

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

M. H. Shaevitz,<sup>†</sup> N. W. Reay, K. Reibel, and N. R. Stanton  
*Physics Department, The Ohio State University, Columbus, Ohio 43210*

and

K. W. Edwards and G. Luxton<sup>‡</sup>  
*Department of Physics, Carleton University, Ottawa, Ontario K1S 5B6, Canada*

and

M. A. Abolins and R. A. Sidwell  
*Physics Department, Michigan State University, East Lansing, Michigan 48823*

and

J. A. Dankowych, G. J. Luste, J. F. Martin, and J. D. Prentice  
*Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada*  
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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 reveals a sizable forward turnover, implying a dominance of the helicity-flip amplitude. A precisely determined  $A_2$  trajectory, linear for  $|t| < 1.0$  (GeV/c)<sup>2</sup>, 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  $\pi^- p \rightarrow \eta^0 n$  at 6.0 GeV/c based on 6730 events from a spectrometer experiment at the Argonne National Laboratory zero-gradient synchrotron. Previous experiments<sup>1-4</sup> 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, provides more detailed information than was previously available on the shape of  $d\sigma/dt$ , especially in the region of the forward turnover.

The  $\eta$  was observed via its decay to  $\pi^+ \pi^- \pi^0$ . Data collection occurred simultaneously with that for our study of  $\omega^0$  production, reported in the following Letter.<sup>5</sup> The apparatus (Fig. 1) combined a large-aperture magnetic spectrometer and a  $\gamma$  detector to measure the vector momenta of the  $\pi^+$ ,  $\pi^-$ , and both  $\gamma$ 's from the  $\pi^0$ ; the recoil neutron was not detected.

A secondary  $\pi^-$  beam with momentum tagged to  $\pm \frac{1}{4}\%$  and direction measured to  $\pm 0.1$  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  $\frac{1}{8}$ -in. scintillator separated by  $\frac{1}{4}$ -in. lead sheets. Additional "picture frame" anti counters guarded the downstream aperture. To avoid loss of good events through vetoing of the recoil neutron or  $\delta$  rays from the target at least two target veto counters were required to fire

for rejection of an event. All target anti counters 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  $\times$  60 in. wide  $\times$  32 in. deep. The five magnetostriuctive 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 thirty-element scintillator hodoscope H2 downstream of the last chamber was used in the trigger to demand that at least two charged particles pass through the spectrometer. Both  $\gamma$ 's from the  $\pi^0$  were required to convert

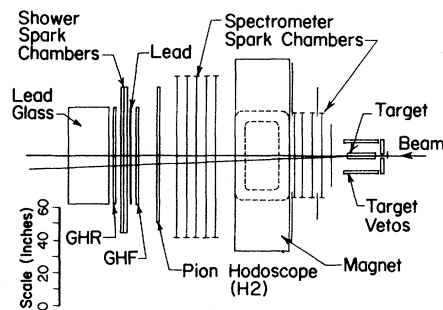


FIG. 1. Layout of the experiment. The scale along the beam direction has been slightly expanded for clarity.

in a 1.60-radiation-length sheet of lead 140 in. downstream of the target. The conversion efficiency, as determined from Messel and Crawford,<sup>6</sup> was  $0.671 \pm 0.018$  per  $\gamma$ . The position of each shower was measured by three closely spaced magnetostrictive spark chambers immediately after the lead, with the planes instrumented for eight to twelve sparks. Two identical sixteen-element scintillator hodoscopes GHF and GHR on either side of the converter-chamber module supplied the  $\gamma$  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 Cherenkov array behind GHR measured the shower energies. Each block was  $7\frac{1}{2}$  in.  $\times$   $7\frac{1}{2}$  in.  $\times$  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  $\alpha$  source was glued to each upstream face. Laser data were recorded automatically once per beam pulse and an  $\alpha$  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  $\eta$  decay and backscattered particles from the lead-glass array are seen by GHF. We have investigated this problem with a sample of 1500  $\omega^0$  events<sup>5</sup> (topologically identical to  $\eta$  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 retained events.

Data collection and on-line 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 cathode-ray-tube display.

Histograms of effective mass for the  $\pi^+\pi^-\pi^0$  and  $\gamma\gamma$  systems, and of nucleon missing mass re-

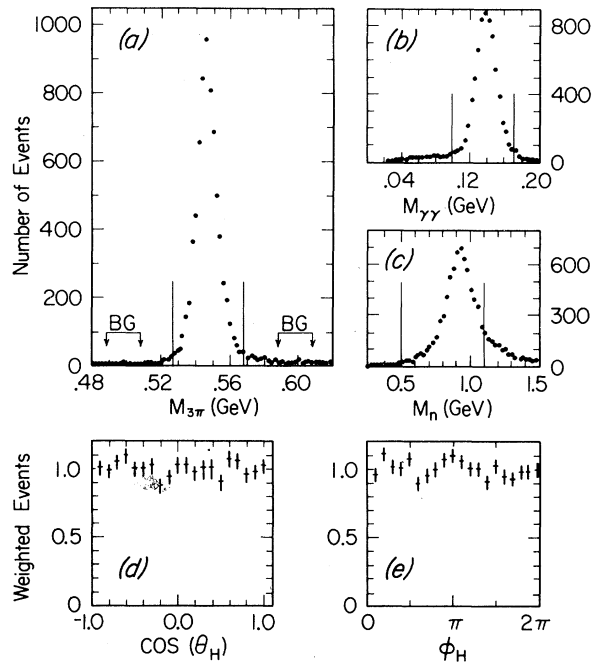


FIG. 2. (a)  $\pi^+\pi^-\pi^0$  effective mass. (b)  $\gamma\gamma$  effective mass. (c) Nucleon missing mass. Vertical lines (arrows) indicate accepted (control) events. (d), (e) Distributions of acceptance-weighted events in polar and azimuthal angles of the decay-plane normal in the  $s$ -channel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

coiling against the  $\pi^+\pi^-\pi^0$ , are shown in Figs. 2(a)–2(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/ $c^2$ ) eliminates a small contamination of  $\eta\Delta^0$  events which survive the anti-coincidence system. Corrections for good events rejected by the cuts in Figs. 2(a)–2(c) are respectively  $(4 \pm 1)\%$ ,  $(1.8 \pm 0.5)\%$ , and  $(14 \pm 2)\%$ . Two control regions [labeled BG in Fig. 2(a)] on either side of the  $\eta$  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  $\pi^0$ -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 the  $\eta$ -decay plane in the  $\eta$  center-of-mass frame. Distributions of acceptance-weighted events in polar and azimuthal an-

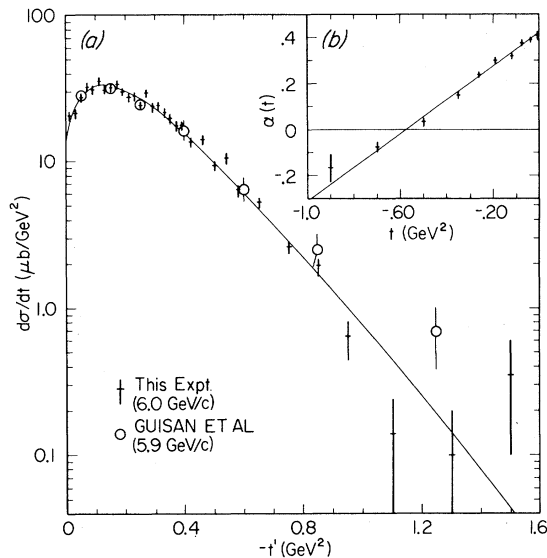


FIG. 3. (a) Differential cross section for  $\pi^-p \rightarrow \eta n$ , with  $\eta \rightarrow \pi^+\pi^-\pi^0$ . Data from Ref. 1 have been multiplied by  $\Gamma(\eta \rightarrow \pi^+\pi^-\pi^0)/\Gamma(\eta \rightarrow \gamma\gamma)$  for comparison. (b) Effective  $A_2$  Regge trajectory for  $\pi^-p \rightarrow \eta n$ , from data of this experiment and preliminary data from Ref. 9. The curves through the data are discussed in the text.

gles of this normal in the  $s$ -channel helicity frame are plotted in Figs. 2(d) and 2(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. 3(a). 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 ratio<sup>7</sup>  $R = \Gamma(\eta \rightarrow \pi^+\pi^-\pi^0)/\Gamma(\eta \rightarrow \gamma\gamma) = 0.629$ ; the agreement is generally excellent. There is a hint of the dip at  $|t'| \approx 1.3$  (GeV/c)<sup>2</sup> found in some other experiments.<sup>3,4,8</sup> A turnover at small  $t'$  is clearly seen in our data, which are fitted quite well for  $|t'| < 1.0$  (GeV/c)<sup>2</sup> by the form  $(A - Bt')e^{\lambda t'}$ , with  $A = 14.2 \pm 1.4$   $\mu\text{b}/(\text{GeV}/c)^2$ ,  $B = 486 \pm 21$   $\mu\text{b}/(\text{GeV}/c)^4$ , and  $\lambda = 6.49 \pm 0.09$  (GeV/c)<sup>-2</sup>. The relative size of  $A$  and  $B/\lambda$  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. 3(b) 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 Barnes *et al.*<sup>9</sup> at energies up to 101 GeV. The trajectory is con-

sistent with that obtained in Ref. 9 using results of Ref. 9 and Ref. 1, but the statistical errors are significantly smaller. For  $-1.0 < t < 0.0$  (GeV/c)<sup>2</sup> the trajectory is fitted quite well by the straight line<sup>10</sup>  $\alpha(t) = (0.426 \pm 0.007) + (0.737 \pm 0.026)t$ . For  $t < -1.0$  (GeV/c)<sup>2</sup> 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 obtained<sup>11</sup> for the  $\rho$  trajectory in  $\pi^-p$  charge exchange,  $\alpha_\rho = 0.53 \pm 0.83t$ . It is interesting to note<sup>11</sup> that the effective  $A_2$  trajectory is not near  $\alpha = -1$  in the region of  $t = -1.3$  (GeV/c)<sup>2</sup>. 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.

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†Present address: Physics Department, California Institute of Technology, Pasadena, Calif. 91125.

‡Present address: Department of Radiology, Stanford University, Stanford, Calif. 94305.

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<sup>10</sup>The errors on the Regge trajectory points are only statistical. A 10% relative systematic error between this experiment and that of Ref. 9 will contribute an ad-

ditional error of 0.017 to  $\alpha(0)$ .

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## High-Statistics Study of $\omega^0$ Production\*

M. H. Shaevitz,<sup>†</sup> N. W. Reay, K. Reibel, and N. R. Stanton  
*Physics Department, The Ohio State University, Columbus, Ohio 43210*

and

K. W. Edwards and G. Luxton<sup>‡</sup>  
*Department of Physics, Carleton University, Ottawa, Ontario K1S 5B6, Canada*

and

M. A. Abolins and R. A. Sidwell  
*Physics Department, Michigan State University, East Lansing, Michigan 48823*

and

J. A. Dankowych, G. J. Luste, J. F. Martin, and J. D. Prentice  
*Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada*  
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We report results from a study of  $\pi^-p \rightarrow \omega^0n$  at 6.0 GeV/c based on 28 000 events from a charged and neutral spectrometer. Background under the  $\omega^0$  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.

Previous work<sup>1-8</sup> 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  $\pi^-p \rightarrow \omega^0n$  at 6.0 GeV/c using a charged and neutral spectrometer at the Argonne National Laboratory zero-gradient synchrotron. Our sample of 28 000  $\omega^0n$  events is 8 times larger than that of any previous  $\omega N$  experiment.

The apparatus, described elsewhere,<sup>9,10</sup> combines a large-aperture magnetic spectrometer with a  $\gamma$  detector employing spark chambers and a lead-glass Cherenkov array. The vector momenta of both charged pions and both  $\gamma$ '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  $\omega^0$ , are shown for three intervals of  $t' = t - t_{\min}$  in Figs. 1(a)-1(f). There is no dependence of the positions or widths of the  $\eta$ ,  $\omega$ , or neutron peaks on  $t'$ . The cuts which define  $\omega$  and neutron events are indicated by vertical lines; control regions BG in Figs. 1(a)-1(c) are used for background subtraction. Background under the  $\omega$  averages 6.6%, and is 9.8% for  $|t| < 0.05$  (GeV/c)<sup>2</sup>. This is

a significant improvement over deuterium-bubble-chamber experiments, where backgrounds typically<sup>1,4</sup> average more than 30% and are considerably worse at small  $t'$ . A correction of  $(7 \pm 1)\%$  has been applied for  $\omega$ 's outside the mass cut (in addition to the 10% for unseen decay modes<sup>11</sup>). The corrected  $\omega$  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/c<sup>2</sup>) has been made on the nucleon mass to reduce further the small contamination of  $\omega^0\Delta^0$  which is not rejected by veto counters<sup>9</sup> 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  $\omega$  events with nucleon missing mass 1.1-1.3 GeV/c<sup>2</sup> 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 back-