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Study of ω Exchange Isolated in the Reactions $\pi p \to \rho N$ at 6 GeV/c*

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Dips are observed at $t \sim -0.45$ GeV^2 in the differential cross sections of the reactions $\pi^\pm p \to \rho^\pm p$ and a break at $t \sim -0.25$ GeV^2 in $\pi^- p \to \rho^0 n$ at 6 GeV/c. The $I=0$ ω-exchange contribution in the t channel is isolated by calculating

$$R^2(t) = \frac{1}{2}\left[\frac{d\sigma}{dt}(\pi^- p \to \rho^- p) + \frac{d\sigma}{dt}(\pi^+ p \to \rho^+ p) - \frac{d\sigma}{dt}(\pi^- p \to \rho^0 n)\right].$$

The function $R^2(t)$ vanishes at $t \sim -0.45$ GeV^2 and is well parametrized by a Bessel function of the first kind, $J_1^{\,2}(r\sqrt{-t})$, with $r \sim 1$ F.

Rarely in the study of quasi-two-body processes can an exchange corresponding to a single particle (or trajectory) be unambiguously isolated from other allowed exchanges. One outstanding example[1] has been the extraction of the $I=0$ ω contribution to ρ production by computing

$$R^2(t) = \frac{1}{2}\left[\frac{d\sigma}{dt}(\pi^- p \to \rho^- p) + \frac{d\sigma}{dt}(\pi^+ p \to \rho^+ p) - \frac{d\sigma}{dt}(\pi^- p \to \rho^0 n)\right].$$

However, no one experiment thus far has measured all three processes at the same energy.[1,2] Differences in normalization and analysis procedures strongly affect the reliability of the determination of the ω trajectory obtained by combining results from different experiments.

We present here the determination of $R^2(t)$ from 6-GeV/c π^- and π^+ exposures of the Brookhaven National Laboratory (BNL) 80-in. hydrogen bubble chamber. Both exposures were measured on the BNL flying spot digitizer and the data were treated identically. There were 3097 events in the $\pi^-\pi^0 p$ final state, 4998 events in the $\pi^-\pi^+ n$ final state, and 2060 events in the $\pi^+\pi^0 p$ final state.[3]

To determine the ρ cross sections, fits were made to the $\pi\pi$ mass spectra with both $l=0$ and 1 Breit-Wigner resonance shapes with various polynomial backgrounds for $|t| < 2.0$ GeV^2 (l is the orbital angular momentum of the $\pi\pi$ system). The cross sections[4] averaged over the different resonance and background assumptions are

$$\sigma(\pi^- p \to \rho^- p) = 0.24 \pm 0.03 \text{ mb},$$
$$\sigma(\pi^- p \to \rho^0 n) = 0.36 \pm 0.04 \text{ mb},$$
$$\sigma(\pi^+ p \to \rho^+ p) = 0.26 \pm 0.03 \text{ mb}.$$

The principal contribution to the errors comes from uncertainties in the estimation of the background level in the ρ mass region.

To determine the differential cross sections,

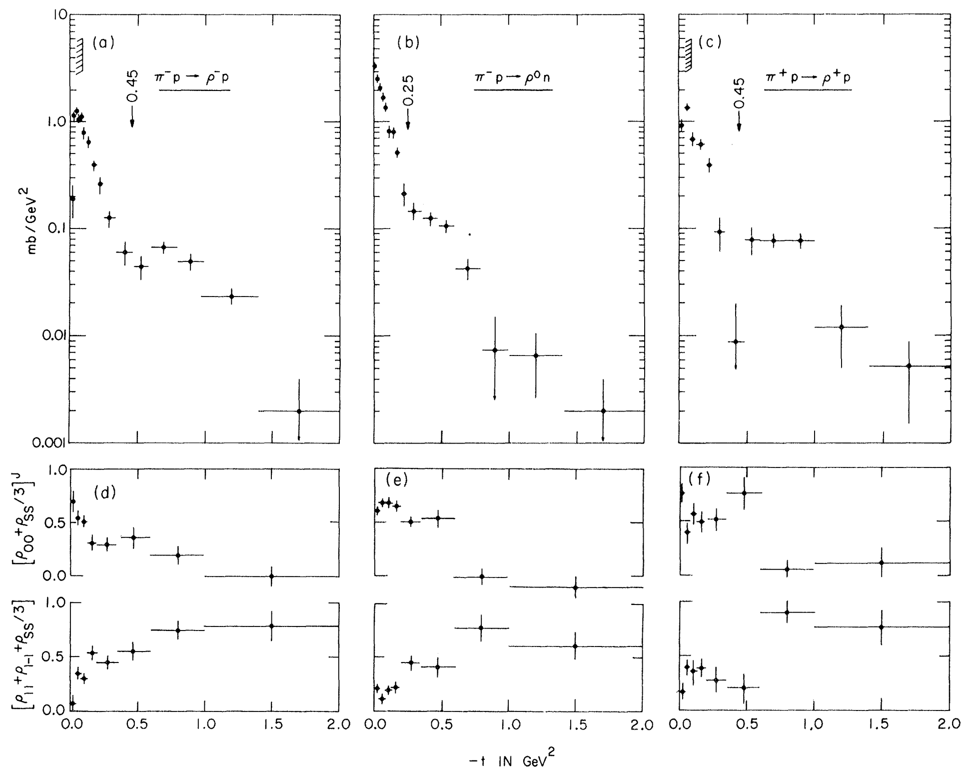

FIG. 1. (a)–(c) Differential cross sections as shown. Cross-hatched area indicates $|t| < 0.1$ GeV^2 where there is a loss of $\rho^\pm$ events (see Ref. 4). (d)–(f) Density-matrix elements versus t.

shown in Figs. 1(a)–1(c), fits were made to the $\pi\pi$ mass spectra in each t interval using the mass and width of the ρ obtained from the fit for $|t| < 2$ GeV^2. We note that the magnitudes and general behaviors of the ρ^+ and ρ^- cross sections are similar whereas the behavior of the ρ^0 cross section is markedly different from those of the $\rho^\pm$. There is a pronounced dip at $t \sim -0.45$ GeV^2 for both ρ^+ and ρ^- followed by a second maximum. The differential cross sections for ρ^+ and ρ^- are fitted by the form $d\sigma/dt \propto e^{bt}$ for $|t| < 0.4$ GeV^2, yielding consistent values of $b_+ = 8.4 \pm 0.9$ GeV^{-2} and $b_- = 9.4 \pm 0.7$ GeV^{-2}. For the ρ^0, however, there is a break in the differential cross section near $t \sim -0.25$ GeV^2. A fit to $d\sigma/dt$ for the ρ^0 yields a slope parameter of $b_0 = 11.4 \pm 0.7$ GeV^{-2} for $|t| < 0.3$ GeV^2.

In Figs. 1(d)–1(f) we present the density-matrix elements $(\rho_{00} + \frac{1}{3}\rho_{ss})^J$ and $\rho_{11} + \rho_{1-1} + \frac{1}{3}\rho_{ss}$ for ρ^-, ρ^0, and ρ^+, respectively.[5] The density-matrix element $(\rho_{00} + \frac{1}{3}\rho_{ss})^J$ receives contributions only from the unnatural parity π and A_1 exchanges. The large values of $(\rho_{00} + \frac{1}{3}\rho_{ss})^J$ at small $|t|$ are usually attributed to the importance of π exchange in this region. Since π exchange (and A_1 in the limit of large s) cannot contribute to the combination $\rho_{11} + \rho_{1-1}$ and since $\frac{1}{3}\rho_{ss}$ is small,[5] the fact that $\rho_{11} + \rho_{1-1} + \frac{1}{3}\rho_{ss}$ is large for ρ^-, ρ^0, and ρ^+ indicates that ω or A_2 exchange is important in ρ production particularly at large $|t|$ values. In particular, the break which occurs in $d\sigma/dt$ for ρ^0 at $t \sim -0.25$ GeV^2 could be explained by the transition from the dominance of π exchange at small $|t|$ to the dominance of A_2 exchange at large $|t|$.[6]

To isolate the ω exchange, we consider the $I=0$ (a_0) and $I=1$ (a_1) t-channel amplitudes for ρ production: $a_0 + a_1$ for ρ^-, $\sqrt{2}\, a_1$ for ρ^0, and $a_0 - a_1$ for ρ^+. Therefore, one can obtain

$$|a_0|^2 = \frac{1}{2}\left[\frac{d\sigma}{dt}(\rho^+) + \frac{d\sigma}{dt}(\rho^-) - \frac{d\sigma}{dt}(\rho^0)\right] = R^2(t),$$

$$|a_1|^2 = \frac{1}{2}\frac{d\sigma}{dt}(\rho^0).$$

Furthermore, the phase of the interference, Φ, between a_0 and a_1 is given by

$$\cos\Phi = \frac{d\sigma(\rho^-)/dt - d\sigma(\rho^+)/dt}{4|a_0||a_1|}.$$

From G-parity conservation, only the ω trajectory can contribute to $|a_0|^2$ while the π, A_1, and A_2 can all contribute to $|a_1|^2$. Figure 2(a) shows the experimental value for $R^2(t)$ (or $|a_0|^2$). The following important features of $R^2(t)$ should be noted: (i) There is a suggestion of a forward dip at $t \sim 0$.[7] (ii) A maximum at $|t| \sim 0.1$ GeV^2 is followed by a *zero* at $t \sim -0.45$ GeV^2.[8] (iii) A second broad maximum centered at about $|t| \sim 0.8$ GeV^2 follows the dip.

To study ω exchange further we calculate $I=0$ density-matrix elements $(R_{m,n})_{I=0}$ in both the t-channel (J) and s-channel (H) helicity frames, where

$$(R_{m,n})_I = \frac{1}{2}\left\{R_{m,n}^{-}\frac{d\sigma}{dt}(\rho^-) + R_{m,n}^{+}\frac{d\sigma}{dt}(\rho^+) - R_{m,n}^{0}\frac{d\sigma}{dt}(\rho^0)\right\}.$$

The density-matrix elements $(\rho_{00}+\frac{1}{3}\rho_{ss})_{I=0}{}^H$, $(\mathrm{Re}\rho_{10})_{I=0}{}^H$, and $(\rho_{11}+\rho_{1-1}+\frac{1}{3}\rho_{ss})_{I=0}$ are shown in Fig. 2(b). If $R^2(t)$ does indeed isolate the $I=0$ ω-exchange contribution to ρ production, then this contribution should only populate the states of the ρ in the t-channel frame with helicity ± 1. We observe that $(\rho_{00}+\frac{1}{3}\rho_{ss})_{I=0}{}^J$ and $(\mathrm{Re}\rho_{10})_{I=0}{}^J$ are consistent with zero (not shown) and that $(\rho_{11}+\rho_{1-1}+\frac{1}{3}\rho_{ss})_{I=0}$ is consistent with 1 as shown. These results support the hypothesis that $R^2(t)$ measures the square of the ω amplitude. We also observe that $(\rho_{00}+\frac{1}{3}\rho_{ss})_{I=0}{}^H$ and $(\mathrm{Re}\rho_{10})_{I=0}{}^H$ are consistent with zero (as shown) indicating that the $I=0$ ω exchange in ρ production is s-channel helicity flip at the meson vertex.

The phase of the $I=0$ ω amplitude relative to the $I=1$ amplitude appears to be $\sim 90°$ with no strong t dependence as shown in Fig. 2(c). Beyond $|t| \sim 0.3$ GeV^2 where we expect ω and A_2 exchanges to dominate, the fact that $\Phi \sim 90°$ may be explained by (ω, A_2) exchange degeneracy.

In the Regge-pole model, the dips which occur in $d\sigma/dt$ for $\rho^\pm$ can be attributed to the wrong-signature nonsense zero (WSNZ) of the ω trajectory. Assuming linearity, the ω trajectory is determined from the ω mass squared and the intercept,[9] $\alpha(t=0) \sim 0.4$. This will give the WSNZ $\alpha(t)=0$ at $t \sim -0.4$ GeV^2 which is consistent with the location of the dips in $d\sigma/dt$ for both ρ^- and ρ^+ ($t \sim -0.45$ GeV^2) and with the zero in $R^2(t)$ ($t \sim -0.45$ GeV^2) observed in this experiment. From the (ρ, ω) exchange-degeneracy conjecture, one would expect that dips due to WSNZ's of the ρ or ω trajectory would occur at the same t. However, we note that the dip in π^-p charge ex-

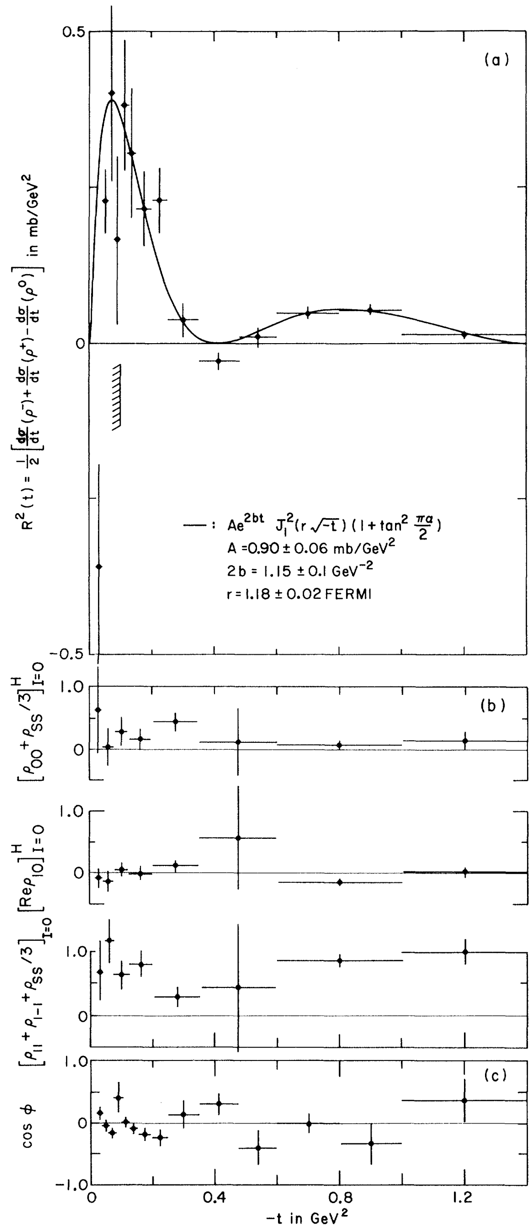

FIG. 2. (a) Experimental determination of $I=0$ exchange amplitude squared $R^2(t)$ in $\pi p \to \rho n$ at 6 GeV/c. Cross-hatched area indicates $|t| < 0.1$ GeV^2 where there is a loss of $\rho^\pm$ events (see Refs. 4 and 6). Solid line is the fit with $R^2(t)$ as described in text. (b) Density-matrix elements for $I=0$ exchange (defined in text). (c) Cosine of phase angle between $I=0$ and $I=1$ amplitude.

change, due to ρ exchange, occurs at $t \sim -0.6$ GeV^2, not at $t \sim 0.45$ GeV^2 as observed here for ω exchange.

The results for the density-matrix elements from this experiment indicate that ω exchange in ρ production is s-channel helicity flip at the meson vertex [see Fig. 2(b)]. Furthermore there is evidence[10] that ω exchange is s-channel helicity nonflip at the nucleon vertex. Thus, the total change of s-channel helicity equals 1 in ρ production. From the point of view of the dual-absorption model, Harari[11] predicts that, for a unit s-channel helicity flip,

$$R^2(t) = Ae^{2bt}J_1^{\,2}(r\sqrt{-t})(1+\tan^2\tfrac{1}{2}\pi\alpha).$$

Using the α deduced for the ω trajectory above, we achieved a good fit $[P(\chi^2) = 50\%]$ to $R^2(t)$ with $r = 1.18 \pm 0.02$ F as shown by the solid curve in Fig. 2(a).[12] The value of $r \sim 1$ F indicates that the geometrical picture of scattering is a reasonable description of our results. We note that the helicity-nonflip ω amplitude has $J_0(r\sqrt{-t})$ behavior[13] whereas the helicity-flip ω amplitude has $J_1(r\sqrt{-t})$ behavior.

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[4]A scanning bias due to low-momentum protons causes a loss of ρ^+ and ρ^- events for $|t| < 0.1$ GeV^2. This effect is t dependent, but because of limited statistics we cannot make a meaningful correction to $d\sigma/dt$ as a function of t. However, the quoted cross sections for $|t| < 2$ GeV^2 have been corrected by 5% for ρ^- and 2% for ρ^+.

[5]The density-matrix elements are calculated by the method of moments for the $\pi\pi$ mass interval 0.65–0.90 GeV. The quantity $(\rho_{00}+\frac{1}{3}\rho_{ss})^J$ is calculated in the t-channel helicity frame (J) while $\rho_{11}+\rho_{1-1}+\frac{1}{3}\rho_{ss}$ is the same in the s-channel and t-channel helicity frames. ρ_{ss} is the s-wave $\pi\pi$ density-matrix element ($\frac{1}{3}\rho_{ss}$ is estimated from the background contribution to the $\pi\pi$ mass spectra to be less than 0.05). In calculating the density-matrix elements, the 3% Δ^{++} overlap with the ρ^+ has been corrected for by subtracting conjugate Δ^{++} events in the Dalitz plot.

[6]A fit to the ρ^0 differential cross section of the form $d\sigma/dt = B\exp(b_0t) + C\exp(c_0t)$ yields values of $b_0 = 15.8 \pm 7$ GeV^{-2} and $c_0 = 3.4 \pm 0.2$ GeV^{-2}, with $P(\chi^2) = 20\%$. The two terms become equal at $t = -0.2$ GeV^2. The value obtained for b_0 is characteristic of π-exchange processes [see for example, G. S. Abrams *et al.*, Phys. Rev. Lett. 25, 617 (1970)]. The value obtained for c_0 is characteristic of A_2-exchange processes [see for example, O. Guisan *et al.*, Phys. Lett. 18, 200 (1965)].

[7]The bias due to low-momentum protons (see Ref. 4) could introduce a dip in $R^2(t)$ at $t \sim 0$. Experimentally, the maximum correction for the first $R^2(t)$ point would raise its value to 0. The suggestion of the dip would remain, however, since the bias correction would also increase the other values of $R^2(t)$ for $|t| < 0.1$ GeV^2.

[8]The definite zero in $R^2(t)$ at $t \sim -0.45$ GeV^2 observed in this experiment was not seen in previous experiments. Previous determinations of $R^2(t)$, having limited statistics (Ref. 1) and normalization difficulties (Refs. 1 and 2), suggested only a minimum at $t \sim -0.45$ GeV^2.

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[12]A fit of $R^2(t)$ with the form $Ae^{2bt}J_0^{\,2}(r\sqrt{-t})$ produced an unacceptable fit $[P(\chi^2) < 0.1\%]$ with $r = 0.75$ F. A fit with the sum $A_0\exp(2b_0t)J_0^{\,2}(r\sqrt{-t}) + A_1\exp(2b_1t)J_1^{\,2}(r\sqrt{-t}) \times (1+\tan^2\frac{1}{2}\pi\alpha)$ required $A_0 = 0$.

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