

Determination of the ω^0 Spin-Density-Matrix Elements in the Reaction $\pi^- p \rightarrow \omega^0 n \dagger$

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We report measurements of the ω^0 spin-density matrix elements in the reaction $\pi^- p \rightarrow \omega^0 n$ at incident momenta of 3.65, 4.5, and 5.5 GeV/c. In the Gottfried-Jackson frame the data exhibit nonzero values of ρ_{00} , indicating the presence of unnatural-parity exchange as well as a large value of $\rho_{11} + \rho_{1-1}$ which does not show a dip in the momentum transfer distribution. The unnatural-parity contribution decreases with respect to the natural-parity contribution as the momentum increases.

The study of final-state spin configurations in quasi-two-body processes is a well-known means of analyzing production mechanisms. With this intent, an investigation of the reaction $\pi^- p \rightarrow \omega^0 n$ at 3.65, 4.5, and 5.5 GeV/c was performed with optical spark chambers and scintillation counters. This particular reaction is well suited to analysis by peripheral models because of the restrictions placed on the possible exchange mechanisms by conservation of isospin and G parity. Of the known low-lying mesons only the $\rho(765)$, a vector meson, and the $B(1235)$, an axial vector meson, have $I^G = 1^+$ and are thus able to couple to the $\pi\omega$ vertex.

The experiment was performed at the Argonne zero-gradient synchrotron. The direction and time of flight of recoil neutrons were measured with a 52-element scintillation-counter hodoscope placed 10 m from a 30-cm-long hydrogen target. Optical spark-chamber photographs were measured to determine the directions of two charged tracks and two photon-induced showers. A one-constraint fit was then made with the hypothesis $\pi^- p \rightarrow \pi^+ \pi^- \pi^0 n$.

The three-pion effective-mass distribution of the final sample of accepted events with a momentum transfer in the range $0.05 \leq -t \leq 1.0$ (GeV/c)² is shown in Fig. 1 for the 4.5-GeV/c data. The width of the ω^0 peak is in agreement with the expected resolution of the neutral missing-mass spectrometer averaged over the momentum-transfer range. After making a straight-line background subtraction, we find agreement with the radial Dalitz plot density expected for ω^0 decay (also shown in Fig. 1).¹ Our final data sample consists of 567, 562, and 398 ω^0 events above background at 3.65, 4.5, and 5.5 GeV/c, respectively.

Our results for the density-matrix elements in both the Gottfried-Jackson and helicity frames² are presented in Table I. Background and acceptance corrections have been made to the data in each t interval. No simplifications or interesting structures are apparent in the helicity-frame density-matrix elements, and we hereafter confine ourselves to a discussion of the density-matrix elements referred to the t -channel axes (Gottfried-Jackson frame). We also list $\rho_{\pm} = \rho_{11} \pm \rho_{1-1}$. In the Regge asymptotic limit these quantities isolate natural- (ρ_+) and unnatural- (ρ_-)

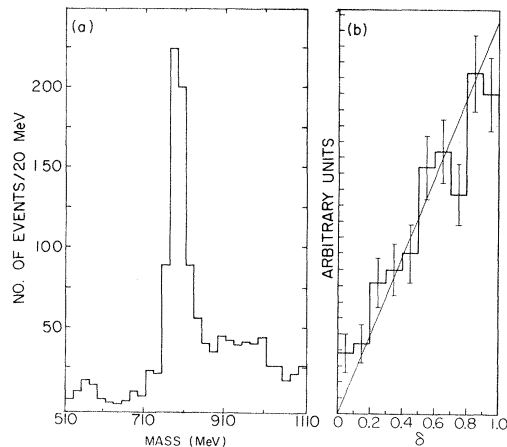


FIG. 1. (a) The three-pion invariant-mass distribution for fitted events at 4.5-GeV/c incident momentum. The distributions at 3.65 and 5.5 GeV/c are similar. The mass distribution is not similar to that found in bubble-chamber experiments because of variations in acceptance. (b) The radial-Dalitz-plot density at 4.5 GeV/c, i.e., the number of subtracted events versus $\delta = |\vec{P}_1 \times \vec{P}_2|^2 / |\vec{P}_1 \times \vec{P}_2|_{\text{max}}^2$, where \vec{P}_1 and \vec{P}_2 are the momenta of the charged pions in the ω^0 rest frame. The straight line corresponds to the distribution expected from a decay amplitude $A \propto |\vec{P}_1 \times \vec{P}_2|$.

TABLE I. The density-matrix elements as a function of momentum transfer.

Density Matrix Element	$-t$	3.65 GeV/c	4.5 GeV/c	5.5 GeV/c	3.65 GeV/c	4.5 GeV/c	5.5 GeV/c
Gottfried-Jackson Frame				Helicity Frame			
ρ_{00}	0.05-0.15	0.51±0.11	0.28±0.09	0.33±0.11	0.29±0.10	0.29±0.10	0.35±0.12
	0.15-0.25	0.27±0.07	0.33±0.07	0.29±0.08	0.17±0.07	0.28±0.08	0.22±0.07
	0.25-0.35	0.20±0.10	0.22±0.07	0.06±0.08	0.42±0.10	0.25±0.07	0.29±0.09
	0.35-0.50	0.25±0.08	0.23±0.07	0.11±0.09	0.32±0.08	0.28±0.08	0.19±0.09
	0.50-0.70	0.38±0.09	0.28±0.09	0.36±0.13	0.22±0.08	0.24±0.09	0.12±0.12
	0.70-1.00	0.48±0.13	0.40±0.13	0.67±0.23	0.25±0.11	0.17±0.13	0.20±0.18
ρ_{1-1}	0.05-0.15	0.26±0.10	0.20±0.08	0.16±0.10	0.15±0.10	0.20±0.08	0.17±0.11
	0.15-0.25	0.17±0.07	0.19±0.07	0.24±0.07	0.12±0.07	0.17±0.07	0.20±0.07
	0.25-0.35	0.05±0.09	0.14±0.07	0.21±0.08	0.16±0.09	0.15±0.07	0.32±0.08
	0.35-0.50	0.10±0.07	0.11±0.07	0.27±0.09	0.13±0.07	0.14±0.07	0.31±0.09
	0.50-0.70	0.07±0.08	0.10±0.09	0.19±0.12	-0.01±0.09	0.08±0.09	0.07±0.12
	0.70-1.00	-0.10±0.09	0.01±0.12	-0.01±0.16	-0.22±0.11	-0.11±0.12	-0.24±0.20
Re(ρ_{10})	0.05-0.15	-0.04±0.06	-0.04±0.05	-0.06±0.07	0.18±0.06	0.03±0.05	0.03±0.06
	0.15-0.25	0.02±0.04	-0.07±0.04	-0.06±0.04	0.00±0.04	0.08±0.04	0.08±0.04
	0.25-0.35	-0.13±0.05	-0.00±0.04	-0.07±0.05	0.09±0.05	-0.01±0.04	0.01±0.05
	0.35-0.50	-0.14±0.04	0.00±0.04	-0.02±0.05	0.13±0.04	-0.02±0.04	0.02±0.05
	0.50-0.70	-0.12±0.05	-0.11±0.06	-0.10±0.07	0.10±0.05	0.09±0.05	0.08±0.07
	0.70-1.00	-0.20±0.07	-0.21±0.08	-0.09±0.12	0.15±0.07	0.17±0.08	0.03±0.13
		$\rho_{11} - \rho_{1-1}$ (Gottfried-Jackson frame)			$\rho_{11} + \rho_{1-1}$ (both frames)		
	0.05-0.15	-0.01±0.10	0.17±0.08	0.18±0.10	0.51±0.12	0.56±0.10	0.49±0.13
	0.15-0.25	0.19±0.07	0.15±0.07	0.12±0.06	0.54±0.08	0.53±0.09	0.60±0.09
	0.25-0.35	0.35±0.09	0.25±0.07	0.26±0.08	0.45±0.11	0.53±0.08	0.68±0.10
	0.35-0.50	0.28±0.08	0.27±0.07	0.18±0.09	0.47±0.08	0.50±0.08	0.72±0.11
	0.50-0.70	0.24±0.09	0.25±0.09	0.12±0.13	0.38±0.10	0.46±0.11	0.51±0.14
	0.70-1.00	0.36±0.11	0.29±0.13	0.17±0.18	0.16±0.12	0.31±0.14	0.16±0.22

parity-exchange contributions.³ In Fig. 2 we have plotted $\rho_{00}(t)$ and $\rho_+(t)$ in the Gottfried-Jackson frame for each of the three incident momenta. We note the following features: (1) ρ_{00} is non-zero, indicating the presence of unnatural-parity exchange; (2) ρ_+ is nonzero, indicating the presence of natural-parity exchange; and (3) $\rho_+(t)$ does not show a dip near $-t=0.6$ (GeV/c)², ruling out simple ρ -trajectory exchange with a nonsense wrong-signature zero (NWSZ) as the sole natural-parity-exchange mechanism. These features are in general agreement with previously observed results in the charge-symmetric reaction $\pi^+n \rightarrow \omega^0 p$.⁴⁻¹¹

We now wish to call attention to two additional phenomena present in our data. First, we observe a broad minimum in $\rho_{00}(t)$ near $-t=0.35$.¹² Such a dip is not easily associated with a B exchange contribution ($|t|$ at the dip is presumably too large to be correlated with a NWSZ on the B trajectory). Neither does the Henyey-Kajantie-Kane absorption model predict such a dip from ρ -Pomeranchukon exchange.¹³ We can conjecture on two possible descriptions: (1) a combination of a

large contribution to $\rho_{00}(t)$ for $-t \leq 0.3$ from B exchange plus a contribution for $-t \geq 0.5$ from the absorption of ρ exchange, or (2) a dominant contribution to $\rho_{00}(t)$ from an unnatural-parity, odd charge-conjugation exchange. The latter might result from double-particle exchange.

Second, we note that the average value of ρ_+ increases with increasing incident momentum. This is more explicitly demonstrated in Fig. 3, where $\bar{\rho}_+/(1-\bar{\rho}_+)$ versus incident momentum is plotted. [Here, $\bar{\rho}_+$ is the value of ρ_+ calculated for all events on the interval $0.05 \leq -t \leq 1.0$ (GeV/c)² at a given incident momentum.] In the asymptotic limit $\bar{\rho}_+$ and $1-\bar{\rho}_+$ are, respectively, the fractions of the cross section produced by natural- and unnatural-parity-exchange processes. If both the natural- and unnatural-parity-exchange cross sections exhibit a power-law dependence on the beam momentum (characteristic of the exchange process), then so does the ratio $\bar{\rho}_+/(1-\bar{\rho}_+)$, i.e.,

$$\bar{\rho}_+/(1-\bar{\rho}_+) \propto p^{2\alpha_n - 2\alpha_u},$$

where p is the incident laboratory momentum and

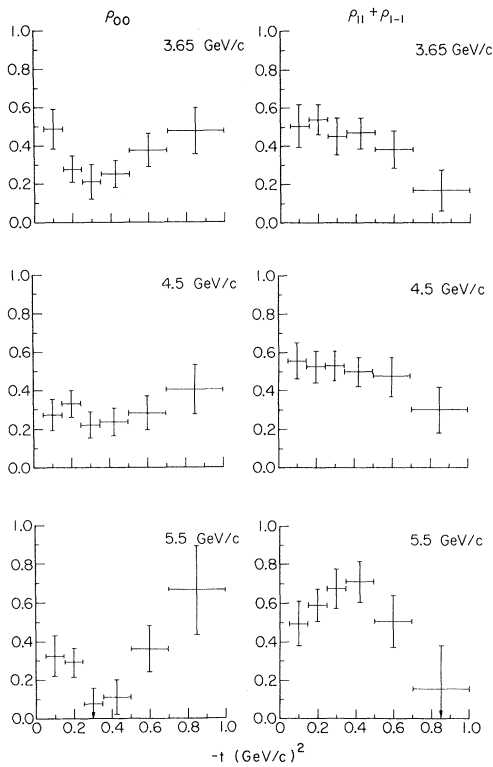


FIG. 2. The Gottfried-Jackson-frame density-matrix elements ρ_{00} and $\rho_+ = \rho_{11} + \rho_{1-1}$ plotted as a function of momentum transfer.

$2\alpha_n$ and $2\alpha_u$ are the power-law dependences of the natural- and unnatural-parity-exchange cross section, respectively. A least-squares fit

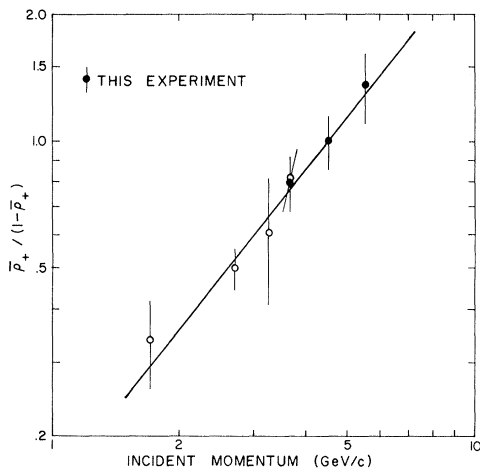


FIG. 3. A plot of the ratio of natural-parity exchange to unnatural-parity exchange averaged over all momentum transfers versus incident laboratory momentum. The points corresponding to the open circles are computed from data published in Refs. 4-7.

to the data with the expression¹⁴

$$\bar{\rho}_+ / (1 - \bar{\rho}_+) = A(p/3)^{2B}$$

yields $A = 0.60 \pm 0.04$ and $B = 0.64 \pm 0.04$.

Data on the reaction $\pi^- p \rightarrow \omega^0 n$ ($\pi^+ n \rightarrow \omega^0 p$) have generally been analyzed in the context of a Reggeized $\rho+B$ exchange, or ρ exchange modified by absorption, or a combination of both. We conclude on the basis of the data presented here that the relative energy dependence of the natural- and unnatural-parity cross sections requires the introduction of unnatural-parity exchange beyond that provided by ρ exchange plus absorption.¹⁵ If ρ exchange dominates the natural-parity cross section, then a trajectory for the unnatural-parity contribution with an intercept $-0.3 \lesssim \alpha_u(0) \lesssim 0$ is strongly suggested. This could result from B exchange or double-particle exchange (e.g., double ρ exchange).¹⁶ We also point out that a value of $\alpha_u(0)$ in the range indicated explicitly precludes associating the dip in $\rho_{00}(t)$ with a NWSZ. The lack of a dip in $\rho_+(t)$ at $-t = 0.6$ presumably must result from a ρ -exchange amplitude without a NWSZ, or perhaps from a large contribution to $\rho_+(-0.6)$ from double-particle exchange.

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¹The data have not been corrected for any variation of acceptance over the ω^0 Dalitz plot; the agreement found attests to both the expected lack of acceptance variation and to the presence of an ω^0 signal.

²Our definitions of coordinate axes are the customary ones, i.e., a right-handed system with the y axis along the production-plane normal ($\vec{\pi}_{inc} \times \vec{\omega}$ in the laboratory) and the z axis either along the incident pion or antiparallel to the recoil neutron in the ω^0 rest frame.

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¹⁴The parametrization was chosen to minimize the correlation between A and B .

¹⁵The energy dependence of double-particle exchange is obtained from the effective trajectory intercept $\alpha(0) = \alpha_1(0) + \alpha_2(0) - 1$. Thus ρ plus Pomeranchukon exchange has the same energy dependence as ρ exchange.

¹⁶We note that the unnatural-parity contribution is of the order expected from double-particle exchange according to H. Harari, *Phys. Rev. Lett.* **26**, 1079 (1971).

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

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Dips are observed at $t \sim -0.45$ GeV² in the differential cross sections of the reactions $\pi^+ p \rightarrow \rho^+ p$ and a break at $t \sim -0.25$ GeV² in $\pi^- p \rightarrow \rho^0 n$ at 6 GeV/c. The $I=0$ ω -exchange contribution in the t channel is isolated by calculating

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

The function $R^2(t)$ vanishes at $t \sim -0.45$ GeV² 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 example¹ has been the extraction of the $I=0$ ω contribution to ρ production by computing

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

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 $|t| < 2.0$ GeV² (l is the orbital angular momentum of the $\pi\pi$ system). The cross sections⁴ averaged over the different resonance and background assumptions are

$$\sigma(\pi^- p \rightarrow \rho^- p) = 0.24 \pm 0.03 \text{ mb},$$

$$\sigma(\pi^- p \rightarrow \rho^0 n) = 0.36 \pm 0.04 \text{ mb},$$

$$\sigma(\pi^+ p \rightarrow \rho^+ p) = 0.26 \pm 0.03 \text{ mb}.$$

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,