Production of $\omega'(1675)$ in the Reaction $\pi^+p \to \Delta^{++}\pi^+\pi^-\pi^0$ at 15 GeV/c

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We present the results of a detailed study of $\omega'(1675)$ production in the reaction $\pi^+p \to \Delta^{++}\pi^+\pi^-\pi^0$ from a high-statistics bubble-chamber experiment at 15 GeV/c. We have measured the mass, width, and cross section as well as differential cross section and spin density matrix elements and compare then to A_2^0 production in the same reaction. We show clear evidence for the resonant phase increase of the 3^- $(\rho\pi)f_{I=0}$ amplitude with $\omega'(1675)$ production.

The existence of a high-mass, $I=0$ resonant state with odd G parity, called $\omega'(1675)$, has been suggested for some time.[1] So far, however, the experimental results have not been entirely consistent.[2-6] Most experiments have been done at low energies ($p_{\text{lab}} \leq 7$ GeV/c) and some were not sensitive enough to isolate the state responsible for the $\omega'(1675)$,[6] while others could not show evidence for its resonant nature.[2,5] The values reported for its width by different experiments are still in disagreement.[2,5]

In this Letter we present new experimental results which clearly identify the spin, parity, and isospin of the $\omega'(1675)$. We also show evidence for the resonant nature of this state and give values for its mass and width. We have studied $\omega'(1675)$ production in the reaction[3]

$$\pi^+p \to \Delta^{++}\pi^+\pi^-\pi^0 \quad (7728 \text{ events}). \qquad (1)$$

We have performed an energy-independent spin and parity decomposition of the 3π system using a partial-wave-analysis program which we have developed for this purpose.[3] This is the most detailed study of $\omega'(1675)$ production in Reaction (1).

Our data have been derived from an 866 000-picture exposure of the Standard Linear Accelerator Center 82-in. hydrogen bubble chamber to an rf-separated 15-GeV/c π^+ beam. The sensitivity of the exposure was determined to be 43.3 ± 0.5 events/μb. All interactions were measured on the Columbia University Hough-Powell Device operated in an automatic pattern-recognition mode. We have selected Δ^{++} production in Reaction (1) by requiring at least one $p\pi^+$ mass combination below 1.4 GeV/c^2.[3,7]

The invariant mass of the 3π system produced opposite the Δ^{++} region is shown in Fig. 1(a). (The resolution on the 3π mass is ~15 MeV/c^2.) The distribution shows distinctive η, ω, and A_2^0 peaks. There is also a broad enhancement around 1.7 GeV/c^2 due to the $\omega'(1675)$. Its significance is difficult to assess because of the uncertainty in the shape of the background. The lower-mass, η and ω resonances have been discussed by Csorna.[8] The present analysis covers the range $0.9 \text{ GeV}/c^2 < M_{3\pi} < 2 \text{ GeV}/c^2$.

We describe the 3π system in the spirit of the isobar model[3,9] as the sum of di-pion states with angular momentum l and relative orbital angular momentum of the third π with respect to the di-pion, L. The 3π system has spin and parity of J^P, t-channel helicity M, and isospin I. The $p\pi^+$ system is characterized by its spin and parity of $J_2^{P_2}$ and t-channel helicity M_2. The decay of the 3π system is parametrized in terms of two Dalitz-plot variables and three Euler angles. The $p\pi^+$ system is described by a Hermitian matrix function of the $p\pi^+$ invariant mass, $m_{p\pi^+}$, and the polar angles of the proton in the $p\pi^+$ rest frame. The probability density function for a fixed region of total energy $\sqrt{s}$, 3π mass $m_{3\pi}$, and momentum transfer t' can be written in terms of the generalized density matrix. We have adopted for the density matrix the "minimal parametrization" suggested by Chung and Trueman.[10] By imposing the proper rank conditions on the density matrix, the number of free parameters in the fit is increasing linearly with the number of amplitudes, rather than quadratic as one might expect in a density-matrix analysis.[4-6] None of the amplitudes included in our fits have been forced to be coherent. The extended maximum-likelihood method[11] has been used to estimate the real and imaginary parts of all density matrix elements from the data.

We have included in our analysis 3π amplitudes with isospin $I=0,1$, spin $J \leq 3$, and t-channel helicity $|M|=0,1$. The notation $\epsilon\pi$, $\rho\pi$, $f\pi$, and $g\pi$ identifies the angular momentum of the di-pion: $l=0$, 1, 2, and 3, respectively. For the $p\pi^+$ system, we have allowed Δ^{++} amplitudes with $|M|=\frac{1}{2}$ or $\frac{3}{2}$ and one $p\pi^+$ s-wave background. A complete

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description of our method and the results of our analysis are given elsewhere.[3] In the following, we will summarize some of the results regarding the production of natural-parity states.

We have studied the dependence of different spin and parity states on the 3π mass and the momentum transfer between the incoming proton and the final Δ^{++}. For the $m_{3\pi}$ dependence, we have made fits in 100-MeV/c^2 intervals with the cut $t' < 0.8$ GeV$^2/c^2$. For the t' dependence, we have chosen relatively large mass intervals in the A_2^0 and $\omega'(1675)$ regions and made fits in several t' intervals between 0.0 and 2 GeV$^2/c^2$. In order to reduce the background in Reaction (1), we have eliminated events with both $m_{p\pi^+}$ mass combinations below 1.4 GeV/c^2. All cuts have been properly taken into account in the fitting procedure.[3] After applying all cuts, there were 6576 events left in Reaction (1).

The only natural-parity states which are important above 0.9 GeV/c^2 are the 2^+ $(\rho\pi)$ $d_{I=1}$ and the 3^- $(\rho\pi)f_{I=0}$. The $M_{3\pi}$ distributions of the two waves [Figs. 1(b) and 1(c)] show clear peaks due to A_2^0 and $\omega'(1675)$ production. The best fits to the two distributions yielded the following Breit-Wigner parameters:

$$M_0(A_2^0) = 1.343 \pm 0.011 \text{ GeV}/c^2,$$
$$\Gamma(A_2^0) = 0.115 \pm 0.014 \text{ GeV}/c^2;$$
$$M_0(\omega') = 1.673 \pm 0.012 \text{ GeV}/c^2,$$
$$\Gamma(\omega') = 0.173 \pm 0.016 \text{ GeV}/c^2.$$

The data required a smooth background (second-order polynomial) under the $\omega'(1675)$ for a good fit. The resulting cross sections, corrected for the loss of events in the Δ^{++} tail, are $\sigma_{A_2^0} = 11.4 \pm 1.6$ μb and $\sigma_{\omega'} = 9.9 \pm 3.7$ μb.

The two states are produced predominantly with t-channel helicity $|M| = 0, 1$. Both natural and unnatural parity exchanges contribute. However, both resonances are produced predominantly by unnatural parity exchange.[12]

The ratio, U_m, of unnatural to natural parity-exchange contribution for the $\omega(780)$, A_2^0, and $\omega'(1675)$ mesons, is $U_\omega = 0.63 \pm 0.12$ (Ref. 8), $U_{A_2^0} = 1.98 \pm 0.24$, $U_{\omega'(1675)} = 3.03 \pm 0.61$. This ratio is clearly higher for higher mass resonances, consistent with the trend predicted by Hoyer *et al.* from duality arguments.[13] For the A_2^0, this ratio compares with $U_{A_2^0} = 3.1 \pm 0.5$ in $\pi^+ p \to A_2^0 \Delta^{++}$ at 7 GeV/c,[2] and $U_{A_2^0} = 3.7 \pm 0.8$ in $\pi^+ n \to A_2^0 p$ at 4 GeV/c,[6] suggesting a decrease of B exchange contribution at higher energies.

Our analysis is sensitive to the interference phase between different amplitudes. Both states interfere coherently with the 2^- $(f\pi)$ $s_{I=1}$ wave [Fig. 2(a)]. The phase variation of both amplitudes is quite consistent with a resonant behavior [solid line in Figs. 2(b) and 2(c)].

The differential cross sections for A_2^0 and $\omega'(1675)$ are shown in Fig. 3(a). Both distributions indicate the existence of a forward dip followed by an exponential falloff. From fits with the expression $Ae^{bt'}$ in the interval $0.1 < t' < 2$ GeV$^2/c^2$, we get $b_{A_2^0} = 3.7 \pm 0.6$ [GeV$^2/c^2$]$^{-1}$ and $b_{\omega'(1675)} = 3.1 \pm 0.7$ [GeV$^2/c^2$]$^{-1}$.

The slope parameter for A_2^0 production can be compared with $b = 3.7 \pm 0.7$ [GeV$^2/c^2$]$^{-1}$ for A_2^0 production in $\pi^+ n \to A_2^0 p$ at 4 GeV/c,[6] and with $b = 3.9 \pm 0.4$ [GeV$^2/c^2$]$^{-1}$ for A_2^+ production in the reaction $\pi^+ p \to A_2^+ p$ in this experiment.[3] There are no

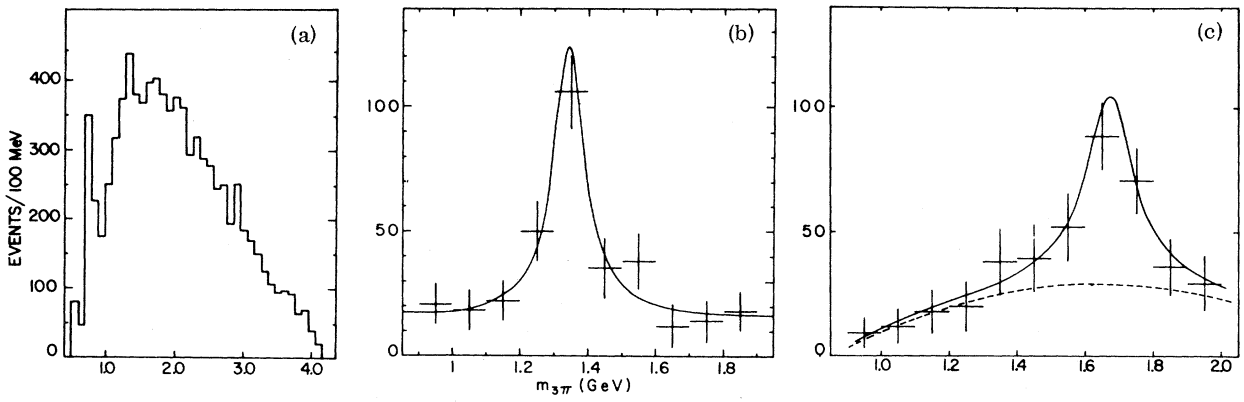

FIG. 1. (a) Invariant-mass distribution of the $\pi^+\pi^-\pi^0$ system produced opposite Δ^{++}. (b),(c) Mass dependence of the 2^+ $(\rho\pi)$ $d_{I=1}$ and 3^- $(\rho\pi)f_{I=0}$ waves.

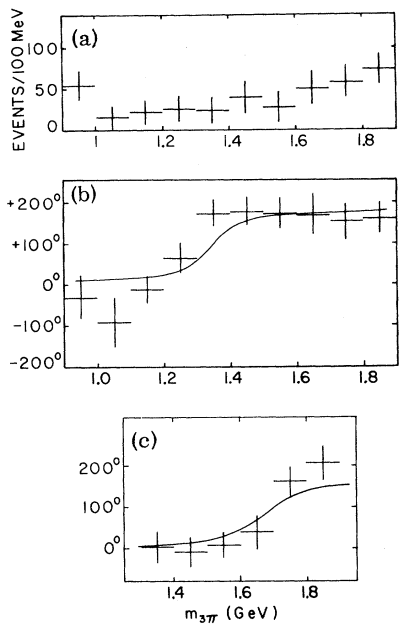

FIG. 2. Invariant-mass distributions of (a) 2^- $(f\pi)$ $s_{I=1}$ wave; (b),(c) the interference phase of 2^+ $d_{I=1}$ and 3^- $f_{I=0}$, respectively, with 2^- $s_{I=1}$.

other measurements of the slope of the $\omega'(1675)$ differential cross section to compare with our result. The slight widening of the differential cross section from A_2^0 to $\omega'(1675)$ is in qualitative agreement with the dual-resonance model.[13]

The t-channel spin density matrix elements for the A_2^0 and $\omega'(1675)$ are shown in Figs. 3(b) and 3(c). Only helicity states 0 and 1 have been included. Both natural and unnatural parity-exchange contributions are important in A_2^0 production below $t' = 1$ GeV$^2/c^2$, whereas at high t' unnatural parity exchange is dominant. The $\omega'(1675)$ production is dominated by unnatural parity exchange at small t'.

Both states, the A_2^0 and $\omega'(1675)$ are produced predominantly in association with Δ^{++} at the baryon vertex, i.e., $(72 \pm 9)\%$ for the A_2^0 and $(87 \pm 17)\%$ for $\omega'(1675)$. The A_2^0 is mostly associated with the $|M| = \frac{3}{2}$ state while the $\omega'(1675)$ is divided between the two helicity states of the Δ^{++}.[3] The 3π background is distributed equally between the Δ^{++} isobar and the $p\pi^+$ s wave.

In conclusion, our results confirm the $J^P = 3^-$ and $I = 0$ assignment for the $\omega'(1675)$. We have measured for the first time the slope of the $\omega'(1675)$ differential cross section and spin density matrix elements up to $|t'| = 2$ GeV$^2/c^2$. We also present clear evidence for the resonant phase increase of the 3^- $(\rho\pi)$ $f_{I=0}$ amplitude associated with $\omega'(1675)$ production in Reaction (1).

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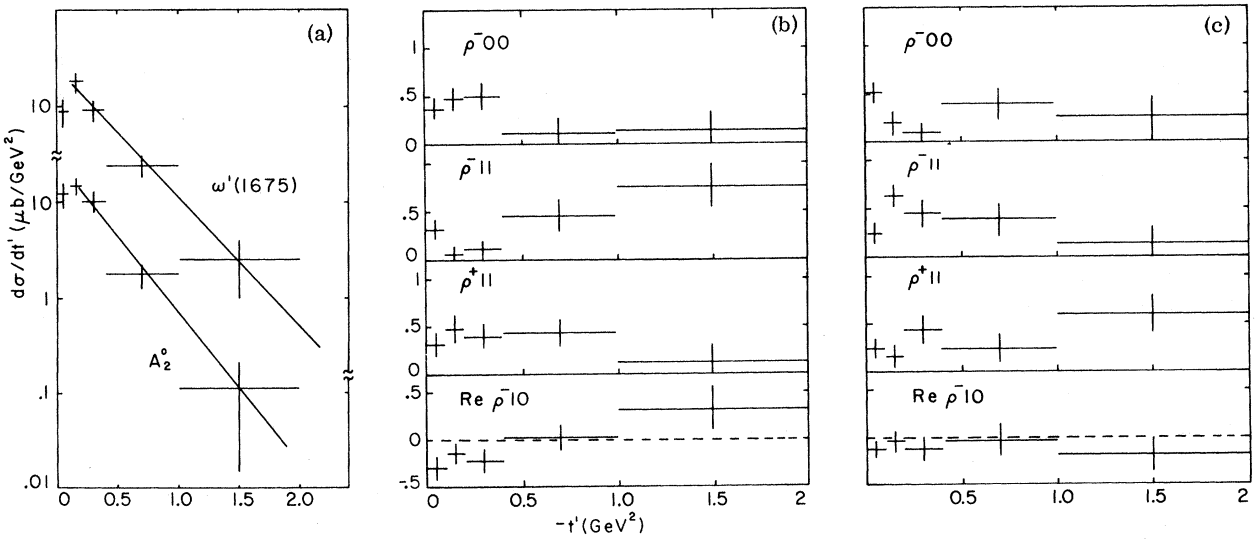

FIG. 3. (a) Differential cross section of 2^+ $d_{I=1}$ and 3^- $f_{I=0}$; (b),(c) spin density matrix elements of A_2^0 and $\omega'(1675)$, respectively.

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Inclusive Production of ρ^0 in Inelastic Muon-Nucleon Scattering

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We measured the inclusive production of ρ^0 mesons in virtual-photon–nucleon collisions. The extracted structure functions are Q^2 independent and approximately equal to those observed in photoproduction, if one excludes the diffractive (elastic) region where a large decrease is observed. A significant fraction of the inclusive $\pi^\pm$ distribution results from the decay of these ρ^0's.

In this Letter, we present first data on the inclusive production of ρ^0 mesons in deeply inelastic muon-nucleon scattering. This process, usually interpreted in terms of the exchange of one virtual photon of four-momentum q ($Q^2 \equiv -q^2$),

$$\gamma_v N \to \rho^0 + \ldots ,$$

is of considerable interest in a number of model interpretations of this process:

(1) In elastic ρ^0 production, this meson is seen as a faithful probe of the incoming photon's hadronic content.[1] Does it do similarly as a leading particle in the beam fragmentation region of the inelastic process?

(2) The photoproduction ($Q^2 = 0$) total cross section is known to contain a much larger fraction of elastic ρ events than the deeply virtual-photon interaction.[2] Does this difference extend into inclusive nonleading ρ^0 production? Are there Q^2 trends?

(3) There has long been the question of to what extent π production in inelastic collisions is "direct" and to what extent due to the decay of heavier mesons ("resonances"). The ρ^0 is the most easily traceable of these "resonances."

(4) In a simple-minded quark-parton model[3] for leading particles, the virtual photon interacting with one of the valence quarks will lead to easily predicted ρ^0/π ratios; i.e., there might be a π (direct) to π (from ρ^0 decay) ratio of 1/3 due to spin factors, in the leading-particle spectrum. Are such ratios in fact observed?

With these points in mind, we have measured ρ^0 cross sections in muon-nucleon scattering, where the muon serves as a source of virtual photons of variable mass. We compare our results to those measured in photoproduction. The experiment from which our data are taken is described in detail by del Papa *et al.*[5] The data sample contains 7750 events on hydrogen and deuterium targets.

Inclusive distributions for the production of a given type of hadron are typically displayed in terms of the Feynman scaling variable[6] x_F, defined to be the longitudinal momentum of the hadron divided by its maximum possible value, in