

Observation of the Reaction $\pi^- p \rightarrow \bar{p} d$ from 4 to 6 GeV/c*

A. J. Pawlicki, D. S. Ayres, R. Diebold, A. F. Greene,† S. L. Kramer, and A. B. Wicklund

Argonne National Laboratory, Argonne, Illinois 60439

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Differential cross sections have been measured for the reaction $\pi^- p \rightarrow \bar{p} d$. At 4 GeV/c the total cross section is $0.58 \pm 0.08 \mu\text{b}$ with an angular distribution consistent with isotropy. At 5 GeV/c a pronounced forward dip occurs. In contradiction to simple baryon-exchange models, the cross section is found to be an order of magnitude smaller than that for the line-reversed reaction $pp \rightarrow \pi^+ d$. Upper limits for $\pi^- d \rightarrow \bar{p} t$ were also found.

About 350 events of the reaction

$$\pi^- p \rightarrow \bar{p} d \quad (1)$$

have been observed with the Argonne National Laboratory effective-mass spectrometer at the zero-gradient synchrotron.

The spectrometer configuration is somewhat different from that described previously^{1,2} and is shown in Fig. 1. Pions in the unseparated beam were identified by threshold Cherenkov counters; a scintillation-counter hodoscope measured the beam momentum to $\pm 0.2\%$, and the incident beam direction at the target was measured to ± 1 mrad by the K_0 chambers. The hole and dE/dx counters were used in the trigger to detect interactions in the hydrogen target; one or more large-angle particles through the hole counter or at least two particles through the dE/dx counter were required. Noninteracting-beam triggers were further suppressed by the beam veto counter. The trigger also required at least two charged particles in the forty-counter hodoscope at the magnet exit. Events with pions were suppressed by the large Cherenkov veto counter,³ C_π ; the counter QC insured that at least one

charged particle entered C_π . Veto counters surrounding the target and lining the magnet aperture reduced triggers from unwanted events.

The spectrometer magnet had a gap of 66 cm, a width of 2 m, an effective length of 1 m, and $\int B dL = 11.4$ kG m. Trajectories of outgoing particles were measured with chamber sets K_1 through K_5 and data were recorded on magnetic tape by an EMR 6050 computer.

Since the momenta and angles of all of the particles in Reaction (1) were measured, four-momentum conservation gave four constraints which could be used to separate events of Reaction (1) from the large amount of background. Instead of doing a fit to the measured quantities, we worked directly with the four-momentum residuals

$$\Delta p = p_f + p_d - p_{\pi^-} - p_p.$$

For the events of interest, the transverse-momentum differences peaked sharply around zero. At 5 GeV/c, for example, the rms width of the peak in each of the transverse directions was found to be 7 MeV/c; this width scaled linearly with momentum so that the measured rms lab angle between the directions of the beam and the

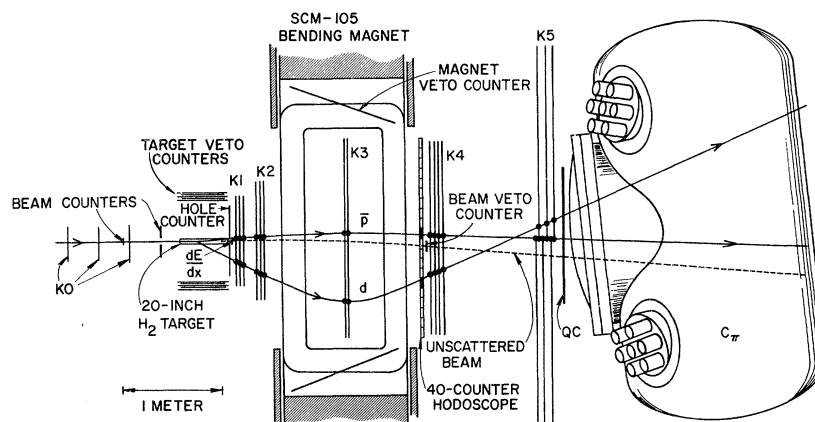


FIG. 1. Sketch of the Argonne effective-mass spectrometer. K_0 through K_5 are magnetostrictive wire spark chambers.

$\bar{p}d$ system remained constant at 2 mrad. The linear momenta of the outgoing particles were adjusted to achieve longitudinal momentum conservation, and the energy residual ΔE was then calculated. This quantity is plotted in Fig. 2(a) for events satisfying three-momentum conservation cuts. The rms widths for ΔE are 1.9, 2.9, and 5.3 MeV at 4, 5, and 6 GeV/c, respectively. These distributions show little or no background, and the cross sections and angular distributions were determined without having to make background corrections.

A correction was made for the limited acceptance of the spectrometer by weighting each event by the reciprocal of the azimuthal interval (rotation about the beam direction) available to events of that topology. At 4 GeV/c some acceptance was available at all c.m. angles, while at 5 and 6 GeV/c there was no acceptance for $\cos\theta_{\bar{p}}^* < -0.6$ and $+0.5$, respectively.

Other systematic corrections varied little with angle and beam momentum. These included the empty-target correction ($1 \pm 1\%$), accidental veto and δ -ray losses ($12 \pm 4\%$), beam contamination by muons and electrons (3 to 6%), losses from kinematic cuts and possible background contam-

ination ($0 \pm 4\%$), secondary interactions in the target and chambers (typically $20 \pm 4\%$), and losses due to spark chamber and software inefficiency ($6 \pm 4\%$).

The corrected angular distributions are shown in Fig. 2(b). The total cross section at 4 GeV/c was found to be $0.58 \pm 0.08 \mu\text{b}$ with an integrated cross section at 5 GeV/c of $0.34 \pm 0.05 \mu\text{b}$ for $\cos\theta_{\bar{p}}^* > -0.6$ and $0.065 \pm 0.014 \mu\text{b}$ at 6 GeV/c for $\cos\theta_{\bar{p}}^* > +0.55$. The error limits on the differential cross sections are statistical only and do not include the 10% overall normalization uncertainty. These values are consistent with the limits of an early experiment⁴ and are in good agreement with the result at 5 GeV/c of Baglin *et al.*⁵ based on fourteen events.

A comparison can be made with the time-reversed reaction through detailed balance,

$$\sigma(\pi^- p \rightarrow \bar{p}d) = 3(p_{\bar{p}d}^*/p_{\pi^- p}^*)^2 \sigma(\bar{p}d \rightarrow \pi^- p), \quad (2)$$

where the p^* 's refer to the appropriate c.m. momenta. A deuterium bubble-chamber experiment⁶ set an upper limit of $2 \mu\text{b}$ for $\bar{p}d \rightarrow \pi^- p$ at 1.6 GeV/c, a momentum yielding a total c.m. energy equivalent to that for an incident π^- of 5.4 GeV/c. At this energy the phase-space factor is almost canceled by the spin factor of 3, and the $2\text{-}\mu\text{b}$ upper limit is still considerably above the value of $0.35 \mu\text{b}$ estimated from the data. Data on $\bar{p}d \rightarrow \pi^- p$ annihilation at rest⁷ have been extrapolated⁵ to estimate $\sigma(\pi^- p \rightarrow \bar{p}d) = 0.7 \mu\text{b}$ at 5 GeV/c, in agreement with both our result and that of Baglin *et al.*

The 4-GeV/c angular distribution shown in Fig. 2(b) is quite consistent with isotropy (χ^2 probability 70%). This is not too surprising since we are close to the threshold momentum, 3.74 GeV/c, and high partial waves are suppressed by the angular-momentum barrier factors. At 5 GeV/c, a pronounced dip appears in the forward- \bar{p} region, suggesting a dominance of net-helicity-flip amplitudes. A hint of this dip is present at 4 GeV/c, while the 6-GeV/c data also show the dip. Agreement with the data of Baglin *et al.* at 5 GeV/c is quite good. In the region $1 < -t < 2 \text{ GeV}^2$, where we have data at all three momenta, $d\sigma/dt$ falls as $p_{\text{lab}}^{-4.3 \pm 0.7}$.

Simple exchange models relate the line-reversed reactions

$$\frac{d\sigma}{dt}(\pi^- p \rightarrow \bar{p}d) = 2 \left(\frac{p_{\bar{p}d}^*}{p_{\pi^- p}^*} \right)^2 \frac{d\sigma}{dt}(p p \rightarrow \pi^+ d), \quad (3)$$

where the cross sections are taken at the same center-of-mass energy and momentum transfer.

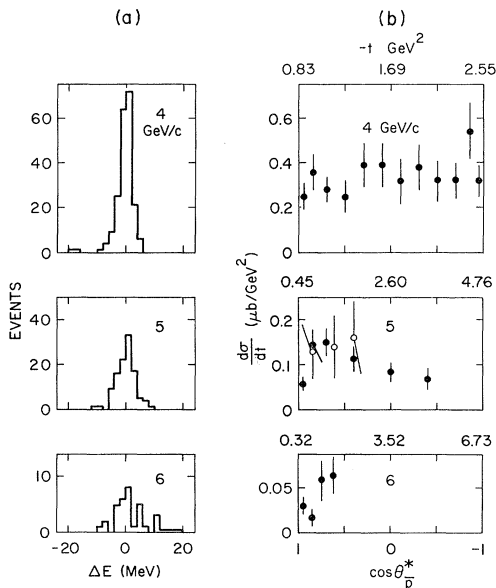


FIG. 2. (a) ΔE distributions at each of the three lab momenta for events satisfying three-momentum conservation cuts. (b) Differential cross sections for $\pi^- p \rightarrow \bar{p}d$; scales are shown for both the cosine of the c.m. angle and for the four-momentum-transfer squared between π^- and \bar{p} . Errors shown do not include the 10% uncertainty in overall normalization. Open circles, results of Baglin *et al.* (Ref. 5).

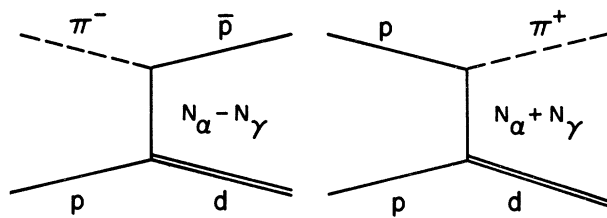


FIG. 3. Exchange diagrams for the two line-reversed reactions.

After one makes the spin and phase-space correction, the prediction from the $pp \rightarrow \pi^+ d$ data of Heinz *et al.*⁸ at $T_p = 2.5$ GeV is higher than our data at 4 GeV/c (same total c.m. energy) by a factor of 10 for most momentum transfers, but increasing to a factor of 30 near $\cos\theta_p^* = -1$.

The experimental difference between the two sides of Eq. (3) is due to interference terms between amplitudes corresponding to exchanges of opposite signature, as indicated in Fig. 3. If only neutron exchange (N_α) were important, there would be no interference. Exchange-degenerate models for N_α and N_γ have both types of amplitudes, but 90 deg out of phase with one another in the complex plane, so again no interference occurs. The more general model of Barger and Michael⁹ has broken N_α - N_γ exchange degeneracy, but still cannot account for the difference between the two reactions near $t = -0.8$ GeV² where the N_γ amplitude has a wrong-signature nonsense zero.

In a similar experiment with a deuterium target, we find upper limits on the total cross section for the reaction $\pi^- d \rightarrow \bar{p} t$ (t for tritium) of

0.07 and 0.12 μb (90% confidence level) at 3 and 4 GeV/c, respectively. Isotropy was assumed in determining these limits (threshold, 2.82 GeV/c).

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†Present address: National Accelerator Laboratory, Batavia, Ill. 60510.

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ASYMMETRIES IN CHARGED PION PHOTOPRODUCTION ON NUCLEONS BY 16-GeV POLARIZED PHOTONS. D. J. Sherden, R. H. Siemann, and C. K. Sinclair [Phys. Rev. Lett. **30**, 1230 (1973)].

The word "polarization" was omitted from the third sentence of the sixth paragraph. It should read, "The beam polarization was found..."

In addition, Ref. 10 should be D. I. Julius, Nucl. Phys. **B40**, 409 (1972).