Title
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The Reaction $\pi^- p \rightarrow \eta n$ Between 20 GeV/c and 100 GeV/c

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ABSTRACT

Preliminary $d\sigma/dt$ distributions are presented for the reaction $\pi^- p \rightarrow \eta n$ ($0 < -t < 1.2$ (GeV/c)$^2$). Incident pion momenta were 20.7, 40.6, 66 and 101 GeV/c, obtained at the NAL Meson Laboratory. The effective Regge $A_2$ trajectory for these data is discussed. Evidence from neutral final states is presented for the production of $\omega^0$ and $\eta'$ mesons as well as for an enhancement in the $f^0$, $A_2$ mass range.

AEC Contract No. W-7405-eng-48 (LBL) and AT(11-1)-68 (CIT)
I. Introduction

An experiment is in progress at NAL to measure neutral final state reactions of $\pi^{-}$ mesons on protons. We report here some preliminary results obtained in the interval between 20 GeV/c and 100 GeV/c for the reaction

$$\pi^{-} p \rightarrow \eta n \rightarrow \gamma \gamma$$

as well as some evidence for production of other neutral final states, for example, $\eta' n$ and $\omega n$. In an accompanying paper [1] we give results for the reaction $\pi^{-} p \rightarrow \pi^{0} n$.

The $\pi^{-} p$ reaction leading to the $\eta n$ final state is considered to be one of the simplest examples of the Regge mechanism because this reaction is dominated by the exchange of a single Regge trajectory, namely the $A_{2}$ trajectory. However, polarization measurements [2] suggest that the interaction is more complicated than the simple exchange of a single trajectory. In order to investigate the Regge character of reaction (1) it is important to obtain measurements at high energy over as large an energy and momentum transfer range as possible. We have therefore measured the differential cross section for the reaction (1) throughout the momentum transfer range from $-t=0$ to $-t \approx 1.2 \text{ (GeV/c)}^{2}$ at momenta from 20 to 100 GeV/c and have determined the effective $A_{2}$ trajectory using these data in conjunction with published data from 2.9 to 18.2 GeV/c. [3].

II. Experimental Description

The data for reaction (1) were taken simultaneously with the data for the reaction $\pi^{-} p \rightarrow \pi^{0} n$. The apparatus and experimental arrangement were identical for studying both reactions, and the reader is referred to the accompanying paper [1] for details.
The trigger condition assured that the final state was completely neutral. The trigger was, of necessity, precisely that trigger used in the charge exchange experiment since the data for both reactions were collected simultaneously. The cut structure used in the selection of the $n\bar{n}$ final state differed from that used in the charge exchange reaction only in restricting the mass cut to the $\eta$ mass peak. For completeness the entire cut structure will be listed here for the $n\bar{n}$ reaction.

1. **The CLEAN requirement.** There must be no pulse in any photon veto counter, thereby eliminating events with photons outside the solid angle of the detector.

2. **Cerenkov tag.** A pulse in the threshold Cerenkov counter is required, thereby eliminating kaons and antiprotons from the beam flux.

3. **Energy in the $\pi^0$ detector.** The measured energy was required to be within the full energy peak corresponding to the incident $\pi^-$ beam energy.

4. **Number of photons.** It was required that two individual showers be resolved by the detector for the $n\bar{n}$ reaction.

5. **Cos $\theta$ cut.** In the decay $\eta \rightarrow \gamma\gamma$, the emission angle $\theta$ of the photons in the $\eta$ rest frame with respect to the $\eta$ line-of-flight can be calculated from the data. Those events with $|\cos \theta| > 0.7$ are eliminated because one photon has very small laboratory energy near $\cos \theta=1$. This arbitrary cut is well outside the region where the detection efficiency falls below 100%.

6. **Mass cut.** For reaction (1), the value of the mass $M$ measured by the detector is required to be within the $\eta$ mass peak.

   In calculating cross sections it is necessary to correct for the loss of genuine reaction (1) events which are eliminated from our data sample by various cuts, and to correct for the inclusion of background events in the data sample. These corrections are listed in Table 1. Most of the corrections
were measured directly from the data or from several special runs inter-
spersed with the data collection. Several of these corrections are for
well-defined physical processes for which a reliable calculation can also
be made; wherever possible the empirically determined corrections were
verified by calculation.

The fraction of recoil neutrons detected by the veto house was empirically
measured by examining the pulse height distribution of π⁻p → π⁻n events as a
function of the azimuthal angle of the π⁰, and thus, of the recoil neutron.
A similar analysis was carried out for the charged veto counters on a sample
of data collected for this purpose. The efficiencies of the veto house counters
as a function of energy for both photons and neutrons were also measured using
a tagged photon beam at the Stanford Mark III accelerator and a tagged neutron
beam at the LBL 184" cyclotron.

As an additional check on our overall normalization, we measured the
π⁻p total cross section at 40 GeV/c using the same beam logic and liquid
hydrogen target. Our result of σ = (24 ± 2) mb is in good agreement with the
50 GeV/c result of 24.1 mb reported by Baker et al. [7]

III. Results

In Fig. 1(a) we plot the square of the mass (M²) for events at 101 GeV/c
satisfying all cuts listed in Secton II except for the mass cut. There is
a prominent peak around M² = 0.3 (GeV/c²)² associated with the η → γγ decay
mode. The level of background on each side of the peak is minimal, permitting
clean separation of η events. In addition there is a large peak at low mass
due to π⁰ production and a small enhancement at M² = 0.9 (GeV/c²)² which
may be associated with η⁻ (958) production, decaying into two γ's.
Figures 1(b) and 1(c) give the $M^2$ spectra at 101 GeV/c for $N_\gamma = 3$ and $N_\gamma \geq 4$, respectively, where $N_\gamma$ is the number of individual photons resolved by the detector. The events in these histograms have been subjected to cuts 1, 2 and 3 from Sec. II. In Fig. 1(b) there is a peak around $M^2 \approx 0.6$ (GeV/c$^2$)$^2$ due to $\omega$ production where the $\omega$ decays into $\pi^0 \gamma$. (A small enhancement in Fig. 1(a) around $M^2 \approx 0.6$ (GeV/c$^2$)$^2$ is due to $\omega \rightarrow \pi^0 \gamma$ events in which the detector distinguishes only two of the three photon showers.) There is evidence in Fig. 1(c) of an enhancement in the region $1.3 < M^2 < 1.9$ (GeV/c$^2$)$^2$ due to $f^0$ and/or $A_2^0$ production. Furthermore, there are peaks in Fig. 1(c) in the $\eta$ and $\eta'$ mass regions, mainly associated with the $3\pi^0$ decay mode of the $\eta$ and the $\pi\eta\eta$ decay mode of the $\eta'$, respectively. (For purposes of analyzing reaction (1) we have not used $\eta$ events in the $N_\gamma \geq 4$ category, but have restricted ourselves to the $\eta \rightarrow \gamma\gamma$ mode as seen in Fig. 1(a).)

The preliminary differential cross sections $d\sigma/dt$ for reaction (1) at 20.7, 40.6, 66, and 101 GeV/c are given in Fig. 2. At 20.7 GeV/c the region of good acceptance for $\eta$'s was confined to a limited range of momentum transfer, and thus we present data for this energy only between $-t=0$ and 0.5 (GeV/c$^2$)$^2$. For the three higher energies the data is presented over the range $0 < -t < 1.2$ (GeV/c$^2$)$^2$. The total number of events at each energy for reaction (1) is listed in Table II. There is a forward peak at each energy which flattens out at small $t$ and which has a smooth exponential falloff in the region $0.2 < -t < 1.0$ (GeV/c$^2$)$^2$. In Table II we list values for

$$
\sigma \left[ \pi^- p \rightarrow \eta \eta \rightarrow \gamma\gamma \right] = \int_{-1.5}^{0} \frac{d\sigma}{dt} dt
$$

at each energy. These values are also plotted in Fig. 3 as a function of $p_{lab}$ along with integrated cross sections for reaction (1) from other experiments [3, 4, 5, 6]. The data points of the present experiment
tend to be systematically lower than those of ref. [4]. The solid curve in Fig. 3 shows the result of a fit to the functional form

$$
\sigma \left( \pi^- p \rightarrow \eta n \gamma \gamma \right) = A p_{\text{lab}}^{-N}
$$

based on the data of this experiment and of ref. [3] over the range of $p_{\text{lab}}$ from 2.9 to 100 GeV/c. The fitted parameters were determined to be $A = (297 \pm 27) \mu b$ and $N = 1.47 \pm 0.03$. Bolotov et al. [4] report values of $A = (230 \pm 30) \mu b$ and $N = 1.35 \pm 0.04$ using their data as well as that of Ref. [3].

A study has been made of the effective Regge $A_2$ trajectory by fitting data from reaction (1) to the form

$$
\frac{d\sigma}{dt} = -\frac{B}{s^{2a}}
$$

where $a$ and $B$ are parameters to be determined as a function of $t$, and $q$ is the CM momentum. An overall fit (Fit 1) from 3 to 100 GeV/c has been carried out at several $t$ values, using the data of Ref. [3] and of the present experiment. The results of this fit are summarized in Table III, and plots of $d\sigma/dt$ versus $p_{\text{lab}}$ are given in Fig. 4 for several representative values of $t$. The curves in Fig. 4 show the best fit to (3) at each of these $t$ values. Fitted values for $a$ are displayed in Fig. 5(a). For purposes of comparison, we also show in Fig. 5(a) the values of $a$ obtained by fitting the data of Refs. [3] and [4] from 6 to 50 GeV/c (Fit 2), as reported in Ref. [h]. We have not attempted a fit including both our data and the data of Ref. [h] because of the inconsistency between their results and our preliminary results. The two sets of $a$'s are in good agreement except at $-t = 0.05$ (GeV/c)$^2$, where $a$ from Fit 1 is larger than $a$ from Fit 2 by about 0.1.
We have also fit separately the data of Ref. [3] from 3-18 GeV/c (Fit 3) and the data of the present experiment from 20-100 GeV/c (Fit 4). (In Fit 4 we have determined values of $\alpha$ only for $-t < 0.5$ GeV/c, since the 20.7 GeV/c data is restricted to this $t$ region. Without the 20.7 GeV/c data, the $s$-interval of the remaining data is too small to obtain a meaningful fit.) The results of Fits 3 and 4 are listed in Table III and are plotted in Fig. 5(b). The points from Fits 3 and 4 are compatible within errors for all $t$ values, indicating that the effective Regge pole parameterization (3) is not incompatible with reaction (l) data from 3 to 100 GeV/c.
V. Acknowledgments

The authors wish to acknowledge those who have made contributions to various phases of this experiment:

J. F. Bartlett for important sections of computer software, particularly for the on-line analysis system;

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D. Fartley for his work on the Cerenkov counter and for on-site logistics and scheduling; the personnel of the Fermi National Accelerator Laboratory, especially P. Koehler, R. Lundy, and H. Haggerty of the Meson Laboratory, for their complete cooperation and assistance in bringing the experiment into operation;

G. C. Fox and R. D. Field for helpful discussions on the theory and phenomenology of charge exchange reactions.
References


4. V. N. Bolotov et al., "$\pi^- p \rightarrow \pi^0 n$ Reaction in the Momentum Range up to 50 GeV/c", Serpukhov Preprint, 1973.


## Table I

Cross Section Corrections for $\pi^- p \rightarrow \eta \gamma$

<table>
<thead>
<tr>
<th></th>
<th>20.7 GeV/c</th>
<th>40.6 GeV/c</th>
<th>66 GeV/c</th>
<th>101 GeV/c</th>
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</thead>
<tbody>
<tr>
<td>Length of LH$_2$ target</td>
<td>40.1 cm</td>
<td>40.1 cm</td>
<td>40.1 cm</td>
<td>60.4 cm</td>
</tr>
<tr>
<td>Spurious charged veto</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta$-rays from $\pi^-$</td>
<td>-5%</td>
<td>-5%</td>
<td>-5%</td>
<td>-7%</td>
</tr>
<tr>
<td>Conversion of $\gamma$-rays</td>
<td>-5%</td>
<td>-5%</td>
<td>-5%</td>
<td>-6%</td>
</tr>
<tr>
<td>Recoil neutron veto*</td>
<td>-2%</td>
<td>-2%</td>
<td>-2%</td>
<td>-2%</td>
</tr>
<tr>
<td>Accidentals</td>
<td>-5%</td>
<td>-2%</td>
<td>-4%</td>
<td>-6%</td>
</tr>
<tr>
<td>Spurious shower veto *</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recoil neutron veto</td>
<td>-5%</td>
<td>-5%</td>
<td>-5%</td>
<td>-5%</td>
</tr>
<tr>
<td>Accidentals</td>
<td>-1%</td>
<td>-1%</td>
<td>-1%</td>
<td>-3%</td>
</tr>
<tr>
<td>$\eta$ detection efficiency *</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geometrical acceptance</td>
<td>-20%</td>
<td>-1%</td>
<td>-1%</td>
<td>-1%</td>
</tr>
<tr>
<td>$N_\pi = 2$ cut</td>
<td>-0.5%</td>
<td>-0.5%</td>
<td>-0.5%</td>
<td>-0.5%</td>
</tr>
<tr>
<td>Cosine $\theta$ cut</td>
<td>-30%</td>
<td>-30%</td>
<td>-30%</td>
<td>-30%</td>
</tr>
<tr>
<td>Background</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target empty</td>
<td>+3%</td>
<td>+5%</td>
<td>+4%</td>
<td>+3%</td>
</tr>
<tr>
<td>$N^*$ contamination</td>
<td>+3%</td>
<td>+3%</td>
<td>+3%</td>
<td>+3%</td>
</tr>
</tbody>
</table>

* Averaged over $t$
Table II
Preliminary Results for $\pi^- p \rightarrow \eta n \rightarrow \gamma \gamma$

<table>
<thead>
<tr>
<th>Velocity (GeV/c)</th>
<th>Number of Events</th>
<th>$\sigma$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.7</td>
<td>530</td>
<td>$(4.0 \pm 0.3)$</td>
</tr>
<tr>
<td>40.6</td>
<td>3925</td>
<td>$(1.29 \pm 0.08)$</td>
</tr>
<tr>
<td>66</td>
<td>1277</td>
<td>$(0.61 \pm 0.04)$</td>
</tr>
<tr>
<td>101</td>
<td>2775</td>
<td>$(0.35 \pm 0.03)$</td>
</tr>
</tbody>
</table>
### Table III

**Effective Regge Trajectory Values for \( \pi^- p \rightarrow \eta n \)**

<table>
<thead>
<tr>
<th>Range of ( p_{\text{lab}} )</th>
<th>Fit 1 ( 3-100 ) GeV/c</th>
<th>Fit 3 ( 3-18 ) GeV/c</th>
<th>Fit 4 ( 20-100 ) GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Used</td>
<td>Ref. 3 and Present Expt. (Prelim. results)</td>
<td>Ref. 3</td>
<td>Present Expt. (Preliminary results)</td>
</tr>
<tr>
<td>Values of ( \alpha ):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(- t = 0.05 ) (GeV/c)^2</td>
<td>0.37 ± 0.02</td>
<td>0.38 ± 0.05</td>
<td>0.38 ± 0.04</td>
</tr>
<tr>
<td>0.15</td>
<td>0.33 ± 0.02</td>
<td>0.30 ± 0.05</td>
<td>0.30 ± 0.04</td>
</tr>
<tr>
<td>0.25</td>
<td>0.27 ± 0.02</td>
<td>0.24 ± 0.05</td>
<td>0.18 ± 0.05</td>
</tr>
<tr>
<td>0.40</td>
<td>0.14 ± 0.02</td>
<td>0.17 ± 0.05</td>
<td>0.08 ± 0.06</td>
</tr>
<tr>
<td>0.60</td>
<td>0.00 ± 0.02</td>
<td>0.13 ± 0.07</td>
<td>---</td>
</tr>
<tr>
<td>0.85</td>
<td>-0.09 ± 0.04</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>
Figure Captions

Fig. 1  Spectra of $M^2$ at 101 GeV/c.
(a): Distribution of events satisfying cuts 1-5.
(b) and (c): Distribution of events with $N_\gamma = 3$ and $N_\gamma \geq 4$,
respectively, where $N_\gamma$ is the number of photon showers resolved
by the detector. Events in these plots satisfy cuts 1-3.

Fig. 2  (a-d): Distributions of $d\sigma/dt$ for reaction (1) at 20.7, 40.6,
66, and 101 GeV/c, respectively. The errors shown are
statistical only.

Fig. 3  A plot of the integrated cross section for reaction (1) as a
function of $p_{lab}$. The solid curve is a fit to the data of
Ref. [3] and the present experiment.

Fig. 4  Plots of $d\sigma/dt$ versus $p_{lab}$ for reaction (1) at several values
of t. The solid curves are the results of fitting the data
of Ref. [3] and of the present experiment to expression (3).

Fig. 5  Effective trajectory values for reaction (1) displayed as a
function of t.
Figure 1

M² Spectra at 101 GeV/c

(a) Nγ = 2

--- = x25 expansion

(b) Nγ = 3

(c) Nγ > 4

COUNTS / 0.015 (GeV/c²)²

COUNTS / 0.025 (GeV/c²)²

M² (GeV/c²)²
Figure 2(a)
Preliminary Data

\[ \pi^- p \rightarrow \eta^0 n \rightarrow \gamma \gamma \]

40.6 GeV/c

Figure 2(b)
Preliminary Data

\[ \pi^- p \rightarrow \eta^0 n \rightarrow \gamma \gamma \]

66 GeV/c

Figure 2(c)
Figure 2(d)

Preliminary Data

\( \pi^- p \rightarrow \eta^0 n \rightarrow \gamma \gamma \)

101 GeV/c

\( d\sigma/dt (\mu b/(GeV/c)^2) \)

\(-t (GeV/c)^2\)
Figure 3

$\sigma(\pi^- p \rightarrow \eta^0 n \gamma \gamma)$

- $\odot =$ Ref. 3
- $\times =$ Ref. 4
- $\square =$ Ref. 5
- $\triangle =$ Ref. 6
- $\bullet =$ Present Work (Prelim. Data)

$297 \cdot p^{-1.47}$

$p_{\text{lab}}$ (GeV/c) vs. $\sigma$ ($\mu$b)
Figure 4
Effective Trajectory for $\pi^- p \to \eta n$

- $x = 6-50 \text{ GeV/c} - \text{Refs. 3 and 4}$
- $\bullet = 3-100 \text{ GeV/c} - \text{Ref. 3 and this experiment (Preliminary Data)}$

(a)

- $\alpha = 3-18 \text{ GeV/c} - \text{Ref. 3}$
- $\bullet = 20-100 \text{ GeV/c} - \text{This experiment (Preliminary Data)}$

(b)

Figure 5
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