η and η' Production near Thresholds and Backward Charge-Exchange Differential Cross Section in π^--p Reactions*

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We have performed an experiment to study the reaction $\pi^-+p\rightarrow\eta+n$ near threshold, preliminary to a forthcoming measurement of charge asymmetry in η-meson decay. The η was identified by the velocity of the associated neutron. We detected neutrons produced in the forward hemisphere in the center-of-mass system corresponding to the most energetic neutrons in the laboratory. Data were taken at π^- momenta between 670 and 805 MeV/c. The four neutron detectors made it possible to detect neutrons at angles of 0° to 21° from the incident pion beam. We present backward differential cross sections for both pion charge exchange and η production calculated from the data. We looked for η' at pion momenta of 1.5 BeV/c and observed none. We obtained $\sigma(\pi^-p\rightarrow n\eta')\leq 60\ \mu$b.

I. INTRODUCTION

We have performed an experiment to study the reaction $\pi^-+p\rightarrow\eta+n$ near threshold, preliminary to a measurement of charge asymmetry in η-meson decay.[1] The η-production events were identified by the velocity of the associated neutrons.

We detected neutrons produced in the forward hemisphere in the center-of-mass system, corresponding to the most energetic neutrons in the laboratory. Data were taken at π^- momenta between 670 and 805 MeV/c. The four neutron detectors made it possible to detect neutrons at angles of 0° to 21° from the incident pion beam. We present differential cross sections for both pion charge exchange and η production calculated from the data.

The η' (960 MeV), discovered[2] in $K^-+p\rightarrow\eta'+\Lambda$, appears to have the same quantum numbers as the η and, like the η, possesses an appreciable radiative decay mode. Speculation[3] that η' decay might show a large charge asymmetry motivated us to search for η' using the same technique. Proposed models based on unitary symmetry schemes link the η and η' in a manner somewhat analogous to ω-ϕ mixing.[4] It might be expected that the η'-production cross section would behave similarly to that of the η, rising rapidly as a function of beam momentum just above threshold. We looked for evidence of η' near the threshold for its production.

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II. DESCRIPTION OF EXPERIMENT

A. Pion Beam

The pion beam was produced at the Brookhaven Cosmotron by interactions of 2.5-BeV protons with a beryllium target. The pion spectrometer was a nearly symmetric double-focusing system[5] (Fig. 1). Each half consisted of a pair of quadrupoles and a dipole which bent the beam through approximately 20°. The momentum-dispersed intermediate focus was at the center of a field lens. A collimator at this position limited the momentum spread of the transmitted beam. The second half of the spectrometer compensated for the momentum dispersion of the first. The momentum bite (rms) is inferred from the observed broadening of the η peak in neutron time-of-flight spectra. Most of the data were taken with a $\pm0.9\%$ momentum bite. For the η' search, the collimator was opened to give an inferred bite of $\pm1.3\%$.

Beam intensities were between 5×10^4 and 2×10^5 per pulse in a 150–200-msec spill. Muon and electron contaminations were measured by a gas Čerenkov counter at 1 BeV/c and found to total 12% of the beam. The liquid-hydrogen target, placed at the second focus, was a cylinder with axis parallel to the beam, 12 in. long and 3.5 in. in diameter. The beam at the hydrogen target was a circle about 2 in. in diameter.

B. η-Decay Detectors

The H_2 target was surrounded by a nearly closed, box-shaped array of scintillation counters, to detect the charged decay products of the η (Fig. 2). Each of the six sides was covered by two counters, and holes were provided for the entry and exit of the beam and for the H_2 target connections. The four counters on the up stream and down stream sides of the target could only be used in anticoincidence, but the signals from the other eight counters ("logic counters") could

[5] The experiment was performed in external beam 2 of the Brookhaven National Laboratory Cosmotron, using a pion beam built by the Wisconsin group of L. Pondrom.

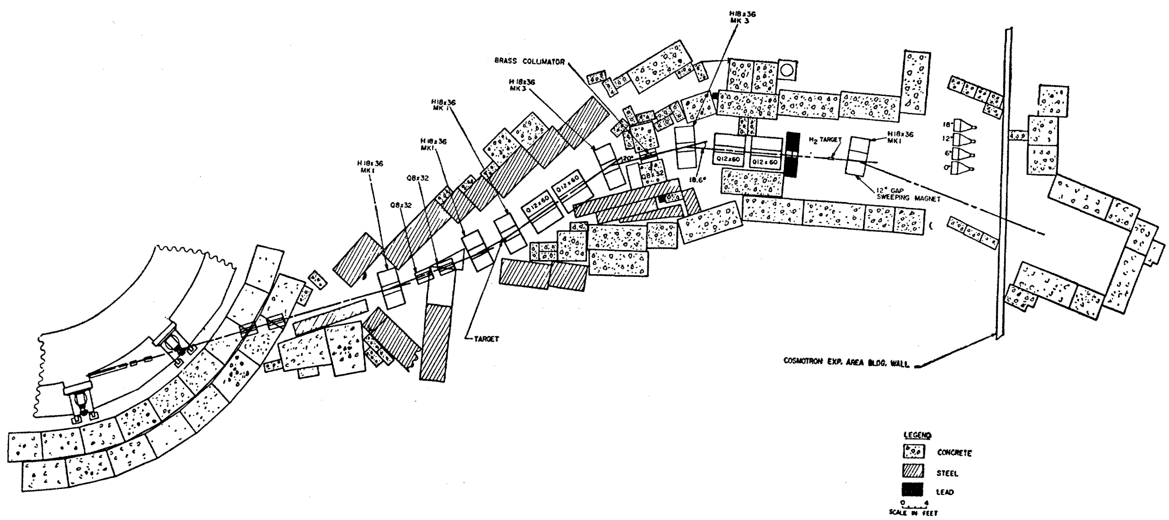

Fig. 1. Beam layout.

be combined in several ways to indicate various decay modes:

(a) Neutral: None of the 12 counters had a pulse.

(b) Charged: At least one of the eight logic counters had a pulse (remaining four counters not used).

(c) All: None of the 12 counters was used.

(d) Selective, 2π: Exactly two of the eight logic counters had pulses, but not two on the same side (other four counters in anticoincidence).

C. Neutron Detectors

Each neutron detector (Fig. 2) consisted of a 2-ft $\times$2-ft$\times$1-ft tank of toluene-PPO-POPOP liquid scintillator viewed by a single 58AVP phototube. The phototube was removed 2 ft from the liquid by a reflecting pyramidal hood. Four detectors, at 0°, 6°, 12°, and 18°, were placed 20 ft from the H_2 target center. Each subtended an arc of 5.7°. Root-mean-square time resolution was ±0.6 nsec for γ's and ±0.8 nsec for neutrons.

Anode pulses firing a 100-mV discriminator provided the timing signal. This was gated by a variable-level discriminator triggered from the dynode pulses, set so as to give good background rejection and good timing without noticeable loss of detection efficiency.

A sweeping magnet deflected charged particles away from the neutron detectors. In addition, the front face of each detector was completely covered by three overlapping scintillation counters which were used to veto charged particles. Two additional anticoincidence counters placed parallel to each other covered the downstream face of the sweeping magnet except along the path of the pion beam. Turning off either the detector antis or magnet antis did not affect the rate of accepted events.

D. Time of Flight

A time-to-pulse height converter (TPC) produced signals proportional in height to the time separation between a start pulse and a stop pulse. The start pulse was generated by counter T_3, placed just upstream of the H_2 target. The stop pulse was provided by the anode output of one of the neutron detectors. These signals to the TPC were gated by logic requirements described in the next section. The TPC output signal was routed and stored in one of four sets of 100 channels in a RIDL 400-channel analyzer. The TPC and analyzer were periodically calibrated. No time variation in the calibration of the system was observed.

E. TPC Gating and Associated Electronics

To provide a gate for the TPC, a 100-nsec-wide coincidence of the following signals was required:

(a) a 6-nsec coincidence $T_1T_2T_3\bar{T}_4$, indicating a beam particle which interacted in the target;

(b) a dynode signal from exactly one neutron detector, in the absence of a signal from any of its three associated veto counters;

(c) a decay signature corresponding to the desired η-decay mode (see Sec. II B).

For the neutral and selective 2π decay signatures, the absence of a pulse in the magnet antis was also required.

A special "confusion-elimination" circuit provided a veto if two beam particles passed through the system separated by less than 100 nsec.

F. Performance Checks

The beam intensity was monitored by the pion telescope $T_1T_2T_3$, by a three-counter monitor telescope looking at the pion production target at 90° to the

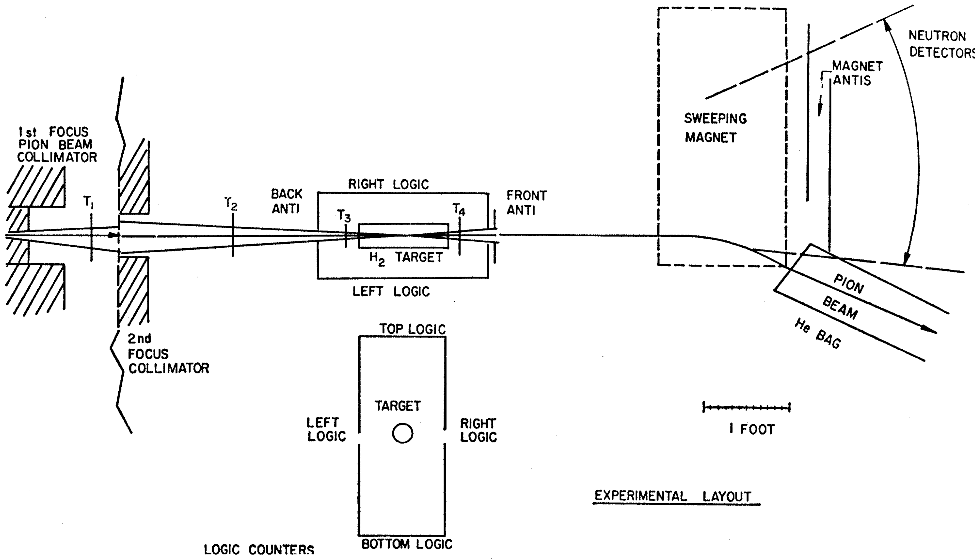

FIG. 2. η-decay detector layout.

proton-beam direction, and by an ionization chamber in the proton beam calibrated against the induced activity in polyethylene foils. Fluxes monitored by the three instruments were proportional. The interaction rate $T_1T_2T_3\bar{T}_4/T_1T_2T_3(\sim 6\%)$ remained very constant. Accidentals in the π^- interacting logic were monitored, as were the rates of the signals making up the TPC gate. Performance of the logic circuitry was periodically checked with pulser-generated signals.

We assured ourselves of the stability of the 58 AVP's (since changes in their gain were the most likely reason for changes in the neutron-counter efficiencies) by photographing pulse heights for beam pions passing through the centers of the counters at regular intervals. We also repeatedly checked the firing levels of the variable-threshold discriminators.

III. EXPERIMENTAL RESULTS

A. Number of Events

Figures 3(a)–3(d) show time-of-flight spectra at 0°, 6°, 12°, and 18°, respectively, with incident-pion momentum of 805 MeV/c and neutral decay signature. Data at the other incident-pion momenta look similar to the data for this momentum. Electron-induced γ's produce the leftmost "prompt" peak. The other two peaks are due to neutrons from the charge-exchange reaction and η production, respectively, with decay to neutral final states. Production of two π^0's and randomly distributed accidentals constitute most of the background. A run below η-production threshold, using 670-MeV/c pions, produced no η peak.

Time-of-flight spectra, excluding the γ peak, were fitted to two Gaussians and a smoothly varying background. Background was assumed to be proportional to the sum of a constant and a modified phase space for $2\pi^0$ production. The modification took the following form. Phase space was written as a function of a variable s defined as

$$s=\left[1-\left(\frac{2M_{\pi^0}}{M(2\pi^0)}\right)^2\right]^{1/2},$$

where $M(2\pi^0)$ is the mass of the two-pion system and M_{π^0} is the π^0 mass. This function was then multiplied by s^n so as to favor production of large $M(2\pi^0)$. The final value of n chosen was 4. The numbers of events in the Gaussians are quite insensitive to the value of n used and agree well with the numbers estimated by inspection. Fitted widths of 16 charge-exchange and 13 η-production peaks are consistent with a time resolution (rms) of ± 0.8 nsec, a momentum bite of $\pm 0.9\%$, and the 5.7° angular resolutions of the counters.

B. Normalization

Neutron detector efficiency was not measured independently during the run. We attempted, however, to equalize the performance of the detectors. We chose phototube voltages to equalize outputs when beam pions passed through the detector. At incident-pion momentum of 780 MeV/c, we made a systematic study of event rate as a function of neutron-detector pulse height by varying the dynode discrimination level. Discriminators were set midway between the region of poor time resolution (low setting) and rapidly dropping event rate (high setting).

C. η Production

Neutron-detection efficiency for η production was calculated by using published total-cross-section mea-

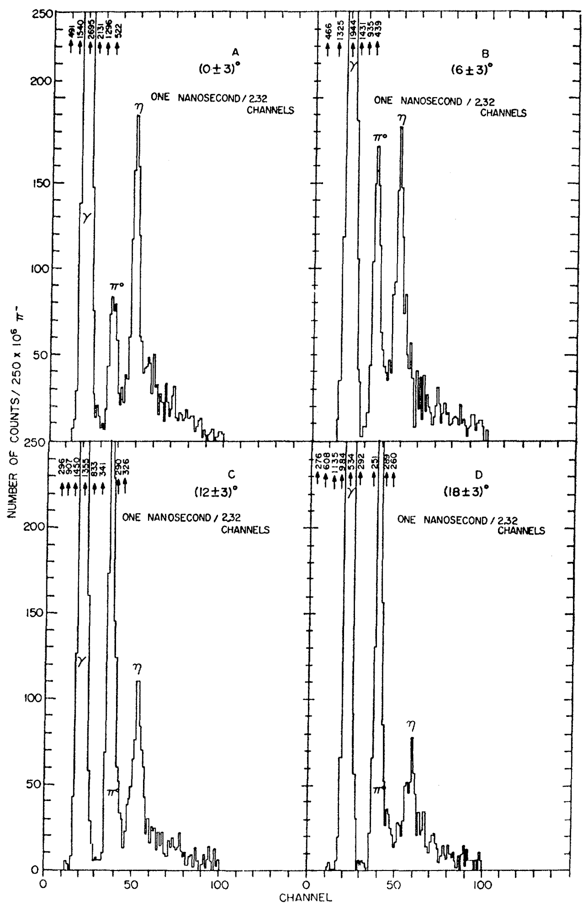

FIG. 3. Time-of-flight spectra at 0°, 6°, 12°, and 18° at π^- momentum of 805 MeV/c.

surements at 720 and 750 MeV/c.[6] We assume that η's are produced isotropically in the center-of-mass system at these momenta.[6] We found an average neutron detection efficiency of 15±1.0%. The calculated relative efficiencies of our detectors were equal within ±15%. Table I shows the differential cross section for $\pi^-+p\rightarrow\eta+n$ at four pion momenta, normalized to 15% detector efficiency. Only the statistical errors are given. There are two principal sources of systematic error:

TABLE I. Differential cross sections for $\pi^-p\rightarrow n\eta$, $\eta\rightarrow$ all neutral. A neutron detection efficiency of 15% is used for all calculations. Only statistical errors are shown.

Momentum (MeV/c)	Kinetic energy (MeV)	$(d\sigma/d\Omega)_{\text{c.m.}}$ ($\pi^-p\rightarrow\eta n$, $\eta\rightarrow$ all neutral) cosθ	$d\sigma/d\Omega$ (mb/sr)
720	594	−1.0 +0.05	0.09 ±0.009
		−0.84±0.11	0.105±0.011
750	623	−1.0 +0.03	0.116±0.012
		−0.90±0.07	0.145±0.014
		−0.63±0.15	0.107±0.011
780	653	−1.0 +0.02	0.116±0.012
		−0.92±0.06	0.124±0.016
		−0.72±0.12	0.110±0.012
		−0.36±0.18	0.094±0.014
805	677	−1.0 +0.02	0.124±0.013
		−0.94±0.04	0.132±0.015
		−0.75±0.1	0.097±0.013
		−0.45±0.15	0.064±0.011

(a) the relative efficiency of the four neutron counters, which contributes a 15% fractional error to each point of the angular distribution at a fixed beam momentum, but no appreciable error to the energy dependence of the cross section;

(b) absolute efficiency of the neutron counters, which contributed a fractional uncertainty of 7% to the scale of *all* the cross section values.

Our data are consistent with the existing data on η production.

D. Charge-Exchange Reaction

Neutrons from pion charge exchange have almost twice the energy of those from η production. We estimate that the detection efficiency for neutrons from charge exchange is not more than 25% over that for neutrons from η production and that the relative efficiencies are, as before, equal within ±15%. For simplicity in presenting results, we have calculated differential cross sections for pion charge exchange, using the same 15% neutron-detection efficiency. Table II shows our data. Our angular distributions at 720 and 780 MeV/c cannot be made consistent with the fitted solution of Chiu *et al.* (Fig. 4).

TABLE II. Differential cross sections for $\pi^-+p\rightarrow\pi^0+n$. A neutron detection efficiency of 15% is used. Only statistical errors are shown.

Pion momentum (MeV/c) \ cos$\theta_{\text{c.m.}}$	−1.0±0.01	−0.97±0.02	−0.88±0.05	−0.76±0.07
720	0.54±0.04	0.51±0.05	0.39±0.03	0.34±0.03
750	0.40±0.03	0.49±0.03	0.53±0.03	0.41±0.03
780	0.23±0.03	0.42±0.04	0.58±0.03	0.56±0.03
805	0.19±0.02	0.38±0.03	0.68±0.04	0.62±0.03

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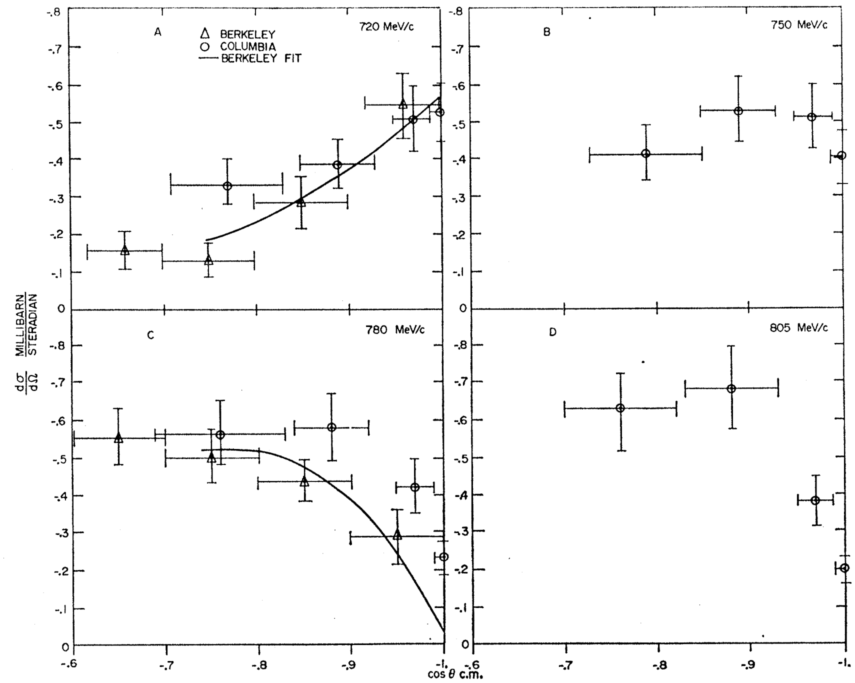

FIG. 4. Differential cross sections for $\pi^- p \rightarrow \pi^0 n$ at four pion momenta; a 15% error for relative neutron counter efficiency is included.

E. η' Production

We investigated η' production from $\pi^- + p$ at 1500 MeV/c, using both charged and neutral triggers. We find no evidence for η' production in our data. An upper limit is calculated for the η' cross section at an incident π^- momentum of 1500 MeV/c, in the form of a ratio of η' to η production at equal final center-of-mass momenta. We calculated the expected rms width σ' of the η' peak from our known time resolution, momentum bite, and angular resolution. The number of η' events, N', is calculated:

$$N' = 0 \pm 2[n'(\pm\sigma')]^{1/2}/0.68,$$

where $n'(\pm\sigma')$ is the number of events within the expected rms width $\pm\sigma'$ of the η' peak. Two standard deviations are assumed for a 90% confidence limit; the denominator 0.68 corrects for the fraction of events within one rms width of a Gaussian distribution. Independent of the branching ratio for η' decay into charged and neutral states, we obtain

$$B = \frac{\sigma(\pi^- p \rightarrow n\eta')}{\sigma(\pi^- p \rightarrow n\eta)} < \frac{1}{40}$$

(at final c.m. momentum of 150 MeV/c).

Our result is independent of neutron-detection efficiency.

A search for η' was made at 1.45, 1.55, and 1.6 BeV/c with much reduced sensitivity and a negative result. Using the 750-MeV/c η cross section of Bulos *et al.*,[6] we obtain

$$\sigma(\pi^- p \rightarrow n\eta') \leq 60\ \mu\text{b}.$$

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