

Session 12

HADRON COLLISIONS AT VERY HIGH ENERGIES

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L. Van Hove, Rapporteur

We shall review a number of recent results and developments concerning hadron collisions, mostly selected among contributions submitted to this Conference. We are mainly concerned with the high energy region $p_{\text{lab}} \geq 4$ or 5 GeV/c, although lower energy collisions will be mentioned occasionally. A systematic review of experimental results, prepared by Dr. A. M. Wetherell, is included in these Proceedings as an Appendix to this paper. The contents of this report are arranged as follows:

- I. Two-body collisions at low momentum transfers
 1. Pion-proton forward collisions
 - a. Real part of the forward elastic scattering amplitude
 - b. $d\sigma/dt$ for $\pi^\pm p$ elastic scattering
 - c. Polarization in $\pi^\pm p$ elastic scattering
 - d. Polarization in $\pi^- p \rightarrow \pi^0 n$
 - e. Other two-body processes in πp collisions
 2. Pion-proton backward scattering
 3. Kaon-proton collisions
 - a. Elastic scattering
 - b. Charge-exchange process $K^- p \rightarrow K^0 n$
 - c. Other two-body processes in Kp collisions
 4. Nucleon-nucleon and antinucleon-nucleon collisions
 - a. Total cross sections and forward elastic scattering amplitude
 - b. Elastic scattering
 - c. Charge-exchange scattering
 5. Isobar excitation and diffraction dissociation
- II. Large-angle scattering
 1. New experimental results
 2. Theoretical aspects
- III. Multiple production of particles
 1. Multiplicity distribution of pions
 2. Correlations
- IV. Theoretical developments
 1. Quark model and associated methods
 2. Regge pole theory
 - a. Parity exchange
 - b. General masses and spins
- V. Concluding remarks

Sections I to III present new experimental data, comments on earlier data, and theoretical considerations directly concerned with the reactions discussed. The more general theoretical developments are grouped in Section IV. Section V mentions a few of the outstanding problems which can be expected to attract considerable attention in the coming years.

I. Two-Body Collisions at Low Momentum Transfers1. Pion-Proton Forward Collisionsa. Real part of the forward elastic scattering amplitude

A Dubna group¹ presented new values of

$$a = \frac{\text{Re}A(s, 0)}{\text{Im}A(s, 0)},$$

the ratio of real to imaginary parts of the scattering amplitude $A(s, t)$ at $t = 0$, for $\pi^\pm p$ at two energies.

They are $a = -0.18 \pm 0.06$ at $p_{\text{lab}} = 3.5$ GeV/c,

$$a = -0.14 \begin{cases} +0.11 \\ -0.10 \end{cases} \text{ at } p_{\text{lab}} = 6.1 \text{ GeV/c.}$$

Figure 12-1, from Barashenkov's contribution,² shows the predicted values of a_\pm for $\pi^\pm p$, as calculated from the forward dispersion relations (lower curves). The new values are fully compatible with the prediction for a . One should note the well-known discrepancies between the high energy experimental values³ of a_\pm and the calculated curves, especially their reversed order ($a_+ > a_-$ experimentally). If this trend were confirmed considerable complications would have to be expected in the theoretical interpretation of the data.^{2, 4}

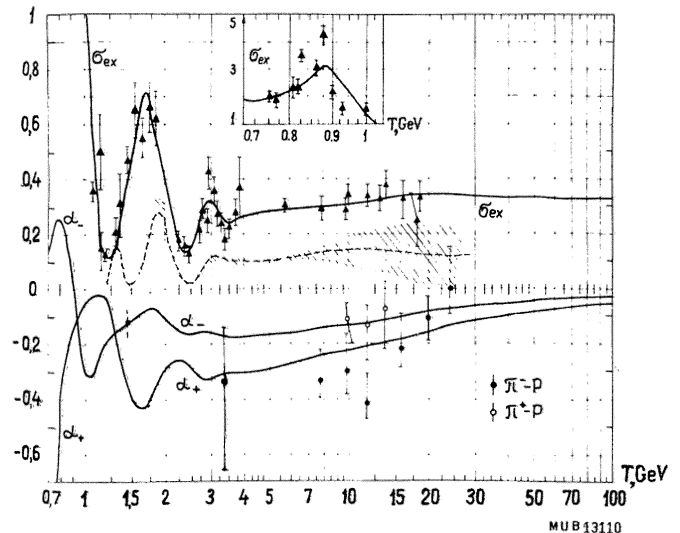


Fig. 12-1. A comparison of the energy dependence of the $\pi^- p$ charge-exchange cross section (σ_{ex}) and of a^\pm (the ratio of real to imaginary part of the forward scattering amplitude in $\pi^\pm p$ scattering) with the predictions of forward dispersion relations as obtained by V. Barashenkov (Ref. 2). The dashed line represents the values of $(\sigma_{\text{ex}})_{\text{minimum}}$, assuming zero real amplitude, and the hatched area shows the inaccuracies due to errors in total-cross-section measurements.

b. $d\sigma/dt$ for $\pi^\pm p$ elastic scattering

New data of a Michigan group for $\pi^\pm p$ from 2.3 to 4.0 GeV/c are reproduced in Fig. 12-2.⁵ They show a dip or shoulder around $t \approx -0.6$ (BeV/c)². As illustrated by the solid lines on the figure, its position coincides closely with the dip of $d\sigma/dt$ for the charge-exchange process $\pi^- p \rightarrow \pi^0 n$. The latter has been successfully explained⁶ in the Regge pole model as being due to vanishing of the spin-flip amplitude for the value of t where the ρ trajectory $\alpha_\rho(t)$ vanishes ("nonsense transition, unphysical signature";⁶ remember that α_ρ is the only Regge trajectory supposed to contribute to $\pi^- p \rightarrow \pi^0 n$).

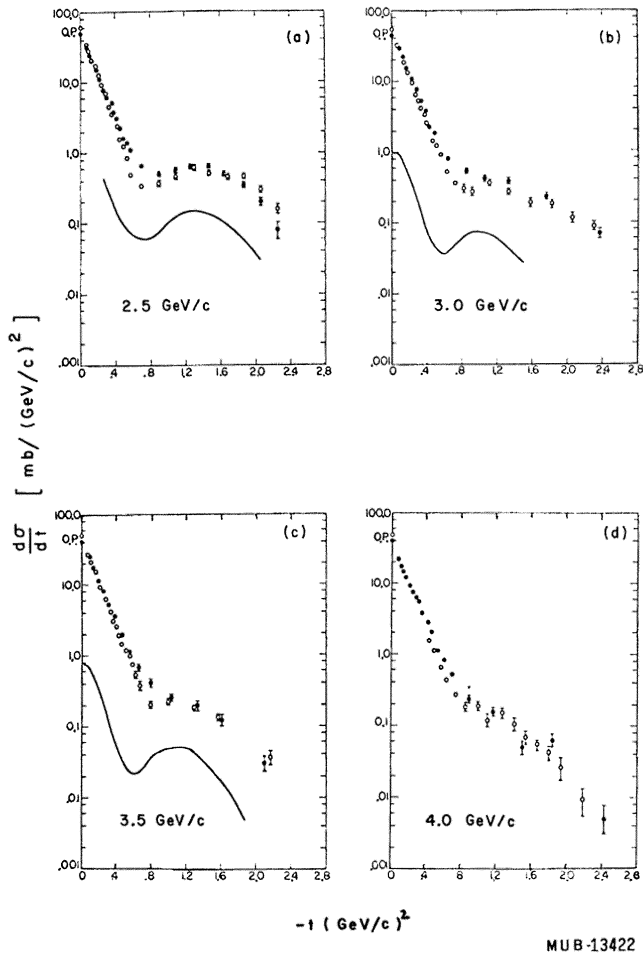


Fig. 12-2. Comparison of π^+p and π^-p elastic-scattering differential cross sections at laboratory-system momenta of 2.5, 3.0, 3.5, and 4.0 GeV/c by Coffin et al. (Ref. 5). Also shown is a freehand fit to the π^-p charge exchange in the same momentum region.
 ● $\pi^+p \rightarrow \pi^+p$, this experiment
 ○ $\pi^-p \rightarrow \pi^-p$, this experiment
 Solid curve, $\pi^-p \rightarrow \pi^0n$:
 (a) Carroll et al., 2.46 GeV,
 (b) Sonderegger et al., 3.07 GeV,
 (c) Sonderegger et al., 3.67 GeV.

Frautschi proposes⁷ that also trajectories in the even-signature nonet give vanishing spin flip when they verify $\alpha(t) = 0$. Since the P' trajectory $\alpha_{P'}(t)$ probably passes through zero at about the same t as $\alpha_0(t)$, this effect could account for the dip or shoulder of $d\sigma/dt$ in elastic scattering. The structure would rapidly disappear with increasing energy, however, because the Pomernanchuk trajectory $\alpha_P(t)$ does not pass through zero (remember that $\pi^\pm p$ elastic scattering is described in terms of the P , P' , and ρ trajectories with isospins and signatures $0+$, $0+$, and $1-$, respectively).

c. Polarization in $\pi^\pm p$ elastic scattering

Data concerning the polarization parameter

$$P(t) = 2 \operatorname{Im} f g^* / (|f|^2 + |g|^2)$$

have been presented by a CERN group for π^-p at 6, 8, and 10 GeV/c, and for π^+p at 6, 10, and 12 GeV/c.⁸ Part of the data and their Regge pole fit⁹ are given in Figs. 12-3 and 12-4. The π^+p data

agree well with the Regge pole prediction of Chiu et al.,⁹ which were based on the earlier π^-p polarization data. In particular, the prediction is confirmed that the polarization originates mainly from interference between the spin-flip contribution of the ρ trajectory and the non-spin-flip part of the P and P' trajectories; this effect accounts for the reversal of sign of $P(t)$ between π^-p and π^+p and for the vanishing of the polarization around $t = -0.6$ (GeV/c)², where the ρ spin-flip contribution vanishes. At a more detailed level, the absence of marked energy variation of $P(t)$ near its maximum around $t = -0.2$ (GeV/c)², especially for π^-p , should be of some concern. As we shall remark again later on, slow energy variations of this sort, if established with good accuracy, may become indications of effects not accounted for in the Regge pole model.

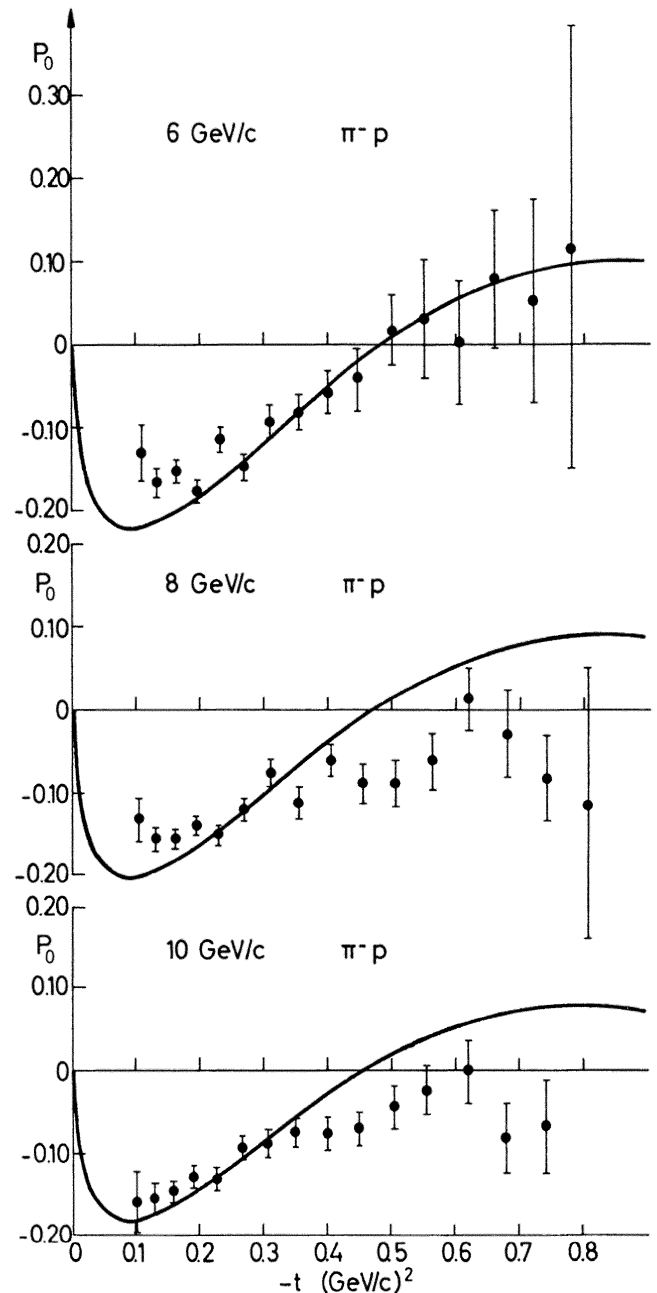
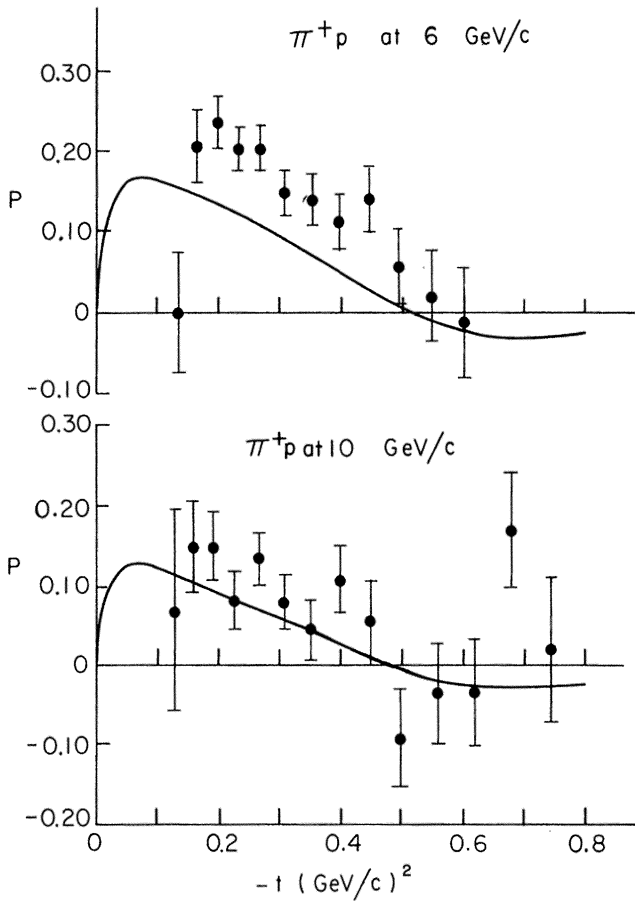


Fig. 12-3. The polarization parameter P_0 versus the invariant four-momentum transfer t for π^-p elastic scattering at laboratory-system momenta of 6, 8, and 10 GeV/c, as given by Borghini et al. (Ref. 8). The theoretical curve is from a fit to the data by Chiu et al. (Ref. 9).



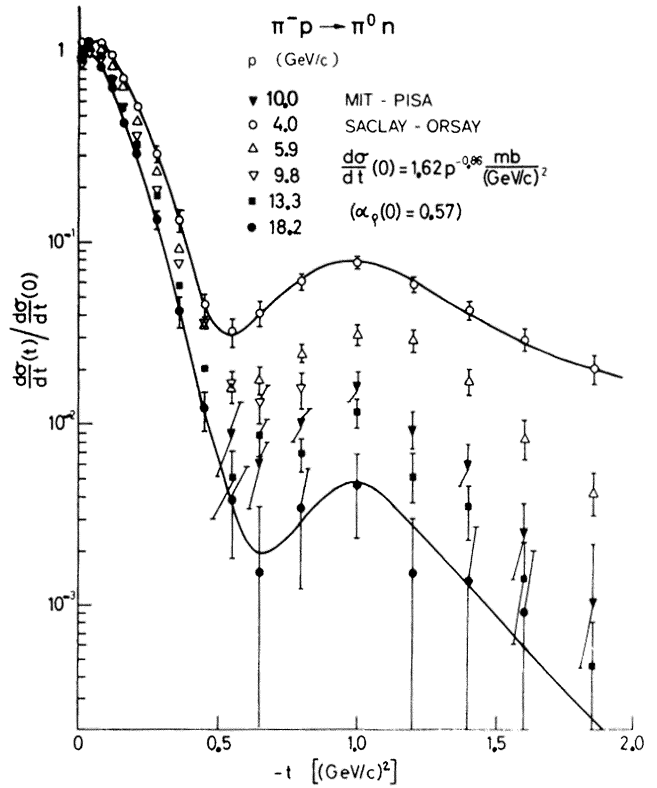
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Fig. 12-4. The polarization parameter P_0 versus the invariant four-momentum transfer t for $\pi^+ p$ elastic scattering at laboratory-system momenta of 6 and 10 GeV/c (Ref. 8). The theoretical curve is a prediction of the polarization by Chiu et al. (Ref. 9) using a Regge pole model.

d. Polarization in $\pi^- p \rightarrow \pi^0 n$

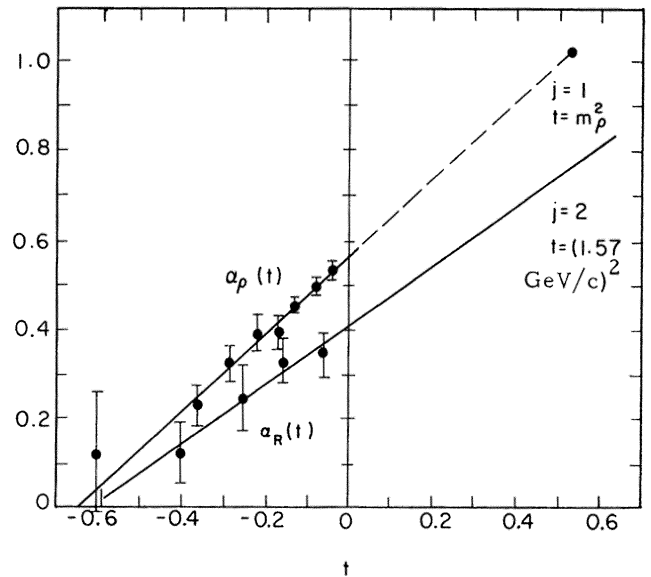
The charge-exchange process $\pi^- p \rightarrow \pi^0 n$ gave the Regge pole model its most striking success by leading to the experimental determination of a linear $\alpha_\rho(t)$ trajectory of slope $\approx 1(\text{GeV}/c)^{-2}$, and by revealing the correctness of the dip mechanism at $t = -0.6(\text{GeV}/c)^2$ mentioned above.⁶ The $d\sigma/dt$ curves are grouped in Fig. 12-5, and the $\alpha_\rho(t)$ trajectory, as well as $\alpha_R(t)$ determined from the sister reaction $\pi^- p \rightarrow \eta n$, are given in Fig. 12-6, taken from a contribution of K. A. Ter-Martirosyan to this Conference.¹⁰ (The R trajectory, of isospin 1 and signature +, is associated with the $A_2(1300)$ meson if the latter is 2^+ .)

The same $\pi^- p \rightarrow \pi^0 n$ reaction now faces the Regge pole model with a new test, and requires inclusion of further corrections, especially at 6 GeV/c. Recent data of a Saclay-Orsay-Pisa Collaboration,¹¹ given in Fig. 12-7 show that the polarization parameter $P(t)$ is as large as about 15% at 6 GeV/c, and that it may remain of the same order up to 11 GeV/c, although the 11-GeV/c results are not accurate enough in their present form to allow drawing any definite conclusion. One finds, for $P(t)$ averaged over two t intervals [p_{lab} in GeV/c, t in $(\text{GeV}/c)^2$] the values shown at the right:



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Fig. 12-5. The $\pi^- p$ charge-exchange differential cross section at various laboratory-system momenta. The leads to experimental data can be found in Refs. 6 and 97.



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Fig. 12-6. The ρ and R trajectories as determined by Ter-Martirosyan (Ref. 10) using a Regge pole fit to $\pi^- p \rightarrow \pi^0 n$ and $\pi^- p \rightarrow \eta n$ experimental data.

t interval	$0.015 \leq -t \leq 0.24$	$0.04 \leq -t \leq 0.24$
$p_{\text{lab}} = 6$	$+0.14 \pm 0.03$	$+0.16 \pm 0.03$
$p_{\text{lab}} = 11$	$+0.19 \pm 0.06$	$+0.24 \pm 0.07$

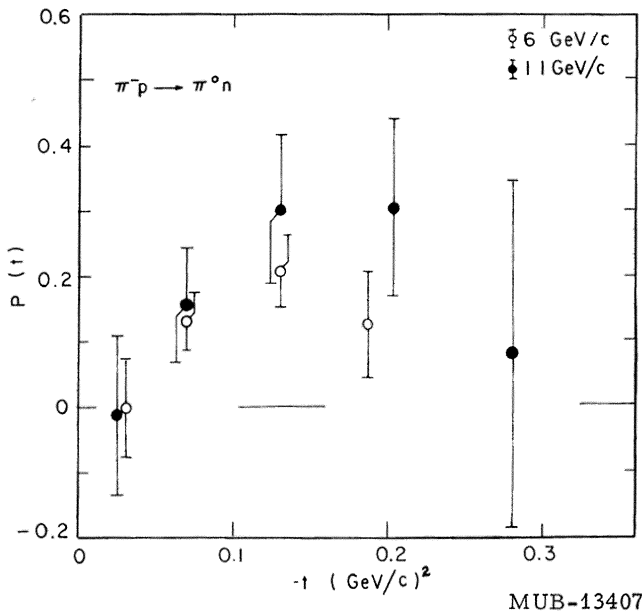


Fig. 12-7. The polarization $P(t)$ in π^-p charge-exchange scattering as measured by Bonamy et al. (Ref. 11) using a polarized target.

The Regge pole model is known to predict vanishing $P(t)$ on the basis of the ρ trajectory alone. To account for the data at 6 GeV/c various authors have introduced contributions of s-channel resonances¹²⁻¹⁴ or an additional Regge pole ρ' with the same quantum numbers as ρ .^{15,16} In all cases $P(t)$ is predicted to drop by at least a factor 2 from 6 to 11 GeV/c.

Although the experimental errors of the very recent 11 GeV/c data are still too large to reveal the energy variation of $P(t)$, one may soon be led to discuss possible mechanisms explaining an eventual weak energy dependence of the $\pi^-p \rightarrow \pi^0n$ polarization. One can envisage a small difference between the powers $s^{\alpha(t)}$, $s^{\alpha_1(t)}$ describing the energy variation of the spin-flip and non-spin-flip amplitudes (such an effect, although impossible in the Regge pole model, is very natural in the coherent-droplet model of Yang and Byers, a point recently studied by Le Bellac¹⁷); or one can complete Regge pole theory with additional singularities close to $\alpha_\rho(t)$, for which the Mandelstam cuts would probably be the most popular candidates. One would hope that these modifications would not affect too much the description of $d\sigma/dt$ for $\pi^-p \rightarrow \pi^0n$, and of $d\sigma/dt$ and $P(t)$ for $\pi^\pm p \rightarrow \pi^\pm p$. One should face, nevertheless, reasonable requirements of consistency, and acknowledge that if a Mandelstam cut associated with the ρ trajectory is important in $\pi^-p \rightarrow \pi^0n$, the same may be true in $\pi^\pm p \rightarrow \pi^\pm p$, at least for the cut associated with the Pomernanchuk trajectory, so that this cut may profoundly affect the P' trajectory contribution.

e. Other two-body processes in πp collisions

All other two-body processes $\pi^\pm p \rightarrow AB$ (A and B being each a particle or a resonance) are of interest for a complete analysis of the high energy behavior of πp collisions. We quoted already $\pi^-p \rightarrow \eta n$,¹⁸ which allows determination of the R

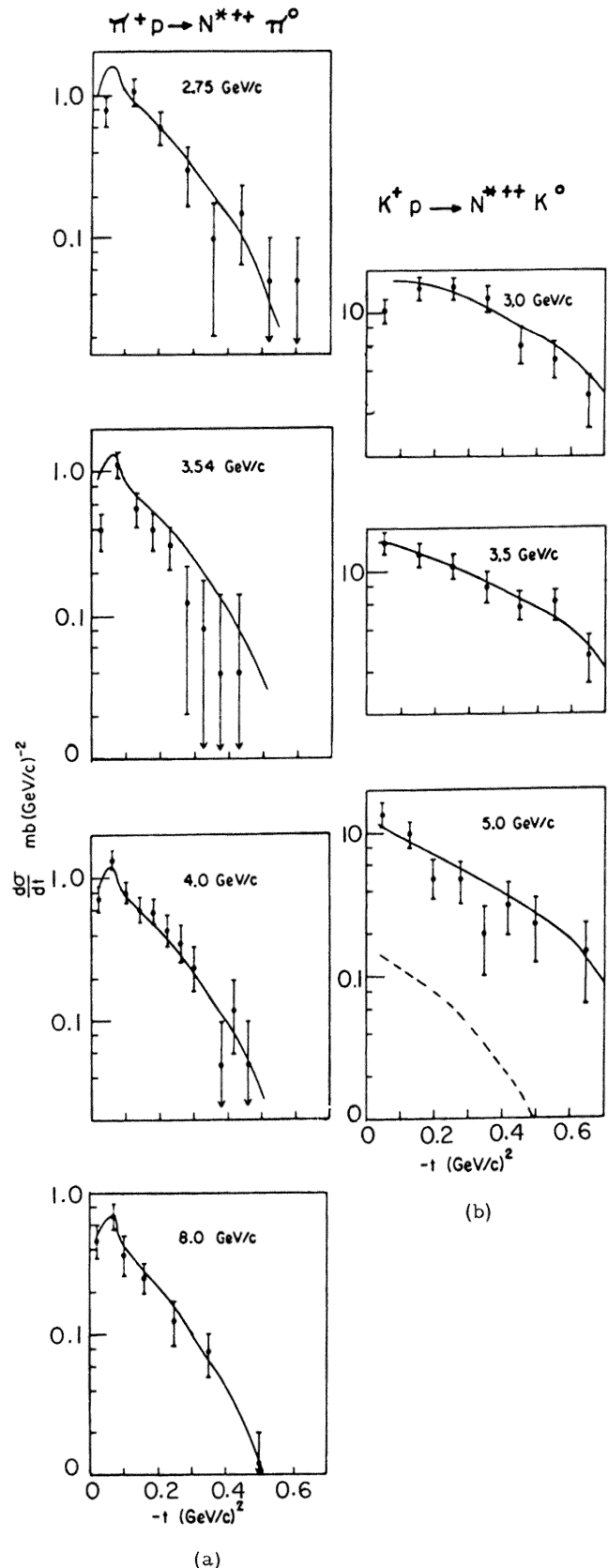


Fig. 12-8. Regge-pole fit to the experimental data for (a) $\pi^+p \rightarrow \pi^0 N^{*++}(1238)$ and (b) $K^+p \rightarrow K^0 N^{*++}(1238)$. The fit was made by R. I. Thews (Ref. 19), assuming a Regge ρ contribution for Reaction (a) and a Regge ρ and R contribution for Reaction (b).

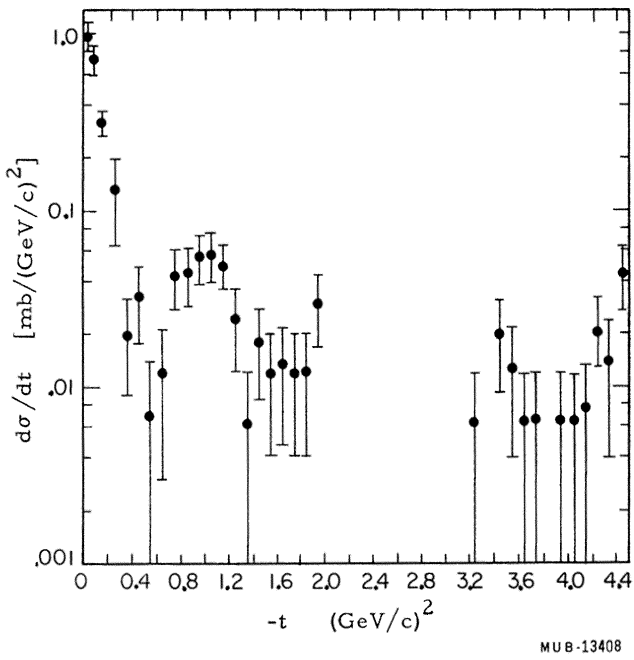


Fig. 12-9. The differential cross section for $\pi^+p \rightarrow \Sigma^+K^+$ for a laboratory-system momentum of 3.23 GeV/c measured by Kofler et al. (Ref. 20). Here t is the momentum transfer from p to Σ . Measurements based on 225 events.

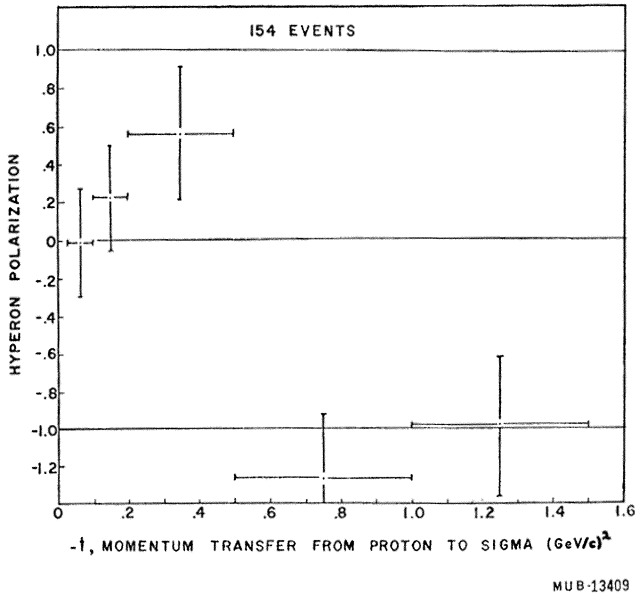


Fig. 12-10. The Σ^+ polarization as a function of t for the reaction $\pi^+p \rightarrow \Sigma^+K^+$ at 3.23 GeV/c, as measured by Kofler et al. (Ref. 20). Measurements based on 154 events.

trajectory. As shown by Thews and illustrated by the curves in Fig. 12-8, reaction $\pi^+p \rightarrow \pi^0N^{*++}$ can be fitted with the ρ trajectory, and $K^+p \rightarrow K^0N^{*++}$ by the ρ and R trajectories.¹⁹ A Wisconsin group presented data on $\pi^+p \rightarrow K^+\Sigma^+$ at 3.23 GeV/c;²⁰ the differential cross section is shown in Fig. 12-9, whereas Fig. 12-10 gives the Σ^+ polarization. The dip of $d\sigma/dt$ near $t \approx -0.6$ (GeV/c)² and the change of sign of the polarization in the same region are of particular interest, because the relevant Regge trajectories belonging to $K^*(890$ MeV, signature $\tau = -$)

and to $K^*(1410$ MeV, $\tau = +$) are likely to vanish around $t \approx -0.6$.

Many other $\pi p \rightarrow AB$ reactions have been studied, and information is available to some extent on $d\sigma/dt$ and on its energy variation. This material has recently been reviewed by Morrison¹⁹ and is discussed in Jackson's report at this Conference. We shall limit ourselves to two comments. Firstly, the undeniable success of the peripheral model with absorption for the processes which experimentally seem to be dominated by π exchange (e.g., $\pi p \rightarrow \rho p$) should be accommodated in the Regge pole approach to high energy scattering (it should be kept in mind that higher trajectories can contribute--e.g., the ω and R trajectories). This requires an extension of the Regge pole model to unequal-mass particles and higher spins, a difficult problem to which we shall return in Section IV of this report. Secondly, the s and t dependence of $d\sigma/dt$ for $\pi p \rightarrow AB$ seems often to remain essentially unchanged when A (or B) is replaced by a nonresonant state of two particles A_1, A_2 having an effective mass $m_{\text{eff}}(A_1A_2)$ close to the mass of A. Several experimental groups have fragmentary results pointing in this direction. They should be regarded as preliminary steps in the systematic study of three-body final states, which are very likely to be amenable to a Regge-pole type of analysis. Ter-Martirosyan¹⁰ remarks on the im-

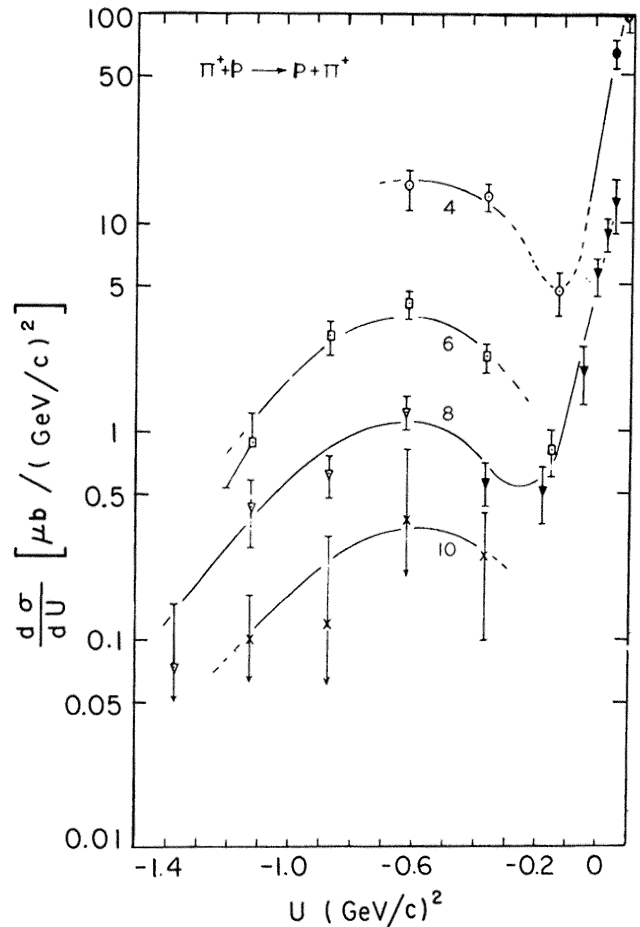


Fig. 12-11. The differential cross section for π^+p elastic scattering near the backward direction. "This experiment" refers to the data of the Pennsylvania group, reported by Selove (Ref. 22). References for other data are also given in Ref. 22. Open symbols, this experiment; solid symbols, Frisken et al.

portance of this problem, which has also been tackled by a theoretical group at CERN.²¹

2. Pion-Proton Backward Scattering

In a contribution to this conference, Selove²² summarized the data on πp elastic scattering near the backward direction, in particular the data of the Cornell-BNL^{23,24} and Pennsylvania groups.²² In addition, very recent data for π^+p in the 2- to 5-GeV range were reported by a Dubna group.²⁵ The Selove summary is presented in Figs. 12-11 (π^+p) and 12-12 (π^-p), where the numbers on the curves denote the laboratory-system momentum, and "this expt" refers to the Pennsylvania group. Although it would be highly desirable to have a single experiment cover, at various energies, the whole range $u \gtrsim -1$ (GeV/c)² [$u = -(\text{four-momentum transfer from incident } \pi \text{ to outgoing } p)^2$], the data are good enough to reveal a remarkable dip around $u = -0.2$ (GeV/c)² in π^+p , no similar structure appearing in π^-p . Furthermore, the qualitative features of the energy variation of $d\sigma/du$ are also apparent.

Two mechanisms are currently invoked to explain πp backward scattering. The first, which is important at not too high energies, considers the effect of s -channel resonances. The relevant baryonic resonances, and their role in backward πp scattering, are treated in a contribution from Barger and Cline.²⁶ These authors group them in three families (Δ_δ , N_α , N_γ) forming remarkably long Regge recurrence series, as shown on Figs. 12-13

and 12-14. [For the two lower members of each family, the spin-parity assignment is known to be correct; some information concerning parity for higher resonances can also be obtained from estimating their contribution to forward $\pi^-p \rightarrow \pi^0n$ scattering¹³ and backward πp elastic scattering.]

At higher energies (perhaps $p_{\text{lab}} \gtrsim 5 \text{ GeV}/c$) the second mechanism for backward scattering is supposed to become dominant. It is the u -channel exchange of the baryonic Regge trajectories $\alpha_\Delta(\sqrt{u})$, $\alpha_N(\sqrt{u})$, $\alpha_{N'}(\sqrt{u})$ of Figs. 12-13 and 12-14 continued to lower u values (we write N for N_α and N' for N_γ). This mechanism is discussed in detail by Chiu and Stack in a contribution to the Conference.²⁷ The situation is complicated by the Gribov phenomenon, according to which, for each value of u , a fermion trajectory $\alpha(\sqrt{u})$ contributes twice, through its values $\alpha(+\sqrt{u})$ and $\alpha(-\sqrt{u})$. [Thus, for $u > 0$, two systems of particles are associated with $\alpha(\sqrt{u})$, one containing particles of mass M such that $\alpha(M) = 1/2, 5/2 \dots$ or $3/2, 7/2 \dots$, and the other containing particles of mass M' such that $\alpha(-M')$ has these values. The particles of mass M, M' have opposite parity. Figures 12-12 and 12-13 show only one such system for each trajectory. If a system contains a particle not found in nature one must assume that the residue of the Regge pole vanishes at the corresponding value of \sqrt{u} ; according to Chiu and Stack this happens for a $1/2^-$ baryon of mass 850 MeV on the N trajectory.] For $u < 0$, the trajectory will give complex conjugate Regge poles $\alpha(\pm i|u|^{1/2})$.

Only α_Δ contributes to backward π^-p scattering, all three trajectories to π^+p . Since $d\sigma/du$ is experimentally smaller for π^-p than for π^+p , and

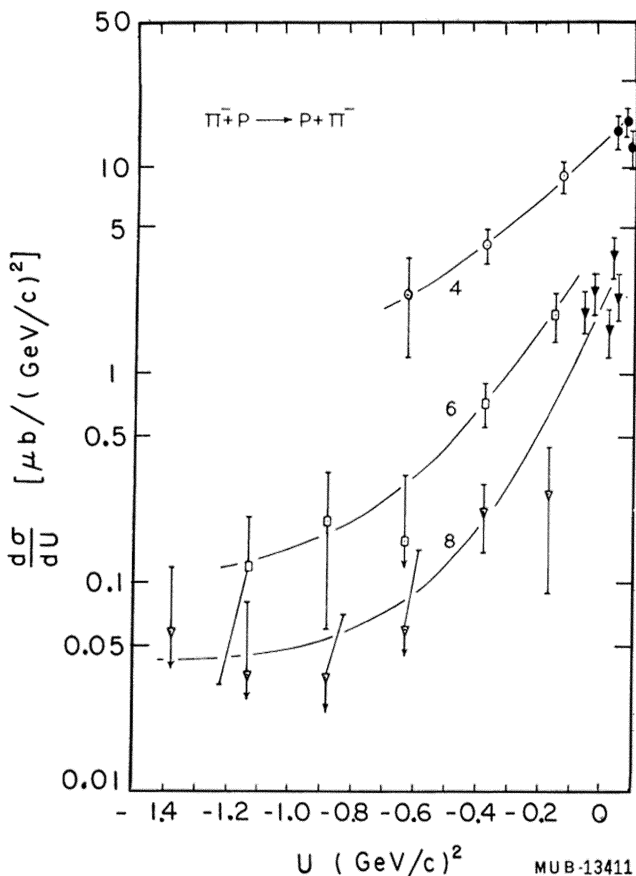


Fig. 12-12. The differential cross section for π^-p elastic scattering near the backward direction. "This experiment" refers to the data of the Pennsylvania group, reported by Selove (Ref. 22). References to other data are also given in Ref. 22. Open symbols, this experiment; solid symbols, Frisken et al.

I = 3/2, Y = +1 Regge Recurrences

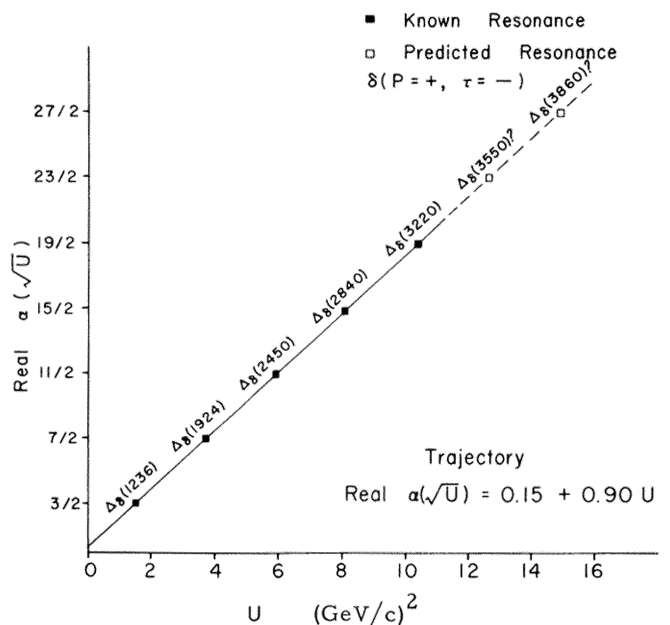


Fig. 12-13. A proposed classification of the known $I = 3/2$ isobars on a Regge trajectory of u versus the isobar spin as suggested by Barger and Cline (Ref. 26). The filled boxes represent experimentally observed isobars, whereas the open boxes represent predicted isobars. Only the two lowest-mass isobars have experimentally determined spin and parity. Analysis of charge-exchange scattering (Ref. 13) and backward π^+p elastic scattering (Ref. 26) suggests positive parity for the 2450 and 2840.

since the a_Δ contribution to π^+p is further reduced by the Clebsch-Gordan coefficient, Chiu and Stack neglect a_Δ altogether in π^+p . [This will have to be revised at higher energies if $a_\Delta(0) > a_N(0) \approx a_{N^*}(0)$, as suggested by Figs. 12-13 and 12-14; the Regge pole theory would then require disappearance of the dip at $u \approx -0.2$ (GeV/c)² for higher energies.] For $a_N(\sqrt{u}) = -1/2$, one has a nonsense transition of unphysical signature, so that the $a_N(\sqrt{u})$ gives vanishing contributions both to spin-flip and non-spin-flip amplitudes. The corresponding value of u is close to -0.2 (GeV/c)², where $d\sigma/du$ for π^+p has its dip. Since a_{N^*} , having opposite signature, would give a nonvanishing contribution in this region, Chiu and Stack suppose that this latter trajectory is coupled very weakly and neglect it also. They are left with a_N as sole contributor to π^+p backward scattering, and obtain a very satisfactory fit of the data, the dip originating from the vanishing of the N-trajectory contribution when $a_N(\sqrt{u}) = -1/2$.

3. Kaon-Proton Scattering

a. Elastic scattering

New data on K^-p elastic scattering have been presented by a Northwestern University-Argonne collaboration at 4.1 and 5.5 GeV/c.²⁸ The diffraction peak is well described by the five-Regge-pole fit of Kp and πp scattering processes due to Phillips and

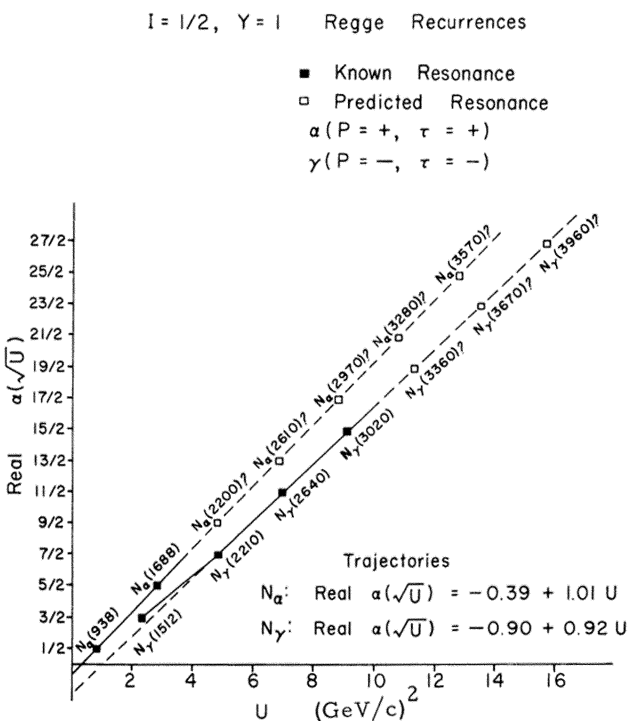


Fig. 12-14. A proposed classification of the high-mass $I = 1/2$ isobars on two Regge trajectories as suggested by Barger and Cline (Ref. 26). The filled boxes represent experimentally observed isobars, whereas the open boxes represent predicted isobars. The two lowest members of each trajectory are known to have the correct spin and parity for the Regge recurrence assignment. Analysis of charge-exchange scattering (Ref. 13) suggests negative parity for the 2640 in accordance with this classification. Analysis of backward π^-p scattering (Ref. 26) also suggests negative parity for the 2640 and the 3020.

Rarita²⁹ (the poles are P, P', R, ρ , and one $I = 0$, odd-signature pole taken for simplicity to replace the ϕ_ω pair). Concerning backward scattering, the authors find an upper bound, $\sigma(\theta_{c.m.} > \pi/2) < 2 \mu\text{b}$ for the backward hemisphere, to be compared to $\sigma(\theta_{c.m.} > \pi/2) \sim 8 \mu\text{b}$ for π^-p at similar energies. This effect, which can be explained by the absence of strangeness 1 baryons, is of course of considerable interest, and a detailed study of $d\sigma/dt$ in the backward hemisphere at various energies would be of great importance as an example of a small-momentum-transfer process for which no known particle or pole is available for exchange.

b. Charge-exchange process $K^-p \rightarrow \bar{K}^0n$

A CERN-ETH (Zürich) collaboration presented new data on $K^-p \rightarrow \bar{K}^0n$ at 5 and 7 GeV/c.³⁰ They are grouped in Fig. 12-15 with the 9.5-GeV/c data obtained earlier by the same authors.³¹ The Regge pole predictions of Phillips and Rarita^{29, 32} are in fair agreement with the data, and the latter will undoubtedly allow an improved adjustment of the Regge

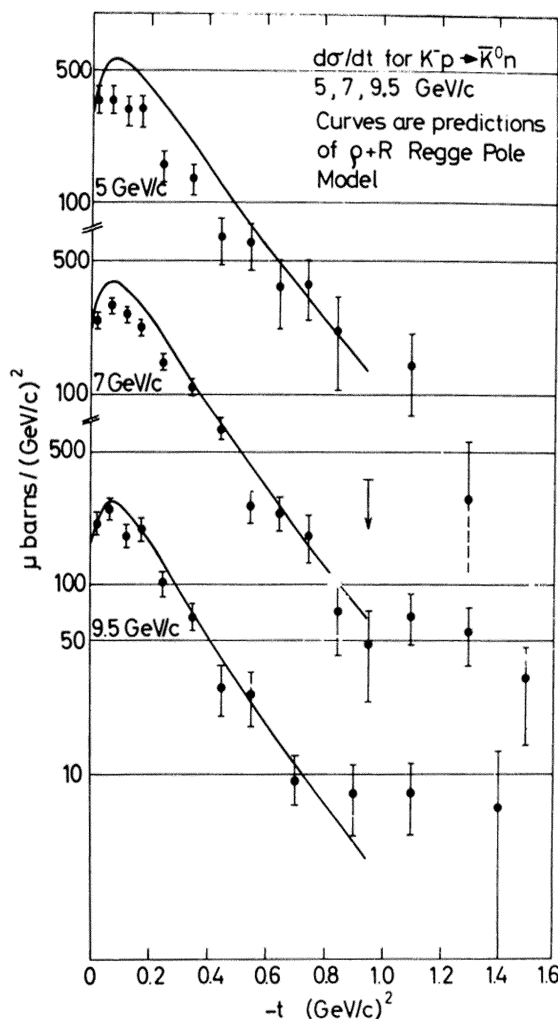


Fig. 12-15. The differential cross section for the reaction $K^-p \rightarrow \bar{K}^0n$ at laboratory-system momenta of 5, 7, and 9.5 GeV/c reported by Astbury et al. (Refs. 30, 31). The theoretical curves are for a Regge-pole model fit by Phillips and Rarita (Ref. 32). In this fit only the 9.5-GeV/c data were used, and therefore the 5- and 7-GeV/c theoretical curves are predictions according to the model.

pole parameters. The data show interesting qualitative features similar to $\pi^-p \rightarrow \pi^0n$; the peak shrinks as the energy increases, and a small dip is present at $t = 0$. There are differences, however. The real part of the amplitude is much smaller than the imaginary one at $t = 0$, due to compensation between ρ and R trajectory contributions. No dip is seen at $t \approx -0.6$ (GeV/c)², a feature which will become of considerable importance if it is confirmed by more accurate measurements.

c. Other two-body processes in Kp collisions

A CERN-Brussels collaboration presented data on a variety of two-body reactions $K^+p \rightarrow AB$, obtained at 3, 3.5, and 5 GeV/c.³³ They observe shrinking peaks and fit them, in oversimplified fashion, with single Regge poles. Although more extensive data and multi-Regge-pole fits are called for, it may be worth noting the interest of this particular set of reactions. Indeed, the absence of s-channel resonances makes it plausible that a Regge-pole analysis will be valid at lower energies than in all other meson-nucleon collisions.

4. Nucleon-Nucleon and Antinucleon-Nucleon Collisions

a. Total cross sections and forward elastic scattering amplitude

A compilation of $\sigma_T(pp)$ and $\sigma_T(pn)$ recently prepared by Wetherell is contained in Fig. 12-16. The inequality $\sigma_T(np) > \sigma_T(pp)$ continues to hold, up to $p_{lab} \approx 19$ GeV/c, but the data suggest that it might be reversed at higher energy. It would be of considerable interest to decide this question by improving the accuracy of the pn data. Since pn scattering data are usually obtained from pd measurements, the whole question of deuteron effects (Glauber correction) is very important, and it would appear desirable to study it for its own sake so as to develop a more accurate description of deuteron effects than is available at present. A number of theoretical investigations of the problem have been carried out recently.³⁴⁻³⁶

Chernev et al. have contributed new data on the

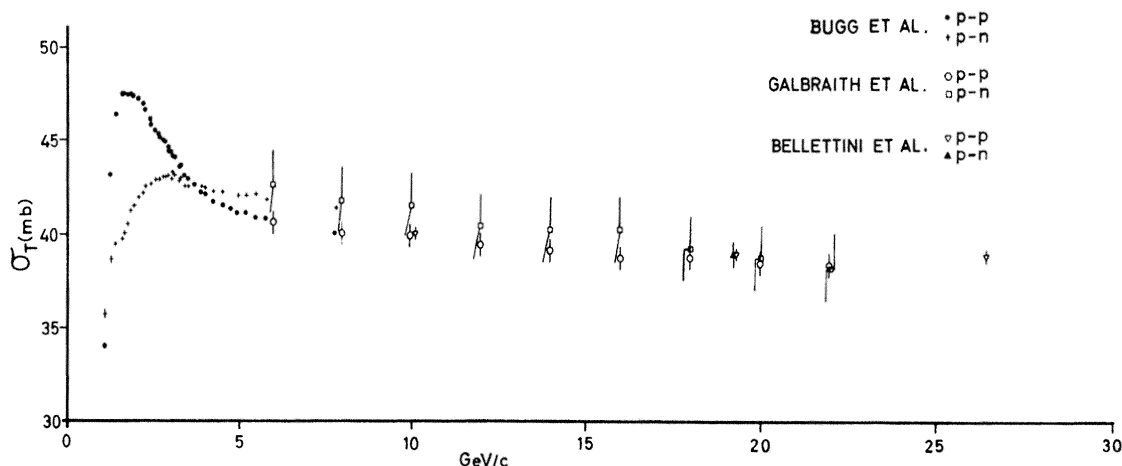


Fig. 12-16. Proton-proton and proton-neutron total cross sections. The errors on the data of Bugg et al. are \leq the size of the points. The data are from D. V. Bugg, D. C. Salter, G. H. Stafford, R. F. George, K. F. Riley, and R. J. Tapper, *Phys. Rev.* **146**, 980 (1966); W. Galbraith, E. W. Jenkins, T. F. Kycia, B. A. Leontic, R. H. Phillips, A. L. Read, and R. Rubinstein, *Phys. Rev.* **138**, B913 (1965); G. Bellettini, G. Cocconi, A. N. Diddens, E. Lillethun, J. Pahl, J. P. Scanlon, J. Walters, A. M. Wetherell, and P. Zanella, *Phys. Letters* **14**, 164 (1965); G. Bellettini, G. Cocconi, A. N. Diddens, E. Lillethun, G. Matthiae, J. P. Scanlon, and A. M. Wetherell, *Phys. Letters* **19**, 341 (1965).

ratio a_{pn} of real to imaginary parts of the forward amplitude for pn scattering from 1 to 10 GeV/c, derived from measurements of a_{pd} .³⁷ All available data are collected in Fig. 12-17, the black dots denoting the new results. The curve is the dispersion-relation prediction of Carter and Bugg,³⁸ the shaded area representing the estimated uncertainties.

It is unfortunate that no data have yet been obtained for the ratio $a_{\bar{p}p}$, a quantity which plays an important role in the high-energy asymptotics of the NN and $\bar{N}N$ systems. This problem is of considerable interest because a_{pp} is known to be of order -0.3 over a large energy range and does not show any tendency to approach zero as $p_{lab} \rightarrow \infty$; $a_{\bar{p}p}$ and a_{pp} are related through crossing symmetry, and information on $a_{\bar{p}p}$ would greatly help the theoretical analysis of the likely asymptotic behavior of both quantities.

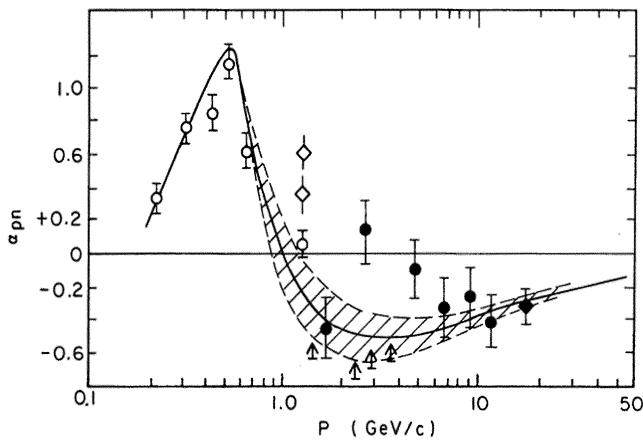
b. Elastic scattering

A Stanford-Michigan group,³⁹ by an interesting method using a neutron beam from the Berkeley Bevatron, carried out extensive measurements on elastic np scattering from 2 to 6 GeV/c. The behavior of $d\sigma/dt$ is found to be very similar to that for pp in the same energy range.

A California Institute of Technology group,⁴⁰ having measured $\bar{p}p$ elastic scattering from 1.0 to 2.5 GeV/c, reports a dip in $d\sigma/dt$ around $t \approx -0.5$ (GeV/c)². Frautschi⁷ connects this phenomenon with the dips in meson-nucleon scattering at similar t values (see Section I. 1. b of this report). It will be very interesting to measure accurately $d\sigma/dt$ in this region at increasing energies. As is known, such dips do not occur in pp scattering.

We mention finally new polarization data for pp scattering at 6 and 10 GeV/c, presented by a CERN group.⁴¹ The polarization is found to be of order 10% for $0.2 \leq -t \leq 0.5$ (GeV/c)² at both energies, but the lower-energy data do not agree with earlier Berkeley work,⁴² which gave an appreciably larger value ($\approx 18\%$). Here again the absence of visible energy variation may have important theoretical implications.

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Fig. 12-17. The ratio of real to imaginary forward scattering amplitude for np elastic scattering. The filled circles represent the data presented by Chernev et al. (Ref. 37). The theoretical curves are dispersion calculations by Carter and Bugg (Ref. 38).

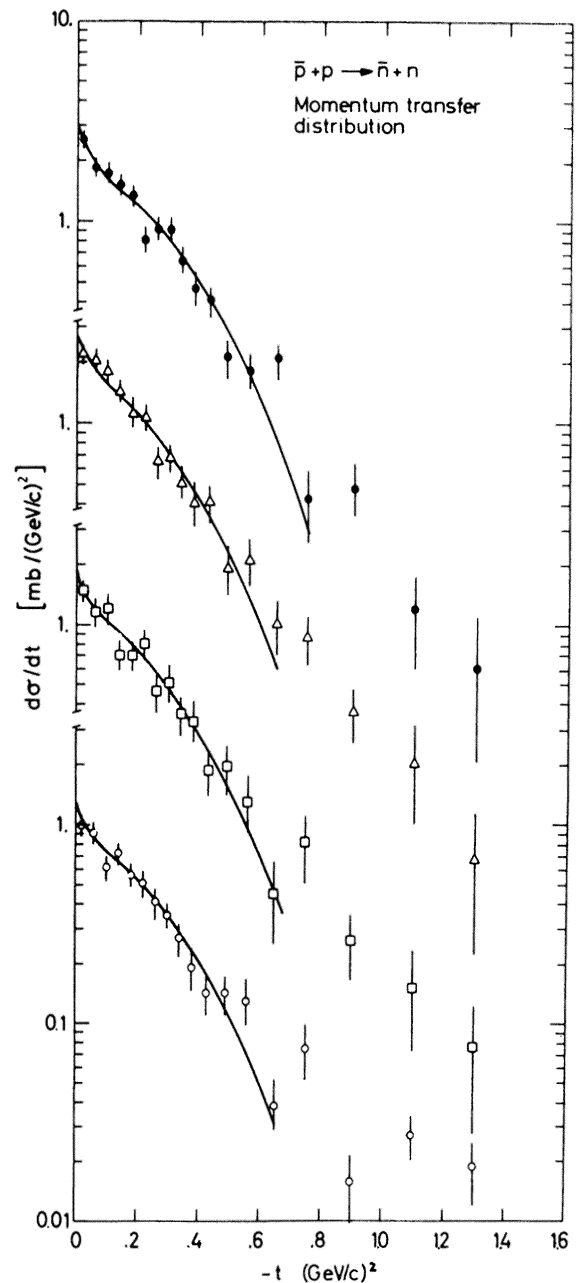
c. Charge-exchange scattering

A CERN-ETH group has measured the charge-exchange process $pp \rightarrow nn$ at 5, 6, 7, and 9 GeV/c.⁴³ The results are presented in Fig. 12-18, where the curves are fits to the coherent-droplet model. A more complete fit to all available np and $\bar{p}p$ charge-exchange data has been carried out by Byers,⁴⁴ who introduces a one-pion-exchange contribution in the coherent-droplet model and is thereby able to reproduce all data, including the very narrow peak in $np \rightarrow pn$ at $|t| \lesssim 0.02$ (GeV/c)².

As is well known, the Regge pole model has been unable so far to account for np and $\bar{p}p$ exchange data. The s dependence of $d\sigma/dt$ for np and $\bar{p}p$ charge exchange at $t = 0$ cannot be fitted with the ρ and R poles. Whereas fits are possible by adding other poles with the same quantum numbers [like the ρ' pole used by Hogaasen et al.^{15, 16} to fit both these charge-exchange processes and the 6-GeV/c polarization data in $\pi^-p \rightarrow \pi^0n$], it seems more natural⁴⁵ to study first the role which would be played by Regge poles belonging to pseudoscalar and axial vector particles, which can couple to nucleons but not to pseudoscalar mesons. As was first recognized by Gribov and Volkov,^{46, 47} the properties of these poles are much more complicated than are properties of those belonging to the 1^- and 2^+ particles, in the sense that their positions and residues at $t = 0$ have to be related to each other in a specified way if the scattering amplitude is to have its most general form without containing unacceptable singularities. This property, which the specialists now refer to as "conspiracy" between Regge poles, has attracted renewed attention recently (see Section IV. 2), but no results have been reported on the use of the pseudoscalar and axial poles for fitting actual NN and $\bar{N}N$ data.

5. Isobar Excitation and Diffraction Dissociation

An extensive study of the process $p + p \rightarrow p + p^*$ by the missing-mass method has been carried out by a BNL-Carnegie Institute of Technology group⁴⁸ in the energy interval 6 to 30 GeV. The excitation of the isobars $N^*(1.23 \text{ GeV}; I = 3/2)$, $N^*(1.52; 1/2)$, $N^*(1.69; 1/2)$ and $N^*(2.19; 1/2)$ is measured as a function of s and t . One observes in addition for small $|t|$ a bump which suggests an isobar $N^*(1.4)$;



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Fig. 12-18. The differential cross section for the reaction $\bar{p}p \rightarrow \bar{n}n$ for the momenta 5, 6, 7, and 9 GeV/c as measured by Astbury et al. (Ref. 43). The theoretical predictions are for the coherent-droplet model. Errors indicated are statistical only. p_{in} (in GeV/c): \bullet 5; Δ 6; \square 7; \circ 9.

the $N\pi$ system with isospin $I = 1/2$ may indeed have a peculiarity at mass 1.4 GeV, although it is regarded as doubtful whether it is a regular resonance. Figure 12-19 gives the energy variation of the production cross sections, combining the above experiment with data at lower energy obtained in a Rutherford Laboratory experiment.⁴⁹ The constancy of the cross section for $N^*(I = 1/2)$ states is of great interest. It undoubtedly illustrates the phenomenon of diffraction dissociation so often predicted to accompany diffraction scattering.^{50, 51} This phenomenon does not occur for the $N^*(I = 3/2)$ because no isospin is exchanged in high energy diffraction. A theoretical discussion of the BNL-Carnegie Tech results has been presented at the Conference by Margolis and

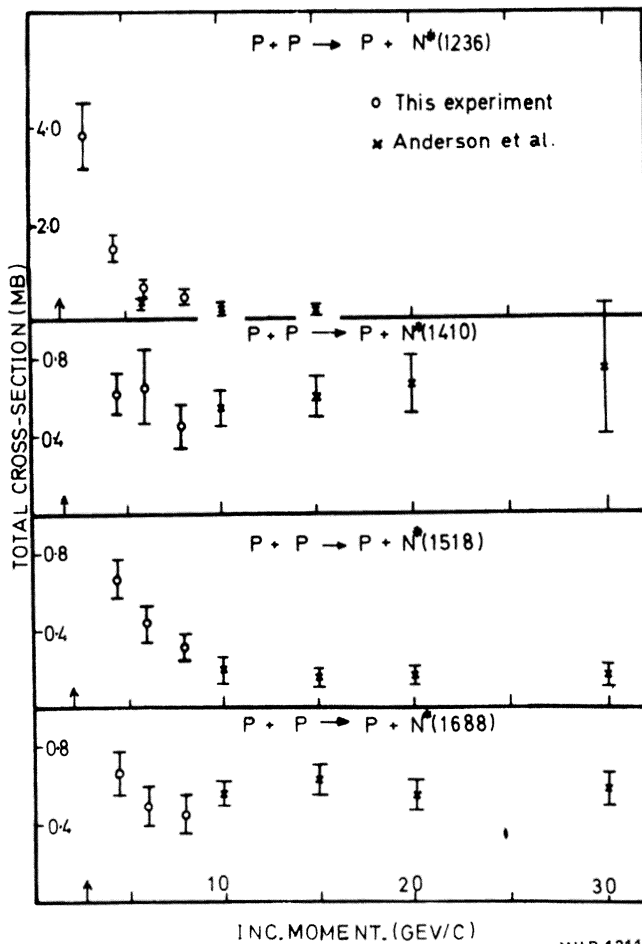


Fig. 12-19. The cross section for isobar production in the process $pp \rightarrow N^*p$ as a function of laboratory-system momentum. The experimental data come from Anderson et al. (Ref. 48) and Blair et al. (Ref. 49).

Rotsstein.⁵² We also note that the pp missing-mass experiment⁴⁸ has been extended to $pp \rightarrow ppX^0$, X unseen, by measuring the momenta of the two outgoing protons.⁵³

The phenomenon of diffraction dissociation is expected to occur also when the excited system is not in an isobar state, and it should manifest itself not only in diffraction on an elementary particle but also on complex objects as atomic nuclei. An illustration is found in the work presented by an Orsay-Milan-Saclay-Berkeley Collaboration,⁵⁴ which observed the process $\pi^- \rightarrow \pi^+ 2\pi^-$ at 16 GeV/c in a heavy-liquid bubble chamber (the liquid being C_2F_5Cl). Figure 12-20 represents the t distribution for three types of $\pi^+ 2\pi^-$ configurations (all, $\rho^0\pi^-$, and $f^0\pi^-$). The sharp peak for $t' = |t| - |t_{\min}| \leq 0.1$ (GeV/c)², which behaves as $\exp(-80 t')$, is evidence for a coherent dissociation on complex nuclei, whereas the slower decrease at larger t' , behaving as $\exp(-8 t')$, is probably produced by dissociation on bound nucleons behaving as quasi-free particles.

II. Large-Angle Scattering

1. New Experimental Results

Among the new results in this field we mention first the np large-angle scattering data from 2 to 6 GeV/c obtained in the Stanford-Michigan experi-

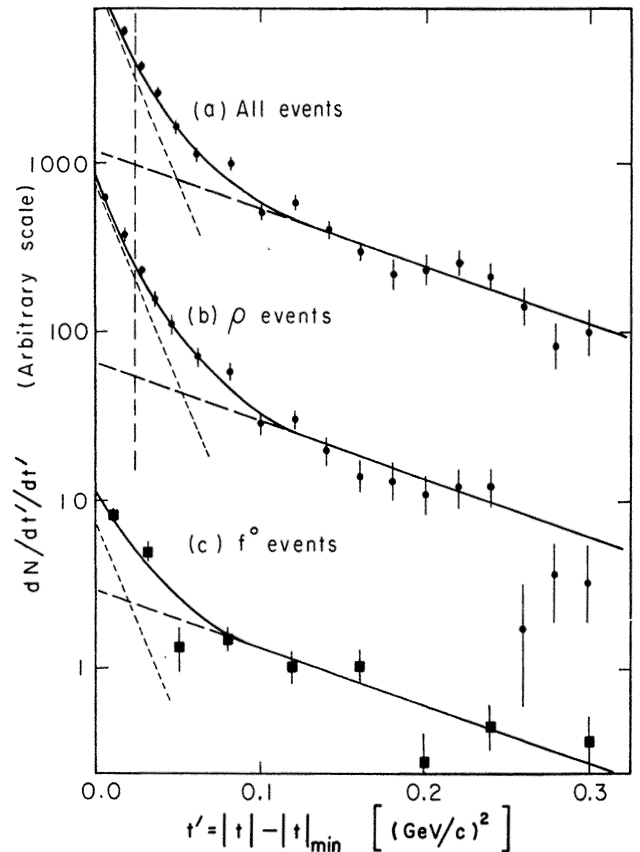


Fig. 12-20. Differential cross section for the process (a) $\pi^+ A \rightarrow \pi^+ + 2\pi^- + A$, where A is a mixture of heavy nuclei (C_2F_5Cl). The 3π system is shown to have an appreciable fraction of events of the type (b) $\pi^+ \rho$ and (c) $\pi^+ f^0$. The differential cross section for the subsample of events is shown as (b) and (c). The experimental results are reported by Allard et al. (Ref. 54).

ment mentioned earlier.³⁹ Here, as in the case of small angles, the np behavior is analogous to that of the pp system. This remains true in the region of $\theta_{c.m.} \approx 90^\circ$, where the data show a remarkable amount of symmetry around the point $\theta_{c.m.} = 90^\circ$. Another important experiment was carried out by a CERN group⁵⁵ to detect possible fluctuations in $d\sigma/dt$ at large angles, as can be expected, following Ericson,⁵⁶ if the statistical model were applied literally to the scattering process [as is well known, the statistical model has been able to predict with remarkable success the magnitude of the cross section⁵⁷]. The fluctuations would originate from the fact that the phase and absolute value of the partial-wave amplitudes would vary essentially at random from one angular momentum value to the next, each amplitude being itself a rapidly and randomly varying function of the energy. Detection of such fluctuations requires an angular resolution

$$\Delta \theta_{c.m.} \ll \ell_{\max}^{-1} \approx (k_{c.m.} r)^{-1},$$

where r is the dimension of the region of interaction, usually taken to be of order of 1 fermi. The experiment was carried out at 16.9 GeV/c, giving $\ell_{\max}^{-1} \approx 6^\circ$, whereas $\Delta \theta_{c.m.}$ was of order 0.8° . The incident momentum had a spread of 10 to 15 MeV/c, leading to a resolution of about 2 MeV in the c.m. energy. Figure 12-21 shows the experimental points and a few curves with simulated Ericson

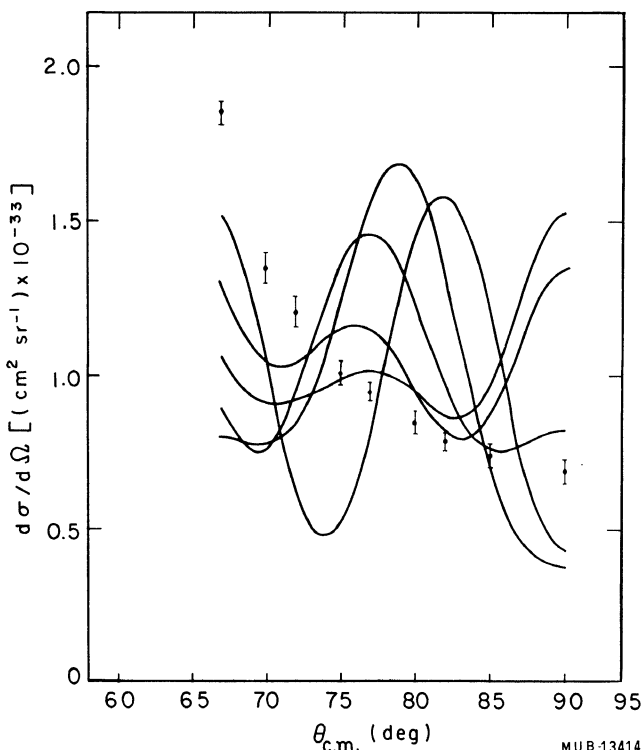


Fig. 12-21. Some cross sections generated according to the Ericson mechanism, compared with the experimental data for pp elastic scattering at 16.9 GeV/c reported by Allaby et al. (Ref. 55).

fluctuations. The latter were obtained by selecting the partial-wave amplitudes $a_l = x_l + iy_l$ at random, with normal distributions for the real variables x_l, y_l verifying

$$\langle x_l \rangle = \langle y_l \rangle = 0, \quad \langle x_l^2 \rangle = \langle y_l^2 \rangle = 1/2 \exp(-l^2/bk_{c.m.}^2);$$

b was given the value $10(\text{GeV}/c)^{-2}$. The experimental results clearly indicate that such fluctuations are very unlikely to exist. The correctness of the statistical model's prediction for the values of $d\sigma/d\Omega$ at $\theta_{c.m.} = 90^\circ$ and all measured energies remains nevertheless as impressive as before. Figure 12-22 shows an Orear-type fit to the data

$$s \left(\frac{d\sigma}{d\Omega} \right)_{cm} = A \exp(-p_\perp/b).$$

One finds $b = 225 \pm 5 \text{ MeV}/c$, a value distinctly different from the slope $b = 158 \pm 3 \text{ MeV}/c$ first proposed by Orear as a universal parameter.⁵⁸ It will be most interesting to have further data on the s and t dependence of large-angle cross sections with the new precision illustrated by the experiment just discussed. It is also clear that large-angle data would be of the greatest importance for inelastic two-body processes of type $A + B \rightarrow C + D$ with C and/or D different from A and B .

2. Theoretical Aspects

Although the statistical model remains unique in its ability to predict the magnitude of the large-angle cross sections, other models have been considered, especially the one proposed by Wu and Yang.⁵⁹ As described in Drell's report at this Conference, this model fits well with the new DESY data for the proton magnetic form factor up to $t \approx -10 (\text{GeV}/c)^2$. In contributions to the present Conference, K. Huang⁶⁰ discusses on a model how an exponential drop of $d\sigma/dt$ with energy can be ob-

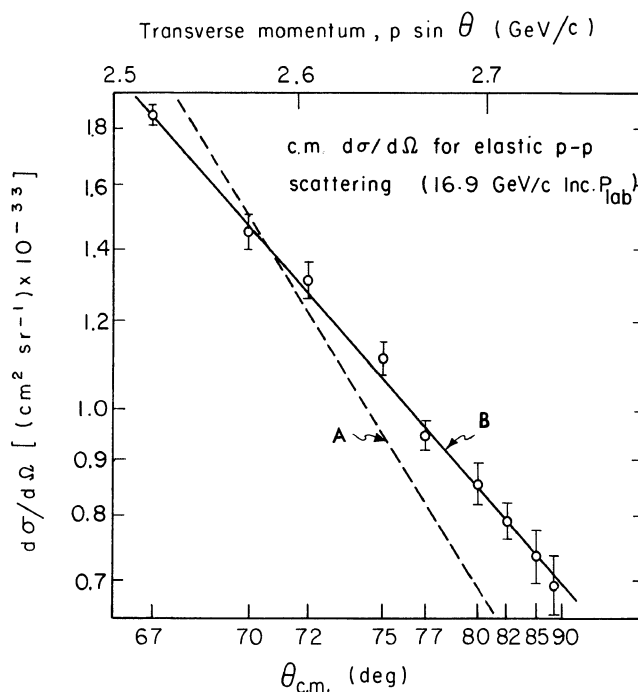


Fig. 12-22. Experimental angular distribution for pp scattering at 16.9 GeV/c on a logarithmic scale. A - Orear's fit. B - Best fit: $\frac{d\sigma}{d\Omega} \propto \exp(-p \sin\theta/0.225)$.

tained along the lines suggested by Wu and Yang, whereas Domokos and Karplus⁶¹ attempt to derive from field-theoretical considerations a relation of the Wu-Yang type between $d\sigma/dt$ and form factors.

Białas and Czyzewski⁶² analyze available data on $\bar{p}p$ and np large-angle scattering, show that the general behavior is the same for both reactions, and note a forward-backward asymmetry which can be used as an argument against the statistical model. In another contribution,⁶³ the same authors propose a new mechanism for large-angle πp scattering; it uses the effect of s -channel resonances, assuming the latter to be given by very long and straight Regge recurrences as described by Barger and Cline²⁶ and illustrated in Figs. 12-13 and 12-14. Finally we note two contributions by Logunov et al., one studying form factors and scattering amplitudes at large t in a new analytical representation⁶⁴ and the other discussing large-angle scattering at high energy by a regular potential in the quasi-classical approximation, the scattering process taking place at classically forbidden angles.⁶⁵

III. Multiple Production of Particles

A large amount of experimental material on multiple particle production is available, especially from bubble chamber work, and this amount will rapidly increase in coming years. It is very unfortunate that up to now no satisfactory procedures have been found for systematic extraction of dynamical information concerning the collision and production mechanisms involved. This is of course due to the great complexity of the material, and is very natural if we remember that the systematics of high energy two-body collisions is being developed only since about 4 years ago ("body" refers here to particles and resonances). The Regge-pole-type analysis on which this systematics is currently based has reached sufficient qualitative success to

attempt its extension to rather broad classes of three- or four-body reactions, a program which is recommended by some theoretical groups^{10, 21} and will probably give practical results if it covers sufficiently large energy intervals.

The other extreme case of high multiplicities probably presents altogether different problems, and the concepts, models, and distribution functions currently used in analyzing the data are not very likely to reveal directly the most important dynamical elements. Strong-interaction theory, on the other hand, has not made the slightest progress in the field of multiple particle production, and it is unlikely to do so before some new clues are obtained--clues that, one hopes, could be given by unconventional ways of grouping and treating the data.

In view of the general situation, we shall not attempt to review the many experimental contributions on multiple particle production presented at this Conference, and we shall rather describe a few of the points made by Czyzewski in a review presented in the Discussion Session on High Energy Experiments. It is expected that this review will be published separately.

1. Multiplicity Distribution of Pions

Bartke and Czyzewski⁶⁶ have been able to test with some success the conjecture that, when one considers all events producing n pions (n is the total number of pions in the final state, including π^0 's), the various isospin states of the n -pion system allowed by charge and isospin conservation have about equal probabilities. If this is so, from the experimentally known cross sections σ_n^0 for producing $n\pi^\pm$, one can predict the cross sections $\sigma_n^{(m)}$ for producing $(n-m)\pi^\pm$, $m \geq 1$. This can be compared with experiment, either by using experimental de-

terminations of $\sigma_n^{(1)}$, or by calculating the sum

$$\sigma_\pi^{(\text{calc})} = \sum_n \sum_m \sigma_n^{(m)}$$

and comparing it with the measured total cross section σ_π for inelastic collisions without strange-particle or antinucleon production. The agreement is surprisingly good in 4- and 8-GeV/c π^+p collisions, as shown in the table:

p_{lab}	4 GeV/c	8 GeV/c
σ_π	20.1 mb	17.9 mb
$\sigma_\pi^{(\text{calc})}$	20.35 mb	18.29 mb

The errors are of the order of one millibarn. One might expect that the above treatment will give reasonable results if the average multiplicities are rather high and if mesonic resonances are produced only weakly. This seems to be the case in the collisions considered (nucleonic resonances should cause only a small violation of the statistical assumption in isospin space, since only one baryon is involved). One might also try to use this method in other cases in order to estimate the abundance of resonance production.⁶⁷ The abundance of resonance production in six-prong interactions of 8-GeV/c π^+p is discussed in a contribution of the Warsaw group.⁶⁸

2. Correlations

Various interesting correlation effects have been seen in high-multiplicity events. Thus, the Krakow group⁶⁹ presented evidence on $\langle p_\perp \rangle$ for nucleons

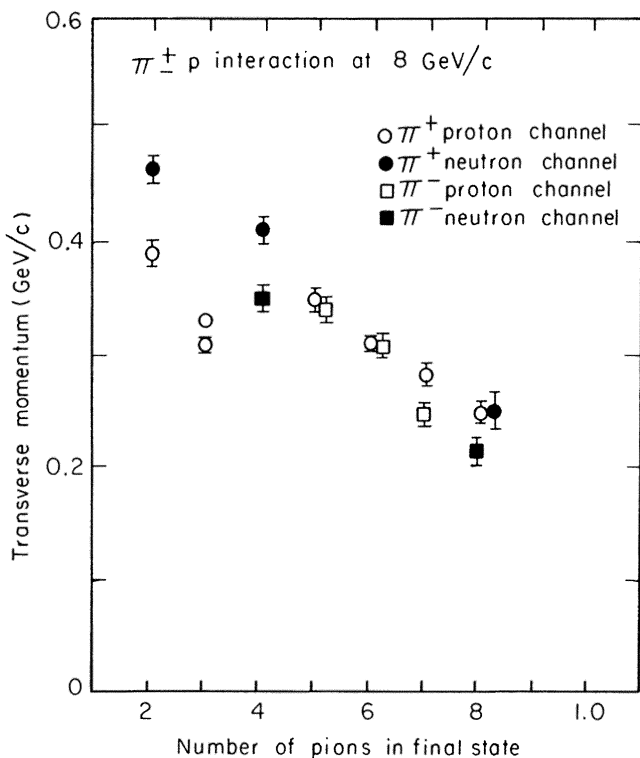


Fig. 12-23. Average transverse momentum of pions as a function of multiplicity for multiple pion production by 8-GeV/c π^+ . The experimental results were compiled by Bartke et al. (Ref. 69).

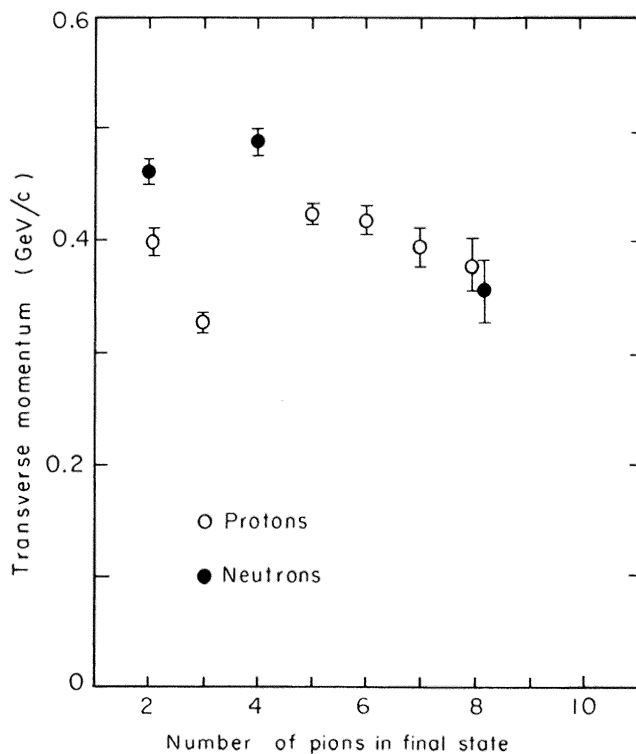


Fig. 12-24. Average transverse momentum of the nucleon as a function of pion multiplicity for multiple pion production by 8-GeV/c π^+ . Included on the graph are channels with a neutron in the final state as well as channels with a proton in the final state. The experimental results were compiled by Bartke et al. (Ref. 69).

and pions produced in 8-GeV/c π^+p collisions, the average being taken over events with given pion multiplicity n (only events with no or one π^0 were considered). Whereas $\langle p_{\perp} \rangle$ decreases markedly for increasing n in the case of the pion transverse momentum, it is approximately constant for nucleons, as shown in Figs. 12-23 and 12-24. One notices large fluctuations at low multiplicities, an effect which is seen more clearly in Fig. 12-25 and is probably due to the abundance of resonance production and of two-body processes in low-multiplicity events. In the same experiment the distribution of c.m. angles between pairs of pions was measured. Figure 12-26 shows a clear difference between pairs of like and unlike pions, in agreement with the effect first observed by G. Goldhaber et al.⁷⁰ and attributed to Bose-Einstein statistics.

Another strong correlation effect is seen in Fig. 12-27, now between $\langle p_{\perp} \rangle$ and p_{\parallel} for charged pions produced in $\pi^- + p \rightarrow p + \pi^+ + 2\pi^- + m\pi^0$ (all m). This effect, which was found in a 7.5-GeV/c exposure in propane as part of an extensive analysis by a Dubna-Bucharest collaboration,⁷¹ can perhaps be interpreted on the basis of relativistic phase space. It should not be separated, however, from the general and unsolved problem of understanding transverse and longitudinal momentum distributions, to which the other effects mentioned previously also belong.

IV. Theoretical Developments

1. Quark Model and Associated Methods

Although discussed little during the Conference,

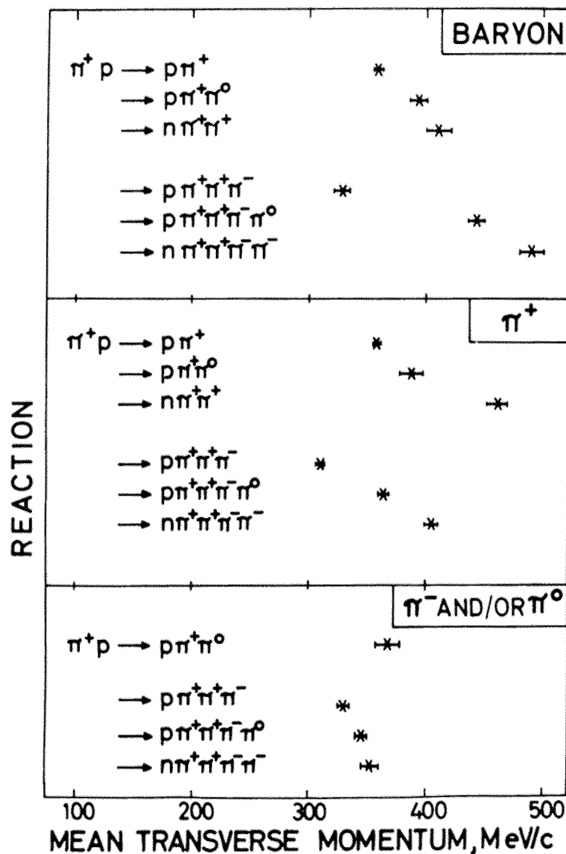


Fig. 12-25. Mean transverse momentum of pions and nucleons in multiple pion production in 8-GeV/c π^+p reactions. The experimental results are compiled by Bartke et al. (Ref. 69).

the quark model of high energy scattering should be mentioned as one of the most important steps in clarifying the relation between high energy collisions and SU(6) symmetry.⁷²⁻⁷⁵ The principal assumption, beyond the quark structure of hadrons, is that the hadron-hadron scattering amplitude is the sum of quark-quark and antiquark-quark amplitudes, as expressed graphically in Fig. 12-28, where the f^i 's denote the form factors for the hadronic transitions. They reduce to 1 for $A^i = A$, $B^i = B$, and $t = 0$. Some interesting relations obtained in the quark model are

$$\sigma_T(\pi N) = \frac{2}{3} \sigma_T(NN) \text{ in the limit of very high energy,} \quad (1)$$

$$\sigma_T(K^+p) - \sigma_T(K^-p) = \sigma_T(\pi^+p) - \sigma_T(\pi^-p) + \sigma_T(K^+n) - \sigma_T(K^-n), \quad (2)$$

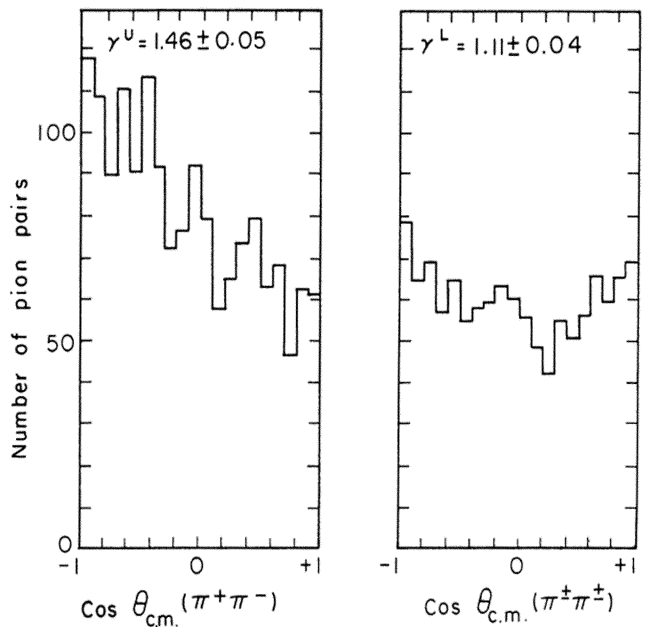


Fig. 12-26. Distribution of c.m. angles between pions plotted separately for pions of like charge and of unlike charge for the reaction $\pi^+p \rightarrow p4\pi^+3\pi^-$ at 8 GeV/c. These results are reported by Bartke et al. (Ref. 67).

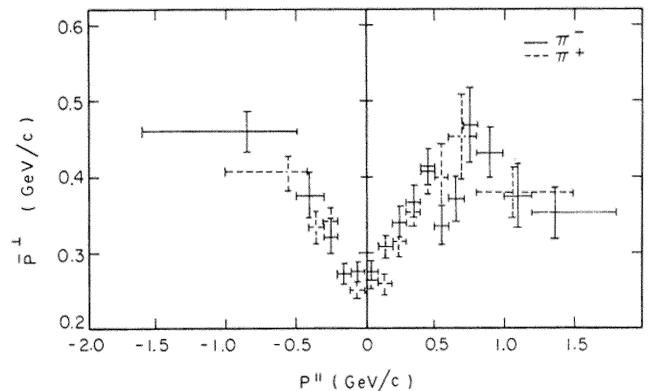


Fig. 12-27. The dependence of the average transverse momenta $\langle P_{\perp} \rangle$ of the π^- and π^+ on different intervals of longitudinal momenta in the c.m. system for the reaction $\pi^-p \rightarrow p\pi^+2\pi^- + m\pi^0$ as reported by Belyakov et al. (Ref. 71).

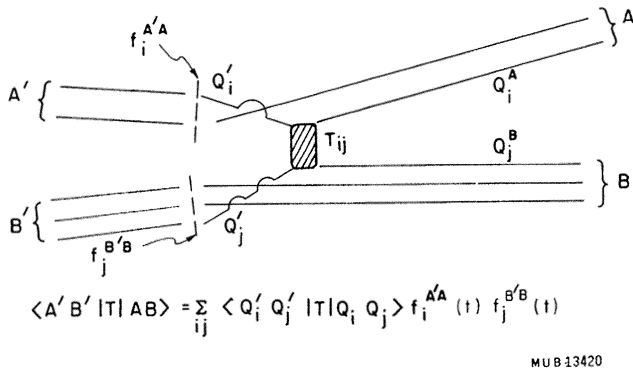


Fig. 12-28. Schematic representation of meson-nucleon interaction as pictured in the quark model; (A, A') represent meson states and (B, B') represent baryon states.

$$\sigma_T(\pi^+ p) - \sigma_T(\pi^- p) = \sigma_T(K^+ n) - \sigma_T(K^- n), \quad (3)$$

$$\sigma_T(K^+ p) = \sigma_T(K^+ n). \quad (4)$$

In addition to the additivity assumption, Eq. 1 uses the asymptotic properties of high energy cross sections (Pomeranchuk limit), Eq. 2 uses isospin invariance, Eq. 3 requires SU(3) symmetry, and Eq. 4 combines isospin invariance with an assumption of the absence of charge-exchange scattering between the two $I = 1/2$ quarks, as proposed by Lipkin.⁷⁶ Equation 1 agrees very well with the measured cross sections extrapolated to constant limits for $s \rightarrow \infty$ [$\sigma_T(\pi N) \rightarrow \approx 22$ mb, $\sigma_T(NN) \rightarrow \approx 36$ mb, if one takes into account the values of $\sigma_T(\bar{N}N)$, which should tend to the same limit as $\sigma_T(NN)$]. Equations 2 and 4 are very well satisfied for $p_{lab} \gtrsim 5$ GeV/c, whereas there is a reasonably small violation of Eq. 3, as is expected, since the relation requires SU(3). Furthermore, the additivity assumption itself should not be better than 10 or 20%.⁷⁵ We note that Eqs. 3 and 4 are the Johnson-Treiman relations originally derived from SU(6).⁷⁷ Under simple assumptions concerning the quark size, one further derives for AB elastic scattering at small momentum transfers and very high energy

$$\frac{d\sigma}{dt} / \left[\frac{d\sigma}{dt} \right]_{t=0} = [G_A(t)G_B(t)]^2,$$

where G_A, G_B are the electromagnetic form factors of A and B (in the Sachs definition for spin-1/2 particles),⁷⁸ i. e., the same relation as proposed by Wu and Yang at high t .⁵⁹ The fit is excellent for pp scattering, if one uses for $d\sigma/dt$ an extrapolation of pp and $\bar{p}p$ data to a common high-energy limit. There is no doubt that the quark model with additive amplitudes has shown a great power of suggesting simple, successful relations of an unconventional type among high energy processes. Spins can be readily incorporated.⁷⁹

As in the case of other successful applications of the quark model, one has tried to reach similar conclusions for hadronic properties by introducing different assumptions which do not require quarks to exist even as bound objects. In high energy scattering this has been done mainly in two ways. Freund has formulated an assumption of universality through dominance of all couplings by meson states.⁸⁰ Cabibbo et al.,⁸¹ on the other hand, combine the Regge pole model for elastic scattering (in the form in which two meson nonets are exchanged) with the concepts of current algebra. They couple the even-signature Regge poles to scalar currents, and the

odd ones to vector currents, and they postulate current commutators as would follow from the quark model. This method can be applied at $t=0$ leaving out the spins; its extension to $t \neq 0$ and spin couplings has not been possible until now. Most of the quark-model relations and some others are obtained, but Eq. 1 now holds only in absence of SU(3) symmetry breaking. Furthermore, the model has the unexpected property that it can be fitted to the total cross section data only if one assumes all σ_T to decrease with s at the slow rate $s^{-\epsilon}$, $\epsilon = 0.075 \pm 0.008$. The resulting cross-section variation at very high energy is illustrated in Fig. 12-29, where the curves from top to bottom refer to (i) the average of $\sigma_T(NN)$ and $\sigma_T(\bar{N}N)$, N denoting nucleons, (ii) the average of $\sigma_T(NN)$, (iii) the average $\sigma_T(\pi N)$, and (iv) the average of $\sigma_T(KN)$. This remarkable suggestion of slowly decreasing total cross sections will be very stimulating for future experimentation at extremely high energies.

2. Regge Pole Theory

a. Parity exchange

In a very interesting contribution, Gribov⁸² studies with respect to parity the effect of the Mandelstam cuts or branch points which are expected to be present in the relativistic scattering problem. He considers in particular the cut generated by exchange of several Pomeranchuk trajectories, the only one that might give sizable contributions at very high energy. Consider the reaction $A + B \rightarrow A' + B'$ with $t = (p_{A'} - p_A)^2$. In the t -channel reaction $A + \bar{A}' \rightarrow \bar{B} + B'$ one can define the "intrinsic" parity $P_r = (-1)^J P$, where J is the total angular momentum and P the parity of the $A + \bar{A}'$ state (we consider meson exchange). Gribov's point is that P_r is +1 for the Pomeranchuk pole contribution to the amplitude, whereas it is ± 1 for the Pomeranchuk cut contribution. This has important observational consequences. Take $B = B' = \text{proton}$. If A and A' are 0^- and 0^+ mesons respectively, the P pole does not contribute, the P cut does

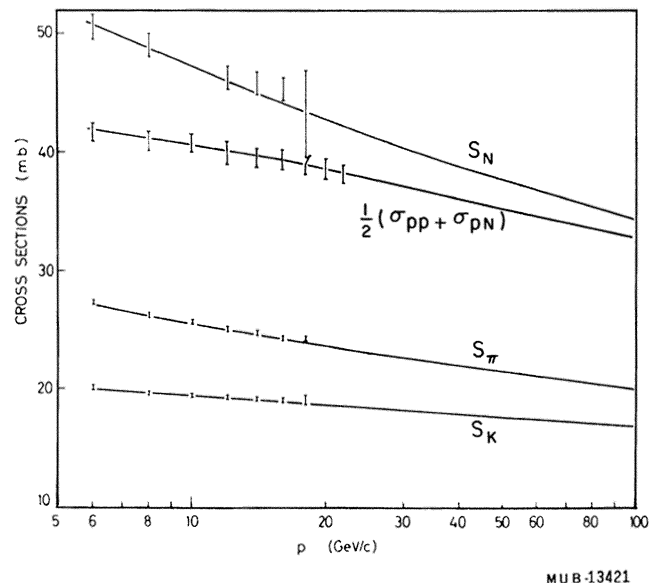


Fig. 12-29. Theoretical fit by Cabibbo et al. (Ref. 81) to total cross section data using a Regge pole-current algebra model with a nonet of mesons. The curves starting from the top refer to (a) the average of the NN and $\bar{N}N$ total cross sections; (b) the average of the NN total cross sections; (c) the average of the πN total cross sections; (d) the average of the KN total cross sections.

(P stands for Pomeranchuk). The cut produces a cross section with a slow, logarithmic decrease for $s \rightarrow \infty$. If there is no P cut, on the other hand, the cross section will decrease rapidly with s (exchange of η trajectory). A less striking difference occurs in the more readily available reaction $0^- + p \rightarrow 1^- + p$. The amplitude for P-pole exchange vanishes as $\sin\theta$ in the forward direction, while the P-cut amplitude is small (in $\sqrt{-t}$) without vanishing. (Remember that $t < 0$ at $\theta = 0$ if the 1^- meson is heavier than the 0^- one). Although Gribov does not discuss such cases, one may mention that the same distinction could be applied when A is a proton and A' a proton isobar, the importance of the P-pole and P-cut contributions being essentially reversed, depending on the parity of the isobar.

b. General masses and spins

The problems of Regge pole theory for reactions with unequal masses or general spin or both, which have been known for some time to contain major complications, have been tackled in some contributions and discussions during the Conference. It was realized that some of the complications which occur in the spin $1/2$ case with equal masses (nucleon-nucleon scattering) had been cleared up several years ago by Gribov and Volkov.^{46, 47}

Among the five amplitudes of the t-channel reaction $NN \rightarrow NN$, only three can remain independent when $t = 0$. Gribov and Volkov write the two resulting relations between the five amplitudes. They derive from them that, if the amplitudes belonging to the singlet state 3J_J and the triplet state 1J_J do not decouple altogether at $t = 0$ (i. e., if there are spin-dependent terms in the NN amplitudes at $t = 0$), their Regge poles must satisfy for $t = 0$ the relation

$$a[{}^1J_J, t=0] = a[{}^3J_J, t=0] \pm 1 = a[{}^3(J\pm 1)_J, t=0],$$

where $a[{}^3(J\pm 1)_J, t=0]$ is a Regge pole belonging to the NN states 3l_J , $l = |J\pm 1|$. In addition, the residues develop singularities at $t=0$, the effects of which must compensate each other in the total amplitude. In short, a "conspiracy" of several trajectories is needed to obtain a nonsingular spin-dependent amplitude at $t=0$. As stressed by Gribov and Volkov, the validity of the above relations between trajectories must be regarded as a consequence of the fact that the space-time symmetry of the system is higher for $t=0$ than for $t \neq 0$.

Regarding collisions $A+B \rightarrow A'+B'$ in the unequal-mass case, every Regge pole, when considered to higher order in the asymptotic expansion for $s = (p_A + p_B)^2 \rightarrow \infty$, is known to generate terms which are singular at $t = (p_A - p_{A'})^2 = 0$ (these singularities are absent if $m_A = m_{A'}$ and $m_B = m_{B'}$). These singularities have been studied by Freedman and Wang⁸³ for spinless particles. To eliminate these singularities from the amplitude, Freedman and Wang propose that each Regge trajectory $a_j(t)$ is necessarily accompanied by daughter trajectories $a_{j,k}(t)$, for $k = 1, 2, \dots$, which verify $a_{j,k}(0) = a_j(0) - k$. The $a_{j,k}$ should have the same quantum numbers as a_j , except for the signature, which is opposite for odd k (being the same for k even). The daughter poles all have singular residues at $t=0$, with such relations among them that the total amplitude remains regular at $t=0$. All this is verified to hold in a model based on the ladder approximation and the Bethe-Salpeter equation.

It was reported that Leader had undertaken a study of the general case of arbitrary masses and spins, where the two types of conspiracies described above must somehow act simultaneously if the amplitude has to have its general spin dependence at $t=0$

without becoming singular. While these developments complicate considerably the formalism of Regge pole theory (remember that each set of poles is expected, furthermore, to generate Mandelstam cuts), they are of great theoretical interest. It should be hoped that their phenomenological implications will not increase too much the complexity of the Regge-pole analysis of experimental data, which is already considerable.

V. Concluding Remarks

In summary, we would like to list some of the classes of questions that can be expected to play an important role in the near future.

1. In two-body meson-nucleon processes near the forward direction, the simple cases in which few sets of quantum numbers can be exchanged and consequently few Regge trajectories contribute will receive continued attention. Is it true that all relevant trajectories except the Pomeranchuk are about the same? Do they all contribute to dips? What is the actual slope α'_P of the Pomeranchuk trajectory? We know that it is much smaller than all other slopes determined so far, which are of order $1(\text{GeV}/c)^2$. Is $\alpha'_P = 0$ favored by the facts, or can one show that $\alpha'_P > 0$ with large probability? And, more immediately, what happens with effects, like polarization in $\pi^-p \rightarrow \pi^0n$, which Regge poles do not explain?

2. In meson-nucleon backward scattering the neat description in terms of Reggeized nucleon exchange will be scrutinized carefully as soon as new accurate data are available. A broad experimental program is here desirable, including charge-exchange and polarization phenomena.

3. The time has come to measure accurately those two-body processes at small momentum transfers at which no known particles or resonances, and hence no Regge trajectories, can be exchanged. Examples are $\pi^-n \rightarrow \pi^+N^{*-}$ forward, $K^-p \rightarrow K^0\Xi^0$ forward, and $K^-p \rightarrow K^-p$ backward.

4. In the whole field of NN and $\bar{N}N$ scattering, and $MN \rightarrow AB$, $NN \rightarrow AB$, $\bar{N}N \rightarrow AB$ reactions ($N = \text{nucleon}$, $M = \text{meson}$, A and B particles or resonances), many new data will accumulate, but a systematic interpretation will be difficult. Regge pole theory must be extended to include 0^- and 1^+ particle trajectories as well as to cope with spins $> 1/2$ and unequal masses, and the "conspiracy" complications described above must be faced. For two-body inelastic processes, any theoretical interpretation must deal with decay distributions and decay correlations, a field in which the absorption model is superior to any other and may therefore inspire further theoretical developments.

5. Large-angle two-body processes have most intriguing properties, and more experimental information--on inelastic two-body reactions also--seems a prerequisite before much further theoretical insight can be gained.

6. The problem of deuteron effects in high energy scattering is of great theoretical and practical interest. It deserves attention for its own sake.

7. Many-body reactions deserve more systematic study than they have received in the past. Rough theoretical ideas inspired by the Regge description of two-body processes are available for analyzing three- and four-body reactions. The search for unconventional statistical properties and correlations in high-multiplicity collisions may eventually lead to important clues for breaking the barrier imposed by the present lack of realistic dynamical models.

In conclusion, we feel that during the last few years, the field of high-energy hadron collisions has made rapid progress, and the interplay between experiment and theory has been particularly close. At each stage, basing itself on known facts, theory

presents various possible descriptions, or conjectures various possible forms of behavior, and new experiments make decisive choices among them. This procedure, which has worked so well in more advanced branches of physics, is beginning to bear fruit in hadron physics. One can be confident that it will continue to do so, provided theory in its development remembers that only nature can guide it through the maze of all suspected and unsuspected mathematical possibilities, and provided adequate experimental facilities, techniques, and results become available for answering without undue delay some of the decisive questions.

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Discussion

Chuvilo (Dubna): The new data about the $\alpha_- = \text{Re}A/\text{Im}A$ in the elastic π^- -p-scattering obtained in Dubna are in good agreement with the dispersion-relation prediction for 3.5 GeV/c and 6.15 GeV/c. I should like to note that the α_- value, calculated from interference effect, depends upon the formula used. The Bethe formula was used in the analysis of the results obtained in Dubna. Analysis with another formula suggested by L. D. Soloviev gives an α_- value which differs by about 15% from the ones Prof. Van Hove presented. This means that in the future, after improving the experimental data, we shall meet the question of what we are testing: dispersion relation or electromagnetic corrections to the effect under consideration.

Peyrou (CERN): In K^- p charge exchange it seems that the experimental data could have a dip, but the Regge fit has not. Why is this fit different from the fit to π^- -p charge exchange?

Van Hove: The difference in the fit comes from the R trajectory of even signature. In the beginning I made a comment on a proposal to extend the dip phenomenon to the spin-flip amplitude for even-signature trajectories, as suggested by Frautschi for elastic scattering. If this proposal works for the R trajectory, we are going to have the whole spin-flip amplitude for the charge-exchange kaon-proton reaction very small at $t \approx -0.5$ (GeV/c), because even- and odd-signature spin-flip contributions would both vanish near this point.

Selove (Pennsylvania): I have a question on the possibility of detecting elementariness of quarks, if quarks exist. The point is this. The nucleon apparently shows Regge behavior. However, Low mentioned that even if one starts with a theory involving an elementary fermion, the fermion may become automatically Reggeized. Thus, even if the nucleon is made of quarks, would it be true that as one follows the nucleon Regge trajectory to far negative t , it would keep falling, because the quarks themselves would be composite in the same way? Secondly, would there be a possibility that mesons might show evidence of elementarity of the quarks--i. e., is there a possibility that a meson Regge trajectory might level off at some fixed value of α , as t goes to large negative values?

Van Hove: I do not know the answer. There were some speculations mentioned in one of the sessions, and somebody may want to bring them up here.

Mandelstam (Berkeley): My comment may possibly answer Selove's question; in any case I think it is relevant. If a composite object is itself composed of elementary objects there would be polynomial terms in any channel where the composite object is exchanged. Thus, if a meson is composed of a quark-antiquark pair, constant terms (s^0) would be present in channels where the meson can be exchanged. If the baryon is composed of three quarks, terms $s^{-3/2}$ (I think) must be present in channels

where the baryons are exchanged. I feel these statements to be roughly on the same level of rigor as the statement that elementary particles are not on Regge trajectories. Thus, in principle, they may provide an experimental test for the hypothesis that mesons and nucleons are composed of quarks. It may be, of course, that those terms are small for very tightly bound quarks.

Nataf (Orsay): Is there actually a clear connection between Regge pole behavior and compositeness of a particle?

Van Hove: I would answer in this way. If a meson or a baryon is a composite system, the idea of the Regge recurrences (i. e., of what everybody used to call rotational series of states, as are well known in many parts of physics) is a very natural one. It would, rather, be surprising if they did not exist. The shape of the rotational series is another matter, but their very existence is a rather immediate consequence of compositeness. However, once you go to t negative, things become more subtle and hard to visualize, and we should remember that going through $t = 0$ is the most important step taken in applying Regge poles to scattering.

Sakurai (Chicago): In addition to the finite polarization observed in π^- -p charge exchange, there are two cases in which the Regge pole analyses have not been too successful--the antishrinkage observed in \bar{p} p elastic scattering and the persistence of the real part in pp scattering. Could you comment on these two points?

Van Hove: Concerning the expansion of the \bar{p} p peak, it seems to me quite clear that this is no problem. If the Pomeranchuk trajectory is flat, as it is likely to be, then at truly asymptotic energies nothing will expand and nothing will shrink. However, the pp and the \bar{p} p peaks should then become the same. Since the pp is now wider than the \bar{p} p, the pp is going to the limit by shrinking and the \bar{p} p is doing it by expanding. This, I think, is no problem. A more serious question is the persistence of the real part of the scattering amplitude. Assume that the real part persists to considerable energies, then either you can take the view that it would be explained, for example, by the assumption that the total cross sections slowly approach zero for $s \rightarrow \infty$ (this would generate a real part with the right sign), or the persistent real part may be due to a cut, which would also allow it to disappear very slowly. Or σ_T and $\text{Re}T/\text{Im}T$ may both stay constant at high energy, which would mean that there is an odd-signature trajectory with $\alpha(0) = 1$.

Sakurai: Isn't the flatness of the Pomeranchuk trajectory itself a failure of the Regge pole theory?

Van Hove: To me the existence of a fixed singularity in the complex-plane angular momentum is no disturbance. For me the Regge pole model of high energy scattering is the model using singularities in the angular momentum plane, and I would not be surprised if some of these singularities were complicated.

Yang (Stony Brook): If the Pomeranchuk pole is flat, what about the previous triumph concerning the f^0 meson?

Van Hove: That is an interesting question because the people who fit total cross sections and real parts in the forward direction seem to run out of Regge poles at a certain stage of accuracy. If you want to make the cross sections constant for $s \rightarrow \infty$, instead of having just a nonet of even-signature trajectories, you are better served with a nonet plus one addition-

al $I = Y = 0$ trajectory. It fits the data better. The additional trajectory could be the Pomeranchuk one, and the nonet would be related to the Z^+ nonet of mesons.

Phillips (Harwell): I would like to comment on the $\pi^\pm p$ polarization data you showed. They are approximately equal and opposite, indicating that the P and P' interference term is small. Hence for $K^\pm p$ polarization, the $P-P'$ term must again be small (from the factorization constraint), and any big effect must come from interference with odd-signature trajectories ρ and ω (neglecting A_2). Similarly with pp and $\bar{p}p$ polarizations. So one expects equal and opposite polarizations for each pair, just as with $\pi^\pm p$. Now the ω term is believed to vanish somewhere near $t = -0.1$ (GeV/c)² to account for the cross-over of pp and $\bar{p}p$ differential cross sections. One expects that ω dominates over ρ , so the polarization will tend to vanish here. It will be interesting to test this prediction of equal and opposite polarizations' vanishing near $t = -0.1$. I notice the CERN pp polarization is consistent with such a zero, incidentally.

Biaľas (Krakow): I would like to point out the importance of the measurements of the decay correlations in the reaction $\pi^+ p \rightarrow \pi^0 N^{*++}$ for testing the Regge pole model. Since only one trajectory (ρ) is exchanged in this case, one has a definite relation between the spin-density matrix elements of N^{*+} (Biaľas-Kotanski, to be published in Acta Phys. Pol.). This relation does not depend on any assumption on residue functions of the ρ trajectory, and therefore may serve as an excellent test of the Regge pole model (in analogy with the polarization in π - p charge exchange).

Van Hove: I agree entirely.

A. Goldhaber (Berkeley): For 0^- meson-baryon collisions there are exact and approximate selection rules depending on the "parity" of the Pomeranchuk exchange. However, such selection rules do not exist for p - p scattering. How would you propose to detect anomalous Pomeranchuk "parity" in this case?

Van Hove: Depending on whether even or odd parity is exchanged, one has to construct different invariants out of, let's say, a nucleon and an isobar, putting together momentum vectors, polarizations, etc. The resulting quantity will be very different, depending on the parity. It will mean additional powers of t and may show up significantly if the mass differences are not too large.

Nauenberg (Santa Cruz): Would you comment on what has been learned about the energy which can be regarded as asymptotic? Is there any success in trying Regge pole fits below the energies which you have shown on the slide?

Van Hove: I would like to comment in this way. The answer to this question can less and less be given in terms of a single, well-defined threshold for the asymptotic region. One works more and more in terms of a rather successful addition of Regge pole exchange amplitudes and direct-channel resonance amplitudes. This procedure has never been properly justified, but there are indications that it works. It mixes asymptotic terms with nonasymptotic ones. I would expect that the region where only terms of purely asymptotic nature contribute is higher than we thought before. Nevertheless the asymptotic techniques are more and more useful, even at low energy, if extra terms are added. Furthermore, there are reactions where direct channel resonances are absent, like the K^+ proton, and these reactions are therefore of particular interest for Regge pole theory even at low energy.

Appendix

High-Energy Elastic Scattering and Charge-Exchange Data

A. Wetherell

1. Elastic Scattering

Table 12-A1 gives a qualitative description of the present situation in the high-energy elastic scattering of hadrons. The following notes are meant merely to introduce a series of figures illustrating some of the entries in the table. The empty boxes indicate the large amount of work which remains to be done to complete the picture.

Beginning with the Coulomb interference region, Fig. 12-A1 gives a collection of results on the ratio of real to imaginary parts of the forward elastic p-p scattering amplitude. The recent points, from LRL (derived by Clyde et al.^{84, 86}) fill in the intermediate-energy region. Figure 12-17 shows the available data for p-n scattering. The six experimental points between 1.7 and 10.9 GeV/c were obtained by Chernev et al.³⁷ by studying coherent p-d elastic scattering; the CERN point at 19.3 GeV/c was obtained in a study of p-d scattering, both coherent and noncoherent, by Bellettini et al.⁹⁰ The curves shown in Fig. 12-17 are the results of an evaluation of the N-N dispersion relations by Carter and Bugg.³⁸ More experimental work between 2 and 10 GeV/c is clearly necessary.

The high-energy π^\pm -p situation is illustrated by Fig. 12-A2, which gives the Coulomb interference results of Foley et al.³ together with some predictions of the forward dispersion relations. The trend of the high-energy π^- -p phase appears either to present difficulties for the dispersion relations or to reflect some interesting behavior in the high-energy total cross sections. New values for the ratio of real to imaginary parts for π^- -p were given by Nomofilov et al.¹ They are as follows: at 3.5 GeV/c, -0.18 ± 0.06 ; at 6.1 GeV/c, $-0.14^{+0.11}_{-0.10}$.

For K^\pm -p scattering, Coulomb interference results are not yet available, and the values^{28, 92} given in the boxes were obtained by comparing extrapolations of angular distributions with the optical-theorem value. All the measurements were made with liquid hydrogen bubble chambers. Comparison of the scattering cross section with the optical theorem value leaves the sign of the real part undetermined.

The main diffraction peak is in general very well fitted by the form $d\sigma/dt \approx \exp(a+bt+ct^2)$. As an approximation the quadratic term can be neglected, and values for the exponent b are given in Table 12-A1 together with the characteristic features of the diffraction peaks, which have been studied in detail by Foley et al.⁸⁵

Measurements of n-p elastic scattering between about 1 and 6 GeV have been recently performed by Kreisler et al.³⁹ and their angular distribution between 5 and 6.3 GeV is shown in Fig. 12-A3. The slope of the diffraction peak seems to be similar to that of the p-p system.

Interesting structure has been found at the ends of some of the diffraction peaks. Figure 12-2 shows data of Coffin et al.⁵ between 2.5 and 4.0 GeV/c, and Figs. 12-A4 and 12-A5 from Orear et al.²⁴ between about 4 and 12 GeV/c. Figure 12-2 also shows smooth curves representing the trend of the elastic π^- -p charge-exchange process, which also shows a similar structure. The latter does not disappear

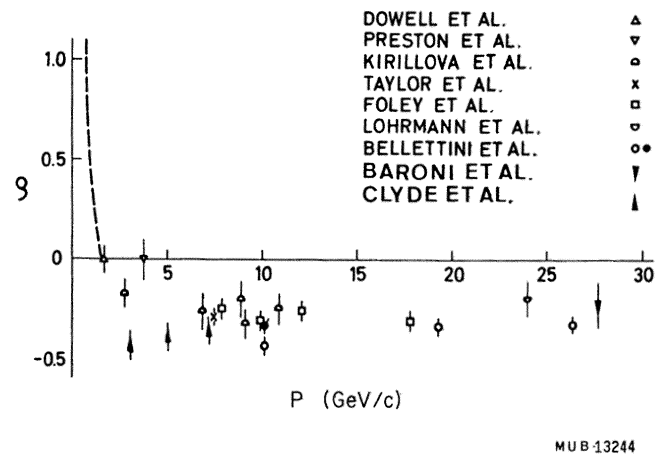


Fig. 12-A1. The ratio ρ of the real and imaginary parts of the forward elastic proton-proton scattering amplitude as a function of momentum. The data are from Ref. 84.

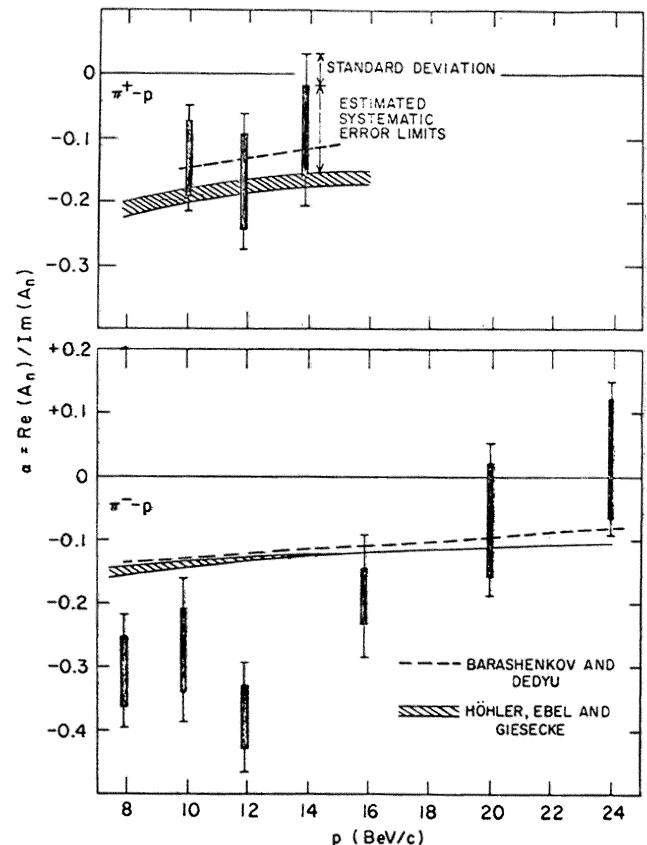


Fig. 12-A2. The ratio of real to imaginary parts of the forward scattering amplitudes for π^+ and π^- -p scattering. The experimental points are from Foley et al. (Ref. 3). The dispersion relation predictions are discussed by S. J. Lindenbaum, in Proceedings of the Oxford Conference, 1965, p. 93.

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MUB-13155

Table 12-A1. Descriptive survey of data on high-energy elastic scattering.

Particle system	Coulomb interference region $ t \lesssim 10^{-2}(\text{GeV}/c)^2$		Diffraction peak $\sim e^{bt}$ $ t \lesssim 0.5 (\text{GeV}/c)^2$		Intermediate angle $0.5 < t < 1.5 (\text{GeV}/c)^2$	Wide angle	Backward angle	Polarization
	Real part $f(0)$ Imaginary part $I(0)$	$b(\text{GeV}/c)^{-2}$	Behavior	Structure	Behavior with energy			
p-p	≈ -0.3 from 5 to 27 GeV/c (Ref. 84)	≈ 7 to 10 (Refs. 84, 85)	Shrinks	No (Ref. 86)	Strong energy variation $\frac{d\sigma}{d\Omega}(90^\circ) \approx \exp(-w/a)$ (Ref. 87)			Decreases from $\approx 60\%$ ^b at 4 GeV/c to $\approx 10\%$ at 12 GeV/c (Refs. 8, 88, 89)
p-n	≈ -0.3 between about 7 and 19 GeV/c (Refs. 37, 90)	Similar to p-p ≈ 2 to 7 GeV/c (Ref. 39)	Shrinks	Shoulder $\approx 1 \text{ GeV}/c^2$? (Ref. 39)	Similar to p-p, isotropic about 90° (Ref. 39)		Very sharp peak (see section on charge exchange)	
\bar{p} -p		≈ 12 to 9 12 to 16 GeV/c (Ref. 85)	Expands	Between 1 and 2.5 GeV/c a dip observed at $t \approx -0.45(\text{GeV}/c)^2$ and a bump at $t \approx -0.8(\text{GeV}/c)^2$. Structure seems to vanish rapidly with increasing energy; probably not seen at 4 GeV/c (Ref. 40)				
π^+ -p	≈ -0.10 to -0.07 between about 10 and 14 GeV/c (Ref. 3)	≈ 9 (Ref. 85)	Constant	Between 2 and 4 GeV/c dip at $t \approx -0.7 \text{ GeV}/c^2$ and a bump at $t \approx 1.2 \text{ GeV}/c^2$. Structure disappears quickly with energy. (Refs. 5, 24)	Strong energy variation from the few measured points at very high energy $\frac{d\sigma}{d\Omega}(90^\circ) \approx \exp(-w/a)$ (Ref. 87)		Sharp peak $\approx e^{du}$ $12 \leq d \leq 20$ at 4 GeV/c, $13 \leq d \leq 27$ at 8 GeV/c (Refs. 24, 91)	$P_{\text{max}} \approx + (20 \text{ to } 10\%)$ at 6 to 12 GeV/c [$t \approx -0.20 (\text{GeV}/c)^2$], approaches zero at $t \approx -0.6$ (Ref. 8)
π^- -p	≈ -0.3 to 0.0 between ≈ 8 and 24 GeV/c (Ref. 3)	≈ 9 (Ref. 85)	Constant	As for π^+ -p (Refs. 5, 24)	As for π^+ -p (Ref. 87)		Peak ($\sim 1/5$ of π^+ p) $3.8 \leq d \leq 10$ at 4 GeV/c, $10 \leq d \leq 15$ at 8 GeV/c (Refs. 24, 91)	$P_{\text{max}} \approx -15\%$ at 6 to 10 GeV/c [$t \approx -0.15 (\text{GeV}/c)^2$], approaches zero at $t \approx -0.6$ (Ref. 8)
K^+ -p	0.31 ± 0.21 at 3.5 GeV/c, 0.45 ± 0.14 at 5.0 GeV/c, sign undetermined (Ref. 92)	≈ 4 to 7 3.5 to 5 GeV/c (Ref. 85, 92)	Shrinks				Small indication of backward scattering at 3.5 and 5.0 GeV/c (Ref. 92)	
K^- -p	0.2 ± 0.2 at 4.1 GeV/c, $0.3^{+0.2}_{-0.3}$ at 5.5 GeV/c sign undetermined (Ref. 28) ^a	≈ 9 (Refs. 28, 85)	Constant				No indication of backward scattering at 4.1 and 5.5 GeV/c (Ref. 28)	

a. Rapporteur's note added subsequently: The values given for the ratios of real to imaginary parts of the forward elastic K^- -p scattering amplitude should be 0.1 ± 0.2 at 4.1 GeV/c, and 0.2 ± 0.2 at 5.5 GeV/c. I am grateful to V. T. Cocconi and D. R. O. Morrison for correcting the values given in Ref. 28.

b. Rapporteur's note added subsequently: The preliminary results of the p-p polarization in Fig. 12-A10 (Borghini et al.⁶) have been revised by the authors, resulting in an increase at 6 GeV/c (maximum average level $\approx 12\%$) and a decrease at 12 GeV/c ($\approx 6\%$). The points of Borghini et al. in Fig. 12-A9 should be changed accordingly.

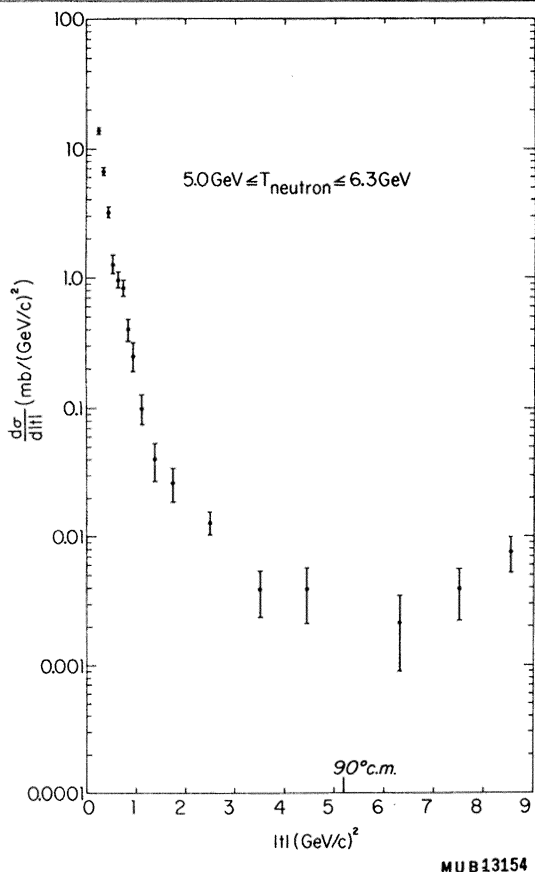


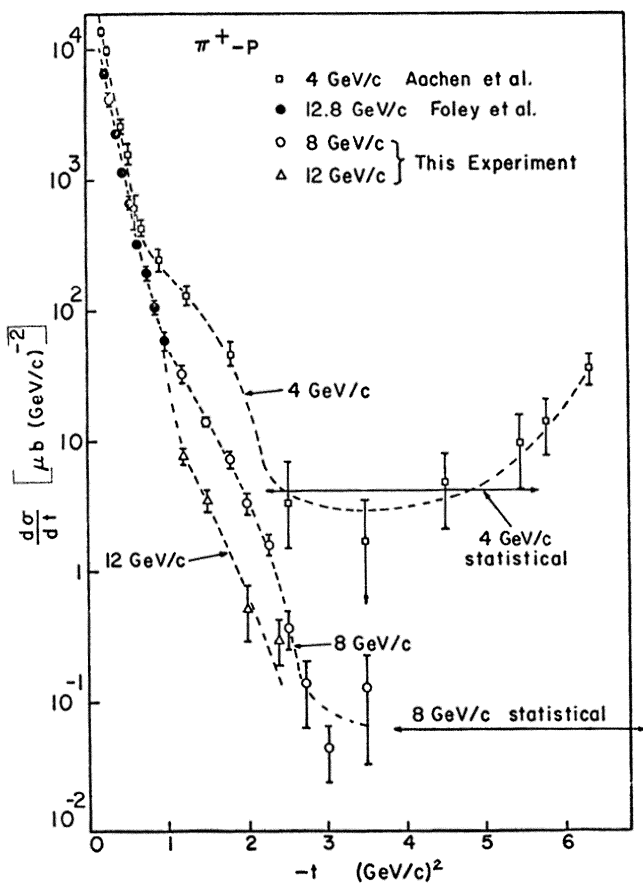
Fig. 12-A3. N-p elastic scattering angular distribution measured by Kreisler et al. (Ref. 39).

rapidly with increasing energy as it does for elastic scattering. Interpretations of the dip and secondary-bump behavior in terms of the passage of a Regge ρ trajectory through spin zero at $t \approx -0.6(\text{GeV}/c)^2$ have been made.^{29, 93}

Measurements of $\bar{p}p$ elastic scattering between 1.0 and 2.5 GeV/c by Barish et al.⁴⁰ are shown in Fig. 12-A6, and exhibit again an energy-dependent dip-bump pattern.

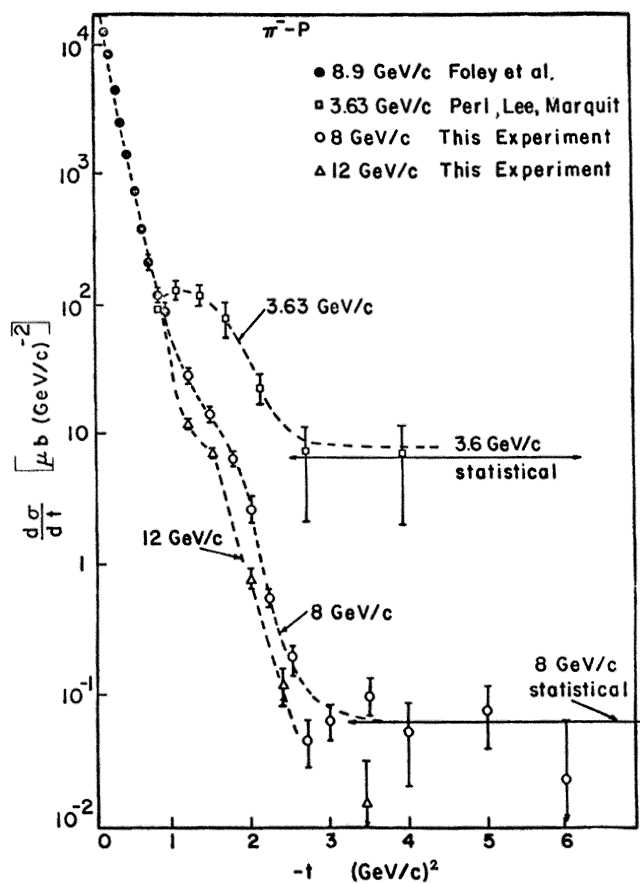
Frautschi⁷ has reviewed the situation in terms of Regge trajectories, concluding that such behavior may be common to many reactions. It is interesting to note, however, that the p-p angular distribution⁸⁶ seems to be very smooth, although the hint of a shoulder (Fig. 12-A3) in the n-p distribution³⁹ may be discussed.

The cross sections for wide-angle scattering ($\approx 90^\circ$ c.m.) for p-p, n-p, and π^\pm -p have a characteristically strong energy dependence,⁸⁷ approximately $\exp(-W/a)$, where W is the total center-of-mass energy. This is represented in Fig. 12-A7 which is a compilation and fit made by G. Cocconi⁸⁷ for the Stony Brook Conference. Such a strong energy dependence has been interpreted as implying a statistical origin of high momentum-transfer scattering. Ericson⁵⁶ has pointed out that a statistical behavior, by analogy with low-energy nuclear physics, should imply strong structure in very-high-energy wide-angle scattering angular distributions. Figure 12-22 shows 16.9-GeV/c proton-proton results of Allaby et al.⁵⁵ plotted logarithmically against the transverse momentum. No structure is evident and the distribution is clearly exponential in transverse momentum, i.e., $d\sigma/d\Omega \approx \exp(-p \sin \theta / \text{constant})$. The constant in the exponent, 225 MeV/c, differs considerably from that found by Orear,⁵⁸ (158 MeV/c)



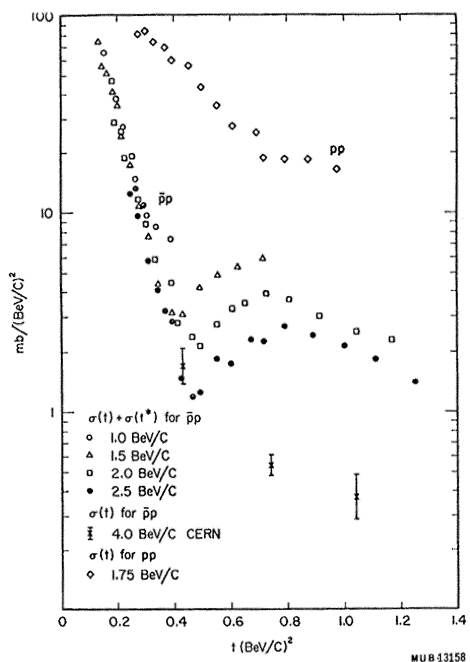
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Fig. 12-A4. π^+ -p elastic scattering distributions between 4 and 12 GeV/c. The data are compiled by Orear et al. (Ref. 24), who gave the points labeled "This Experiment."



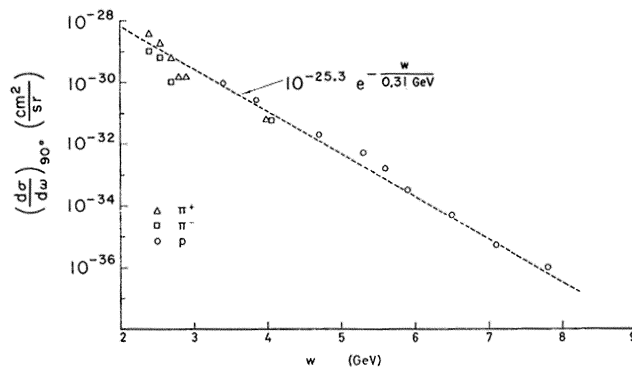
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Fig. 12-A5. π^- -p elastic scattering distributions between 3.6 and 12 GeV/c. The data are compiled by Orear et al. (Ref. 24), who gave the points labeled "This Experiment."



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Fig. 12-A6. \bar{p} -p elastic scattering distribution according to Barish et al. (Ref. 40); also shown for comparison is a p-p distribution at 1.75 GeV/c. The \bar{p} -p points at 4.0 GeV/c are from Czyzewski et al., Proc. Siena International Conference, I, p. 252.



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Fig. 12-A7. Center-of-mass differential cross sections in the 90° region for πp and pp elastic scattering as a function of the total available energy W . This compilation is from a report by G. Cocconi (Ref. 87).

using previous data. In fact it is found that the data of Clyde et al.⁸⁶ at 3, 5, and 7 GeV/c also show different exponential slopes. The lack of Ericson-type structure at 16.9 GeV/c implies that the wide-angle p-p scattering is not dominated by a statistical process, and re-examination in terms of diffraction or potential models seems necessary.

Backward peaks have been found in n-p and π^\pm -p angular distributions. The n-p charge-exchange peak

will be discussed later. The π^\pm -p backward peaks are shown in Fig. 12-A8, from a collection of data made by Orear²⁴ and others.⁹¹ The π^+ -p peak is about five times as high as the π^- -p peak, and rather more sharp. Also in the π^+ -p distribution there appears to be a dip at $u \approx -0.2$ (GeV/c)², but it should be remarked that the graph shows a collection from different experiments and that no single experiment has yet surveyed the whole region between $u=0$ and -1 (GeV/c)². Bubble chamber work on K^+ -p scattering⁹² between 3.5 and 5.0 GeV/c indicates some backward scattering, but the number of events is too small to say anything about structure; similar measurements on K^- -p scattering²⁸ at 4.1 and 5.5 GeV/c show no evidence of backward scattering ($\leq 2 \mu\text{b}$ cross section beyond $\theta = \pi/2$).

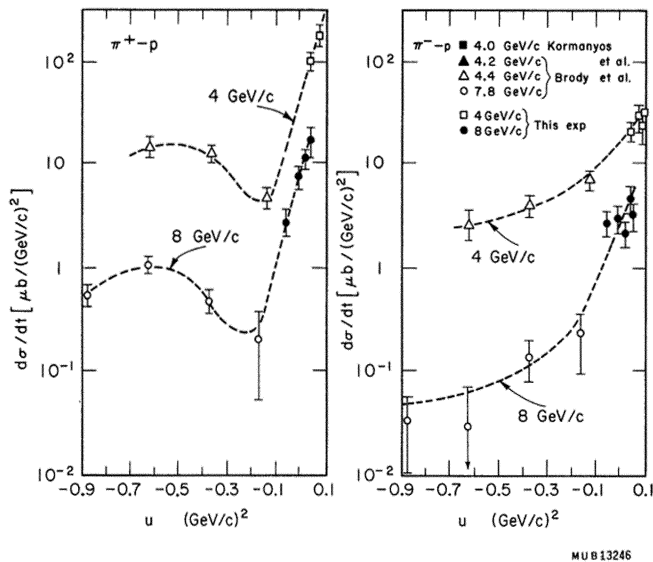


Fig. 12-A8. Pion-proton backward elastic scattering distributions at 4 and 8 GeV/c; see Refs. 24 and 91.

The study of spin effects in high energy scattering has been made feasible by the introduction of polarized proton targets. Figure 12-A9 shows the trend of the maximum polarization found in p-p scattering at lower energies together with some higher-energy points from Dubna,⁸⁸ from Berkeley,⁸⁹ and (at this Conference) from CERN.⁸ The peak in the figure ($\approx 60\%$) occurs at the point where the p-p total cross section is rising to its maximum. The polarization falls to $\approx 5\%$ at 12 GeV/c, and it will be interesting to see how it behaves at even higher momentum. Figure 12-A10 shows the new p-p data of Borghini et al.,⁸ illustrating the angular distributions of the polarization between 6 and 12 GeV/c. There is considerable difference between the CERN and Berkeley values around 6 GeV/c, possibly due to systematic uncertainties in target polarization.

Figures 12-3 and 12-4 show new data of Borghini et al.⁸ on the polarization found in π^- -p and in π^+ -p scattering. The effects are large and there seems to be some difference between the π^+ and the π^- -p behavior. It will be important to shrink the error bars and uncertainties in order to study this difference.

2. Charge-Exchange Scattering

A qualitative survey of experimental data available on "elastic" charge-exchange processes is given in Table 12-AII and some accompanying remarks as follows:

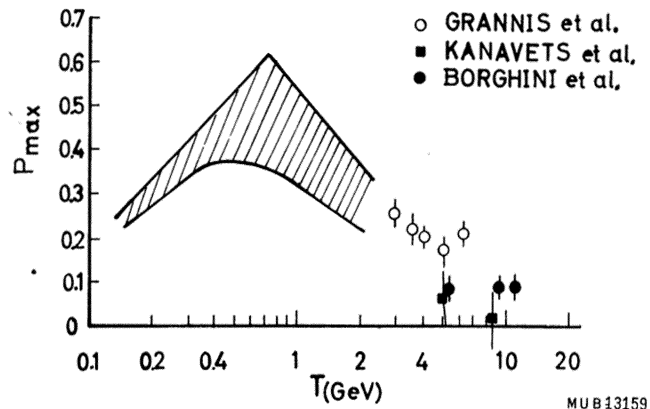


Fig. 12-A9. Maximum value of polarization found in p-p elastic scattering; the cross hatched region shows the trend given by the lower-energy experiments, the higher-energy points are from Refs. 8, 88, 89.

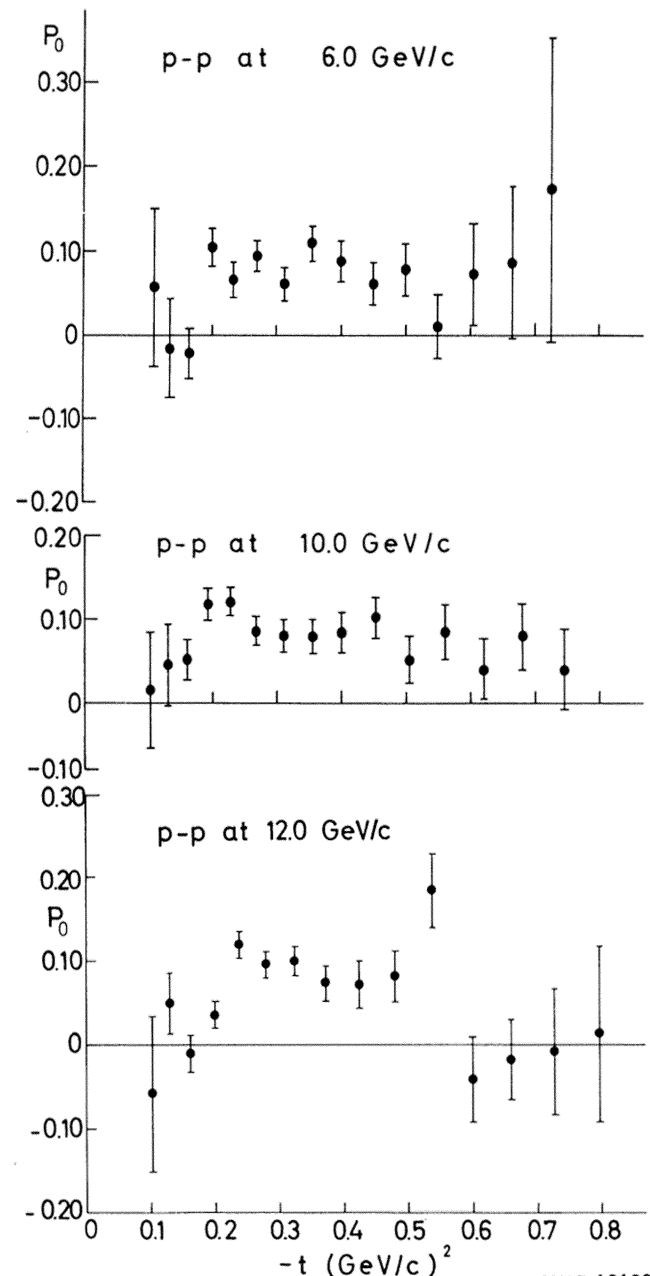


Fig. 12-A10. The polarization parameter P_0 versus the invariant four-momentum transfer t in pp scattering, measured by Borghini et al. (Ref. 8).

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Table 12-AII. Descriptive survey of data on high-energy charge-exchange processes.

Reaction	Structure in angular distribution	Forward peak $\approx e^{bt}$ $b(\text{GeV}/c)^{-2}$	Shrinking	$\frac{d\sigma(0)}{dt} >$ Optical-theorem value	Variation of $\sigma_{\text{tot}} \propto (\text{momentum})^{-n}$	Cross Sections Momentum σ_{tot} (GeV/c) σ_{tot} (μb)	Polarization effects
$p + n \rightarrow n + p$	Very sharp forward peak (Ref. 94)	For forward peak $ t \leq 0.02(\text{GeV}/c)^2$, $b \approx 50$, for larger $ t $, $b \approx 5$ (Ref. 94)	yes (between 2 and 8 GeV/c (Ref. 94))	yes (Ref. 94)	Rapid decrease	3.0 1100±25 3.67 430±16 8.00 60±30 (Refs. 94, 95)	
$\bar{p} + p \rightarrow \bar{n} + n$	No (Ref. 43)	≈ 4.5 (Ref. 43)	no (5 to 9 GeV/c (Ref. 43))	Not clear (Ref. 43)	$\approx p^{-1.5}$ (Refs. 43, 96)	5.0 598±86 ⁻¹ 6.0 563±82 7.0 373±54 9.0 284±41 (Ref. 43)	
$\pi^- + p \rightarrow \pi^0 + n$	Forward dip. Minimum at $t \approx -0.6 (\text{GeV}/c)^2$, bump at $t \approx -1 (\text{GeV}/c)^2$ (Ref. 97)	≈ 11 (Ref. 97)	yes (Ref. 97)	Yes (Ref. 97)	$\approx p^{-1.3}$ (Ref. 97)	3.67 191±18 4.83 128±15 5.85 96±5 13.3 37±2 18.2 25±3 (Ref. 98)	$\approx +15\pm3\%$ at 6 GeV/c $\approx +20\pm7\%$ at 11 GeV/c Maximum at $t \approx -0.15 (\text{GeV}/c)^2$ (Ref. 11)
$K^- + p \rightarrow \bar{K}^0 + n$	Forward dip (Ref. 30)	≈ 5 (Ref. 30)	yes (Ref. 30)	Probably not (Ref. 30)	$\approx p^{-1.0}$ (Ref. 30)	5.0 124±20 7.0 94±10 9.5 70±10 (Ref. 30)	

a. $p + n \rightarrow n + p$

Figure 12-A11 shows the 8-GeV/c nucleon charge-exchange data of Manning et al.⁹⁴ and illustrates the very sharp forward peaks (or backward n-p elastic scattering peak) followed by a flatter distribution. The shape of the angular distribution remains similar down to 1 to 2 GeV/c. The sharpness of the forward peak suggests a long-range force, possibly explicable as a one-pion-exchange effect. A very strong energy dependence is observed in this reaction; the numbers that are given in the table are susceptible to large systematic errors due to normalization difficulties. Comparing the forward cross section with the optical-theorem value seems to show that there is a difference in the real parts of the p-p and p-n elastic amplitudes or spin dependence or both. Figures 12A-1 and 12-17 indicate that the phases of the p-p and p-n amplitudes are similar, but it is hard to make any firm conclusion about spin effects in small-angle scattering. There is clearly room for new n-p or p-n experiments.

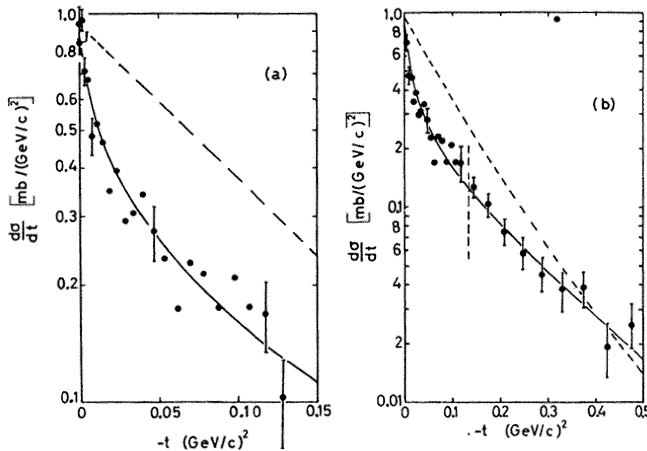


Fig. 12-A11. Differential cross-section for proton-neutron charge exchange at 8 GeV/c (Manning et al., Ref. 94): (a) covers laboratory angles 0 to 45 mrad; (b) 0 to 90 mrad. The broken line shows the trend of the p-p elastic cross section at 8.9 GeV/c.

b. $\bar{p} + p \rightarrow \bar{n} + n$

This process has been measured recently by Astbury et al.⁴³ at 5, 6, 7, and 9 GeV/c, using a magnetic spark chamber setup. Figure 12-18 shows new results, and it is evident that the distributions of $d\sigma/dt$ as a function of t are well represented by exponentials $\sim e^{bt}$. It is found that b is constant

over the momentum range covered, that is, there is no shrinking. Figure 12-A12 gives a representation of the total cross section as a function of momentum;^{43, 96} lower-energy data are included. The trend above 2 GeV/c is essentially $\sim p^{-1.5}$.

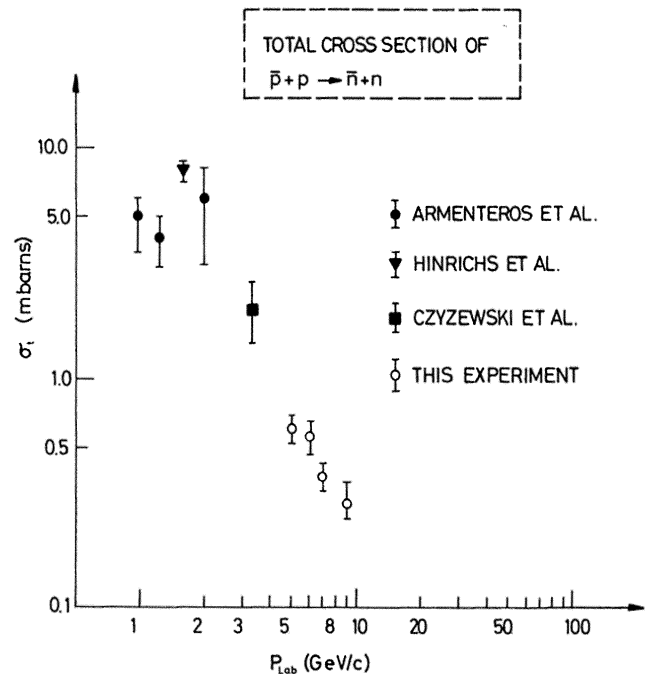


Fig. 12-A12. The total cross section for $\bar{p} + p \rightarrow \bar{n} + n$ as a function of momentum. "This Experiment" signified the work of Astbury et al. (Ref. 43); the other data are from Ref. 96.

c. $\pi^- + p \rightarrow \pi^0 + n$

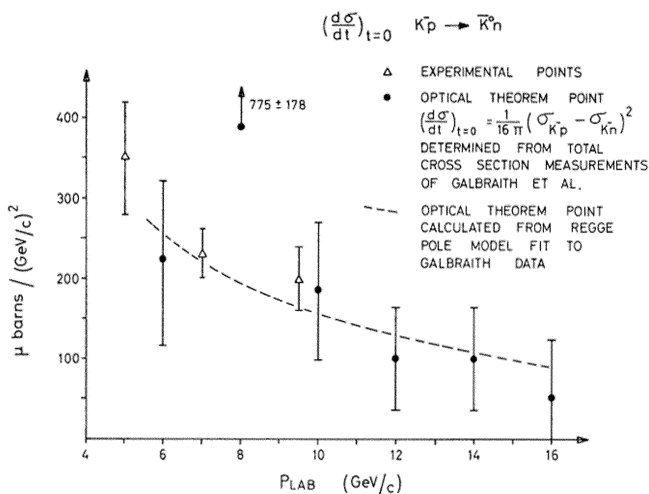
The results of the extensive measurements by Borgeaud et al.⁹⁷ are shown in Fig. 12-5; the essential features are noted in Table 12-AII. The forward cross sections exceed the optical-theorem value, indicating sizable real amplitudes. As noted above for elastic scattering, the $0.6-(\text{GeV}/c)^2$ dip is very suggestive of the operation of a ρ Regge pole passing through spin zero, and indeed it was the π^-p charge-exchange data which greatly stimulated thought^{29, 93} in this direction. A single ρ -pole model can be made to fit the data very well. New data of Bonamy et al.¹¹ on $\pi^- + p \rightarrow \pi^0 + n$, with a polarized target, give a large polarization parameter at 6 and 11 GeV/c. Figure 12-7 shows the new results, and the table gives average values.

Momentum (GeV/c)	P(t)	
	0.015 < t < 0.24	0.04 < t < 0.24
6	+ 14 ± 3	+ 16 ± 3
11	+ 19 ± 6	+ 24 ± 27

P(t) is quite large, and does not (within errors) decrease with increasing momentum. This is difficult to explain on the basis of simple Regge pole models, and may indicate the necessity for the inclusion of absorption effects or the operation of cuts in the complex angular-momentum plane.

d. $K^- + p \rightarrow \bar{K}^0 + n$

Astbury et al.³⁰ have measured this process at 5, 7, and 9.5 GeV/c with the CERN magnet spark chamber apparatus, and the angular distributions are shown in Fig. 12-15. There seems to be a forward dip, as for $\pi^-p \rightarrow \pi^0n$, and an exponential drop, after which there is the suggestion of a flattening, although a dip cannot be excluded. Figure 12-A13 gives the values of the forward differential cross section together with values obtained from the optical theorem and the measured K-nucleon total cross sections. Evidently the forward cross sections do not deviate greatly from the optical-theorem values.



MUB 13165

Fig. 12-A13. Comparison of forward K^- -p charge-exchange cross sections of Astbury et al. (Ref. 30) with optical-theorem values obtained from total-cross-section measurements.

In conclusion one may remark that the experiments described above are difficult, the cross sections at high energy become rather small, and in the case of K^- and \bar{p} the beam fluxes are low. It seems that considerable advances in technique have been made in the last few years to allow such measurements to be made at all.

References and Footnotes

(Note that this list is a continuation of that for the Rapporteur's paper)

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