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Interference between ρ and ω Production in $\pi^{\pm} N \to \pi^+\pi^- N$ at 3, 4, and 6 GeV/c*

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The ρ-ω interference patterns observed in the reactions $\pi^- p \to \pi^+\pi^- n$ and $\pi^+ n \to \pi^+\pi^- p$ are used to measure the relative phases between ρ and ω production amplitudes. The interference is observed to be largely constructive (destructive) for the π^-- (π^+-) induced reaction in both natural- and unnatural-parity exchange amplitudes. This sign of the interference agrees with that predicted from exchange-degenerate π-B trajectories, but disagrees with the corresponding prediction for the natural-parity amplitudes using exchange-degenerate ρ-A_2 trajectories.

In this Letter we present results from a detailed study of ρ-ω interference in the reactions

$$\pi^- p \to \pi^+\pi^- n, \tag{1}$$

$$\pi^- d \to \pi^+\pi^- n n_s, \tag{2}$$

$$\pi^+ d \to \pi^+\pi^- p p_s, \tag{3}$$

at 3, 4, and 6 GeV/c. Except for the ρ-ω interference term which changes sign, the cross sections for the π^-- and π^+-induced reactions should be equal by isospin conservation. Consequently the ρ-ω interference effect can be directly isolated from the difference of the reactions, yielding precise information on the relative ρ-ω production amplitudes. The high statistics of this experiment ($\approx 6\times10^5$ events) have permitted a detailed study of ρ-ω interference for natural- and unnatural-parity exchange amplitudes, presenting severe constraints on vector-meson–production models.[1]

The data were obtained by using the Argonne National Laboratory effective mass spectrometer.[2] The trigger required a $\pi^{\pm}$ beam particle incident on a 20-in. liquid hydrogen or deuterium target, an interaction in the target producing two or more charged particles through the spectrometer, and no signals from the beam veto or target and magnet veto counters. The recoil baryon was not detected, but events were selected with appropriate missing-mass-squared (M_X^2) cuts, assuming the observed particles were pions. The rms resolution on M_X at 4 GeV/c for Reaction (1) was $\pm$ 28 MeV and was essentially independent of $M_{\pi\pi}$ and t. The Fermi motion of the deuterium target had little effect on this resolution (kinematic smearing of M_X^2 being roughly proportional to $\sqrt{-t}$) which increased to about $\pm$ 40 MeV at 4 GeV/c and $|t| \approx 0.4$ GeV^2. The background corrections for Reactions (1) and (3) were comparable ($\approx 5\%$) and for Reaction (2) nearly twice as large.

The data on Reaction (2) were taken in order to better understand the systematic differences between Reactions (1) and (3) due to deuterium effects. Reactions (2) and (3) have been corrected for Glauber screening (3%) and exclusion-principle effects.[3] All data have been corrected for event losses due to spectrometer acceptance, veto-counter losses, final-state particle interactions ($\approx 10\%$ for H_2 and $\approx 15\%$ for D_2), pion decays (2–10%), chamber and program inefficiencies ($\approx 7\%$), and the effect of M_X^2 cuts (typically 1%). The corrected cross sections for Reactions (1) and (2) agreed to typically better than 3%, pro-

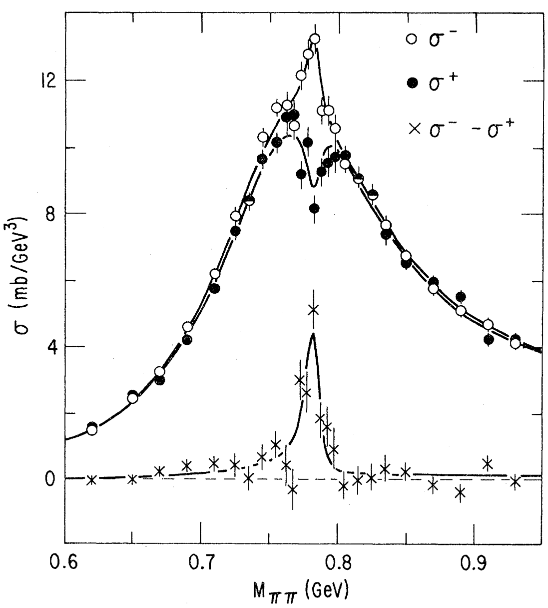

FIG. 1. Differential and difference cross sections at 4 GeV/c with $0.08 < -t < 0.2$ GeV^2. The curves are the result of the fit by Eq. (5) described in the text.

viding a good check of the deuterium corrections. The overall normalization uncertainty is estimated to be ±12% and the relative normalization uncertainty between Reactions (1) and (3) is approximately ±8%. However, isospin conservation requires that, except for the ω mass region, the cross sections for the π^+ and π^- reactions should be equal. This constraint is satisfied by the corrected cross sections to better than 5%.

A sample of the corrected differential cross sections, $\sigma = d^2\sigma/dt\,dM_{\pi\pi}$, as a function of $M_{\pi\pi}$ is presented in Fig. 1. A narrow peak is observed at the ω mass for the π^--initiated reaction and a dip for the π^+ one. The interference term between ρ and ω production amplitudes can be obtained directly from the difference between the π^- and π^+ cross sections, $\Delta = \sigma^- - \sigma^+$, also shown in Fig. 1.

Additional information can be obtained by using the s-channel density matrix elements (ρ_{ij}) to isolate the various exchange mechanisms[4]:

$$\begin{aligned} \sigma_{00} &= \rho_{00}\sigma + \sigma_s/3, \\ \sigma_{1-} &= (\rho_{11} - \rho_{1-1})\sigma + \sigma_s/3, \\ \sigma_{1+} &= (\rho_{11} + \rho_{1-1})\sigma + \sigma_s/3. \end{aligned} \tag{4}$$

With the neglect of the small incoherent s-wave contribution ($\sigma_s = \rho_{ss}\sigma$), σ_{1+} asymptotically projects out the natural-parity exchange cross section while σ_{00} and σ_{1-} project out the unnatural-parity exchange cross sections.

We have fitted the differential cross sections for incident $\pi^\pm$ by a first-order mass-mixing formula,[5]

$$\sigma_{ij}^{\pm} = f(M_{\pi\pi})[|A_\rho B_\rho|^2 + |\epsilon A_\omega B_\omega|^2 \pm 2\xi|\epsilon A_\rho A_\omega|\mathrm{Re}(e^{i\varphi}B_\omega B_\rho^*)] + \text{background}. \tag{5}$$

$A_{\rho,\omega}$ and $B_{\rho,\omega}$ are the ρ, ω production and Breit-Wigner decay[6] amplitudes, respectively, and $f(M_{\pi\pi})$ is the $\pi\pi$ kinematic factor ($M_{\pi\pi}^2/q$) of Ref. 6. The strength of the decay $\omega \to \pi^+\pi^-$ is related to ϵ, where

$$|\epsilon| = |\delta/[(m_\rho^2 - m_\omega^2) - i(m_\rho\Gamma_\rho - m_\omega\Gamma_\omega)]| \tag{6}$$

and δ is the mass-mixing parameter.[5] The relative phase between A_ρ and A_ω (for incident π^+) is given by

$$\beta^+ = \beta_\omega^+ - \beta_\rho^+ = \varphi - \arg(\epsilon) \approx \varphi - 105°, \tag{7}$$

where δ has been assumed to be real.[7] Since the σ_{ij} are actually incoherent sums over the nucleon spin states, the quantities $|A_{\rho,\omega}|^2$ are similarly defined and the spin coherence is accounted for by the factor ξ ($0 \leq \xi \leq 1$). The s-wave background was adequately parametrized by a linear $M_{\pi\pi}$ dependence in the last term of Eq. (5).

The π^+ and π^- cross sections were fitted simultaneously,[8] with the resonance parameters constrained to $m_\rho = 0.765 \pm 0.005$ GeV, $\Gamma_\rho = 0.150 \pm 0.010$ GeV, $m_\omega = 0.783$ GeV,[9] and $\Gamma_\omega = 0.010 \pm 0.002$ GeV. To allow for any residual normalization error, a relative π^+ to π^- normalization parameter was included in the fit. Typically this parameter differed from unity by less than 3%. Since the fits were generally consistent with $\xi = 1$, this value was assumed. The difference cross sections Δ_{00} and Δ_{1+} are presented in Fig. 2 together with the results of this fit.

In Fig. 3 the relative production phase obtained from Eq. (7) is presented for all cross sections showing significant ρ-ω interference. If exchange-degenerate (EXD) π and B trajectories dominate the unnatural-parity exchange amplitudes,[10] then

$$A_\omega^+/A_\rho^+ \propto -i\tan\tfrac{1}{2}\pi\alpha(t). \tag{8}$$

With $\alpha(t) < 0$ in the region of interest, the phase β^+ is then predicted to be 90°. For σ_{00} we find an average value for this phase of $122° \pm 6°$, with

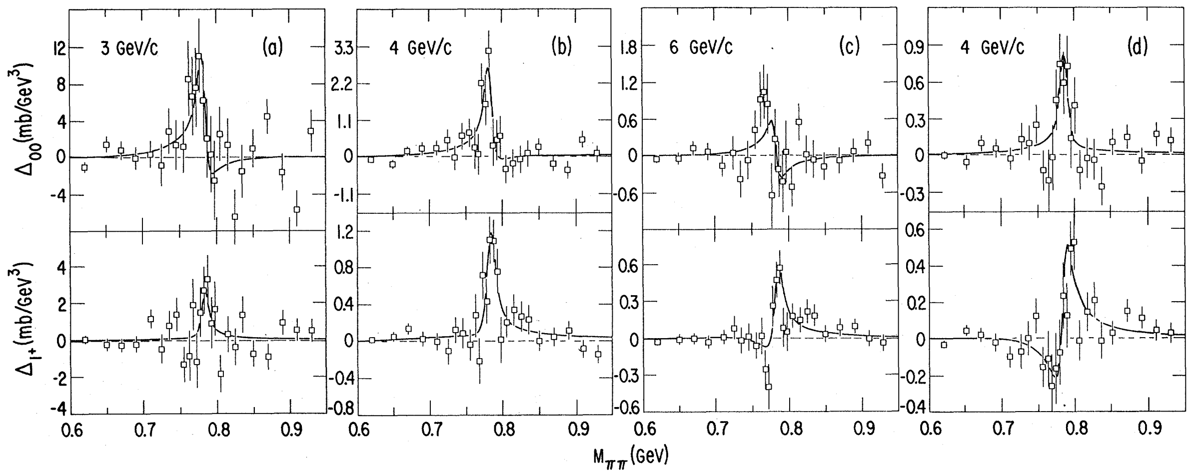

FIG. 2. Difference cross sections Δ_{00} and Δ_{1+} at 3, 4, and 6 GeV/c for (a) $0.0<-t<0.08$ GeV^2, (b) and (c) $0.08<-t<0.2$ GeV^2, and (d) $0.2<-t<0.4$ GeV^2. The curves are the result of the fit by Eq. (5).

little s or t dependence, in qualitative agreement with this prediction. Our phase for σ_{1-} agrees well with the EXD prediction, the average value being $\beta^+=96°\pm 9°$.

If the natural-parity exchange amplitude were dominated by EXD ρ and A_2 trajectories, Eq. (8) would predict $\beta^+=-90°$ for $-t\lesssim 0.6$ GeV^2. This value is contradicted by our data, which show a variation from about $+90°$ at small $-t$ to 0° near $-t=0.3$ GeV^2 and little s dependence within the errors. This effect has been explained qualitatively by Estabrooks, Martin, and Michael[11] who assume that at small $-t$, σ_{1+} for ρ production is dominated by π cut with A_2 exchange becoming more important at larger $-t$ and s. For ω production only ρ exchange was considered, which predicts a variation in β^+ from $\approx 40°$ at small $-t$ and s to $-90°$ for large $-t$ and s. An extension of this model by Irving and Michael[12] yields somewhat better quantitative agreement for σ_{1+}, at low $-t$.

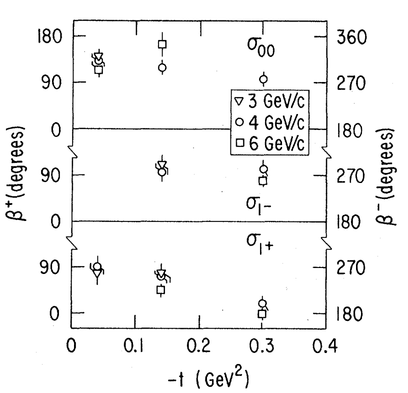

FIG. 3 The relative production phases, $\beta_\omega-\beta_\rho$, measured for σ_{00}, σ_{1-}, and σ_{1+} as a function of t for those cases with a significant ρ-ω interference effect.

Earlier work[13,14] on ρ-ω interference has been limited in statistics and consequently the phases have been given mainly for the differential cross section σ. The previous results in our energy region are consistent with our phase for σ ($\beta^+=90°\pm 10°$ at $-t=0.2$ GeV^2).

With data for both Reactions (1) and (3) we can in principle extract the $|\epsilon A_\omega B_\omega|^2$ term from the sum of the two mass spectra, allowing independent determination of ξ. In practice this term is small and a precise measurement is difficult and highly correlated with the relative π^+ to π^- normalization. However, the shapes of the mass spectra are generally consistent with $\xi=1.0$ and yield a branching ratio for $\omega\to\pi\pi$ of $R\approx 1\%$. A more complete determination of ξ and R is beyond the scope of this Letter and will be discussed in a future publication.

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Note added in proof.—After submitting this Letter for publication we received a preprint[15] on ρ-ω interference measurements at 17.2 GeV/c. As expected,[11,12] the pion-cut contribution to σ_{1+} is relatively less important at higher energies, the phase of σ_{1+} being closer to the EXD prediction for ρ and A_2 exchange. This observation is supported by the results of Ratcliff *et al.*[14] However, the unnatural-parity phases at 17.2 GeV/c are unexpectedly lower than our phases for $|t| \leq 0.2$ GeV^2.

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[3]All cross sections off deuterium have been corrected by the Pauli exclusion-principle factor $(1 - S(\Delta)/3)^{-1}$, where $S(\Delta)$ is the deuterium form factor. This correction is appropriate for all cross sections except the nonflip natural-parity cross section, which must vanish as $t \rightarrow t_{min}$ by angular momentum conservation and should therefore contribute little to the observed σ_{1+} in the t range where $S(\Delta)$ is large. The largest correction was 13% for the $|t| \leq 0.08$-GeV^2 bin.

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[7]This assumption is based on theoretical arguments (see Ref. 5). A complex $\hat{o}$ would be equivalent to a shift of origin for β^+ by $-\arg(\hat{o})$.

[8]Since the results from Reactions (1) and (2) were consistent, we have averaged these cross sections in order to reduce the errors.

[9]m_ω has been fixed to the value preferred by our data, since it is highly correlated with β^+. The value assumed is consistent with the world average value for m_ω (782.7 ± 0.6 MeV), quoted by N. Barash-Schmidt *et al.*, Phys. Lett. 50B, 1 (1974). A ±1 MeV change in m_ω typically introduces a ±5° change in β^+.

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[13]See Ref. 5 for a discussion of early experiments. See also I. J. Bloodworth *et al.*, Nucl. Phys. B35, 133 (1971).

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Influence of Meson Charge Exchange on $\bar{p}$-Absorption Evidence for Neutron Halos*

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Pion charge exchange within the nucleus is shown to be an important effect in antiproton absorption experiments. It must be incorporated into any analysis which attempts to use absorption data to deduce the relative abundance of neutrons and protons at the annihilation site.

There have been several attempts to verify experimentally the unconfirmed, albeit reasonable, conjecture that in the periphery of heavy nuclei there is a preponderance of neutrons over protons which exceeds the N-to-Z ratio for that element.[1] The most recent attempt to track the elusive neutron halo is that of Bugg *et al.*,[2] who use the numbers of charged pions resulting from absorption of antiprotons in C, Ti, Ta, and Pb to deduce that such halos are present in medium and heavy nuclei. We find, however, that inclusion of the hitherto neglected effects of pion charge exchange within the nucleus eliminates any need to invoke a neutron halo to explain their