$M = 350$ MeV.

[11]A. H. Rosenfeld, A. Barbaro-Galtieri, W. H. Barkas, P. L. Bastien, J. Kirz, and M. Roos, Rev. Mod. Phys. 37, 633 (1965).

[12]A. Yokosawa, S. Suwa, R. E. Hill, R. J. Esterling, and N. E. Booth, Phys. Rev. Letters 16, 714 (1966).

REGGE-POLE THEORY AND p-n AND $\bar{p}$-n CHARGE-EXCHANGE SCATTERING AT SMALL ANGLES

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The sharp forward peak observed in high-energy p-n charge-exchange scattering[1,2] has so far eluded a theoretical explanation. Various attempts based on π- and ρ-exchange models[3,4] and on π and ρ exchange with absorption[5,6] have been unsuccessful. We propose here an explanation based on the Regge-pole theory with exchange of the ρ and R trajectories. The other known possible candidate, the π trajectory, does not contribute in the forward direction[7] and it lies lower than ρ and R. We are concentrating on large energies and small angles and disregarding the π contribution.

The amplitude for p-n charge-exchange scattering, $A(pn, \mathrm{ce})$, is related by general isotopic-spin arguments to the difference between the amplitudes for p-p scattering, $A(pp)$, and p-n scattering, $A(pn)$, in the form

$$A(pn, \mathrm{ce}) = A(pn) - A(pp). \tag{1}$$

The total cross-section difference $\sigma(pn) - \sigma(pp)$ is very small at high energies,[8,9] and in fact, becomes zero at about 9 GeV^2 according to recent measurement of $\sigma(pn)$ and $\sigma(pp)$.[10] The optical theorem, Eq. (1), and this result imply that $\sigma(pn, \mathrm{ce}) = 0$ at this energy. This conclusion is general; that is, not based on any model.

In the Regge-pole theory the information regarding the real and imaginary parts of the amplitude for each pole contribution is contained in the so-called signature factor ξ_p, which can be factored out. Because of the spin $\frac{1}{2}$ of the nucleons there are five amplitudes, but three of these become zero in the forward direction and the remaining two become identical at $t = 0$. Each may be written in the ρ and R model as

$$\Phi_i(pn, \mathrm{ce}) = \varphi_i(s, t)\left[\xi_\rho(t) g_\rho(t)\left(\frac{2s}{4m^2 - t} - 1\right)^{\alpha(\rho, t)} + \xi_R(t) g_R(t)\left(\frac{2s}{4m^2 - t} - 1\right)^{\alpha(R, t)}\right], \tag{2}$$

where

$$\xi_\rho = \tfrac{1}{2}\{i + \tan[\tfrac{1}{2}\pi\alpha(\rho, t)]\},$$
$$\xi_R = \tfrac{1}{2}\{-i + \cot[\tfrac{1}{2}\pi\alpha(R, t)]\}, \tag{3}$$

$\alpha(t)$ is the trajectory, and t the four-momentum invariant.

At energies above 7.5 GeV^2 the imaginary part of the amplitude is very small in the forward direction, and this must be the case near $t = 0$. In this region the amplitude consists mainly of its real part, which in the present model becomes

$$\Phi_i(pn, \mathrm{ce}) \approx f_i(s, t)\{\tan[\tfrac{1}{2}\pi\alpha(\rho, t)] + \cot[\tfrac{1}{2}\pi\alpha(R, t)]\}. \tag{4}$$

We propose to explain the forward peak by a combination of two factors. (a) We assume that $\alpha_\rho(0) > 0.5$ and the slope of ρ is large, and that $\alpha_R(0) < 0.5$ and the slope of R is small. Then $\tan[\frac{1}{2}\pi\alpha(\rho, t)]$ is a rapidly decreasing function for small angles while $\cot[\frac{1}{2}\pi\alpha(R, t)]$ is slowly increasing. (b) In addition, $g_\rho(t)$ is assumed to decrease faster than $g_R(t)$ (or vice versa). These two conditions are sufficient to accentuate the forward p-n charge-exchange peak so as to agree with experiments.[1,2] The mechanism described is independent of the energy; therefore the peak should be observed at very high energies. This is in agreement with the fact that at 8.0 $(\mathrm{GeV}/c)^2$, which is the highest energy at which experiments have been done, the peak has the same slope as observed previously at 3.0 GeV/c.[1] This mechanism depends only on the fact that the difference $\sigma(pn) - \sigma(pp)$ is small. The ρ and R model accounts for this and for the intersection of $\sigma(pn)$ and $\sigma(pp)$.

The conditions imposed on the trajectories are in agreement with determinations in con-

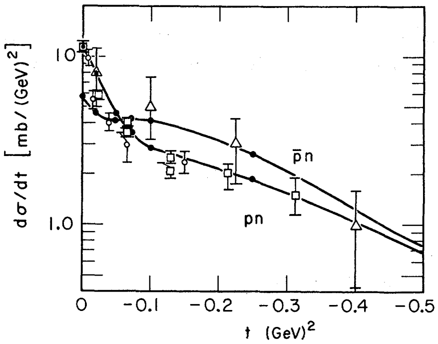

FIG. 1. Charge-exchange differential cross sections: □, pn at $P_0 = 3.0$ GeV/c (Ref. 1); ○, pn at $P_0 = 2.85$ GeV/c (Ref. 1); Δ, $\bar{p}n$ combined results of runs at 3.0 and 3.6 GeV/c (Ref. 14); ●, pn and $\bar{p}n$, calculated, at 3.0 GeV/c.

nection with π-N scattering[11,12] and with the general N-N scattering problem.[13]

In $\bar{p}$-n charge-exchange scattering the amplitude becomes

$$\Phi_i(\bar{p}n, \mathrm{ce}) = \varphi_i(s,t)\left[\zeta_\rho(t) g_\rho(t)\left(\frac{2s}{4m^2-t}-1\right)^{\alpha(\rho,t)} - \zeta_R(t) g_R(t)\left(\frac{2s}{4m^2-t}-1\right)^{\alpha(R,t)}\right]. \quad (5)$$

The ρ and R model implies no corresponding intersection of $\sigma(\bar{p}p)$ and $\sigma(\bar{p}n)$. This seems to be in agreement with experiment, although present $\sigma(\bar{p}n)$ determinations are subject to large errors. The calculated charge-exchange differential cross sections at 3.0 GeV/c are shown in Fig. 1. The trajectories assumed in these calculations are $\alpha(\rho, t) = 0.60 + 0.87t$ and $\alpha(R, t) = 0.35 + 0.35t$, with residue functions as shown in Fig. 2. An equally good experimental fit of p-n is also obtained when $g_R(t)$ decreases faster than $g_\rho(t)$. Nevertheless, we prefer the first choice since this seems to agree better with the general behavior of residues of even- and odd-signature trajectories found in Ref. 13. Further evidence in support of the choice of a ρ residue function that is rapidly decreasing at small angles comes from independent work on π-N scattering.[14]

In contrast to the p-n case, the $\bar{p}$-n differential cross section has a smaller forward slope, since here the imaginary part of the amplitude has a forward peak that the real part tends to cancel. This is in agreement with a few recent $\bar{p}$-n differential cross-section measurements at 3.0 and 3.6 GeV/c.[15] Here again a π-exchange model with absorption[16] seems

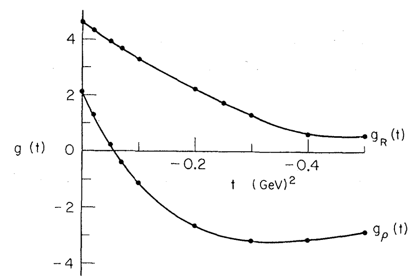

FIG. 2. The ρ and R most important residue functions near the forward direction, used in the calculations of p-n and $\bar{p}$-n charge-exchange differential cross sections.

unsuccessful, since it predicts again a sharp peak at very small angles. In the range of energies above 7.5 GeV^2 the ρ and R model gives $\bar{p}$-n charge-exchange total cross sections larger than for p-n, in which actually the cross section becomes zero at the $\sigma(pn)$ and $\sigma(pp)$ intersection.

Experimental p-n and $\bar{p}$-n charge-exchange measurements at energies in the neighborhood of the $\sigma(pn)$ and $\sigma(pp)$ intersection will be helpful in the investigation of the charge-exchange amplitudes. Finally we point out that our choice of residue functions predicts a crossover point for the p-n and $\bar{p}$-n charge-exchange differential cross sections that should be observed experimentally.

In conclusion, the present calculations seem to constitute further theoretical evidence in support of the role of the R and ρ trajectories in charge-exchange scattering.

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[1]J. L. Friedes, H. Palevsky, R. L. Stearns, and R. J. Sutter, Phys. Rev. Letters 15, 38 (1965).

[2]G. Manning, A. G. Parham, J. D. Jafar, H. B. van der Raay, D. H. Reading, D. G. Ryan, B. D. Jones, J. Malos, and N. H. Lipman, Nuovo Cimento 41, A167 (1966).

[3]I. J. Muzinich, Phys. Rev. Letters 11, 88 (1963).

[4]M. M. Islam and T. W. Preist, Phys. Rev. Letters 11, 444 (1963).

[5]E. M. Henley and I. J. Muzinich, Phys. Rev. 136, B1783 (1964).

[6]G. A. Ringland and R. J. N. Phillips, Phys. Letters 12, 62 (1964).
[7]I. J. Muzinich, Phys. Rev. 130, 1571 (1963).
[8]A. N. Diddens, E. Lillethun, G. Manning, A. E. Taylor, T. G. Walker, and A. M. Wetherell, Phys. Rev. Letters 9, 32 (1962).
[9]W. Galbraith, E. W. Jenkins, T. F. Kycia, B. A. Leontić, R. H. Phillips, A. L. Read, and R. Rubinstein, Phys. Rev. 138, B913 (1965).
[10]R. F. George, K. F. Riley, R. J. Tapper, D. V. Bugg, D. C. Salter, and G. H. Stafford, Phys. Rev. Letters 15, 214 (1965).
[11]G. Höhler, J. Baacke, H. Schlaile, and P. Sonderegger, Phys. Letters 20, 79 (1966).
[12]R. J. N. Phillips and W. Rarita, Phys. Rev. Letters 15, 807 (1965).
[13]V. Flores-Maldonado, "High Energy N-N Scattering from Regge Poles" (to be published).
[14]R. J. N. Phillips and W. Rarita, Phys. Rev. 139, B1336 (1965); B. R. Desai, Phys. Rev. 142, 1255 (1966); C. Chiu (University of California Lawrence Radiation Laboratory), private communication.
[15]O. Czyzewski, B. Escoubès, Y. Goldschmidt-Clermont, M. Guinea-Moorhead, D. R. O. Morrison, and S. De Unamuno-Escoubès, Phys. Letters 20, 554 (1966).
[16]R. J. N. Phillips and G. A. Ringland, Phys. Letters 20, 205 (1966).