Title
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The Reaction $\pi^- p \rightarrow n n$ at High Energies

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ABSTRACT

Measurements on the reaction $\pi^- p \rightarrow n n$ have been carried out at Fermilab with beam energies from 20 to 200 GeV in the same experiment in which pion charge exchange scattering was studied. The differential cross sections have a pronounced dip in the forward direction. The data can be described well by a simple Regge pole model but the resulting $A_2$ trajectory is not degenerate with the $\rho$ trajectory extracted from the charge exchange data.

*Work supported in part by the U.S. Energy Research and Development Administration. Prepared under Contract E(11-1)-68 at Caltech and Contract W-7405-ENG-48 at LBL.

remaining solid angle except for that subtended by the detector.

The detector (Fig. 1b) is a hodoscope shower detector developed for this experiment. Photons from \( \pi^0 \), \( \eta \), or other particle decays produce showers in a set of 19 parallel lead plates normal to the direction of the beam, each plate being 1.12 radiation length in thickness and 75 cm square. Gaps between the lead plates are filled (except for the two end gaps) with scintillation plastic rods 1.05 em wide, oriented vertically and horizontally in alternate gaps. Eight scintillation rods with the same x or y coordinate (z is along the beam direction; y is up) are connected optically by curved light pipes at one end and form one counter. A number of special tricks have been employed in the construction of these counters in order to achieve a pulse height uniformity over their full length of approximately \( \pm 3\% \). There are 70 x-counters and 70 y-counters, whose pulse heights give the x and y distributions of the energy deposited by all photons hitting the detector.

The moments of these energy distributions may be used to obtain the combined energy \( \langle E \rangle \), weighted mean position \( \langle x,y \rangle \), and invariant mass \( \langle m \rangle \) of the detected photons. Many "cuts" and corrections have been applied to the data. Fortunately it has been possible to study most of these by using the data collected in the experiment and considerable effort has been devoted to this investigation.

The results of our measurements for the reaction \( \pi^+ p \rightarrow n n \) \((n = 2y)\) at energies 20 to 200 GeV are presented in Table 1. The differential cross sections at three of the six energies studied are also shown in Fig. 3. These data have been corrected for the effects of instrumental t-resolution and finite t bins by the procedure described in the preceding Letter on charge exchange scattering.

According to Regge ideas, the \( A_2 \) Regge pole is expected to dominate the \( n \) reaction so that an analysis of these data should give information about the \( A_2 \) trajectory. As in the case of pion charge exchange, our data on \( \pi^+ p \rightarrow n n \) can be described remarkably well by the simplest Regge pole model with a power law energy dependence and a nearly linear trajectory, \( a(t) \).

A good phenomenological description of our data is provided by the following parameterization:

\[
\frac{d \sigma}{d t} (s,t) = \beta(t) \, s^a(t) \, e^{bt}
\]

with \( a(t) = a_0 + a_1 t + a_2 t^2 \), \( \beta(t) = (C_1 + C_2 t) \, e^{bt} \), and \( v = (s - u)/4M \). The following values for the parameters have been found by a fit:

\[
\begin{align*}
\alpha_0 &= .371 \pm .008 ; \quad \alpha_1 = .79 \pm .04 ; \quad \alpha_2 = .03 \pm .04 \\
C_1 &= 306 \pm 27 ; \quad C_2 = -9800 \pm 800 ; \quad b = 3.80 \pm .31
\end{align*}
\]

The units are such that \( t \) is in GeV\(^2\), \( \nu \) in GeV, and \( \frac{d \sigma}{d t} \) in \( \text{mb/GeV}^2 \). This fit gives a \( \chi^2 = 109 \) for 108 degrees of freedom. Curves calculated from the above expression are shown in Fig. 3 including an extrapolation to 5.9 GeV for comparison with the lower energy data. The above parameterization, obtained by fitting our data alone, agrees only qualitatively with the lower energy data.
The trajectory $a(t)$ obtained from the fit is shown by the solid curve in Fig. 4, along with "data points," $a^*(t)$, obtained in the conventional manner by fitting the data at each value of $t$ separately, using the form (1). According to the idea of "exchange degeneracy," the $A_2$ and $p$ trajectories should be the same. Our results show that they are not, in agreement with a conclusion already reached from the previous experiments. In comparison with the $p$ trajectory obtained from the charge exchange data, the $A_2$ trajectory found above has a smaller intercept $a_0$ and a smaller slope $a_1$ at $t=0$.

References and Footnotes
5. At 20 GeV the upstream beam hodoscope was removed in order to minimize multiple scattering, and the Cerenkov counter was used to eliminate electrons rather than to tag pions.
6. The detector will be described elsewhere in greater detail: A. V. Barnes, A. V. Tollesrurp and R. L. Walker, manuscript in preparation.
7. The moments algorithms were developed in 1970-71 while planning the experiment. They are described in the reports listed under reference 1 of the preceding Letter on charge exchange scattering.
Table 1. Differential cross sections in \( \text{mb/GeV}^2 \) and other results for
\( \pi^- p \rightarrow nn, \eta \rightarrow 2\gamma \). These data have been corrected for the effects
of instrumental \( t \)-resolution and finite bin widths. Only statistical errors and errors in \( t \)-dependent corrections are given for
\( \frac{d\sigma}{dt} \) but all systematic errors are included in the integral cross
sections \( \sigma_1 \). The right-hand column, \( a(t) \), contains values of the
trajectory obtained by fitting the data at each value of \( t \) separately.

Figure 1. (a) Schematic arrangement of the experimental apparatus (not to scale).
The distance between hydrogen target and detector was scaled with energy:
\( L = (16 \text{ m})(E/100 \text{ GeV}) \). The location and window openings of \( V_2, V_3 \) and
\( V_4 \) were adjusted accordingly. (b) The detector.

Figure 2. Mass histogram for two-photon events from the 64.4 GeV data. The events
comprising this histogram have passed all cuts used to define charge
exchange scattering or the \( \pi^- p \rightarrow nn \) reaction with the exception of the
mass cuts.

Figure 3. Differential cross sections for the reaction \( \pi^- p \rightarrow nn \) with \( \eta \rightarrow 2\gamma \) at
20.8, 64.4 and 199.3 GeV from this experiment and at 5.9 GeV from the
experiment of reference 2. The curves are the result of a fit de-
scribed in the text.

Figure 4. The effective trajectory \( a(t) \).
### Table 1

<table>
<thead>
<tr>
<th>-t (GeV²)</th>
<th>Bin Width (GeV²)</th>
<th>Beam Momentum in GeV</th>
<th>$\sigma(t=0)$ from fit</th>
<th>$\int_{-1.5}^{0} \frac{d\sigma}{dt} dt$</th>
<th>Number of events</th>
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<td>0.004</td>
<td>0.008</td>
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<td></td>
<td></td>
<td>4500</td>
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<td>0.012</td>
<td>0.008</td>
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<td>3.14 ± 0.36</td>
<td>20.8 ± 0.36</td>
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<td>40.8 ± 0.44</td>
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<td>64.4 ± 0.44</td>
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<td>0.102 ± 0.023</td>
<td>0.019 ± 0.006</td>
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</table>

$\sigma_1 (\mu b) = \int_{-1.5}^{0} \frac{d\sigma}{dt} dt$

$\frac{d\sigma}{dt}(t=0)$ from fit

$\int_{-1.5}^{0} \frac{d\sigma}{dt} dt$
Fig. 1

(a) Beam Hodoscopes
Cerenkov Counter
Liquid $\text{H}_2$

(b) Detector

Fig. 2

Number Per 5 MeV

Mass $m$ (MeV)

644 GeV DATA
\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{\textit{Fig. 4}}
\end{figure}

The top graph shows a plot of $d\sigma/dt$ versus $t$ (GeV$^2$) for different values of $\rho$ and $A_2$ mesons. The data points are marked with symbols, and the curves represent different values of $\hat{t}$.

The bottom graph illustrates a straight line through points corresponding to $\rho$, $A_2$ and $g$ mesons. The line is labeled as $\alpha(t)$ from Fit. Additionally, there is another line labeled as $\alpha^*(t)$ from Table I.
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