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π–p CHARGE EXCHANGE POLARIZATION AND THE POSSIBILITY OF A SECOND ρ MESON*

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The π–p charge exchange (CEX) reaction, $\pi^- + p \to \pi^0 + n$, at high energies is a particularly simple reaction from the standpoint of Regge-pole phenomenology because only the quantum numbers of the ρ may be exchanged in the crossed channel, t. The domination of the scattering amplitude by a single ρ Regge trajectory is verified by several analyses[1-3] of the differential cross section, $d\sigma/dt$.[4-6] If this domination were complete and only the ρ contributed, one would expect to observe zero polarization because the Regge flip and nonflip amplitudes have the same phase. The detection of a nonzero polarization by Bonamy et al.[7] shows that another term which went undetected in the measurement of $d\sigma/dt$ is also contributing to the scattering amplitude.

It was shown[8,9] that a qualitative explanation of the polarization can be obtained by assuming that this extra term is due to resonance exchange in the direct channel, s. Alternative explanations assume that the extra term arises either from a cut[10] or from a second ρ meson, the ρ'.[11] We shall extend our previous analysis[8] to the more recent 11.2-GeV data and show that the quantitative agreement is improved by the introduction of the ρ'. We shall also review the growing evidence for the existence of a ρ'.

It was shown[8] that the direct-channel resonances can affect the polarization at energies as high as 20 GeV. While there is some question as to the accuracy of the extrapolation of the Breit-Wigner formula to energies considerably above the resonances, we feel it is important to include the resonance contributions. We shall therefore consider the following three models: (I) ρ + resonances, (II) $\rho + \rho'$ + resonances, (III) $\rho + \rho'$, and compare their agreement with experiment. The third model is presented since there is some skepticism concerning the contribution of the direct-channel resonances at energies above 6 GeV. The prediction of the three models at different energies will also be presented, thus providing an experimental test for distinguishing them.

Before we turn to this task, however, we shall review the independent support (i.e., support from sources other than the πp CEX polarization) for the introduction of the ρ'. This support comes from a variety of sources. The first of these is a recent analysis of Högaasen and Fischer[11] of high-energy, nucleon-nucleon, charge-exchange scattering where they show the introduction of a ρ' is necessary to obtain a consistent Regge-pole description of the forward differential cross section and the total cross-section data. Evidence for the ρ' arises from two recent unitary symmetry analyses. Nelson[12] has constructed a mass operator for the SU(3) harmonics which gives the correct masses of the well-known 1^- nonet of mesons. This operator also predicts a 1^- meson with the quantum numbers of the ρ at 984 MeV. A recent SU(3)⊗SU(3) calculation of Bose[13] also predicts a ρ' of mass 1000 MeV. Further evidence for the ρ' comes from the failure to explain the behavior of the nucleon isovector electromagnetic form factor with just a single ρ. The introduction of a ρ' with a mass of 890 MeV in one analysis[14] and 1100 MeV in another[15] eliminates this discrepancy.

The missing-mass spectrometer experiment of Kienzle et al.[16] indicates a narrow state at 963 ± 5 with $I \geq 1$ which they call the δ. Allen et al.[17] have tentative evidence for an $I \geq 1$ dipion state of unknown spin and parity at ≈965 MeV. Both the SU(3) and form-factor arguments for the ρ' predict a mass in this energy region. We shall assume, therefore, for the purposes of our analysis that the state (or states) observed by Kienzle et al.[16] and Allen et al.[17] is the ρ'. If we further assume that the ρ' trajectory has a linear t dependence with the same slope as the ρ, we must choose $\alpha_{\rho'}(0)=0.17$ in order that $\alpha(t=963^2)=1.0$. Extrapolating this trajectory to $\alpha_{\rho'}=3$, we expect the first recurrence of the ρ' to occur at a mass of 1770 MeV, which is very close to the third peak of the R which Focacci et al.[18] observe at 1748 MeV.

Let us now turn to a consideration of the $\pi^- p$ CEX polarization. The charge-exchange scattering amplitude is given by

$$m=f+i\frac{\sigma\cdot\vec{q}'\times\vec{q}}{q^2}\tilde{f}, \tag{1}$$

where f and $\tilde{f}$ are the spin-nonflip and spin-flip amplitudes and $\vec{q}$ and $\vec{q}'$ are the center-of-mass momenta of the initial and final states. The differential cross section, $d\sigma/dt$, and the polarization, P, are related to f and $\tilde{f}$ by

$$\frac{d\sigma}{dt}=\frac{\pi}{q^2}\left\{|f|^2-\frac{4t}{s}|\tilde{f}|^2\right\} \tag{2}$$

and

$$P=-\frac{2\,\mathrm{Im}(f\tilde{f}^*)\sin\theta}{|f|^2-(4t/s)|\tilde{f}|^2}, \tag{3}$$

where θ is the scattering angle in the s channel.

We shall consider the following three models in which

$$\text{(I)}\quad f=f_\rho+f_{\mathrm{RES}},$$

$$\text{(II)}\quad f=f_\rho+f_{\rho'}+f_{\mathrm{RES}},$$

$$\text{(III)}\quad f=f_\rho+f_{\rho'}, \tag{4}$$

where RES stands for the contribution of all the direct-channel resonances and ρ and ρ' for the contribution of the corresponding trajectories. The amplitudes f_{RES}, $\tilde{f}_{\mathrm{RES}}$, f_ρ, and $\tilde{f}_\rho$ are exactly identical to the amplitudes in Ref. 8 except for the change of the label REG to ρ:

$$f_{\mathrm{RES}}=\frac{\sqrt{2}}{3q}\sum_{\mathrm{Resonances}}(-1)^{I+\frac{1}{2}}\frac{(J+\frac{1}{2})\eta_l P_l(1+t/2q^2)}{W_l-W-(i\Gamma_l/2)}, \tag{5}$$

where $W=s^{1/2}$ and J, l, W_l, Γ_l, and η_l are the total spin, orbital angular momentum, energy, width, and elasticity of the resonance, respectively (the values of the resonance quantities can be found in Table I of Ref. 8);

$$\tilde{f}_{\mathrm{RES}}=\frac{\sqrt{2}}{3q}\sum_{\mathrm{Resonances}}(-1)^{I+\frac{1}{2}}(-1)^{J-l-\frac{1}{2}}\frac{\eta_l P_l'(1+t/2q^2)}{W_l-W-i(\Gamma_l/2)}, \tag{6}$$

where P_l' is the first derivative of the Legendre polynomial;

$$f_\rho=\frac{-M\mu b_1(t)}{4\pi W}\left[\frac{S-M^2-\mu^2}{s_0}\right]^{\alpha_\rho(t)}\left[i+\tan\frac{\pi}{2}\alpha_\rho(t)\right], \tag{7}$$

$$\tilde{f}_\rho=\frac{\mu}{16\pi}[b_1(t)-\alpha_\rho(t)b_2(t)]\left[\frac{S-M^2-\mu^2}{s_0}\right]^{\alpha_\rho(t)}\left[i+\tan\frac{\pi}{2}\alpha_\rho(t)\right], \tag{8}$$

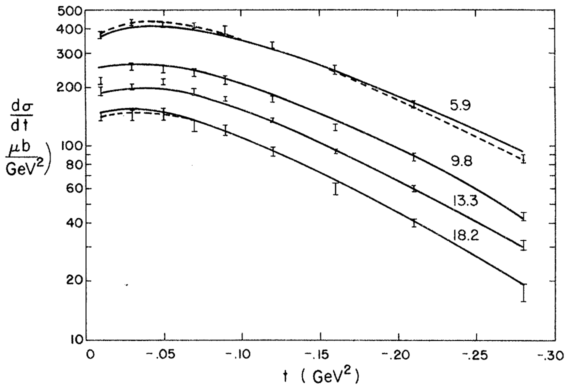

FIG. 1. The fit of $d\sigma/dt$ at 5.9, 9.8, 13.3, and 18.2 GeV with models II and III. Where both the dashed line and the solid line occurs the dashed line represents model III and the solid line model II. Otherwise the two curves more or less overlap.

where M and μ are the nucleon and pion masses, $\alpha_\rho(t)$ is the trajectory of the ρ, and $b_1(t)$ and $b_2(t)$ are the residues of the Regge pole. The total center-of-mass energy squared, s, is related to the pion lab energy E by $s=2ME-M^2-\mu^2$, so that choosing $s_0=2M\mu$, $(s-M^2-\mu^2)/s_0$ reduces simply to E/μ. With this choice of s_0 it was shown[1] that the residue functions $b_1(t)$ and $b_2(t)$ do not have very strong t dependences. We have in fact chosen the residues to be constants. One can obtain a better fit to $d\sigma/dt$, naturally, by giving the residues more complicated t dependence. Since our purpose here is to explain the polarization and since P does not depend sensitively on small variations of $b_1(t)$ and $b_2(t)$, we will not complicate our model with t-dependent residues. In the same spirit we take a simple linear relationship for the t dependence of $\alpha_\rho(t)$, viz., $\alpha_\rho(t)=0.58+0.90t$.

The formula for $f_{\rho'}$ $(\tilde{f}_{\rho'})$ is identical to that for f_ρ $(\tilde{f}_\rho)$ except for the appearance of the primed quantities b_1', b_2', and $\alpha_{\rho'}$, and hence

$$f_{\rho'}=\frac{-M\mu b_1'(t)}{4\pi W}\left[\frac{E}{\mu}\right]^{\alpha_{\rho'}(t)}\left[i+\tan\frac{\pi}{2}\alpha_{\rho'}(t)\right], \quad (9)$$

$$\tilde{f}_{\rho'}=\frac{\mu}{16\pi}[b_1'(t)-\alpha_\rho(t)b_2'(t)]\times\left[\frac{E}{\mu}\right]^{\alpha_{\rho'}(t)}\left[i+\tan\frac{\pi}{2}\alpha_{\rho'}(t)\right]. \quad (10)$$

The ρ' residues b_1' and b_2' are also taken to be constant. The ρ' trajectory is given by $\alpha_{\rho'}(t)=0.17+0.9t$. This means there are four free parameters altogether, b_1, b_2, b_1', and b_2', to fit $d\sigma/dt$ and P. (For model I where ρ' is not included there are naturally only two free parameters.)

The parameters b_1 and b_2 are essentially constrained to fit $d\sigma/dt$. In models II and III, b_1' and b_2' are varied to fit P, whereas in model I there are no free parameters to fit P. All three models give excellent fits of $d\sigma/dt$. The fit of $d\sigma/dt$ of II and III are shown in Fig. 1, while that of model I is essentially identical to the one in Fig. 1 of Ref. 8. The fits of P at 5.9 and 11.2 GeV are shown in Fig. 2. Table I lists the values of the free parameters

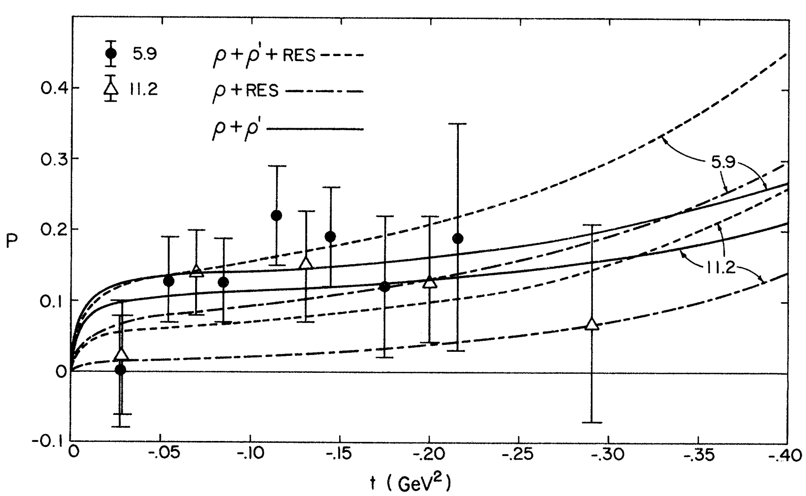

FIG. 2. The fit of the polarization data at 5.9 and 11.2 GeV with models I, II, and III.

Table I. Regge-pole parameters and χ^2.

	b_1 (mb$^{1/2}$/GeV)	b_2 (mb$^{1/2}$/GeV)	b_1' (mb$^{1/2}$/GeV)	b_2' (mb$^{1/2}$/GeV)	χ^2 from 36 $d\sigma/dt$ data points	χ^2 from 12 P data points	χ^2 total
ρ +RES	13.2	170	···	···	99	13.8	113
$\rho'+\rho'$+RES	12.0	167	11.9	134	70	6.6	77
$\rho+\rho'$	10.5	172	26.1	220	67	5.9	73

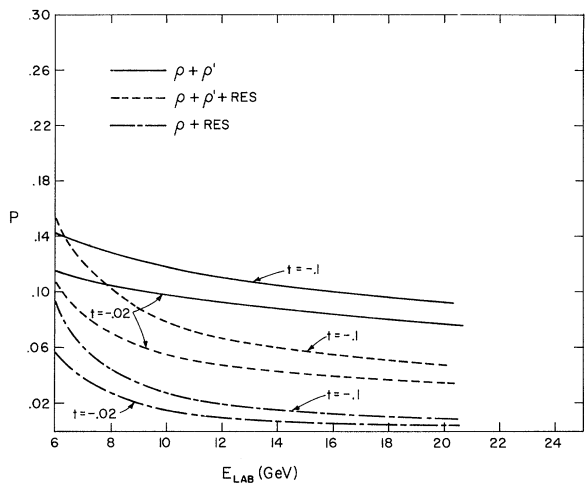

FIG. 3. The prediction of P for the three models in the energy range 6 to 20 GeV at $t=-0.02$ and $t=-0.10$.

and χ^2 for the best fits. [Note that while the ρ' residues are of the same order of magnitude as the ρ residues, $f_{\rho'} \ll f_\rho$ because of the energy factor, $(E/\mu)^\alpha$, and the fact that $\alpha_{\rho'} \ll \alpha_\rho$.] It is apparent that the introduction of a ρ' with mass 963 greatly improves the values of χ^2. A similar reduction in χ^2 for P can be obtained over a fairly large range of $\alpha_{\rho'}(0)$ and $\alpha_{\rho'}'(0)$ [$-0.2 < \alpha_{\rho'}(0) < 0.3$ or $0.8 < \alpha_{\rho'}'(0) < 1.2$]. This means that πp CEX polarization cannot be used to determine $m_{\rho'}$, but that the experimental data are consistent with the value of $m_{\rho'}$ obtained from the various sources discussed above.

All three models give reasonable fits to the existing polarization data. Future measurements of P over a wider range of energies will determine which, if any, of these models is correct. Figure 3 shows the predictions

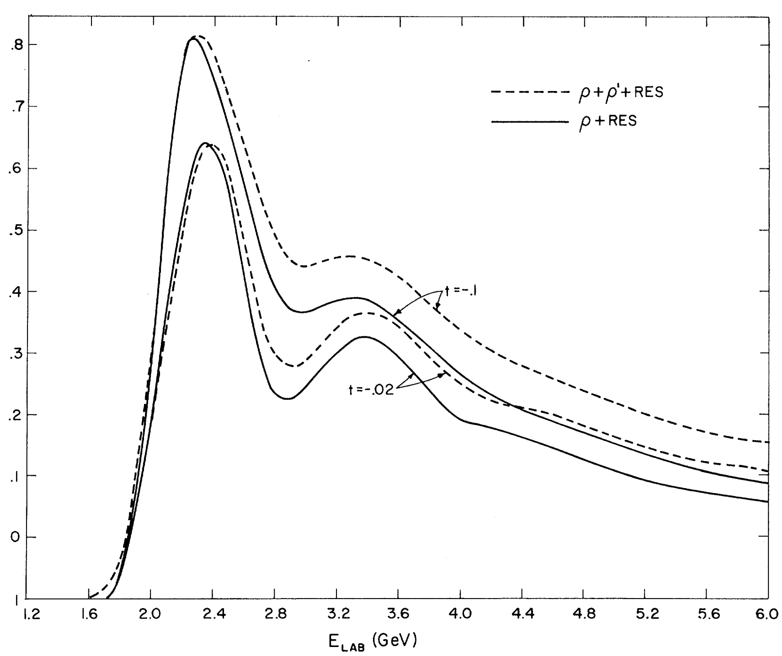

FIG. 4. The prediction of P for model II and III in the resonance region 1.7 to 6 GeV at $t=-0.02$ and $t=-0.1$.

of the three models in the energy range 6 to 20 GeV. The predictions of models I and II in the resonance region 1.7 to 6.0 GeV are also presented in Fig. 4. The prediction of models II and III depends on $m_{\rho'}$ which we have chosen to be 963 MeV.

In conclusion we would like to make the following points:

(i) While the ρ + resonance model gives a consistent fit of the data, a greater reduction in χ^2 can be obtained by introducing a ρ'. With the ρ' one can also fit P without resorting to the use of the resonances at high energies.

(ii) Support from a number of independent sources indicates the possibility of a ρ' at 963 MeV. Our analysis of πp CEX polarization is consistent with this hypothesis. At the same time the idea of introducing a ρ' does not depend on the identification of the δ with the ρ' since there is a fairly wide range of $m_{\rho'}$ which will fit polarization data.

(iii) Polarization measurements over a wider range of E and t will permit the discrimination of the various models proposed to explain polarization.

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