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Highlights of the reaction $\pi^- p \to \pi^- \pi^+ n$ at 100 and 175 GeV/c

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We present a summary of the physics results from an experimental study of the reaction $\pi^- p \to \pi^- \pi^+ n$ at 100 and 175 GeV/c incident-beam momentum. Our data show the continuing dominance of one-pion exchange in these reactions with the characteristic $1/p_{\rm lab}{}^2$ momentum dependence. We extract the pion Regge trajectory from our data on $\pi^- p \to \rho^0 n$ and study the zero structure of the $\pi\pi$ differential cross section up to $s_{\pi\pi} = 12$ GeV^2.

This paper summarizes the main results from an experiment which measured the reaction $\pi^- p \to \pi^- \pi^+ n$ at beam momenta of 100 and 175 GeV/c. A complete discussion of our data may be found in another paper[1] and the theses of Fredericksen[2] and Stampke.[3] The experiment, E110, used a multiparticle spectrometer set up to the M6W beam line at Fermilab. This spectrometer was originally used to study jet production (E260) in high-transverse-momentum collisions.[4] The data reported here were taken simultaneously with those for the reactions $\pi^- p \to K\bar{K}\pi X$ (Ref. 5), $\pi^- p \to A_2^- p$ (Ref. 6), and $K^- p \to K^{*-} p$ (Ref. 7).

The experimental apparatus is described in detail elsewhere.[1-7] The final-charged-particle momenta were analyzed by a large-aperture superconducting dipole magnet and a combination of proportional and spark wire chambers. The trigger for the reaction

$$\pi^- p \to \pi^- \pi^+ n \tag{1}$$

required two and only two hits in several of the proportional wire chambers [combined with the requirement of no signal in neutral-particle (photon) detectors placed near the target]. The recoil neutron was not detected but rather was identified by a missing-mass technique. The secondary-particle species were identified by two large atmospheric-pressure segmented Cherenkov counters placed after the magnet.

After a careful analysis[1-3] to ensure clean data samples, we obtained about 10 000 events of reaction (1) at each of our two beam momenta. The acceptance in final-state $\pi^- \pi^+$ mass extends to about 3 (3.5) GeV at 100 (175) GeV. All data presented have been corrected for known experimental biases and acceptance losses. The uncertainty in these corrections is substantially less than the statistical errors for all distributions presented here. The corrections were all rather uniform as a function of the dynamical variables with the exception of that for the geometric acceptance of very asymmetric decays of the $\pi^- \pi^+$ system when one of the pions is at large angles and has low momentum. This effect is negligible at the ρ^0 mass but can be seen as a loss at low $t_{\pi\pi}$ in the distributions of Fig. 4 at high $\pi\pi$ mass.

Our experiment is able to probe both the dynamics of the two-body peripheral process $\pi^- p \to \rho^0 n$ and the nature of the low-energy $\pi^+ \pi^-$ scattering amplitude. The extension to high energy of earlier measurements is important for several reasons. The two-body description becomes extremely clean with no contamination from competing processes such as $\pi^- p \to \pi^- N^{*+}$. Further, the asymptotic Regge theory becomes reliable at high energies. Finally, it becomes possible to produce high-mass $\pi^- \pi^+$ states in the region (small momentum transfer t_{pn}) where the interpretation as $\pi\pi$ scattering becomes possible.

Figure 1 shows the conventional (Regge) particle-exchange interpretation of the reaction (1). It also indicates

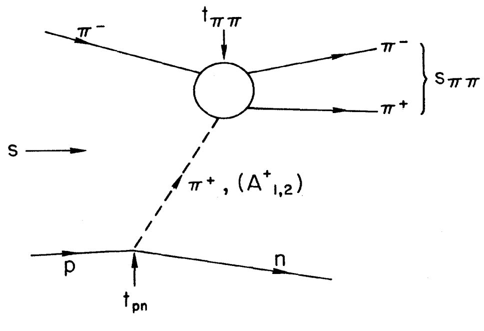

FIG. 1. The Regge-exchange diagram for the peripheral process $\pi^- p \to \pi^- \pi^+ n$ and the invariants s, $s_{\pi\pi}$, $t_{\pi\pi}$, and t_{pn}.

the invariants $s_{\pi\pi} = m_{\pi\pi}{}^2$ and $t_{\pi\pi}$ for the $\pi\pi$ scattering interpretation as well as the overall variables s and $t_{pn} \approx -p_\perp{}^2$ of significance for the two-body dynamics. At low $\pi\pi$ mass the process (1) is dominated by ρ^0 production and it becomes appropriate to describe (1) in terms of the two-body process

$$\pi^- p \to \rho^0 n \quad . \tag{2}$$

We define the ρ^0 by the same $\pi\pi$-mass cut, $0.7 \leq m_{\pi\pi} \leq 0.85$ GeV, used in Ref. 8, and in Fig. 2 we compare the differential cross section for (2) at 17.2, 100, and 175 GeV. We find a similar shape at all energies and the cross section roughly scales in the $p_{\mathrm{lab}}{}^{-2}$ fashion expected from one-π exchange.

We can use the measured density-matrix elements of the ρ^0 to break up the cross section into the contributions of different exchanges and find the (effective) Regge trajectories as a function of t for each component. There are three contributions C_i. C_N is found from $(\rho_{11} + \rho_{1-1}) d\sigma/dt$ and corresponds to natural-parity (A_2) exchange. C_{U0} is

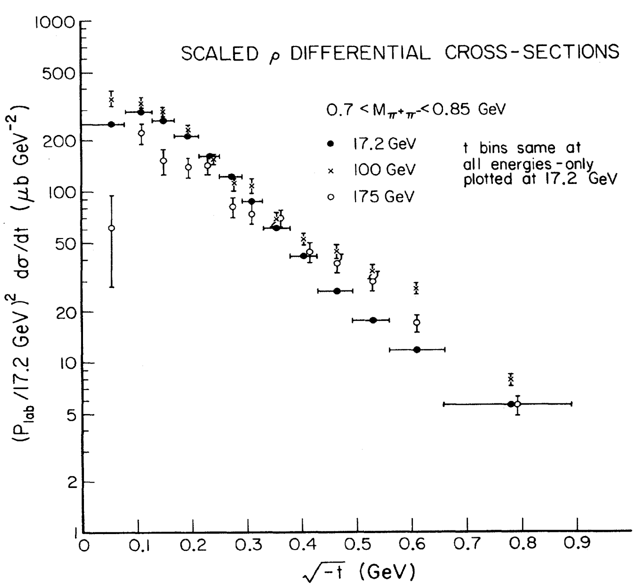

FIG. 2. The differential cross sections vs $(-t_{pn})^{1/2}$ for $\pi^- p \to \rho^0 n$ at 17.2 GeV (Ref. 8), 100, and 175 GeV (this experiment). The cross sections are scaled by $(p_{\mathrm{lab}}/17.2\ \mathrm{GeV})^2$.

found from $\rho_{00} d\sigma/dt$ and corresponds to the helicity-zero unnatural-parity exchange (A_1 and dominantly π). C_{U1} is found from $(\rho_{11} - \rho_{1-1}) d\sigma/dt$ and corresponds to the helicity-one coupling of the unnatural-parity contribution. Further, one can evaluate the decomposition in any Lorentz frame L, which we denote by a superscript. We consider the two conventional frames; s-channel (or helicity frame, denoted by $L = s$) and t-channel (or Gottfried-Jackson frame, denoted by $L = t$). For each of the contributions we can find a t-dependent effective Regge trajectory $\alpha_i^L(t)$. These are shown in Fig. 3 together with the overall trajectory $\alpha_{\mathrm{tot}}(t)$ found from the s dependence of $d\sigma/dt$. The natural-parity-exchange contribution C_N is essentially independent of the Lorentz frame. The corresponding trajectory $\alpha_N(t)$ is near zero at small t as is expected from the usual interpretation in terms of the dominance of absorptive corrections to the π-exchange contribution.[9,10] At larger $-t_{pn}$ we see $\alpha_N(t)$ rising above zero, which can be understood from A_2 exchange whose expected trajectory is marked in Fig. 3(b). $\alpha^s_{U0}(t)$ and $\alpha^t_{U0}(t)$ are quite different, with a trajectory that reflects the dominance of π exchange. We do *not* see convincing evidence for the Regge nature of the pion; conventional wisdom[11] would expect a trajectory

$$\alpha_\pi(t) \sim 0.9(t - m_\pi{}^2) \quad , \tag{3}$$

which is marked in Fig. 3. Our data agree with (3) for $-t_{pn} \lesssim 0.2$ GeV^2 in the t-channel frame but lie significantly above the form (3) at larger $-t_{pn}$ for $\alpha^t_{U0}(t)$ and at all t_{pn} for the s channel. We note that $\rho_{00} d\sigma/dt$ is dominated by an amplitude corresponding to one unit of spin flip. It has been thought for a long time that such amplitudes would have small absorptive corrections and so provide clean determinations of Regge trajectories. For instance, the spin-flip-dominated reactions $\pi^- p \to \pi^0 n$, $\pi^- p \to \eta n$, and $K^- p \to \bar{K}^0 n$ show linear trajectories and little evidence for absorptive effects out to far larger $-t_{pn}$ values than those where our data in Figs. 3(c) and 3(d) show deviations from the linear trajectory.[12] In an absorptive approach, one would expect the s-channel trajectories to show better agreement than the t channel with the simple pole prediction. Our data contradict this and suggest that either the linear trajectory seen for the ρ, A_2, f, and ω poles is invalid for the π, or the simple absorption model is inadequate to calculate the (Regge-cut) corrections to the π Regge pole. The unselected data give an $\alpha_{\mathrm{tot}}(t)$ in Fig. 3(a) which is quite similar to $\alpha_N(t)$; this reflects the dominance of the natural-parity contribution at large $-t_{pn}$. The final graphs, Figs. 3(e) and 3(f) of $\alpha^{s,t}_{U1}(t)$, are not easy to interpret and they are probably a mixture of small effects, e.g., a π-exchange contribution that vanishes at the pion pole, the A_1, and absorptive corrections to A_2 exchange.

The possibility of extracting the $\pi\pi$ scattering amplitude from reaction (1) has been known for over thirty years.[13] In fact, our data do not have sufficient statistical precision to improve our knowledge of the low-energy $(\sqrt{s_{\pi\pi}})$ $\pi\pi$ amplitude.[8,14] However, we can study $\pi\pi$ scattering over a broad mass range as there is no kinematic suppression of the high mass region at our energies. Rather than perform a detailed extrapolation to the pion pole $t_{pn} = m_\pi{}^2$, we study the structure in the $\pi\pi$ decay distribution using all our data in the region $0 \leq -t_{pn} \leq 0.15$ GeV^2. The interpretation in terms of dynamics of an underlying $\pi\pi$ scattering can be partly justified *a posteriori* by the fact that we get essentially

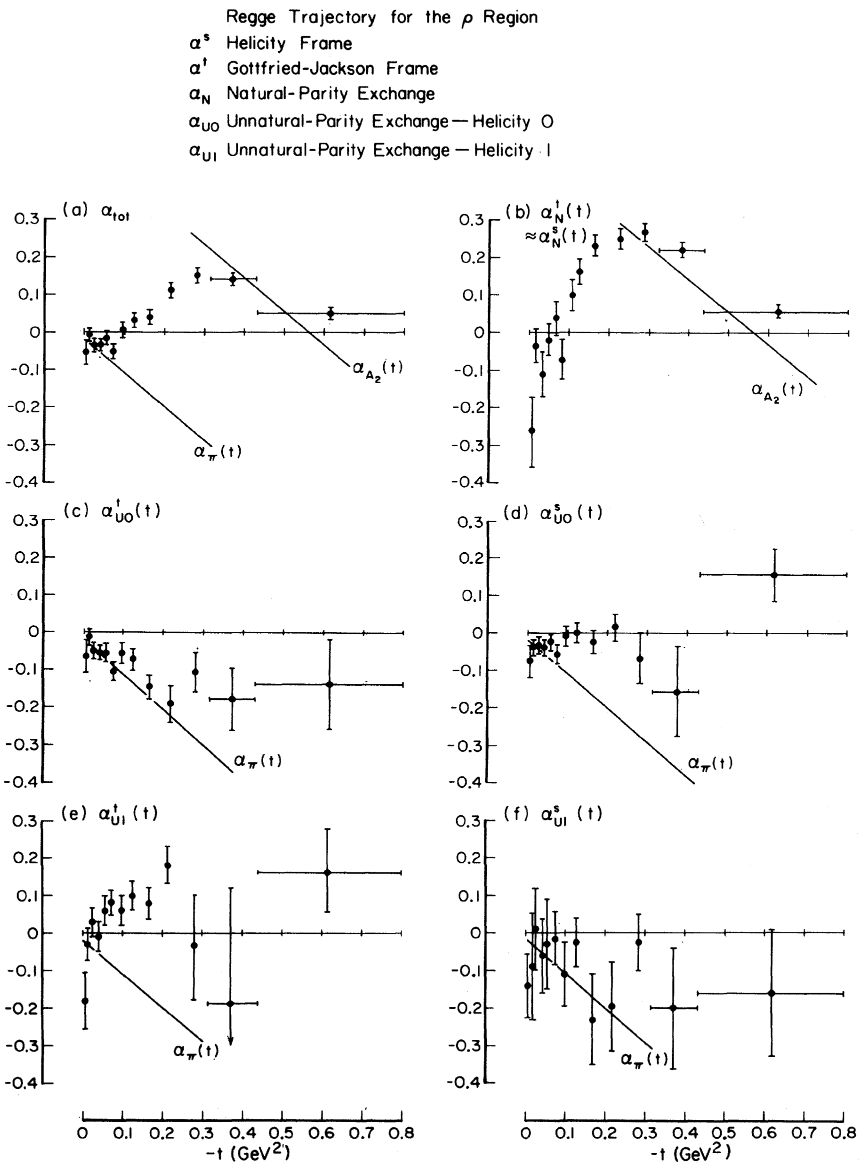

FIG. 3. The Regge trajectories $\alpha_i^L(t)$ defined in the text and extracted from the energy dependence of fixed-t data at 17.2, 100, and 175 GeV.

the same results at our two energies. We use the technique developed in Refs. 15 and 16, and Fig. 4 shows a sample of our data; the quantity called I_0 is essentially the $\pi\pi$ elastic differential cross section.[1,3]

Of interest here is the pattern of decay-distribution dips and breaks. These can be interpreted as the location in $s_{\pi\pi}$ and $t_{\pi\pi}$ of the scattering-amplitude zeros.[17] A particularly striking feature of Fig. 4 is the dip at $t_{\pi\pi} \sim -1$ GeV^2, which becomes a break at higher masses. The difference between a break and a dip is probably not significant as a dip can easily be "turned into" a break by superimposing the same amplitude structure on a more rapidly falling $t_{\pi\pi}$ dependence as is in fact seen at the highest masses. Thus we are motivated to catalog the dips and breaks in the $\pi\pi$ scattering region probed by our experiment. Dips are found as the minima of the $d\sigma/dt_{\pi\pi}$ distributions while breaks are located at the maxima of the second derivative of the logarithm of $d\sigma/dt_{\pi\pi}$. Our results, given in Fig. 5, show good agreement between our two energies in accord with the $\pi\pi$-scattering interpretation.

In Fig. 5, we see two lines of zeros at fixed values of $u_{\pi\pi}$ at approximately 0 and -1. Our data suggest other fixed $u_{\pi\pi}$ structure (the figure shows the start of a possible $u_{\pi\pi} \sim -2$ GeV^2 zero) but it is not statistically significant. These lines of zeros are termed Odorico[18] or Lovelace-Veneziano zeros.[19,20] In the Veneziano model, the $\pi^+\pi^-$ amplitude has zeros at

$$u_{\pi\pi} \sim 4m_\pi{}^2 - 0.9n \ , \tag{4}$$

where n is a non-negative integer. The $n=0$ and 1 zeros of this simple theory are clearly indicated by our data. Lovelace pointed out that the $n=0$ zero becomes the

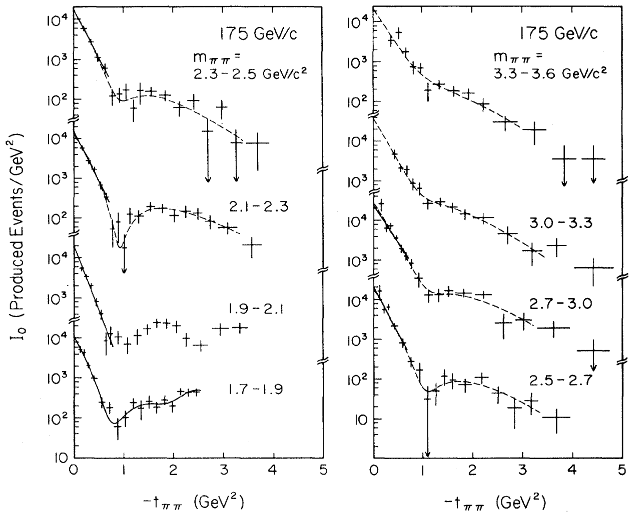

FIG. 4. I_0, essentially the $\pi^+\pi^-$ differential cross section, plotted as a function of $t_{\pi\pi}$ for various $m_{\pi\pi}$ bins. These illustrative data come from our 175-GeV/c sample. The solid (dashed) lines above 1.9 GeV correspond to single- (double-) exponential fits.

$s_{\pi\pi} = t_{\pi\pi} = u_{\pi\pi} = 0$ PCAC (partial conservation of axial-vector current) zero and this is consistent with an extrapolation of the $u_{\pi\pi} \sim 0$ line of zeros seen in our data.

The $t_{\pi\pi} = -1$ GeV^2 dip which extends to $s_{\pi\pi} = 12$ GeV^2 seems to have a different origin. This is *not* present in the model, which is not surprising as diffraction (the Pomeron) is absent from the Veneziano formalism. Comparing with the expected formula for a shell $[J_0(R\sqrt{-t})]$ or a sphere $[J_1(R\sqrt{-t})]$, we find pion radii of 0.5 and 0.75 fm, respectively. The latter appears to be in better agreement with the pion (charge) radius measurements[21] than the 0.5-fm value. $\pi\pi$ scattering provides a unique laboratory for studying diffraction as geometrical structure translates into very different zero positions in the different spin amplitudes. Only in $\pi\pi$ scattering do we find but one amplitude and no confusion from the many possible spin states. The $t_{\pi\pi} = -1$ GeV^2 zero may turn and exit the physical region near $s_{\pi\pi} = 2$ GeV^2. On the other hand, as mentioned above, the zeros for $0 \leq -t_{\pi\pi} \leq 1$ GeV^2 starting at $s_{\pi\pi} = 2$ GeV^2 may be the start of the $n = 2$ fixed-$u_{\pi\pi}$ zero.

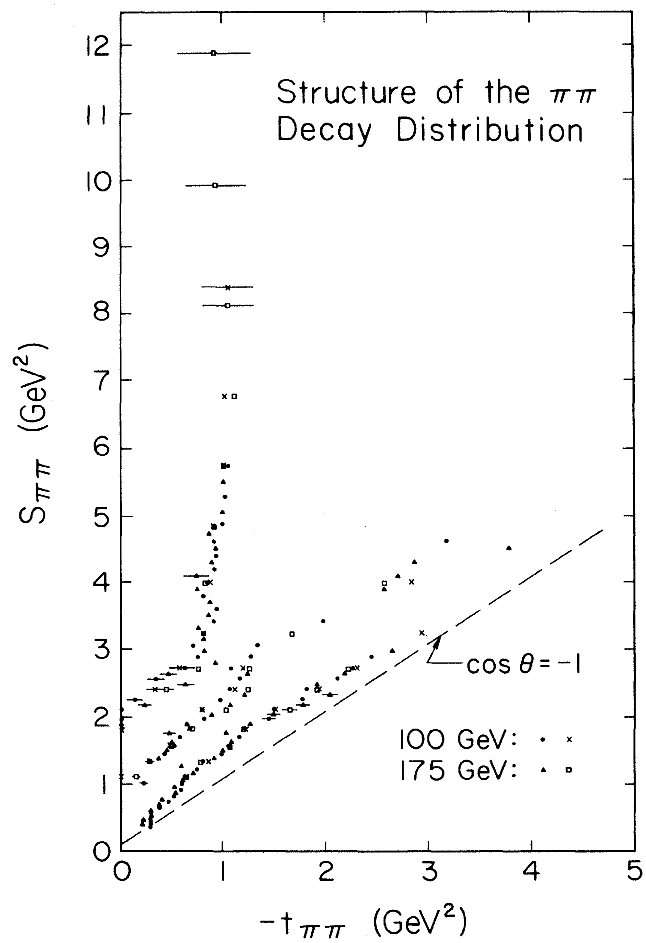

FIG. 5. Positions of the dips and breaks in our $\pi^-\pi^+$ decay distributions in the region $-t_{pn} < 0.15$ GeV^2. Points with horizontal bars (an estimate of the uncertainty) correspond to breaks, the remainder to dips.

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