Comparison of Exclusive Reactions at Large t

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Cross sections or upper limits are reported for twelve meson-baryon and two baryon-baryon reactions for an incident momentum of 9.9 GeV/c, near 90° c.m.: $\pi^{\pm}p \rightarrow p\pi^{\pm}, p\rho^{\pm}, \pi^{+}\Delta^{\pm}, K^{+}\Sigma^{\pm}, (\Lambda^0/\Sigma^0)K^0$; $K^{\pm}p \rightarrow pK^{\pm}$; $p^{\pm}p \rightarrow pp^{\pm}$. By studying the flavor dependence of the different reactions, we have been able to isolate the quark-interchange mechanism as dominant over gluon exchange and quark-antiquark annihilation.

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In a single experiment, with a single experimental arrangement, we have measured or set upper limits on twelve meson-baryon and two baryon-baryon cross sections in a small angular region about $\theta_{c.m.} = 90°$. The reactions measured at 9.9 GeV/c incident momentum ($s = 19.5$ GeV^2) included

$$\pi^{\pm}p \rightarrow p\pi^{\pm}, \quad (1),(2)$$

$$K^{\pm}p \rightarrow pK^{\pm}, \quad (3),(4)$$

$$\pi^{\pm}p \rightarrow p\rho^{\pm}, \quad (5),(6)$$

$$\pi^{\pm}p \rightarrow \pi^{+}\Delta^{\pm}, \quad (7),(8)$$

$$\pi^{\pm}p \rightarrow K^{+}\Sigma^{\pm}, \quad (9),(10)$$

$$\pi^{-}p \rightarrow \Lambda^0K^0, \Sigma^0K^0, \quad (11),(12)$$

$$p^{\pm}p \rightarrow pp^{\pm}. \quad (13),(14)$$

The experiment, carried out at the Brookhaven Alternating-Gradient Synchrotron (AGS), was designed to study the quark-flavor dependence of large-angle two-body scattering in the hard-scattering domain where elastic cross sections show a power-law energy dependence at fixed angle. The observed energy dependence follows the expectations from very general dimensional-scaling arguments.[1] The reactions have $-t = 9$ (GeV/c)^2, corresponding to a scattering distance of 0.2 fm, so that one expects such processes to probe the interactions between the constituents of the hadrons.[2]

The major features of the apparatus have been describe in our publication concerning $\pi^{-}p$ elastic scattering and exclusive ρ^{-} production.[3] A magnetic spectrometer with a horizontal acceptance of $\pm 2.5°$ at 22° in the laboratory accurately measured the direction and momentum of the stable, positive particle in the final state. This range of angles approximately corresponds to $|\cos\theta_{c.m.}| < 0.12$. All the results given correspond to a more restrictive angular region ($-0.05 < \cos\theta_{c.m.} < 0.10$) where all fourteen reactions have good acceptance. An array of three large-area proportional chambers (seven sensing planes) provided acceptance from 5° to 75° for the recoil particles. At $\theta_{c.m.} = 90°$, the azimuthal acceptance for the spectrometer was $\pm 7.5°$ and the azimuthal acceptance in the side array was $\pm 20°$. Two threshold Cherenkov counters filled with Freon 12 to thresholds of $\gamma = 9$ and 21 were used to identify pions, kaons, and protons in the spectrometer. The trigger requirement was based solely on a p_t measurement in the magnetic spectrometer, with uniform acceptance for all particles in the spectrometer within 90% of the elastic momentum. The acceptance fell off to zero at about 65% of the elastic momentum.

There were two data-taking periods. During the first period 4.7×10^{12} incident negative particles were recorded with only a threshold counter to identify the incident pions. During the second period, two differential Cherenkov counters were installed. One counter identified pions and kaons, and the other identified kaons and protons. For the negative run, 6.0×10^{12} incident particles were recorded with a $\pi^{-}:K^{-}:p^{-}$ ratio of 98:1.1:0.34. In the positive run, 3.4×10^{12} particles were recorded, and the ratio of $\pi^{+}:K^{+}:p$ was 43:1.3:55.

The reactions were identified by a combination of beam and spectrometer-arm Cherenkov tags, the three kinematic constraints for elastic events, the side missing mass, and topological constraints such as the presence of a vee. With use of kinematic constraints, a large sample of pp elastic events were gathered; the extraction of 700 $\pi^{-}p$ elastic events was described previously.[3] To extract the π^+p signal, first the π^+p and pp elastic events were separated from the inclusive background by a missing-mass cut. The pp elastic background was minimized by our requiring identification of (1) a spectrometer π^+, or (2) a spectrometer proton and an incident π^+. A fit to opening angle yielded 500 π^+p elastic events.

The separation of $K^\pm p$ and $\bar{p}p$ elastic events from πp elastic events was more difficult as the kaons and $\bar{p}$ were only a small fraction of the incident particles. The kinematic separation of Kp from πp elastic events was comparable to our experimental resolution. The requirement of double identification of beam kaons and no additional beam track within a 10-ns time window limited the πp contamination. Figures 1(a)-1(c) show missing-mass distributions for $K^+p \to K^+X$, $K^+p \to pX$, and $K^-p \to pX$, after cuts on beam and spectrometer Cherenkov response, coplanarity, and elastic opening angle. In 1(a) no π^+p and two pp elastic events [$(\mathrm{MM})^2 = 1.15 \pm 0.15$ GeV^2 for the $Kp \to KX$ hypothesis, where $(\mathrm{MM})^2$ is square of missing mass] were expected; of the 21 events in 1(b) within the $(\mathrm{MM})^2 = 0$–1 GeV^2 region, ten pp elastics [$(\mathrm{MM})^2 = 0.52 \pm 0.15$ GeV^2] and no π^+p elastic events were expected. The final K^+p elastic sample was 14 ± 4 events, selected by a χ^2 cut combining opening angle and missing mass; no background and 70% of the K^+p elastics would survive the χ^2 selection. In 1(c), two π^-p elastics were expected [$(\mathrm{MM})^2 = 0.16 \pm 0.15$ GeV^2], giving a final sample of 5^{+4}_{-3} K^-p elastic events. One possible $\bar{p}p$ elastic event with $(\mathrm{MM})^2 = 0.66$ GeV^2, 1.5σ from the proton mass, was found, giving an upper limit for $\bar{p}p$ elastic events based on 3.7 events.

Reactions (5) through (10) were identified by a combination of Cherenkov-counter identification of the particle type in the spectrometer and a determination of the missing mass of the recoil particle. These reactions are also distinguished by a single charged particle from the decay of the recoil particle such as $\Delta^+ \to \pi^+ n$ or $\to p\pi^0$. A single recoil-array track cut was imposed to enhance the exclusive signal over the multiparticle inclusive background. Corresponding distributions for reactions (5) and (7)-(9) are shown in Fig. 1. [Reaction (6) is shown in Ref. 3.] Cross sections or upper limits were determined by our fitting the missing-mass-squared distribution by a power series for the inclusive background, and Gaussian(s) for the exclusive peak(s). The parameters of the Gaussians were a combination of the resolution width (measured in the elastic channel) plus decay widths and masses from Aguilar-Benitez *et al.*[4] Various fits were performed to demonstrate the existence of the signals for reactions (5) and (7). The masses and widths of the Gaussians were varied and fitted within errors to the expected values. The probability that either reaction is a statistical fluctuation is less than 0.002. In the ρ^- analysis, the decay tract was used to determine the ρ spin alignment, as described in Ref. 3. In the Δ^+ analysis, the decay track was used to verify that the

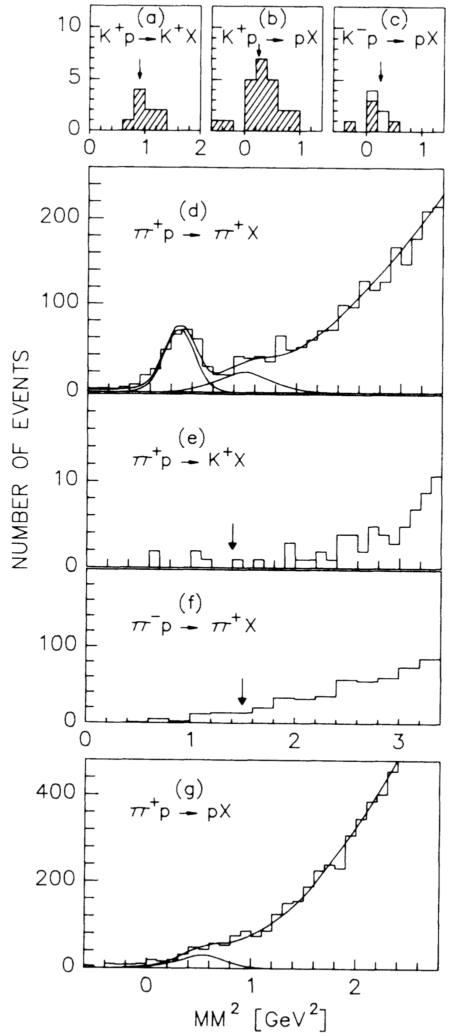

FIG. 1. Missing-mass distributions for the reactions. In (a)-(c) the position of the Kp elastic peak is indicated. Beam kaons, coplanarity, and elastic opening angle were required; the shaded events require also no beam pion or proton tag. In (d) a Δ^+ (1232) resonance is included in the fit, as well as the elastic peak and inclusive background. Arrows in (e) and (f) indicate where Σ^+ and Δ^- signals should appear. In (g) elastics were removed and a ρ^+ resonance is included in the fit.

branching ratio, $(\Delta^+ \to p\pi^0)/(\Delta^+ \to n\pi^+)$, was consistent with the expected value of 2. A search for the reaction $\pi^-p \to \pi^+\Delta^-$ yielded no events above background [Fig. 1(f)].

To search for the reaction $\pi^+p \to K^+\Sigma^+$, the data were cut on events with an identified beam pion, an identified spectrometer kaon, and an angular separation from elastic kinematics in the recoil array of > 40 mrad, to exclude π^+p elastics. The recoil array cut was required since the $(\mathrm{MM})^2$ for misidentified π^+p elastics was close to the $(\mathrm{MM}_{\Sigma^+})^2$. The vertex had to be consistent with the expected decays. In this sample, there was a pion contamination from $\pi^+p \to \pi^+X$ due to inefficiency of the spectrometer low-pressure Cherenkov counter. By our invoking a further cut on the pulse height in the high-pressure Cherenkov counter signals ($< \frac{1}{2}$ pion pulse height), 80% of the pions were rejected while 100% of the kaons were accepted. The resulting $(\mathrm{MM})^2$ distribution in Fig. 1(e) shows no excess of events above background at $(\mathrm{MM}_{\Sigma^+})^2$. Similar methods were employed in the determination of the upper limit to $\pi^- p \rightarrow K^+\Sigma^-$.

The reaction $\pi^- p \rightarrow \Lambda^0 K^0$ was identified in the spectrometer by a momentum-analyzed proton from the decay $\Lambda^0 \rightarrow p\pi^-$, and a track in the forward chambers from the decay π^-. After the assumption that the Λ^0 decayed with the proton forward (75% acceptance), the Λ^0 momentum and direction were reconstructed. Candidate $\pi^- p \rightarrow \Lambda^0 K^0$ events must have had a good beam vertex (<12 mm rms) within the target (100% acceptance), a decay distance greater than 8 cm (85% acceptance), and a track separation greater than 35 mrad (83% acceptance). In the recoil direction we searched for events which had a missing mass near that of the kaon, and which had either no tracks indicating a K_L^0 or $K_S^0 \rightarrow 2\pi^0$, or a two-particle vertex indicating a $K_S^0 \rightarrow \pi^+\pi^-$. One event was found corresponding to the upper limit at 90% confidence level given in Fig. 2. In the reaction $\pi^- p \rightarrow \Sigma^0 K^0$, the photon from the decay $\Sigma^0 \rightarrow \Lambda^0 + \gamma$ was not detected, leading to an upper limit 3 times larger.

The acceptance of the apparatus was extensively investigated by Monte Carlo calculations which included measured inefficiencies. The efficiencies of the detectors were checked by internal consistency and by use of the over-constrained elastic reactions. The acceptance of the apparatus in azimuth varied from 0.011 for reaction (9) to 0.043 for reaction (2). Corrections were made for particle absorption (0.85–0.90), selection cuts for particle identification (0.50–0.75) and kinematic selection (0.75–0.89), and trigger efficiency (0.63–0.71).[8]

Figure 2 shows a plot of all the meson-baryon and baryon-baryon reactions measured in this experiment along with some elastic cross sections from other experiments scaled to 9.9 GeV/c with the dimensional scaling rules.[1] The pp and $\pi^- p$ elastic cross sections are in good agreement with previous measurements.[6,7] However, there is a factor of 2.2 discrepancy between our $\pi^+ p$ result and that of Baglin *et al.*[5] Similarly, our $K^+ p$ cross section is larger than their upper limit.[5] The source of this disagreement is not known.

A variety of theoretical approaches has been used to describe two-body scattering at large angles, including phenomenology and a difficult first-order perturbative QCD (PQCD) calculation which is in progress.[9] Statistical models, where all SU(3) amplitudes are assumed to be equal, lead to similar cross sections for the different reactions.[10] These are clearly ruled out by variations in measured cross sections of greater than 10.

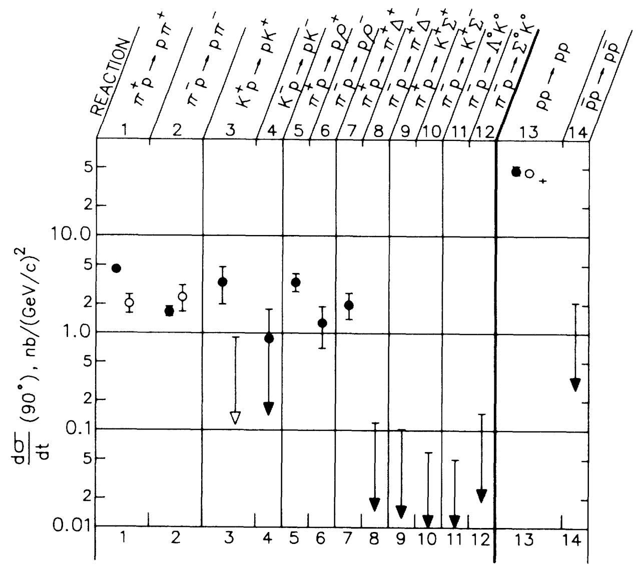

FIG. 2. The cross section and upper limits (90% confidence level) measured by this experiment are indicated by the filled circles and arrowheads. Values from this experiment and from previous measurements represent an average over the angular region of $-0.05 < \cos\theta_{\mathrm{c.m.}} < 0.10$. The other measurements were obtained from the following references: $\pi^+ p$ and $K^+ p$ elastic, Ref. 5; $\pi^- p \rightarrow p\pi^-$, Ref. 6; $pp \rightarrow pp$, Ref. 7: Allaby, open circle; Akerlof, cross. Values for the cross sections [(Reaction), cross section in nb/(GeV/c)^2] are as follows: (1), 4.6 ± 0.3; (2), 1.7 ± 0.2; (3), 3.4 ± 1.4; (4), $0.9^{+0.7}_{-0.9}$; (5), 3.4 ± 0.7; (6), 1.3 ± 0.6; (7), 2.0 ± 0.6; (8), <0.12; (9), <0.1; (10), <0.06; (11), <0.05; (12), <0.15; (13), 48 ± 5; (14), <2.1.

A second approach assumes that exclusive reactions at large s and t occur through the hard scattering of some of the valence quarks. The quarks that do interact may do so freely (involving a PQCD calculation) or may be exchanged as s- or t-channel mesons or baryons. The calculations of Nardulli, Preparata, and Soffer are the most detailed.[11] When they assume the dominance of meson exchange over baryon exchange, they predict equal $\pi^{\pm} p$ elastic cross sections and no $\pi^+\Delta^+$. Both predictions derive from equal s- and t-channel exchange amplitudes, with destructive interference for $\pi^+\Delta^+$. Our results are in disagreement with the model's predictions.

In the PQCD approach of Farrar,[9] it is assumed that all the valence quarks undergo hard scattering, which is the basis for the application of dimensional scaling to these reactions. The reaction amplitudes are written in terms of four major classes corresponding to gluon exchange (GEX) between the hadrons, quark interchange (QIN), quark annihilation (ANN), and a combination of interchange and annihilation (COM) (Fig. 3). The different reactions involve different quark diagrams, and this is illustrated in Fig. 3. By comparing, for example, proton-proton and antiproton-proton elastic scattering at 90°, one can see that QIN is strongly favored. If gluon

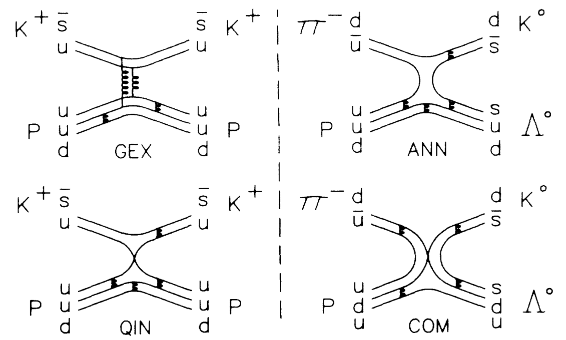

FIG. 3. The four broad classes of quark-flow diagrams for pseudoscalar-meson–baryon scattering are gluon exchange (GEX), quark interchange (QIN), quark annihilation (ANN), and combined quark interchange and annihilation (COM). For example, in K^+p elastic scattering, only GEX and QIN contribute, whereas in $\pi^-p\rightarrow\Lambda K^0$, only ANN and COM contribute.

exchange dominated, the cross sections would be equal. As can be seen in Fig. 2, the cross sections for the reactions which do not include QIN are small.

Domination by QIN amplitudes would have several other ramifications which can be seen in the data: For example, π^+p reactions should be favored over π^-p because of the larger number of combinations for u-quark interchange between the π^+ and proton.[12] To make a more quantitive comparison, it is necessary to limit the set of amplitudes which contribute to the reactions. If reaction amplitudes are extracted from the helicity-conserving fraction of the cross sections,[13] the amplitudes satisfy the condition QIN/ANN > 10 and QIN/GEX > 2.5.[8] Helicity nonconservation between initial and final states was observed in the $\pi^-p\rightarrow\rho^-p$ data.[3] However, it has been argued that this effect may be due to an interference term and that helicity-nonconserving amplitudes may be relatively small.[13]

The fourteen reaction cross sections presented here clearly indicate that exclusive reactions are dominated by quark interchange.[14] It will be very interesting to see if more refined theoretical calculations indicate the same underlying simplicity.

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