^+ p \) backward peak has a larger cross section than the \( \pi^- p \) backward peak.

The differential cross section distributions for small \( u \)-values can be interpreted in terms of the relationship

\[
\frac{d\sigma}{du} = \text{const.} \ e^{-Au} \quad \text{(V.1)}
\]

although as can be seen from Fig. 19, the experimental results are not sufficient to prove that this relation holds. The values of the slope, \( A \), for backward peaks is found to vary widely, probably because of the small number of events observed, though production of intermediate hyperon states could influence the results, e.g. in the reaction \( K^- p \rightarrow \pi^- \pi^+ \), at 3.0 GeV/c there is a sharp backwards peak with \( A \approx 10 \) for \( |u| \) values up to 0.4 (GeV/c)\(^2\) while at 3.5 GeV/c there is very little backwards peaking as can be seen in Fig. 19. If we consider \( |u| \) values from the kinematic minima up to about 2.0 (GeV/c)\(^2\), the slope for backwards peaks is \( \approx 2 \) (GeV/c)\(^{-2}\) and for forward peaks in other \( K^- p \) reactions the slope of the \( d\sigma/dt \) distributions for \( t \) values up to
2.0 (GeV/c)^{-2} is about 2 to 3 (GeV/c)^{-2}. It is clear that more data are required on backward peaks.

VI. THE VARIATION OF CROSS SECTION WITH INCIDENT MOMENTUM

In Fig. 20, the cross section values are plotted against the incident momentum on log-log scales for the four reactions \( \pi^+ p \rightarrow p \rho^+ \) and \( K^+ p \rightarrow p K^{*+} \). Two things may be noted in this figure. Firstly, for incident momenta well above threshold, the points are consistent with the relationship \( \sigma = \text{const.} \ p_{\text{in}}^{-n} \), where the exponent, \( n \), is the slope of the line through the points. Secondly, for a given momentum, the cross sections have all about the same value, that is, the constant in the suggested relationship, has about the same value for each of the four reactions.

Similarly in Fig. 21, where the cross section is plotted against \( p_{\text{in}} \) for the reactions \( K^- p \rightarrow \Lambda \pi^0 \), \( K^- p \rightarrow \Lambda \omega \), \( K^- p \rightarrow \Sigma^+ \pi^- \) and \( K^- p \rightarrow \eta_{1385} \); the experimental values fit the relationship \( \sigma = \text{const.} \ p_{\text{in}}^{-n} \) and the constant is the same for all reactions.

We may write this relationship in the dimensionally simpler form

\[
\sigma = K \left( \frac{p_{\text{in}}}{p_0} \right)^{-n}
\]

(6.1)

where \( p_0 \) is a constant which we may take as 1 GeV/c, and \( K \) is a constant which is then the cross section extrapolated to 1 GeV/c.

Further proof of this relationship is given in Fig. 22 for a number of reactions whose common feature is that they can be interpreted in terms of the exchange of a meson. It should be emphasised at this point that the cross sections have generally been determined at different momenta by different groups and it may happen that the groups have different methods of analysis and of estimating the background\(^{33}\). Hence,
as can be seen in Fig. 22, the results are sometimes inconsistent. The inconsistencies are particularly important for reactions with double resonance production where the resonances have large width, such as $\pi^{-} p \rightarrow \pi^{0} n$, as can be seen in Fig. 22i and the reactions are not included in the analysis below.

The results for the charge exchange reactions $\pi^{-} p \rightarrow \pi^{0} n$, $K^{-} p \rightarrow K^{0} n$ and $\bar{p} p \rightarrow \bar{m} m$ are shown in Fig. 22a. The three slopes are all of the same order, but the constant, $K$, (i.e. the cross sections) for the antiproton charge exchange is larger than for the meson charge exchange reactions. The results for the charge exchange reaction $p n \rightarrow n p$ are rather poor. However they are shown together with the other three charge exchange reactions in Fig. 23. It may be seen that the $n p$ charge exchange reaction has an exponent different from that of the other reactions. It is not clear whether this difference is due to the poor experimental results or to some feature of the $n p$ charge exchange reaction, e.g. the very sharp peak near $t = 0$ is not yet fully understood.

To demonstrate that from the standpoint of cross sections, charge exchange is not a special type of reaction, we have compared in Fig. 22b the reaction $\pi^{-} p \rightarrow n \pi^{0}$ and $\pi^{-} p \rightarrow n \eta^{0}$. It may be seen that the exponents are similar.

To allow the points plotted to be read more easily, Figures 22 c, 22 e, 22 g, 22 h and 22 i have been repeated in Figures 25, 26, 27, 28 and 29 respectively.

In Fig. 30 results are presented for reactions involving baryon exchange. In Fig. 30a the reactions $K^{-} p \rightarrow \Sigma^{+} n^{-}$ and $K^{-} p \rightarrow \Sigma^{+} n^{-}$ are compared. At low momenta the cross sections are similar as would be expected since hyperons are produced as an intermediate state (i.e. $K^{-} p \rightarrow \Xi^{0} \rightarrow \Sigma^{+} n^{-}$) but at higher momenta the $\Sigma^{-}$ production cross
section falls much more sharply than the $\Sigma^+$ cross section, being an
order of magnitude lower at 3.5 GeV/c. As pointed out in Chapter V, the reaction $K^- p \rightarrow \Sigma^- \pi^+$ at high energy consists only of a backward peak unlike the reaction $K^- p \rightarrow \Sigma^+ \pi^-$ whose cross section mainly comes from
the forward peak. Similar results can be seen in Fig. 30 b where the
reactions $K^- p \rightarrow \Sigma^+ \pi^-$ and $K^- p \rightarrow \Sigma^- \pi^+$ are compared.

In Fig. 30 c, the $K^- p$ interactions which produce $\Sigma^-$, $\Sigma_1^{\pm} \pi$, and $\Xi^-$
in two body reactions are compared. It may be noted that apart from
threshold effects all the points lie on one curve although in the first
two cases a non-strange baryon exchange is postulated whereas in $\Xi^-$
production a strange baryon exchange is required. The exponent corres-
ponding to this curve is about 4. Backward elastic scattering is another
reaction which would require baryon exchange. As cross sections for back-
ward elastic scattering are not available, we have plotted in Fig. 30 d
the values for the differential cross section ($d\sigma/dt$), at 180°(34)(35)
or near 180°(36)(37) for reaction $\pi^- p \rightarrow pn^-$. Because of constructive
and destructive interference between the isotbars produced, the values
of $d\sigma/dt$ fluctuate considerably, but it can be seen that if these
fluctuations are ignored, a rough fit to the data can be obtained with a
line having the equation:

$$ (d\sigma/dt)_{180°} = 7.3 \left( \frac{p}{p_0} \right)^{-4.0} \quad (6.2) $$

Figures 30a, 30b, 30c and 30d have been repeated on a larger scale in
Figures 31, 32, 33 and 34 respectively.

Anderson et al. (38) have reported at this conference on the
reactions

$$ p + p \rightarrow p + N^- \quad (6.3) $$

where $N^-$ isotars are of mass 1238, 1400, 1520, 1690 and 2190 MeV. Their
results on the variation of cross section with momentum for these 5
reactions are reproduced in Fig. 35. While the cross section for $N^-_{1238}$
falls with momentum as might be expected, the striking result, first indicated by Cocconi et al \(^{(39)}\), is that the cross section for the other reactions is constant over the range 10 to 30 GeV/c. This constant cross section satisfies the relation suggested above when the exponent \( n \approx 0 \).

In Table 4, the values of the exponent, \( n \) and of the constant \( K \), are given for the reactions discussed above (reactions 5, 6 and 7 of the Table are discussed in the next chapter). Also given is the momentum range over which \( n \) and \( K \) are calculated. To avoid threshold effects, the incident momentum was generally taken as about 2 GeV/c or more. As the constant \( K \) is obtained by extrapolation rather than interpolation it does not show very well the constancy of cross sections of similar reactions because of fluctuations in the exponent \( n \). Hence the interpolated cross sections at 3 GeV/c are also given.

It may be seen that values of the exponents fall into three broad groups. Firstly reactions 1 to 6 have approximately constant cross section, \( n \approx 0 \), as is demonstrated in Fig. 35. Secondly reactions 8 to 34 which are shown in Fig. 22 have exponents roughly about 1.5 to 2.0 (the extreme values are 1.1 and 2.8). Thirdly reactions 35 to 37 have appreciably larger exponents \( n \approx 4 \), as is shown in Fig. 33. The above is a phenomenological grouping.

It would be preferable to group them in a physically meaningful way. If we classify the reactions in terms of the particle exchanged in the appropriate Feynmann diagram, it is possible to distinguish four groups. The four groups and the average value of their exponents, are:

1. \( n \approx 0.2 \), "diffraction-like" – explained in Chapter VIII.
2. \( n \approx 1.5 \) non-strange meson exchange
3. \( n \approx 2.0 \) strange meson exchange
4. \( n \approx 4.0 \) baryon exchange.

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The values of the exponent corresponding to this grouping are shown in Fig. 36.

As elastic scattering reactions have approximately constant cross section at high momenta, i.e. \( n \approx 0 \), elastic scatters may be considered to belong to group (1).

It is possible to group these reactions in the framework of the Regge Pole model. In this model the differential cross sections are expressed in terms of the square of the total energy, \( s \), but at high energies this is directly proportional to \( \pi n \). A comparison of these results with the Regge Pole model cannot be made directly, since the model predicts the variation of the differential cross section with \( s \) at a fixed value of \( t \), whereas we report here on the total cross sections, \( \sigma \), integrated over all \( t \)-values. In the Regge Pole model, the differential cross section \( d\sigma/dt \) is proportional to \( s^{2\alpha(t)-2} \).

As small \( t \)-values yield most of the reaction cross section, the exponent, \( n \), should be approximately equal to \( \frac{1}{2} \{ 2\alpha(0) - 2 \} \). If the value of \( \alpha(t) \) decreases as \( t \) decreases, then the exponent \( n \) will be slightly greater than \( \frac{1}{2} \{ 2\alpha(0) - 2 \} \). For group (1) reactions, exchange of the Pomeronchuk trajectory is postulated and as \( \alpha(0) = 1 \), the exponent is expected to be about zero. For group 2 reactions exchange of the \( \rho \) or \( R \) trajectory is expected and as \( \alpha(0) \) is about 1/2 and as \( \alpha(t) \) decreases as \( t \) decreases, the exponent \( n \) is expected to be slightly greater than one. For group (3) reactions the \( k^* \) trajectory is expected to dominate and as this has a \( \alpha(0) \) value slightly less than that for the \( \rho \) or for the \( R \) trajectory, the value of the exponent \( n \) should be slightly greater than for group (2) reactions as is observed. The trajectories for nucleons, isobars and hyperons are all believed to have negative values of \( \alpha \) at \( t = 0 \), and hence the exponent will be appreciably larger than that for groups (2) and (3). If for backward elastic scattering of negative pions the differential cross section, \( d\sigma/dt \), is plotted against \( s \), the exponent

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is about 4.5 taking all the results above 800 MeV/c but is about 4.0 if one takes only the higher energy results.

In one-meson exchange models, such as the absorption model, one expects different values of the exponent, $n_k$, according to whether a pion or a vector meson is exchanged. But the exponent for reactions 9 to 22 of Table 4 show no difference due to the mass or spin of the exchanged particle. For interactions requiring pion exchange, one instead considers in the Regge Pole model the exchange of the R-trajectory. As the $R$ and $\rho$ trajectories are believed to be similar, we would expect similar values of the exponent for all reactions for which the $R$ or $\rho$ trajectory is the dominant one. Hence this may be considered evidence in favour of the Regge Pole model.

One of the most striking features of Fig. 22 and 25 is that for a given value of $p_{in}$, similar reactions tend to have the same cross section. Thus at 3 GeV/c, if we consider the 9 reactions (numbers 23 to 31) requiring exchange of a strange meson, 8 of them have approximately the same cross section, as can be seen in Table 4. It can be seen in Fig. 33, that ignoring threshold effects, the cross section at a given $p_{in}$ for reaction 37 which requires the exchange of a strange baryon (e.g., $\Lambda^0$) is similar to that for reactions 35 and 36 where exchange of a non-strange baryon is required.

Although the processes are not two body ones, it is interesting to consider the cross sections for the production of antilambdas and hyperons in $\pi$-$p$ interactions and $\Omega^-$ hyperons in $K$-$p$ interactions. In each case there must be at least two other particles produced so that the results are not strictly comparable with the preceding results. The cross sections are plotted in Fig. 37 and it may be noted that all the cross sections are of the same order, of a few millibarns.
VII. POSSIBLE EXPLANATION OF THE CONSTANT CROSS SECTION OF CERTAIN REACTIONS

In this chapter we attempt to explain the surprising result reported by Anderson et al.\(^{36}\) that in the reaction

\[ p + p \rightarrow p + N^\# \]  \hspace{1cm} (7.1)

the cross section is constant for the 1400, 1520, 1690 and 2190 MeV isobars but not for the 1238 MeV isobar. We use the idea of a diffraction scattering process at one vertex followed by a final state interaction and stress the importance of the relative velocity of the particles. This concept is then extended to reactions produced by incident pions, kaons, antiprotons and gammas.

It is assumed that two body inelastic reactions can be interpreted in terms of Feynmann diagrams in which a "particle" carrying definite quantum numbers is exchanged between the two vertices. Cocconi et al.\(^{39}\) showed in counter experiments that reaction (7.1) gave a strong forward diffraction-like peak and Morrison\(^{40}\) showed in bubble chamber experiments with incident $\pi^-$ and protons that diffraction-like distributions for out-going $\pi^-$ and protons are obtained. Anati and Frentki\(^{41}\) and Drell and Hida\(^{42}\) suggested that diffraction scattering at one vertex could be responsible for these effects. The idea of diffraction dissociation on nuclei, previously proposed by Good and Walker\(^{43}\), is equivalent to this idea.

The conventional Feynmann diagram of reaction (7.1) is shown in Fig. 38a where the virtual pion from the top vertex undergoes diffraction scattering at the bottom vertex. It is, however, perhaps easier to understand this process if we consider Fig. 39. Here a proton, $p_A$, entering from the left, dissociates at A into a virtual pion (shown dotted) and a nucleon, $N_A$. At B, the other proton, entering from the right, which we will call $p_B$, makes an elastic interaction; the nucleon leaving B
must be the same as the proton \( p_B \). The pion leaving \( B \) then interacts
with the nucleon from \( A \) and may, in some cases, produce an isobar.
There are a number of important points about this mechanism.

1. The virtual pion and \( N_A \) have about the same velocity as \( p_A \).

2. The differential cross section for the dissociation \( p_A \rightarrow N_A + \pi \)
may be taken as independent of the momentum of \( p_B \).

3. In the rest system of \( p_B \), the virtual pion is a high energy particle,
thus the elastic scattering process at \( B \) is a high energy process.

4. In a high energy elastic reaction, the scattering is of a diffraction
type, so that the outgoing \( \pi \) and proton will have almost the same
momentum as before, but the direction will be slightly different -
this is independent of the momentum of \( p_B \).

5. From (1) and (4), \( N_A \) and the pion leaving \( B \) have approximately the
same velocity, and therefore the cross section for them to combine
together to form an isobar will be large, this being a low energy
effect, and will be approximately independent of the momentum of \( p_B \).

6. For a high energy elastic reaction, the cross section is approximately
independent of energy. Thus the cross section for the reaction at \( B \)
is independent of the momentum of \( p_A \) and \( p_B \).

We may draw the following conclusions:

(a) Since the 3 cross sections for the interactions at \( A \), at \( B \) and
for the final state formation of the isobar are all independent
of the incident momentum, then the overall cross section for the
reaction (7.1) may be expected to be approximately constant
with respect to the incident momentum.
(b) In elastic scattering, charge, baryon number, strangeness number and isotopic spin cannot be exchanged between the vertices. Since at vertex B these quantum numbers cannot be exchanged as we postulate an elastic scattering, then the $N^*$ will have the same value of these quantum numbers as the incident proton. In particular the isotopic spin of the isobar must be 1/2. The spin and parity of the isobar may however change (as can be seen experimentally from the fact that the isobars produced in reaction (2) can have different spins and different parity from that of the proton).

(c) The scattered pion may or may not interact with $N_A$ to produce an isobar. Hence, one expects there to be an appreciable background below the isobar peak and one expects this background to be constant with respect to variation of the incoming momentum.

(d) The production of the isobar and the background should both be of a peripheral nature with a differential cross section similar to that for $\pi$-p elastic scattering.

(e) If in reaction (7.1), the $N^*$ produced has $T = \frac{3}{2}$, then the model discussed here does not apply and the cross section may be expected to decrease with incident energies, with the normal exponent, 1.5, as described in chapter VI.

In general, the experimental results of Cocconi et al. (39) and Anderson et al. (38) seem to agree with these predictions except that, as shown in Table II, the slope of the $d\sigma/dt$ distribution for the production of $N^*(1400)$ is different from those of the other $T = \frac{1}{2}$ isobars. It may, however, be noted that only the $N^*(1400)$ has the same spin and parity as has the proton.
Reactions such as (7.1) can proceed by other mechanisms, e.g. pion exchange, and the cross section for such mechanisms may be expected to decrease as shown in Chapter VI. Thus it may be expected that the cross section for reactions such as (7.1) will initially decrease with momentum and only become constant at higher energies.

The interaction mechanism described in Fig. 38a or 39 can be applied to other incoming particles such as π or K-mesons, antiprotons or gammas, i.e., to the reactions:

\[
\begin{align*}
\pi + p & \rightarrow \pi + N^x \quad (7.2) \\
K + p & \rightarrow K + N^x \quad (7.3) \\
p + \bar{p} & \rightarrow p + \bar{N}^x \quad (7.4) \\
p + \bar{p} & \rightarrow N^x + \bar{p} \quad (7.5)
\end{align*}
\]

where \( N^x \) and \( \bar{N}^x \) have \( T = \frac{1}{2} \), or to the reactions:

\[
\begin{align*}
\pi + p & \rightarrow p + A \quad (7.6)
\end{align*}
\]

where A is a resonance with \( T = 1 \) which has a \( \pi \rho \) decay mode e.g. \( A_1, A_2 \). Also if there exists a \( (\pi\pi^0) \) resonance, P say, with \( T = 1 \), then the reaction:

\[
\begin{align*}
\pi + p & \rightarrow p + P \quad (7.7)
\end{align*}
\]

may also be considered.

\[
\begin{align*}
K + p & \rightarrow p + L \quad (7.8)
\end{align*}
\]

where L may be taken as a general name for \((K\pi\pi)\) resonances with \( T = \frac{1}{2} \) which decay into \( K^\pm \pi \) and/or \( K\rho \). One may extend reaction (7.8) further to include possible resonances of \( K^\pm(1400) \) \( \pi \) or \( K\pi^0 \).

\[
\begin{align*}
\gamma + p & \rightarrow p + \rho \quad (7.9)
\end{align*}
\]

Similarly for the reaction \( \gamma\rho \rightarrow p\pi^0 \).

The Feynmann diagrams corresponding to reactions (7.2) and (7.3) are the same as that of Fig. 38a, but with the proton at the bottom vertex replaced by a \( \pi \) (or \( K \)) meson. The Feynmann diagrams corresponding to
reactions (7.4), (7.6), (7.7) and (7.9) are shown in Figs. 38b, 38c, 38d and 38g respectively, while that for the reaction (7.8) is shown in Fig. 38e and 38f. Other variations can be imagined, e.g. in Fig. 38c, one could consider the \( \pi \) and \( p \) being interchanged so that the \( p \) undergoes the diffraction scattering on the proton.

In all these reactions (7.1) to (7.9), it is required that the resonance produced has the same isospin as that of the corresponding incident particle. It is then predicted that the cross section will be approximately constant with incident momentum, and that there will be an appreciable background under this resonance which will also be approximately constant with the incident momentum. For reactions (7.2), (7.3), (7.4) and (7.5) there are insufficient data to test this prediction, but it may be noted that the reaction \( pp \rightarrow N\bar{N}\pi \) varies little with incoming momentum over the range 3 to 6.9 GeV/c, unlike other 3-body reactions. The cross section for the production of the \( A_1 \) and \( A_2 \) mesons which have the same isospin as the \( \pi \)-meson, is approximately constant over the range 4 to 11 GeV/c\(^{(45)}\), though it should be noted that the background is difficult to determine. The resonance in the \((K\pi\pi)\) system from reaction (7.8) observed near 1320\(^{(46)(47)(48)}\) and 1800 MeV\(^{(48)}\) are believed to have \( T = \frac{1}{2} \) as has the \( K \)-meson.

For reaction (7.7), it may be noted that the Aachen - Berlin - CERN collaboration observed \(^{(5)}\) with 8 GeV/c positive pions that if in the reaction where \( f^0 \) decays into \( \pi^+\pi^- \) or \( \pi^0\pi^0 \) one excludes events having a (\( p \pi^+ \)) effective mass in the \( N^{*}_{3,3} \) mass region (1.12 to 1.34 GeV), then a peak is observed in the \((\pi^+f^0)\) mass spectrum near 1650 MeV. The present experimental data are not sufficient to establish whether this peak is a resonance or a kinematic effect. The photnuclear reaction (7.9) is found \(^{(50)}\) to have a constant cross section \(^{(51)}\), whereas the cross section for other photnuclear reactions such as \( \gamma p \rightarrow N^{*}\pi \) and \( \gamma p \rightarrow p\omega \), which cannot be simply interpreted as having a diffraction scatter at one vertex, are found to decrease rapidly with increasing gamma momentum \(^{(50)}\).
In general, charge cannot be exchanged in the type of reactions considered here (group I of Chapter VI). If charge is exchanged, the reaction is of the second group and the cross section will decrease rapidly with energy. Thus at sufficiently high energy one reaction will have a larger cross section than the similar reaction with charge exchange. For example with 10 GeV/c K^- mesons, reaction (7.5) is observed (48) with frequent production of L-mesons of mass 1320 and 1790 MeV, but in the reaction

$$K^- + p \rightarrow n + K^0 + \pi^+ + \pi^- \quad (7.10)$$

no peak is observed in the (Knp)\(^0\) effective mass distribution near 1320 or near 1790 MeV, and the number of events is much smaller as is shown in Fig. 40.

In the experimental results of reaction (7.1), there is a smooth background on which are superimposed peaks which correspond to isobars. Here it is suggested that these isobars are not produced directly but only in final state interactions. If there were no isobars to form, then there would be no peaks (other than the broad maximum due to the background).

Deck (52) and Maor and O'Halloran (53) have used the idea of a diffraction scattering at one vertex to calculate the background to reaction (7.6) and suggest that the A\(_1\) is not a resonance but only the maximum in this background. Here we consider in addition a final state interaction, so that the A\(_1\) (and A\(_2\)) are resonances whose production cross section in reaction (7.6) is enhanced by the special consequences of a diffraction scattering occurring at one vertex. The A\(_1\) (and A\(_2\)) can also be produced directly with \(\rho\)-meson exchange, but then the cross-section would be expected to fall with an exponent \(n = 1.5\) as described in the previous chapter. Maor and O'Halloran (53) also consider the production of the B-meson in the reaction:

$$\pi + p \rightarrow p + B \rightarrow p + \pi + \omega \quad (7.11)$$
to be due to a kinematic effect. However, this process, shown in Fig.28h, does not involve a diffraction scatter at one vertex and hence it is not considered in this context. We would expect the cross section for reaction (7.11) to decrease with increasing momentum with an exponent $n \approx 1.5$ as described in chapter V1(54).

We have discussed a diffraction-like mechanism that gives an approximately constant cross section of a few hundred microbarns to certain reactions at high momenta. It is, however, important to note that these reactions can proceed also by normal meson-exchange process, e.g. the reaction $p p \rightarrow p n^-$ can proceed by pion exchange. At low momenta, a few GeV/c, the meson exchange processes will dominate with cross sections of the order of a millibarn, but as these cross sections decrease with an exponent of 1.5 to 2.0, as described in Chapter 6, at higher momenta the cross section for meson exchange processes will be less than that for the diffraction-like mechanism. Thus for reactions which can proceed by a diffraction-like mechanism, the cross section is expected to rise quickly from the threshold, then in the region of a few GeV/c, to decrease according to a power law of the momentum with exponent about 1.5 or 2.0, and then to flatten off in the region of 5 to 10 GeV/c and finally to be constant at higher momenta.

CONCLUSIONS

Although a beginning has been made to the study of two-body reactions at intermediate and high energies, it is clear that a great deal more data is required. The most outstanding problems are probably:

1. to understand the values of the slopes $A$, of differential cross section distributions,

2. to combine the advantages of the Regge Pole Model and of the Absorption Model in one Theory.

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44) The manner in which spin and parity change is not altogether clear, though it appears that when the spin changes by one unit, the parity changes also. Thus the isobars of mass 1400, 1520, 1690 and 2190 MeV studied by Anderson et al.(36) have probable \( J^P \) assignments of 1/2\(^+\), 3/2\(^-\), 5/2\(^+\) and 7/2\(^-\) (note that there exists another isobar of mass 1690 MeV with \( J^P = 5/2^- \)). Similarly the \( A \)-mesons would be expected to belong to the series 0\(^-\), 1\(^+\), 2\(^-\)… The \( A_1 \) is believed to be 1\(^+\), but it will be interesting to discover whether the \( A_2 \)-meson has \( J^P = 2^+ \) or 2\(^-\).

45) The cross sections for \( \pi^+ p \rightarrow p A_1 \rightarrow p \pi^+ \pi^- \) are 0.1 mb with 4 GeV/c \( \pi^+ \) \((23)\), 0.12 \( \pm \) 0.02 with 8 GeV/c \( \pi^+ \) \((11)\) and 0.12 \( \pm \) 0.02 with 11 GeV/c \( \pi^- \) \((6)\) while for reaction \( \pi^+ p \rightarrow p A_2 \rightarrow p \pi^+ \pi^- \), the cross sections are 0.25 mb with 4 GeV/c \( \pi^+ \) \((23)\), 0.115 \( \pm \) 0.02 with 8 GeV/c \( \pi^+ \) \((11)\) and 0.15 \( \pm \) 0.02 with 11 GeV/c \( \pi^- \) \((6)\).


49) The $(\pi^0 \pi^0)$ decay mode is observed as a peak at 1250 MeV in the mass spectrum of the neutral system in the reaction $\pi^+ p \rightarrow p + \pi^+ +$ neutrals.


51) S.M. Berman and S.D. Drell, Phys. Rev. 137, B 791 (1964) have calculated that the cross section for reaction (7,9) decreases slowly with increasing momentum, but a different process is assumed.


54) Experimentally the B-meson is clearly observed at 3.2 GeV/c but much less at 4.2 GeV/c\(^{(a)}\) while with 8 GeV/c \(\pi^+\), the production cross section is less than 21 \(\mu b\)\(^{(b)}\). (a) R.I. Hess et al., Int. Conf. on High Energy Physics, Dubna (1964). (b) ref. (7).
FIGURE CAPTIONS

Fig. 1 Variation of reaction cross sections with the total c.m. energy in \( K^+ - \) proton interactions.

Fig. 2 Variation of the total inelastic and of quasi-two-body cross sections with total c.m. energy in \( K^+ - \) proton interactions.

Fig. 3 (a) Plot of the \( (pA^+) \) effective mass against the \( (\pi^+ p^-) \) effective mass in the reaction \( \pi^+ p \rightarrow p A^+ p^- \) where \( |t| \) of \( (pA^+) \) is smaller than the \( |t| \) for \( (pB^+) \). (b) \( (pA^+) \) effective mass distribution for smaller \( |t| \). (c) \( (\pi^+ p^-) \) effective mass distribution for smaller \( |t| \).

Fig. 4 Chew-Low plot of the \( (\pi^+ \pi^-) \) effective mass against the \( t \) of the \( (\pi^+ \pi^-) \) system for the reaction \( \pi^+ p \rightarrow p \pi^+ \pi^- \) when the other \( \pi^+ \) lies in the \( N^+ \) mass region (1.12 to 1.34 GeV).

Fig. 5 Plot of the \( d \sigma / dt \) distribution against \( t' = t - t_{\text{minimum}} \) for the \( (\pi^+ \pi^-) \) system produced by (a) 6 GeV/c \( \pi^- \) in Freon \( C_2F_3Br \), (b) 16 GeV/c \( \pi^- \) in Freon \( C_2F_5Cl \), (c) 15 GeV/c \( \pi^- \) in Pb. The experimental curves are fitted by the sum of 2 exponentials.

Fig. 6 Plot of the number of events against \(-t\) in various \( K^+ - p \) interactions at 3.0, 3.5 and 5.0 GeV/c. The slope, \( \alpha \), of the distribution is given in each case.

Fig. 7 Plots of differential cross section against \(-t\) for the reactions \( \pi^+ p \rightarrow pp \) and \( \pi^+ p \rightarrow N^+ p^0 \) at 8 GeV/c. The curves drawn are calculated from the Absorption Model.

Fig. 8 Plots of differential cross section against \(-t\) for the reactions \( \pi^+ p \rightarrow N^{\pi^+} \pi^0 \), \( \pi^+ p \rightarrow p A_2 \) and \( \pi^+ p \rightarrow N^\omega \) at 8 GeV/c. The curves drawn are calculated from the Absorption Model.

Fig. 9 Plots of differential cross section against \(-t\) for the reactions \( \pi^+ p \rightarrow N^{\pi^+} K^0 \) at the various momentum indicated. The curves are from Regge Pole Model calculations by Thews.¹⁸

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Fig. 10 Plots of the differential cross section against $-t$ for the $\pi^+ p$ reactions indicated. The curves are Absorption model predictions.

Fig. 11 (a) Differential cross section for the reaction $\pi^- p \rightarrow \pi^0 n$, (b) Total cross section integrated over the forward peak ($0 < |t| < 0.5$) and second peak ($0.5 < |t| < 1.5$ (GeV/c)$^2$).

Fig. 12 $\pi^+ p$ elastic scattering differential cross section at 4 and 8 GeV/c.

Fig. 13 Chew-Low plot of the $(\pi^+ \pi^0)$ effective mass against the $t$ of the $(\pi^+ \pi^0)$ system for the reaction $\pi^+ p \rightarrow p \pi^+ \pi^0$ at 8 GeV/c. The curve drawn corresponds to a $\cos \theta_{cm}$ value of the $(\pi^+ \pi^0)$ of $-0.8$.

Fig. 14 Number of events observed in the reactions $\pi^+ p \rightarrow N^* p$ and $\pi^+ p \rightarrow p\rho$ at 8 GeV/c plotted against $\cos \theta_{cm}$ of the $N^{*+}$ and proton system respectively. Also shown is the corresponding $t$-value.

Fig. 15 Number of events as a function of $t^2$ (i.e., $-t$) for the reactions of 4 GeV/c $\pi^+$ on protons, (a) $\pi^+ p \rightarrow \pi^+ p$, (b) $\pi^+ p \rightarrow p\rho$, (c) $\pi^+ p \rightarrow N^* \pi^0$, (d) $\pi^+ p \rightarrow N^* \rho^0$, (e) $\pi^+ p \rightarrow N^* \omega$ and (f) $\pi^+ p \rightarrow p A_2$.

Fig. 16 Differential cross sections versus $-t$, for $K^- p$ reactions at 3.0 and 3.5 GeV/c where the outgoing particles are $\Sigma^+ \pi^-$, $\Sigma^+ \rho^-$, $\Xi^{++}, \Xi^{+} \pi^-, \Lambda \pi^0, \Lambda \omega^0$ and $\Lambda \phi$.

Fig. 17 Differential cross sections versus the cosine of the angle of the $\Lambda^0$ in cm, for the reactions $K^- p \rightarrow \Lambda \omega$ and $K^- p \rightarrow \Lambda \phi$ at 3.0 GeV/c. The Feynmann diagrams assume baryon exchange for backwards scattering.

Fig. 18 For the reactions $K^- p \rightarrow \Sigma^+ \pi^-$ and $K^- p \rightarrow \Sigma^- \pi^+$ at 3.5 GeV/c, number of events versus the cosine of the angle of the $\Sigma$ in the cm.
Fig. 19 Differential cross sections versus $-t$, for $K^-p$ interactions at 3.0 and 3.5 GeV/c where the outgoing particles are $\Sigma^+\pi^-$, $\Sigma^-K^+$ and $\Xi^-K^+$. 

Fig. 20 Variation of cross section with incident momentum for the reactions $\pi^-p \rightarrow p \pi^+$ and $K^-p \rightarrow p K^\pm$. 

Fig. 21 Variation of cross section with incident momentum for the reactions $K^-p \rightarrow \Lambda\pi^0$, $K^-p \rightarrow \Lambda\omega$, $K^-p \rightarrow \Sigma^+\pi^-$, and $K^-p \rightarrow \Sigma^+\pi^-$. 

Fig. 22 Variation of cross section with incident momentum for the reactions (a) $\pi^-p \rightarrow \pi^0n$, $K^-p \rightarrow K^0n$, $\bar{p}p \rightarrow \bar{m}n$ (b) $\pi^-p \rightarrow \pi^0n$, (c) $\pi^-p \rightarrow \pi^0\eta$, $\pi^+p \rightarrow \eta\pi^0$, $\pi^+p \rightarrow N^0\pi^0$, (d) $\pi^-p \rightarrow \eta\pi^0$, $K^+p \rightarrow K^-\pi^0$, (e) $\pi^-p \rightarrow N^0\pi^0 \rightarrow p\pi^0\pi^0$, (f) $K^-p \rightarrow \Lambda\pi^0$, $K^-p \rightarrow \Lambda\omega$, $K^-p \rightarrow \Sigma^-\pi^+$, $K^-p \rightarrow \Sigma^+\pi^-$, (g) $\pi^+p \rightarrow \Sigma^+K^+$, $\pi^-p \rightarrow \Sigma^0K^0$, (h) $\pi^-p \rightarrow \Sigma^+K^+$, $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, $\bar{p}p \rightarrow \Sigma^0\Lambda^0 + \bar{\Lambda}\Sigma^0$, $\pi^-p \rightarrow \Sigma^+\pi^-p \rightarrow N^0\rho^0$, $K^+p \rightarrow N^0\pi^0$. 

Fig. 23 Variation of cross section with incident momentum for $\pi^-p \rightarrow \pi^0n$ $K^-p \rightarrow K^0n$, $\bar{p}p \rightarrow \bar{m}n$, $np \rightarrow pn$. 

Fig. 24, 25, 26, 27, 28 and 29 are enlargements of figures 22b, c, e, g, h and i respectively. 

Fig. 30 (a)(b)(c), Variation of cross section with incident momentum for (a) $K^-p \rightarrow \Sigma^+\pi^-$ and $K^-p \rightarrow \Sigma^-\pi^+$, (b) $K^-p \rightarrow \Xi^0\pi^+$ and $K^-p \rightarrow \Xi^+\pi^-$, (c) $K^-p \rightarrow \Sigma^+\pi^-$, $K^-p \rightarrow \Xi^-\pi^+$, $K^-p \rightarrow \Xi^-K^+$. (d) Differential cross section at 180° for the elastic reaction $\pi^-p \rightarrow p\pi^-$, versus incident momentum. 

Figures 31, 32, 33 and 34 are enlargements of figures 30a, b, c and d respectively.
Fig. 35 Cross section versus incident momentum for the reaction \( p p \rightarrow p N^\pm \) where \( N^\pm \) is (a) 1.24 GeV, (b) 1.40, (c) 1.52, (d) 1.69, (e) 2.19 GeV isobar.

Fig. 36 Number of reactions versus exponent, \( n \), from fit of \( \sigma \propto \text{const.} p_{\text{in}}^{-n} \) for reactions of the type (a) Elastic-like (b) having non-strange meson exchange (c) having strange meson exchange (d) having baryon exchange.

Fig. 37 Total production cross section for \( \Xi^- \), \( \Omega^- \) and \( \Lambda \) particles as a function of the incident momentum.

Fig. 38 Feynmann diagrams as discussed in the text for the reactions
(a) \( pp \rightarrow p N^\pm \) (b) \( \bar{p} p \rightarrow \bar{N}^\pm p \) (c) \( \pi p \rightarrow p A \)
(d) \( \pi p \rightarrow p F \rightarrow p f^0 \pi^+ \) (e) \( K p \rightarrow p L \rightarrow p K \pi \pi \)
(f) \( K p \rightarrow p L \rightarrow p K \pi \pi \) (g) \( \gamma p \rightarrow p p \) (h) \( \pi p \rightarrow p \Xi \rightarrow p \omega \pi \).

Fig. 39 Diagram for the reaction \( pp \rightarrow p N^\pm \), as explained in text.

Fig. 40 (K\pi\pi) effective mass distributions for (a) Sum of reactions \( K^- p \rightarrow p K^- \pi^+ \pi^- \) (with events having a \( p \pi^+ \) mass in the \( N^\pm \) region -1.12 to 1.34 GeV - excluded) and \( K^- p \rightarrow p K^0 \pi^- \pi^0 \) where the \( K^0 \) is observed, (b) \( K^- p \rightarrow n K^0 \pi^+ \pi^- \) where the \( K^0 \) is observed. This in 10 GeV/c \( K^- p \) interactions, with the restriction |t| of proton < 0.6 (GeV/c)^2.
TABLE CAPTIONS

Table 1 Variation of the slope of differential cross section distributions for small $|t|$ values, $|t| \leq 0.3 \text{ (GeV/c)}^2$.

Table 2 Values of the slope for reactions averaged over the momentum range given. The slope is taken over the $t$-range from the kinematic limit to about $0.3$ to $0.4 \text{ (GeV/c)}^2$, except for the three reactions involving $\eta$ or $\omega$- meson production when the $t$-range from $0.2$ to $0.5 \text{ (GeV/c)}^2$ was taken (to avoid spin-flip effects). Also for the charge exchange reaction, $np \rightarrow pn$, values for small $|t|$ ($|t| < 0.02 \text{ (GeV/c)}^2$) and for large $|t|$ ($0.15 < |t| < 0.5 \text{ (GeV/c)}^2$) are given.

Table 3 Values of the density matrix elements found from the reaction $K^+ p \rightarrow K^{*0} N^{++}$ at $5 \text{ GeV/c}$ \textsuperscript{(4)} and for the reaction $\pi^+ p \rightarrow \rho^0 N^{++}$ at $4 \text{ GeV/c}$ \textsuperscript{(22)} and $8 \text{ GeV/c}$ \textsuperscript{(21)} and also the absorption model calculation for this latter reaction at $8 \text{ GeV/c}$.

Table 4 Values of the constant $K$, and exponent $n$ obtained by fitting the cross sections for the reactions listed over the momentum range listed to the formula (6.1). The cross section at $3 \text{ GeV/c}$ is also calculated from the fit of formula to the experimental values.
### TABLE I

<table>
<thead>
<tr>
<th>INCIDENT MOMENTUM, GeV/c</th>
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<td>SLOPE FOR $\bar{p}p \rightarrow N^+N^-$, (GeV/c)$^{-2}$</td>
<td>$5.4^{+0.4}_{-0.4}$</td>
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<tr>
<td>SLOPE FOR ELASTIC SCATT, (GeV/c)$^{-2}$</td>
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### TABLE II

<table>
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<th>SLOPE (GeV/c)$^{-2}$</th>
<th>REACTION</th>
<th>MOMENTUM GeV/c</th>
<th>SLOPE (GeV/c)$^{-2}$</th>
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<td>$K^- p \rightarrow K^0 n$</td>
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<td>5</td>
<td>$\pi^+ p \rightarrow p \rho^+$</td>
<td>8 - 11</td>
<td>9</td>
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<tr>
<td>$\bar{p} p \rightarrow n n$</td>
<td>7</td>
<td>4</td>
<td>$\pi^- p \rightarrow N^0 p$</td>
<td>8 - 11</td>
<td>9</td>
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<tr>
<td>$n p \rightarrow p n$ (Large t)</td>
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<td>5</td>
<td>$\pi^- p \rightarrow n \pi^0$</td>
<td>6 - 18</td>
<td>11</td>
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<td>$\pi^- p \rightarrow n \eta$</td>
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<td>$\pi^+ p \rightarrow N^0 p^0$</td>
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<td>14</td>
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<td>5</td>
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<td>10 - 30</td>
<td>6</td>
<td>$K^+ p \rightarrow K^0 N^\pm$</td>
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<td>11</td>
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<td>$p p \rightarrow p N^\pm_{1690}$</td>
<td>10 - 30</td>
<td>6</td>
<td>$p p \rightarrow p N^\pm_{1238}$</td>
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<td>17</td>
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<td>$p p \rightarrow p N^\pm_{2190}$</td>
<td>10 - 30</td>
<td>6</td>
<td>$p p \rightarrow p N^\pm_{1400}$</td>
<td>10 - 30</td>
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<td>$0.77 \pm 0.04$ 4 GeV/c EXP.</td>
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<td>$-0.06 \pm 0.03$</td>
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<td>$0.05 \pm 0.03$</td>
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<td></td>
<td>$-0.076 \pm 0.033$</td>
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<td>( M_{\text{GeV/c}} )</td>
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<td>( \text{Max} )</td>
<td>( \text{Constant, K.} )</td>
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<td>( - )</td>
<td>( - )</td>
<td>( - )</td>
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<td>( 1.5^{+0.2}_{-0.1} )</td>
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<td>( \pi^- + p \rightarrow A_1^{\pi^+\pi^-} )</td>
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<td>( 1.5^{+0.5}_{-0.2} )</td>
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<td>( 1.5^{+0.2}_{-0.2} )</td>
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<td>( 5.0 )</td>
<td>( 6.3^{+7.7}_{-3.5} )</td>
<td>( 1.8^{+0.6}_{-0.2} )</td>
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<td>( K^- + p \rightarrow p + K^- \rightarrow p K^0 )</td>
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<td>( 10.1 )</td>
<td>( 6.4^{+4.5}_{-2.6} )</td>
<td>( 1.9^{+0.5}_{-0.2} )</td>
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<tr>
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<td>----------------------------------------------</td>
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| 20  | $\pi^+ + p \rightarrow N^\ast + \pi \rightarrow p + \pi^0$ | $4.0$  
|     |                                              | $8.0$  
|     |                                              | $1.2^{+1.7}_{-0.7}$  
|     |                                              | $1.3^{+0.6}_{-0.3}$  
|     |                                              | $0.30^{+0.39}_{-0.17}$  
| 21  | $K^+ + p \rightarrow N^\ast + K^0$          | $1.73$  
|     |                                              | $5.0$  
|     |                                              | $5.3^{+0.6}_{-0.4}$  
|     |                                              | $1.8^{+0.2}_{-0.3}$  
|     |                                              | $0.78^{+0.06}_{-0.05}$  
| 22  | $p + p \rightarrow p + N^\ast(1238)$        | $6$  
|     |                                              | $15$  
|     |                                              | $7^{+}_{-2}$  
|     |                                              | $1.3^{+0.6}_{-0.3}$  
|     |                                              | $0.90^{+1.9}_{-0.61}$  
| 23  | $\pi^- + p \rightarrow \Lambda + K^0 or \Sigma^0 + K^0$ | $3.0$  
|     |                                              | $4.65$  
|     |                                              | $1.3^{+5.0}_{-1.0}$  
|     |                                              | $1.6^{+1.4}_{-0.8}$  
|     |                                              | $0.23^{+0.87}_{-0.18}$  
| 24  | $\pi^- + p \rightarrow \Sigma^+ + K^+$       | $2.08$  
|     |                                              | $8.0$  
|     |                                              | $1.0^{+1.2}_{-0.6}$  
|     |                                              | $2.1^{+0.5}_{-0.3}$  
|     |                                              | $0.10^{+0.13}_{-0.05}$  
| 25  | $\pi^- + p \rightarrow \Sigma^+(1385) + K^+$ | $2.08$  
|     |                                              | $8.0$  
|     |                                              | $0.8^{+0.6}_{-0.3}$  
|     |                                              | $2.6^{+0.5}_{-0.3}$  
|     |                                              | $0.04^{+0.04}_{-0.02}$  
| 26  | $K^- + p \rightarrow \Lambda + \pi^0$        | $2.24$  
|     |                                              | $10.1$  
|     |                                              | $1.2^{+1.0}_{-0.6}$  
|     |                                              | $1.9^{+0.3}_{-0.2}$  
|     |                                              | $0.15^{+0.14}_{-0.07}$  
| 27  | $K^- + p \rightarrow \Lambda + \omega$       | $2.24$  
|     |                                              | $10.1$  
|     |                                              | $3.1^{+2.4}_{-1.1}$  
|     |                                              | $2.8^{+0.3}_{-0.2}$  
|     |                                              | $0.14^{+0.04}_{-0.03}$  
| 28  | $K^- + p \rightarrow \Sigma^+ + \pi^-$       | $2.24$  
|     |                                              | $3.5$  
|     |                                              | $2.2^{+2.4}_{-1.1}$  
|     |                                              | $2.6^{+0.5}_{-0.3}$  
|     |                                              | $0.24^{+0.26}_{-0.13}$  
| 29  | $K^- + p \rightarrow \Sigma^+(1385) + \pi^-$ | $2.24$  
|     |                                              | $10.1$  
|     |                                              | $1.2^{+1.0}_{-0.5}$  
|     |                                              | $2.2^{+0.25}_{-0.15}$  
|     |                                              | $0.11^{+0.09}_{-0.05}$  
| 30  | $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda$ | $3.0$  
|     |                                              | $6.94$  
|     |                                              | $0.9^{+1.0}_{-0.5}$  
|     |                                              | $1.9^{+0.3}_{-0.2}$  
|     |                                              | $0.11^{+0.12}_{-0.06}$  
| 31  | $\bar{p} + p \rightarrow \Lambda \Sigma^0 or \Lambda \Sigma^0$ | $3.0$  
|     |                                              | $6.94$  
|     |                                              | $0.6^{+0.8}_{-0.4}$  
|     |                                              | $1.8^{+0.4}_{-0.2}$  
|     |                                              | $0.09^{+0.12}_{-0.05}$  
| 32  | $\pi^+ + p \rightarrow N^\ast + \rho^0$     | $\bar{3.0}$  
|     |                                              | $6.94$  
|     |                                              | $0.6^{+0.8}_{-0.4}$  
|     |                                              | $1.8^{+0.4}_{-0.2}$  
|     |                                              | $0.09^{+0.12}_{-0.05}$  
| 33  | $\pi^- + p \rightarrow N^\ast + \rho^0$     | $\bar{3.0}$  
|     |                                              | $6.94$  
|     |                                              | $0.6^{+0.8}_{-0.4}$  
|     |                                              | $1.8^{+0.4}_{-0.2}$  
|     |                                              | $0.09^{+0.12}_{-0.05}$  
| 34  | $K^+ + p \rightarrow N^\ast + K^*$           | $\bar{2.24}$  
|     |                                              | $3.5$  
|     |                                              | $1.9^{+2.4}_{-1.1}$  
|     |                                              | $3.8^{+0.8}_{-0.4}$  
|     |                                              | $0.28^{+0.07}_{-0.05}$  
| 35  | $K^+ + p \rightarrow \Sigma^- + \pi^0$       | $\bar{2.24}$  
|     |                                              | $3.5$  
|     |                                              | $1.9^{+2.4}_{-1.1}$  
|     |                                              | $3.8^{+0.8}_{-0.4}$  
|     |                                              | $0.28^{+0.07}_{-0.05}$  
| 36  | $K^+ + p \rightarrow \Sigma^- + \pi^-$       | $\bar{2.24}$  
|     |                                              | $3.5$  
|     |                                              | $1.9^{+2.4}_{-1.1}$  
|     |                                              | $3.8^{+0.8}_{-0.4}$  
|     |                                              | $0.28^{+0.07}_{-0.05}$  
| 37  | $K^+ + p \rightarrow \Sigma^- + K^+$          | $\bar{2.24}$  
|     |                                              | $3.5$  
|     |                                              | $1.9^{+2.4}_{-1.1}$  
|     |                                              | $3.8^{+0.8}_{-0.4}$  
|     |                                              | $0.28^{+0.07}_{-0.05}$  
| 38  | $(\pi^- + p \rightarrow p + \pi^-)_{180^0}$ | $\bar{2.24}$  
|     |                                              | $3.5$  
|     |                                              | $1.9^{+2.4}_{-1.1}$  
|     |                                              | $3.8^{+0.8}_{-0.4}$  
|     |                                              | $0.28^{+0.07}_{-0.05}$  

PS/5579/mk
FIG. 1

$P_K \text{ GeV/c}$

$K^+p$ inelastic and quasi two body reactions.

$\sigma$ inel.

$\sigma (K^*N + K N^* + K^* N^*)$

$E_{c.m.} \text{ (GeV)}$

$b$

$K^{*0} N^{*++}$
$K^{*+} N^{*+}$

$K^* N^{*++}$
$K^+ N^{*+}$
$K^{*+}p$

threshold
\[ \pi^+ p \rightarrow p \pi^+_A \pi^+_B \pi^- \]

**FIG. 3**

At 8 GeV/c

**SMALLER \( |t| \) COMBINATION OF (\( p\pi^+ \)) SELECTED**

(a) 

(b) 

N\(^*_3,3\) 

(c) 

\( \rho \)

\( f^0 \)

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$\pi^+ p \rightarrow (N^*) \pi^+_B \pi^-_B \rightarrow p \pi^+_A \pi^+_B \pi^-_B$ AT 8 GeV/c

CHEW-LOW PLOT FOR ($\pi^+_B \pi^-_B$)

$(\pi^+_B \pi^-_B)$ EFF. MASS, GeV.

$t$, $(\text{GeV/c})^2$.

FIG. 4
FIG. 5

$\frac{d\sigma}{dt}$, ARBITRARY SCALE

$T^1 = T - T_{MIN}$, (GeV)$^2$

- 6 GeV/c $\pi^-\pi^+\pi^- C_2 F_3 Br$
  (a)

- 16 GeV/c $\pi^-\pi^+\pi^- C_2 F_5 Cl$
  (b)

- 15 GeV/c $\pi^-\pi^+\pi^- Pb$
  (c)
FIG. 9

$\pi^+ p \rightarrow N^{*+} \pi^+$

- 2.75 GeV (a)
- 3.5 GeV (b)
- 4.0 GeV (c)
- 8.0 GeV (d)

$K^- p \rightarrow N^{***} K^+$

- 3.0 GeV (a)
- 3.5 GeV (b)
- 5.0 GeV (c)
FIG. 10

π⁺-p INTERACTIONS AT 8 GeV/c

— ABSORPTION MODEL CALCULATION —
Differential cross sections for $p^+p^+\to\pi^0\pi^0$. The MIT-Prov results at 10 GeV/c are from ref. 1. The broken lines are smooth lines through the results of ref. 3.

**FIG. 11**

Total cross sections over the forward and the second peak versus pion laboratory momentum.
$\pi^+ p \rightarrow \pi^+ p$ at 8 GeV/c

FIG. 12

$\frac{d\sigma}{dt}$ vs $t, (GeV/c)^2$

$\cos \theta^*$

4 GeV/c

8 GeV/c
\( \pi^+ p \rightarrow \pi^0 \pi^0 \) AT 8 GeV/c

\[ -t, (\text{GeV/c})^2 \text{ FOR } (\pi^0 \pi^0) \]

\[ \cos \theta = -0.8 \]
FIG. 15

π⁺p INTERACTIONS AT 4 GeV/c

(a) pπ⁺

(b) pρ⁺

(c) N⁹⁺⁺⁺⁺ ᵃ°

(d) N⁹⁺⁺⁺⁺ ᵃ°

(e) N⁺⁺⁺⁺ ᵃ°

(f) pA₂⁺
FIG. 19

Graphs showing the cross sections for various decay processes, labeled as

- $K^0 \rightarrow \Xi^+ \eta^1$
- $K^0 \rightarrow \eta \eta^2$
- $K^0 \rightarrow \Sigma^+ \Lambda^*$
- $K^0 \rightarrow \Sigma^0 \Lambda^*$
- $K^0 \rightarrow \Xi^0 \eta^1$
- $K^0 \rightarrow \Xi^1 \eta^2$
- $K^0 \rightarrow \Xi^0 \Lambda^*$
- $K^0 \rightarrow \Xi^1 \Lambda^*$

Each graph plots the differential cross section in units of $\text{pb/(GeV)}^2$ versus the square of the momentum transfer in units of $(\text{GeV}/c)^2$. The data are represented by plus signs with error bars.
FIG. 20

CROSS SECTION, mb

\[ \pi^+ p \rightarrow p \rho^+ \]
\[ \pi^- p \rightarrow p \rho^- \]
\[ K^+ p \rightarrow p K^{*+} \rightarrow p K^0 \pi^+ \]
\[ K^- p \rightarrow p K^{*-} \rightarrow p K^0 \pi^- \]

INCIDENT LAB. MOMENTUM, GeV/c
FIG. 21

CROSS SECTION, mb

\[ K^- p \rightarrow \Lambda \pi^0 \]
\[ K^- p \rightarrow \Lambda \omega \]
\[ K^- p \rightarrow \Sigma^+ \pi^- \]
\[ K^- p \rightarrow \gamma^*_{1385} \pi^- \]

INCIDENT LAB. MOMENTUM, GeV/c
FIG. 23

CROSS SECTION, mb

\[ \pi^- p \rightarrow \pi^0 n \]
\[ K^- p \rightarrow K^0 n \]
\[ \bar{p} p \rightarrow \bar{n} n \]
\[ n p \rightarrow p n \]

INCIDENT LAB. MOMENTUM, GeV/c
**FIG. 26**

CROSS SECTION, mb

\[ \begin{align*}
\pi^+ p &\rightarrow N^{*+} \pi^0 \rightarrow p \pi^+ \pi^0 \\
\pi^+ p &\rightarrow N^{*+} \pi^+ \rightarrow p \pi^+ \pi^0 \\
K^+ p &\rightarrow N^{*+} K^0 \\
p p &\rightarrow N^{*+} p
\end{align*} \]
\[ \pi^+ p \rightarrow \Sigma^+ K^+ \]
\[ \pi^+ p \rightarrow \Upsilon^{++}_{1385} K^+ \]
\[ \pi^- p \rightarrow (\Lambda K^0 + \Sigma^0 K^+) \]
\( \pi^+ p \rightarrow \Sigma^+ K^+ \)
\( \phi p \bar{p} \rightarrow \Lambda \bar{\Lambda} \)
\( \Lambda p \bar{p} \rightarrow \Lambda \bar{\Sigma}^0 + \Sigma^0 \bar{\Lambda} \)
FIG. 29

CROSS SECTION, mb

\( \pi^+ p \rightarrow N^{*++} \rho^0 \)

\( \pi^- p \rightarrow N^{*0} \rho^0 \)

\( K^+ p \rightarrow N^{*++} K^{*0} \)

INCIDENT LAB. MOMENTUM, GeV/c
FIG. 31

CROSS SECTION, mb.

\[ K^- p \rightarrow \Sigma^+ \pi^- \]

\[ K^- p \rightarrow \Sigma^- \pi^+ \]

INCIDENT LAB. MOMENTUM, GeV/c
FIG. 33

\[ K^- p \rightarrow \Sigma^- \pi^+ \]
\[ K^- p \rightarrow \Sigma^+ \pi^- \]
\[ K^- p \rightarrow \Xi^- \bar{K}^+ \]

CROSS SECTION, mb

INCIDENT LAB. MOMENTUM
\[ \left( \frac{d\sigma}{dt} \right)_{180^\circ} = 7.3 \left( \frac{p_{\text{IN}}}{p_0} \right)^{-4.0} \]

FIG. 34

\(
\pi^- p \rightarrow p\pi^- 
\)

\( (d\sigma/dt)_{180^\circ}, \text{ mb/(GeV)}^2 \)

\( \text{INCIDENT LAB. MOMENTUM, GeV/c} \)
FIG. 36

a) ELASTIC-LIKE

b) NON-STRANGE MESON EXCHANGE

c) STRANGE MESON EXCHANGE

d) BARYON EXCHANGE

NUMBER OF REACTIONS

EXPONENT, n
TOTAL PRODUCTION CROSS SECTIONS
FOR $\Xi^-$, $\Omega^-$ AND $\bar{\Lambda}$ PARTICLES

- $\pi^- p \rightarrow \Xi^-$
- $\pi^+ p \rightarrow \Xi^-$
- $K^- p \rightarrow \Omega^-$
- $\pi^- p \rightarrow \bar{\Lambda}$
- $\pi^+ p \rightarrow \bar{\Lambda}$
\[ K^- p \rightarrow p (K \pi \pi)^- \]

AT 10 GeV/c

\[ |t| < 0.6 \text{ (GeV/c)}^2 \]

(a)

\[ K^- p \rightarrow n (K \pi^+ \pi^-)^0 \]

AT 10 GeV/c

\[ |t| < 0.6 \text{ (GeV/c)}^2 \]

(b)

(K\pi\pi) EFF. MASS, GeV.