TOTAL AND DIFFERENTIAL CROSS SECTIONS FOR $\pi^- + p \to \eta + n$ FROM THRESHOLD TO 1300 MeV*

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We have measured the total and differential cross sections for the reaction

$$\pi^- + p \to \eta + n, \quad \eta \to 2\gamma \tag{1}$$

at seven different pion energies from threshold to 1300 MeV. We find that the total cross section for (1) rises steeply from threshold to a value of nearly 1 mb at an incident-pion kinetic energy (T_{π^-}) between 655 and 704 MeV, and then falls gradually to 0.25 mb at 1300 MeV. This agrees with previous work.[1] Our η angular distributions are isotropic near threshold, but in contrast to Ref. 1, require terms through $\cos^2\theta_\eta^*$ for an adequate fit at $T_{\pi^-} = 655$ MeV, with higher order terms gradually appearing with increasing energy.

The experimental setup consisted of a cubic array of six steel-plate spark chambers (4π solid angle) surrounding a liquid-hydrogen target at the center of a 1-m^3 cavity. Only events with neutral final particles were allowed to trigger the spark chambers. This apparatus will be described more fully elsewhere.[2]

A Monte Carlo study was made of the detection efficiency of the spark chambers for high-energy photons. For the gammas from η decay this turned out to be close to 100%.

Two-shower events were accepted for analysis when (a) each shower produced sparks in three of five consecutive gaps, (b) no sparks appeared in the first four gaps (the first four plates were $\frac{1}{16}$-in. Al), and (c) the event appeared to originate near the target. About 3400 η events survived these selection criteria. The η events were separted from the π^0 events (from $\pi^- + p \to \pi^0 + n$) by means of the distribution in opening angle of the two gamma rays. Figure 1 shows the opening-angle distribution obtained at $T_{\pi^-} = 704$ MeV. Opening-angle distributions were calculated by Monte Carlo techniques for various reactions contributing to the background. A linear combination of the expected opening-angle distributions was fitted to the experimental distribution by the method of least squares, yielding the relative strength of the various competing reactions. The ratio of η production to π-N charge exchange was multiplied by the charge-exchange cross section, also measured in this experiment,[2] to yield the "partial" η-production cross section. This ratio is listed in Table I. The cross section is plotted in Fig. 2, along with the results from Ref. 1. The agreement is excellent. It should be emphasized that these numbers represent the "partial" production cross section for $\eta \to 2\gamma$ only.

To form the angular distribution at each energy, two-shower events were selected within opening-angle limits from 3 deg below the minimum to a maximum angle which included 75% of the η events. We were not able to measure the relative energy of the two showers well enough to resolve the two-fold ambiguity in the η direction. Consequently, we used the angular distributions of the bisector between the two observed showers to determine the η

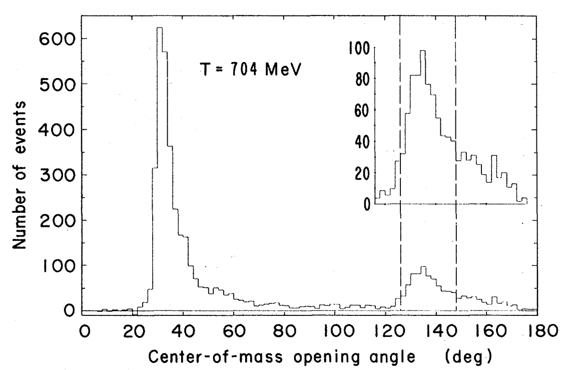

FIG. 1. Histogram showing the experimental opening-angle distribution at $T_{\pi^-} = 704$ MeV. The inset shows the region of the η peak with an expanded vertical scale. Events were chosen from the region between the vertical lines to form the angular distribution of the bisectors.

Table I. Coefficients of Legendre-polynomial expansion of the η differential cross section, normalized to the partial production cross section. Errors shown do not include error of normalization.

T_{π^-} (MeV)	$\sigma(\pi^- + p \to \eta + n; \eta \to 2\gamma)$ (mb)	η/π (%)	Coefficients (μb/sr) A_0	A_1	A_2	A_3	A_4
592	0.60 ± 0.06	7.8 ± 0.6	46 ± 3				
655	0.93 ± 0.08	17.1 ± 0.9	73 ± 4	7 ± 8	49 ± 14		
704	0.93 ± 0.08	19.5 ± 1.1	74 ± 3	38 ± 6	36 ± 9		
875	0.41 ± 0.06	6.4 ± 0.8	33 ± 2	16 ± 3	19 ± 5	-34 ± 9	
975	0.46 ± 0.06	15.5 ± 1.4	36 ± 2	52 ± 4	1 ± 6	-33 ± 9	
1117	0.45 ± 0.05	20.7 ± 1.6	36 ± 1	39 ± 2	-6 ± 3	-26 ± 5	
1300	0.25 ± 0.03	11.8 ± 1.1	20 ± 1	31 ± 1	9 ± 2	-21 ± 3	-20 ± 4

angular distributions. If we write the distribution of bisectors

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{bis}} = \sum_i A_i P_i(\cos\theta_{\text{bis}}),$$

then the true angular distribution is

$$\left.\frac{d\sigma}{d\Omega}\right|_{\eta} = \sum_i (A_i/\zeta_i) P_i(\cos\theta_\eta).$$

Here we define

$$\zeta_i = \int_{\beta^{-1}(\varphi_{\max}/2)}^{1} \frac{(1-\beta^2)xP_i(x)dx}{(1-x^2)^{1/2}(1-\beta^2x^2)^{3/2}}, \tag{2}$$

where $\varphi_{\max}$ is the upper limit of the opening-angle interval from which the sample was taken, and β is the c.m. velocity of the meson. Expression (2) is valid only if the γ-ray detector subtends 4π solid angle and has 100% efficiency.

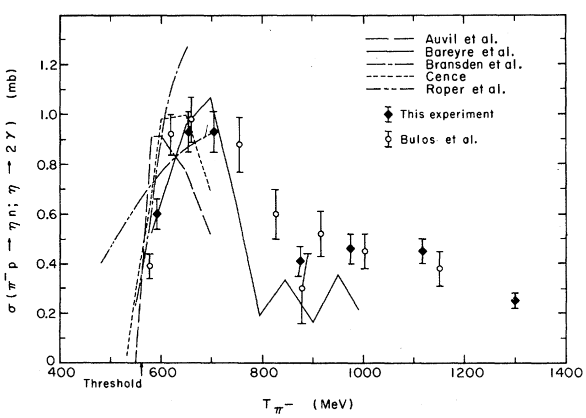

FIG. 2. Partial cross section for η production from this experiment and from Ref. 1, compared with the S_{11} inelastic cross section predicted by various phase-shift analyses.

Figure 3 shows the angular distributions, normalized to the partial cross sections listed in Table I.

The coefficients of the Legendre-polynomial expansion of the bisector distribution were divided by the factors of Eq. (2), normalized so that $\zeta_0 = 1$, and the solid line in each graph is a plot of the new expansion, representing the true η angular distribution. Table I contains the Legendre-polynomial coefficients of the η angular distribution.

These distributions may be compared with

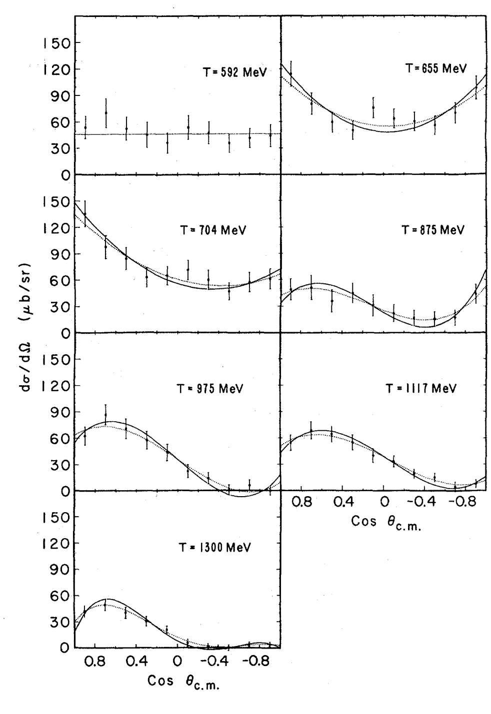

FIG. 3. Partial differential cross section for η production. The dotted line is the best fit to the bisector-distribution data points, and the solid line is the η differential cross section.

those of Ref. 1, where the production angular distributions are found to be isotropic up to $T_{\pi^-} \simeq 950$ MeV. The major difference between the two experiments is our use of six spark chambers, as opposed to only four chambers in Ref. 1. (There were no chambers above and below the hydrogen target in that work.)

In a Monte Carlo calculation we simulated both experiments for $T_{\pi^-} = 700$ MeV and found that, without the top and bottom spark chambers, the experimentally observed bisector distributions that would result from isotropic and from $(1+\cos^2\theta)$ angular distributions are quite similar. We conclude that the authors of Ref. 1, with only enough events to subdivide the scattering solid angle into five bins, had insufficient data to detect with certainty a possible $\cos^2$ component in their angular distributions.

As the authors of Ref. 1 point out, the first two data points on a plot of production cross section versus η c.m. momentum fall closely on a straight line through the origin. Our first data point is intermediate between their two and falls near this line. This and the fact that our angular distribution at this first energy is isotropic reinforce their conclusion that η production proceeds through S wave at threshold.

Comparison with the results of recent phase-shift analyses of elastic π-N scattering suggests strongly that the observed absorption in the π-N S_{11} state in this energy region may be explained entirely by the η production. Figure 2 shows a plot of the inelastic cross section calculated from the S_{11} absorption parameter (b_{11}) of different phase-shift analyses,[3-7] using

$$\sigma_{\rm inel}(S_{11}) = 0.35 \times \frac{2\pi}{3k^2}(1-b_{11}{}^2).$$

Here 0.35 is the branching ratio $R(\eta \to 2\gamma/\eta \to \text{all decays})$,[8] and $\frac{2}{3}$ is an isotopic-spin projection factor. It is seen that the experimental η production and the S_{11} absorption cross section are very similar below the η peak, while above the peak the η production seems to be greater than can be explained by absorption in only the S_{11} π-nucleon state. Recently, two detailed analyses have been completed, relating η production to π-N phase shifts.[9,10]

To explain our angular distributions at 655 and 704 MeV, it is sufficient to invoke S_{11}, P_{11}, and D_{13} waves, which have been found to be highly inelastic in this energy region in π-N phase-shift analyses. However, by the Minami ambiguity we could replace the D_{13} wave by a P_{13} wave.

Even though the phase-shift analysis of Bareyre et al.[4] shows that at the $N^*(1688)$ resonance F_{15} and D_{15} waves are highly absorptive, the lack of any enhancement in the η-production cross section near $T_{\pi^-} = 900$ MeV plus the absence of high-order terms in the η angular distributions near this energy show that this resonance does not decay with an observable rate into the η-N channel.

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