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A High Statistics Study of ω^0 Production*

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ABSTRACT

We report results from a study of $\pi^- p \rightarrow \omega^0 n$ at 6.0 GeV/c based on 28,000 events from a charged and neutral spectrometer. Background under the ω^0 is only 7%, a large improvement over deuterium bubble chamber work. Density matrix elements, projected cross sections and effective trajectories for natural and unnatural exchanges are presented.

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Previous work¹⁻⁸ on $\pi N \rightarrow \omega N$ has been limited by the difficulties of dealing with neutral particles in the final state, and the best data have so far come from deuterium bubble chamber experiments. We report here the results of a study of $\pi^- p \rightarrow \omega^0 n$ at 6.0 GeV/c using a charged and neutral spectrometer at the Argonne ZGS. Our sample of 28,000 $\omega^0 n$ events is 8 times larger than that of any previous ωN experiment.

The apparatus, described elsewhere^{9,10}, combines a large-aperture magnetic spectrometer with a γ -detector employing spark chambers and a lead-glass Cerenkov array. The vector momenta of both charged pions and both γ 's from $\omega \rightarrow \pi^+ \pi^- \pi^0$ are measured; the neutron is unseen.

Histograms of $\pi^+ \pi^- \pi^0$ effective mass, and of nucleon missing mass recoiling against the ω^0 , are shown for three intervals of $t' = t - t_{\min}$ in Figs. 1a - f. There is no dependence of the positions or widths of the η, ω or neutron peaks on t' . The cuts which define ω and neutron events are indicated by vertical lines; control regions BG in Figs. 1a-c are used for background subtraction. Background under the ω averages 6.6%, and is 9.8% for $|t| < .05 \text{ GeV}/c^2$. This is a significant improvement over deuterium bubble chamber experiments, where backgrounds typically^{1,4} average more than 30% and are considerably worse at small t' . A correction of $7 \pm 1\%$ has been applied for ω 's outside the mass cut (in addition to the 10% for unseen decay modes¹¹). The corrected ω yield is stable against reasonable changes in the width and location of the control regions.

A rather tight cut (0.5 to 1.1 GeV) has been made on the nucleon mass to further reduce the small contamination of $\omega^0 \Delta^0$ which is not

rejected by veto counters⁹ surrounding the target; a correction of $13 \pm 2\%$ was applied for good neutrons rejected by this cut. The remaining $\omega\Delta$ contamination ($3.8 \pm 0.5\%$) has been estimated and removed by examining events for which one target veto counter fired, and also by fitting the departure of the neutron peak from a symmetric shape. Since ω events with nucleon missing mass 1.1 - 1.3 GeV are found to have density matrix elements and t' distributions very similar to those inside the neutron cut we are confident that the effects of $\omega\Delta$ contamination in our data are negligible.

A large change in t' -dependence of the background occurs for events with $\pi^+\pi^-\pi^0$ mass $M(3\pi)$ just above the ω , from a forward turnover at $M(3\pi) = 0.8$ GeV to a sharp forward peak by $M(3\pi) = 0.9$ GeV. It is important to understand the origin of these very peripheral events, most of which have $|t'| < .05 \text{ GeV}^2$, because our background subtraction is based in part on the control region $.845 < M(3\pi) < .890$ GeV. We find that most of these events have the mass of the negatively-charged dipion $M(\pi^-\pi^0)$ in the ρ region¹². Thus the peripheral events are probably associated $\rho^- N^{*+}$ production, possibly produced via pion exchange¹³, and should not be subtracted as background under the ω . We have excluded them by the cut $M(\pi^-\pi^0) < 0.6$ GeV applied to both signal and background; this cut was used in the spectra shown in Figs. 1a-c. Its effect for $|t'| < 0.05$ is shown in Fig. 1g, where the shaded events are those removed by the cut. We emphasize that the effect on the ω peak is always negligible, and that the effect on the background is negligible for $|t'| > 0.08$. (The penalty for not making this dipion cut is as follows:

The forward peaking of the density matrix element ρ_{00} is increased even more, by 20% in the most forward bin of t' ; the turnovers in $d\sigma/dt$ and $\rho_{+} d\sigma/dt$ become even more pronounced; but $\rho_{00} d\sigma/dt$ remains nearly unchanged.)

The method of moments was used to extract the density matrix elements from the angular distribution $f(\cos\theta, \phi)$ of the normal to the decay plane in the s-channel helicity frame. A Monte Carlo program simulated the acceptance limitations of experimental geometry, interaction and decay of final state particles and cuts on the π^0 decay asymmetry and minimum shower energy. Both the data and the several million Monte Carlo events were binned in a 40×36 grid of $\cos\theta, \phi$; events in the BG control regions were subtracted in each bin. The Monte Carlo acceptances used to weight the data showed a maximum variation (as a function of $\cos\theta, \phi$) of a factor 3 at a given t' .

The moments of the spherical harmonics $Y_M^L(\cos\theta, \phi)$, obtained with the same method, test our understanding of the experimental acceptance: imaginary parts of Y_M^L 's should be zero, and Y_M^L 's with $L > 2$ are expected to be small. We find these "illegal" moments are very small in the ω^0 region, with the largest contributing 2% of the cross section. An additional check is available from the ω Dalitz plot density, where a linear population of events is expected in $R_D = |\vec{p}_+ \times \vec{p}_-| / |(\vec{p}_+ \times \vec{p}_-)_{MAX}|$ for the simplest decay matrix element; here $\vec{p}_+, \vec{p}_-$ are the $\pi^+ \pi^-$ momenta in the ω center of mass. Fig. 1h demonstrates that our data satisfy this linear relation quite well even before the acceptance correction is made.

It has been predicted¹⁴⁻¹⁶ that $\rho\omega$ interference effects could lead to a sizable difference in the projected cross sections $\rho_{00} d\sigma/dt$ at small t' for the charge-symmetric reactions $\pi^- p \rightarrow \omega n$ and $\pi^+ n \rightarrow \omega p$. We are presently measuring this effect by collecting data on both reactions in deuterium. Very preliminary results indicate that $\rho_{00} d\sigma/dt$ for the $\pi^+ n$ reaction is roughly 20% above that for $\pi^- p$ for $|t'| < 0.1 \text{ GeV}^2$; this difference must be kept in mind when comparing our data with those from $\pi^+ n$ experiments.

Our results are presented in Fig. 2. The error flags do not include an overall normalization uncertainty of $\pm 8\%$. Density matrix elements ρ_{ij} in the s-channel helicity frame are shown in Figs. 2a-d, and the corresponding projected cross sections $\rho_{ij} d\sigma/dt$ in Figs. 2f-i. To leading order in $1/s$, $\rho_{00} d\sigma/dt$ and $\rho_{+} d\sigma/dt$ ($\rho_{-} d\sigma/dt$) are respectively the cross sections for producing ω 's of helicity 0 by unnatural parity exchange and of helicity 1 by natural (unnatural) parity exchange. Coherence between unnatural parity exchange amplitudes for ω 's with helicity 0 and 1 is measured by $\cos\Delta = \sqrt{2} \text{Re} \rho_{10} / \sqrt{(\rho_{00} \rho_{-})}$ (Fig. 2e). Rough information on the energy dependence has been obtained by combining our data with those from a $\pi^- p$ counter experiment³ at an average momentum of 35 GeV/c, and from a 3500 event deuterium bubble chamber experiment¹ at 4 GeV/c. Fig. 2j shows the effective trajectory $\alpha(t)$ for $d\sigma/dt$ (from $d\sigma/dt \propto P_{\text{LAB}}^{2\alpha-2}$); the points obtained from 6 and 35 GeV/c and those from 4 and 6 GeV/c are in satisfactory agreement. Separate trajectories for the natural and unnatural-parity cross sections $\rho_{+} d\sigma/dt$ and $(\rho_{00} + \rho_{-}) d\sigma/dt$ from the 4 and 6 GeV/c data are shown in Fig. 2k. The ρ trajectory determined from $\pi^- p \rightarrow \pi^0 n$ is indicated for comparison

by a dashed line.

Several features of the data deserve special comment:

- 1) $\rho_{00} d\sigma/dt$ has no strong forward turnover, implying a sizable helicity-nonflip contribution. Unless absorption causes large helicity-mixing effects, this nonflip contribution cannot be accommodated^{17,18} by models employing only ρ and B exchanges with the associated cuts. An alternative is to invoke the exchange of another unnatural parity object "Z"¹⁸ whose simplest quantum numbers would be $J^{PC} = 2^{-+}$. No experimentally-observed particle has these quantum numbers.
- 2) $\rho_{+} d\sigma/dt$ shows a dramatic forward turnover of nearly an order of magnitude which is responsible for most of the turnover in $d\sigma/dt$. This is in pronounced contrast to the behavior of $\rho_{+} d\sigma/dt$ in $\pi^{-} p \rightarrow \rho^{0} n$, which shows a sharp forward peak usually attributed to absorptive effects (cuts); in a pure Regge pole model $\rho_{+} d\sigma/dt$ will vanish at $t = 0$. On the other hand $\rho_{+} d\sigma/dt$ does not behave as if it is dominated at all t by ρ -pole exchange. There is only a suggestion of a dip near $|t| = 0.6$ where the ρ trajectory crosses zero. Also, the trajectory α_N for natural parity exchange lies increasingly below the accepted ρ trajectory at high $|t|$.
- 3) The coherence factor $\cos\Delta$, which would be unity in simple B-pole exchange models, has a maximum near $t = -.4$ and is small both near $t = 0$ and also at large $|t|$, implying spin and/or phase incoherence there.
- 4) The effective trajectory α_u for unnatural parity exchange lies considerably below α_N in the vicinity of $t = -.4$. Since this is also

the region of maximum coherence it is perhaps the most reliable estimate of a point on the B trajectory. The small- t behavior of α_u is dominated by the "Z" effect.

We have profited greatly from conversations with A.C. Irving, R.D. Field and A.B. Wicklund. We wish to thank H. Barton, P. Brockman, G. Hartner, R. Kammerud, D. Legacey, P. Patel and C. Zanfino for their contributions to various phases of the experiment. We are indebted J. Heimaster for software development, to H. Coombes, B. Dodge, J. Fitch, A. Kiang and C. Rush for technical support, and to the staff of the ZGS for efficient operation.

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FIGURE CAPTIONS

Fig. 1. (a)-(c) $\pi^+\pi^-\pi^0$ effective mass for $|t'|$ intervals 0.0-0.05, 0.05-0.30, and 0.30-1.20 $(\text{GeV}/c)^2$ respectively. (d)-(f) Nucleon missing mass for ω events in the same $|t'|$ intervals. (g) Effect of the dipion mass cut on the $\pi^+\pi^-\pi^0$ spectrum for $|t'| < 0.05$. The shaded events are removed by the cut. (h) Radial Dalitz plot density for events in the ω region.

Fig. 2. (a)-(e) Density-matrix elements and coherence factor $\cos\Delta$ in the s-channel helicity frame for $\pi^-p \rightarrow \omega^0 n$ vs. t' . (f)-(i) Differential cross section and projected differential cross-section vs. t' . (j) Effective trajectory for $d\sigma/dt$, from our data and those of Ref. 3 (triangles) and of Ref. 1 (circles). (k) Effective trajectories for natural and unnatural parity exchange from our data and those of Ref. 1.

Differential Cross Section for $\pi^- p \rightarrow \eta^0 n$ at 6.0 GeV/c*

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ABSTRACT

We have measured the differential cross section for $\pi^- p \rightarrow \eta^0 n$ at 6.0 GeV/c from 6730 very clean events in which the decay $\eta \rightarrow \pi^+ \pi^- \pi^0$ was detected. The high statistics reveal a sizable forward turnover, implying a dominance of the helicity flip amplitude. A precisely-determined A_2 trajectory, linear for $|t| < 1.0$, is found from combining our data with those at energies up to 101 GeV.

We report a measurement of the differential cross section $d\sigma/dt$ for $\pi^- p \rightarrow n^0$ at 6.0 GeV/c based on 6730 events from a spectrometer experiment at the Argonne ZGS. Previous experiments¹⁻⁴ in the intermediate energy region have been limited to < 2000 events at any one beam momentum. The improved statistics, along with very low background and good t -resolution, provide more detailed information than was previously available on the shape of $d\sigma/dt$, especially in the region of the forward turnover.

The n was observed via its decay to $\pi^+ \pi^- \pi^0$. Data collection occurred simultaneously with that for our study of ω^0 production, reported elsewhere⁵. The apparatus (Fig. 1) combined a large-aperture magnetic spectrometer and a γ -detector to measure the vector momenta of the π^+ , π^- and both γ 's from the π^0 ; the recoil neutron was not detected.

A secondary π^- beam with momentum tagged to $\pm 1\%$ and direction measured to ± 0.1 mrad was incident on a 16-in. liquid hydrogen target. The target was surrounded on the four lateral sides by an anticoincidence system consisting of four layers of 1/8 in. scintillator separated by 1/4 in. lead sheets. Additional "picture frame" anticounters guarded the downstream aperture. To avoid loss of good events through vetoing the recoil neutron or δ -rays from the target at least two target veto counters were required to fire to reject an event. All target antis were latched to allow studies of the events for which one counter fired.

The charged particle spectrometer was built around a wide-aperture magnet with a gap 40 in. high x 60 in. wide x 32 in. deep. The five

magnetostrictive spark chambers on both the upstream and the downstream sides were instrumented to handle up to four sparks apiece; two of each five chambers were rotated to resolve x-y pair ambiguities. A 30-element scintillator hodoscope H2 downstream of the last chamber was used in the trigger to demand at least two charged particles through the spectrometer.

Both γ 's from the π^0 were required to convert in a 1.60 radiation length sheet of lead 140 in. downstream of the target. The conversion efficiency, as determined from Ref. 6, was 0.671 ± 0.018 per γ . The position of each shower was measured by three closely-spaced magnetostrictive spark chambers immediately after the lead, with the planes instrumented for 8 to 12 sparks. Two identical 16-element scintillator hodoscopes GHF, GHR on either side of the converter-chamber module supplied the γ -trigger: a count in an element of GHR with no count in the corresponding element of GHF indicated a shower. At least two such no-yes pairs were required.

A 56-element lead glass Cerenkov array behind GHR measured the shower energies. Each block was $7\frac{1}{2}$ in. x $7\frac{1}{2}$ in. x 10 radiation lengths and was viewed by a 5-in. photomultiplier. Two redundant systems monitored gain drifts: the light output from a nitrogen laser was piped to each block through fiber optics, and a small button of NaI containing an α -source was glued to each upstream face. Laser data

were recorded automatically once per beam pulse and an α -run was taken once a day. An absolute calibration of each block was obtained from the $6 \times 10^5 \pi^0$ decays recorded during data taking.

The GHF-GHR trigger requirement was a potential source of bias since charged particles from η decay and backscatters from the lead glass are seen by GHF. We have investigated this problem with a sample of 1500 ω^0 events⁵ (topologically identical to η events) taken with a weaker trigger which required only one no-yes pair. We find the loss of good events in the strong trigger to be $12 \pm 1\%$, with a t-distribution indistinguishable from kept events.

Data collection and online analysis were performed by a General Automation SPC 16/85 computer interfaced to the experiment through CAMAC. Approximately 40% of the events were analyzed between beam pulses to display $\gamma\gamma$ and $\pi^+\pi^-\pi^0$ mass spectra and monitor equipment performance. Off-line analysis was done on a CDC 6500, an IBM 370/195 and the SPC 16. Losses from double beam tracks and chamber inefficiencies (typically 20% and 15%) were monitored and compensated in each run. Software reconstruction inefficiencies for pairs of charged particles ($2.4 \pm 0.5\%$) and for pairs of showers ($2 \pm 2\%$) were measured by hand-scanning events on a CRT display.

Histograms of effective mass for the $\pi^+\pi^-\pi^0$ and $\gamma\gamma$ systems, and of nucleon missing mass recoiling against the $\pi^+\pi^-\pi^0$, are shown in Figs. 2a b,c. The cuts which define the accepted events are marked by vertical lines; the events plotted in each histogram have passed the cuts on the other two masses. The tight nucleon mass cut (0.5 to 1.1 GeV) eliminates

a small contamination of $\eta\Delta^0$ events which survive the anticoincidence system. Corrections for good events rejected by the cuts in Figs. 2a, b, c, are respectively $4 \pm 1\%$, $1.8 \pm 0.5\%$, and $14 \pm 2\%$. Two control regions (labeled BG in Fig. 2a) on either side of the η were used to subtract background (averaging 2.4%) in each bin of t' .

Losses of events due to geometrical acceptance, interaction and decay of final state particles, and cuts on π^0 decay asymmetry and minimum shower energy were calculated as a function of t by a Monte Carlo program. Cuts more stringent than those imposed by the actual equipment were applied to both real and simulated data. As one of our checks on our understanding of the acceptance we have examined the angular distribution of the normal to η decay plane in the η center of mass. Distributions of acceptance-weighted events in polar and azimuthal angles of this normal in the s-channel helicity frame are plotted in Figs. 2d, e; they show the isotropy expected of a 0^- particle.

The differential cross section for $\pi^- p \rightarrow \eta n$, $\eta \rightarrow \pi^+ \pi^- \pi^0$, is displayed as a function of $t' = t - t_{\min}$ in Fig. 3a. The resolution in t' is everywhere smaller than the bin width. The error bars do not include an overall normalization uncertainty of $\pm 8\%$. Also shown are results from Ref. 1, multiplied by the relative branching ratio⁷ $R = \Gamma(\eta \rightarrow \pi^+ \pi^- \pi^0) / \Gamma(\eta \rightarrow \gamma\gamma) = 0.629$; the agreement is generally excellent. There is a hint of the dip at $|t'| \approx 1.3$ found in some other experiments^{3,4,8}. A turnover at small t' is clearly seen in our data, which are fit quite well for $|t'| < 1.0$ by the form $(A - Bt')e^{\lambda t'}$, with $A = (14.2 \pm 1.4) \mu\text{b}/\text{GeV}^2$, $B = (486 \pm 21) \mu\text{b}/(\text{GeV})^4$, $\lambda = (6.49 \pm .09) \text{GeV}^{-2}$. The relative size of A and B/λ indicates a dominance of the helicity

flip amplitude, with the nonflip cross section contributing only about 19% according to this parametrization.

As an example of what can be done with precise data at both ends of a long lever arm, Fig. 3b shows the effective A_2 Regge trajectory $\alpha(t)$ (where $d\sigma/dt \propto P_{\text{LAB}}^{2\alpha-2}$) obtained from our work and preliminary results from Ref. 9 at energies up to 101 GeV. The trajectory is consistent with that obtained in Ref. 9 using results of Ref. 9 and Ref. 1, but the statistical errors are significantly smaller. For $-1.0 < t < 0.0$ the trajectory is fit quite well by the straight line¹⁰, $\alpha(t) = (.426 \pm .007) + (.737 \pm .026)t$. For $t < -1.0$ there is an indication of a less steep energy dependence (possibly suggesting a disappearance of a dip with increasing energy) but the statistical error is large. Both the intercept and the slope of this A_2 trajectory are significantly lower than those obtained¹¹ for the ρ trajectory in $\pi^- p$ charge exchange, $\alpha_\rho = .53 + .83t$. It is interesting to note¹¹ that the effective A_2 trajectory is not near $\alpha = -1$ in the region of $t = -1.3$. This implies that some mechanism other than an A_2 wrong-signature nonsense zero would be responsible for a dip there, and suggests that absorption effects may be present in helicity flip amplitudes.

We wish to thank H. Barton, P. Brockman, G. Hartner, R. Kammerud, D. Legacey, P. Patel and C. Zangino for their contributions to various phases of the experiment. We are indebted to J. Heimaster for software development, to H. Coombes, B. Dodge, J. Fitch, A. Kiang and C. Rush for technical support, and to the staff of the ZGS for efficient operation.

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FIGURE CAPTIONS

Fig. 1. Layout of the experiment. The scale along the beam direction has been slightly expanded for clarity.

Fig. 2. (a) $\pi^+\pi^-\pi^0$ effective mass. (b) $\gamma\gamma$ effective mass. (c) Nucleon missing mass. Vertical lines (arrows) indicate accepted (control) events. (d), (e) Distributions of acceptance-weighted events in polar and azimuthal angles of the decay plane normal in the s-channel helicity frame.

Fig. 2. (a) Differential cross section for $\pi^-p \rightarrow \eta n$, with $\eta \rightarrow \pi^+\pi^-\pi^0$. Data from Ref. 1 have been multiplied by $\Gamma(\eta \rightarrow \pi^+\pi^-\pi^0)/\Gamma(\eta \rightarrow \gamma\gamma)$ for comparison. (b) Effective A_2 Regge trajectory for $\pi^-p \rightarrow \eta n$, from data of this experiment and preliminary data from Ref. 9. The curves through the data are discussed in the text.