Polarization in $\pi^- p \rightarrow \pi^0 n$ and Asymptotic Theorems

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The surprising results of the recent 40-GeV/c Serpukhov measurement of the polarization in $\pi^- p \rightarrow \pi^0 n$ are shown to support the conjecture that hadronic amplitudes may grow asymptotically as fast as they are permitted to by general principles.

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One of the most fundamental discoveries at the CERN intersecting storage rings (ISR), beautifully confirmed by recent $p\bar{p}$ collider data,[1] is the $\ln^2 s$ growth of total cross sections—fundamental because it asserts that the growth with energy is as fast as is permissible on very general theoretical grounds. Theoretically the growth is associated with an $s\ln^2 s$ behavior of the imaginary part of the asymptotic, forward, *crossing-even* amplitude F_+, accompanied by an $s\ln s$ behavior for its real part. An immediate question of great interest is: does the *crossing-odd* amplitude F_- also grow as fast as it is permitted to?

Some time ago, from a careful analysis of the high-energy data on $\pi^+ p$, $\pi^- p$, and πp charge-exchange reactions,[2] we were indeed led to speculate that also F_- might grow as fast as the general theorems permit it to do,[3–5] namely, asymptotically

$$F_-(s,0) \propto s[\ln(se^{-i\pi/2})]^2 \sim s(\ln^2 s - i\pi \ln s), \tag{1}$$

a behavior which, in the literature, is now generally referred to as due to the "exchange of an odderon."[4] For precision, we shall call the behavior (1) "maximal odderon" asymptotic behavior. This behavior corresponds to the presence of an $l=1$ singularity (double pole at $t=0$) in F_-. Of course, conventionally, F_- is assumed to be dominated by standard Regge poles (located $l \lesssim \frac{1}{2}$), giving rise to an $s^{1/2}$ behavior, and so any term of the form (1) could be present with only small magnitude in F_- up to Fermilab energies.

Because of the generality of the arguments involved it is natural to assume that the behavior (1) will be universal and will be present in all hadronic reactions. With the advent of the $\bar{p}p$ collider several analyses have sought the odderon in nucleon-nucleon scattering. But total-cross-section data is not the best place to look for a term of such small magnitude, and all the analyses have been inconclusive.[5,6] (At ISR energies the odderon contribution is actually comparable in magnitude with the conventional Regge contributions to F_-,[5,6] but the experimental errors on the cross-section differences are at present too large to test for the odderon term. Also, it should be remembered that F_- itself is small when compared with F_+ at ISR and at collider energies.)

In searching in our earlier work[2] for an experimental method to expose such a term, we noticed that, because its phase is so different from those of the conventional Regge poles, there would be strong interference effects, resulting, despite its small magnitude, in a large and surprising polarization in $\pi^- p \rightarrow \pi^0 n$ scattering at high energies. Indeed we showed that the 10%–30% positive polarization seen in the range $0 < |t| \lesssim 1$ (GeV/c)^2 at $p_L = 5$ GeV/c would change shape dramatically with energy, resulting in large negative polarizations at $|t| \simeq 0.5$ for $p_L \simeq 100$–200 GeV/c. This is in sharp contrast to the *elastic* scattering cases, where tiny polarizations would be expected, and have since been confirmed by experiments.[7]

There is, as yet, no measurement of the charge-exchange polarization in the $p_L \sim 200$ GeV/c range, but we wish to report here that a recent measurement[8] at $p_L = 40$ GeV/c seems to confirm the expected changes in the polarization P. A zero in P has appeared at $|t| \simeq 0.3$ to 0.4, with an accompanying minimum at $|t| \simeq 0.5$. It appears that this new experimental effect cannot be explained[8] by any of the existing conventional models, including the absorption model. We shall show below that the new polarization data of Ref. 8 conform to our earlier description of the crossing-odd amplitude in πp scattering[2] and thus lend support to the odderon-type behavior (1).

Our amplitudes are of the following form[2]:

$$A' = A'_{\rho} + A'_{\rho'} + A'_{0}, \quad (2)$$

$$B = B_{\rho} + B_{\rho'}, \quad (3)$$

where, for Reggeon $R = \rho$ or ρ',

$$A'_R = [i + \tan\tfrac{1}{2}\pi\alpha_R(t)]a_R(t)[\alpha_R(t)+1]e^{\lambda_R t}s^{\alpha_R(t)}, \quad (4)$$

$$B_R = [i + \tan\tfrac{1}{2}\pi\alpha_R(t)]b_R(t)\alpha_R(t)[\alpha_R(t)+1]e^{\lambda_R t}s^{\alpha_R(t)-1}, \quad (5)$$

$$a_\rho(t) = a_\rho(1+ct), \quad a_{\rho'}(t) = a_{\rho'} = \text{const}, \quad b_R(t) = b_R = \text{const}, \quad (6)$$

and the odderon term[9] is

$$A'_0 = Cs[\ln^2(s/s_0) - i\pi\ln(s/s_0)]\exp(\lambda_0 t). \quad (7)$$

In formulas (4)–(6) the trajectories are taken to be linear and an overall scale factor 1 GeV^2 is implicitly present. The detailed form (2)–(7) of our amplitudes was fully explained in Ref. 2. The exponential in Eq. (7) is a good and convenient numerical approximation (involving the minimum number of free parameters) of a scaling function in $t\ln^2 s$, for our range of kinematics.

We have taken into account more the 300 data points, namely $\Delta\sigma = \sigma_{\pi^- p} - \sigma_{\pi^+ p}$ in the range $p_L = 8$–340 GeV/c,[10] $d\sigma/dt$ in the range $p_L = 5.85$–199.3 GeV/c,[11] and polarization measurements by Hill *et al.*[12] (Bonamy *et al.*[13]) and Apokin *et al.*[8] The polarization data of Refs. 12 and 13 at 5 GeV/c are not compatible, and so we did all fits twice, using either the data of Ref. 12 or those of Ref. 13. The results for both cases are similar, with the analytic form of our amplitudes showing a slight preference for the data of Ref. 12. We therefore quote here only the results based upon the data of Ref. 12.

We have obtained a satisfactory description of all the data, with $\chi^2 \simeq 1.6$/point. The best-fit values of the parameters are shown in Table I.

As can be seen from Fig. 1, the change of shape of the polarization between 5 and 40 GeV/c is correctly described. (It should be noted that such a change cannot be described by the existing simple conventional models, e.g., $\rho + \rho'$.[8]) At low energies the $\rho \otimes \rho'$ interference term dominates and therefore the polarization is positive everywhere [with P small near $|t| \simeq 0.6$ because of the zero in $\alpha_\rho(t)$]. Towards $p_L = 30$ GeV/c the polarization changes sign (see Fig. 2), showing two zeros: One of them is the familiar fixed-t zero produced by the zero of $\alpha_\rho(t)$, while the new dynamical zero at smaller t is produced as a result of a cancellation between the $\rho \otimes \rho'$ and $\rho \otimes$ odderon contributions. The position of the new zero will clearly vary with energy, approaching $t = 0$ as the energy increases (see Fig. 2). At the same time, the polarization becomes more and more negative at small t, as a result of the increasing dominance of the $\rho \otimes$ odderon contribution.

At Fermilab energies, the polarization, which is essentially given by the $\rho \otimes$ odderon term, is negative everywhere in the small-t region, $0 < |t| \lesssim 0.6$

TABLE I. Best-fit parameters in the maximal odderon case.

	a (μb$^{1/2}$)	c (GeV^{-2})	b (μb$^{1/2}$ GeV^{-1})	$\alpha(0)$	α' (GeV^{-2})	λ (GeV^{-2})	C (μb$^{1/2}$)	S_0 (GeV^2)
ρ	93.8	2.53	3404.6	0.48	0.82	0.13	···	···
ρ'	−130.3	···	714.3	0	0.11	2.65	···	···
odderon	···	···	···	···	···	1.76	−0.008	0.08

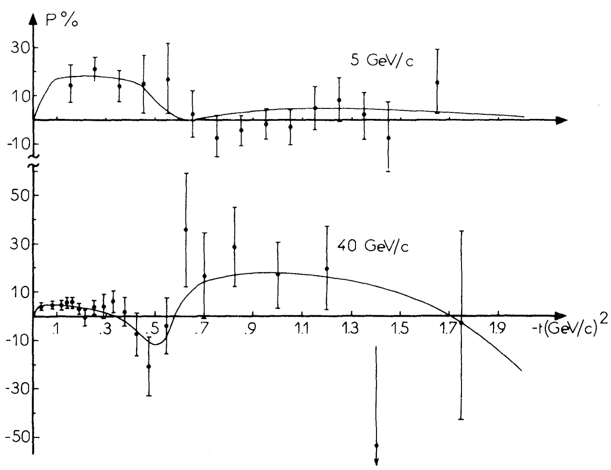

FIG. 1. Polarization in $\pi^- p \to \pi^0 n$ at $p_L = 5$ GeV/c and 40 GeV/c. The curves correspond to the maximal odderon asymptotic behavior for F_-, as given in the text.

(see Fig. 2), showing a pronounced negative minimum at $|t| \simeq 0.5$ with a value $\simeq -50\%$ at $p_L = 100$ GeV/c and $\simeq -80\%$ at $p_L = 200$ GeV/c.

As a further check of our analysis, we have also studied the isospin bounds on the charge-exchange polarization[14,15] at $p_L = 40$ GeV/c,[16] and at $p_L = 100$ GeV/c.[7,17] Remarkably the t dependence of these bounds seems to follow the t dependence of the data measured by Apokin *et al.*[8] and of our calculation at 100 GeV/c.

It is highly desirable to measure the πp charge-exchange polarization in the energy range 100–200 GeV/c. The confirmation of the behavior (1) for the crossing-odd amplitude would be of fundamental interest for any theory of strong interactions, including QCD.[18]

In the general context of asymptotic behavior it should be noted that the $\bar{p}p$ collider $d\sigma/dt$ data in the dip-shoulder region can be said to have invalidated all previous models[19] (including geometrical scaling) which make the conventional assumption that the crossing-even amplitude dominates at such high energies. The discrepancy might possibly be due to the crossing-odd amplitude,[20] but clarificiation will require *both pp* and $\bar{p}p$ data at collider energies. Ultimately, the experimental ability to compare hadron-hadron with hadron-antihadron scattering will be vital in testing our understanding of the strong interactions.

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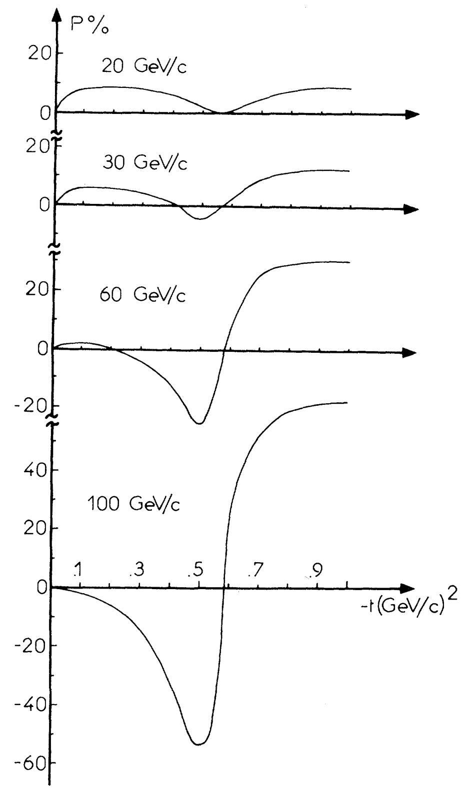

FIG. 2. Theoretical predictions based on the maximal odderon asymptotic behavior, showing the development and subsequent movement towards $t = 0$ of a new zero in the polarization.

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[9] We also considered the case of a simple odderon, i.e., an $l=1$ pole,

$$A_0' = a_0[1-\alpha_0(t)] \times [i+\tan\tfrac{1}{2}\pi\alpha_0(t)]\exp[\lambda_0(t)]s^{\alpha_0(t)}.$$

For brevity we only present the results for the "maximal odderon" (7). The description of the data in the pole case is very similar. In the pole case, ρ' was taken to be a daughter of the odderon.

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