Radiative Decay of the Δ Resonance: Analyzing Powers for $\pi^- \vec{p} \to \gamma n$

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The polarized target asymmetry A_N for $\pi^- \vec{p} \to \gamma n$ has been measured by coincident detection of the γ and the neutron at several angles across the Δ resonance energy region. A high-resolution NaI γ spectrometer together with good time-of-flight information for the neutron resulted in excellent separation of this radiative capture reaction from the much higher cross-section charge exchange reaction $\pi^- \vec{p} \to \pi^0 n$. Statistical uncertainties are $\Delta A_N = 0.02 - 0.04$, representing a significant improvement over previous results. The new data are discussed in the context of recent theoretical models.

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Although pion photoproduction, $\gamma N \to \pi N$, has been studied for about four decades, this fundamental medium-energy reaction continues to receive experimental as well as theoretical attention. This includes both nucleon and nuclear targets and also, in particular, spin observables [1–3]. We report here on an experiment representing the inverse reaction of pion photoproduction, namely the *radiative capture* (RC) reaction $\pi^- \vec{p} \to \gamma n$. Pion photoproduction off the neutron can only be studied using a deuteron target, $\gamma d \to \pi^- pp$, with the associated complications of Fermi motion, Pauli blocking, and final state interactions. The $\pi^- \vec{p} \to \gamma n$ reaction avoids these uncertainties, and should therefore result in much cleaner spectra and more reliable data. There are no data for the analyzing powers of $\pi^- \vec{p} \to \gamma n$ around the Δ resonance except for a LAMPF experiment [4] with relatively large statistical errors. Likewise, no recoil-proton polarization measurements have been carried out in pion photoproduction on the deuteron in this important energy range. The main experimental hurdle to be overcome for $\pi^- \vec{p} \to \gamma n$ is the separation of these events from the major background of charge exchange (CEX), $\pi^- \vec{p} \to \pi^0 n$, which occurs at a rate up to 100 times higher. Events from the two processes can be separated by detecting both the γ and the n with sufficiently good resolution.

The most sensitive method for improving the present knowledge of the reaction amplitudes is to measure spin observables. Only polarization experiments are able to determine the small amplitudes via their interference terms, resulting in the observed asymmetries. Thus, we focused on the (transversely) polarized target asymmetry for $\pi^- \vec{p} \to \gamma n$ at pion kinetic energies of 100, 150, and 200 MeV at center of mass angles $\theta_\gamma^{\text{c.m.}}$ of 45°, 90°, and 135°; and also at 250 MeV at 90°. Time-reversal invariance requires our analyzing power to be identical to the recoil-proton polarization in the inverse photoproduction reaction $\gamma n \to \pi^- \vec{p}$. The $\Delta \to \gamma N$ transition is well known to be dominated by an $M1$ multipole, with a small contribution from $E2$. Below the Δ the $E1$ is also significant. In typical multipole expansions for photoproduction the amplitudes are labeled as electric or magnetic, and by $L_{\pi N}$ with an additional $\pm$ to designate the total angular momentum states $J = L \pm \frac{1}{2}$. A_N can be written (neglecting E_{2-}, M_{2-}, and higher contributions):

$$A_N \sim \sin\theta(a + b\cos\theta + \cdots),$$

$$a \sim \operatorname{Im}[E_{0+}^*(M_{1+} + 2M_{1-} + 3E_{1+})],$$

$$b \sim \operatorname{Im}[M_{1-}^*(M_{1+} + 3E_{1+})].$$

Therefore, at 90° A_N is most sensitive to the large E_{0+}/M_{1+} interference ($E1/M1$ in conventional multipole language). The b term is responsible for an asymmetry about 90°, and its measurement provides additional sensitivity to small amplitudes through their interference effects. Away from 90° we are increasingly sensitive to the M_{1-}/M_{1+} interference. The A_N measured in this experiment is not particularly sensitive to the $E2/M1$ ratio, but is sensitive to higher order multipoles.

Data were collected in the M11 channel of TRIUMF using a frozen spin target [5]. For each measured A_N the typical running time was about a day. The experimental setup is shown in Fig. 1. The apparatus in the beam consisted of two plastic scintillators, S0 and S2. S0 had good timing resolution and was used as timing reference for the other detectors. The much smaller S2 was placed closer to the target, with the purpose of defining the size of the beam. For diagnostic purposes high rate wire chambers [6] were used to image the pion beam onto the 28 mm wide target cell. The target consisted of

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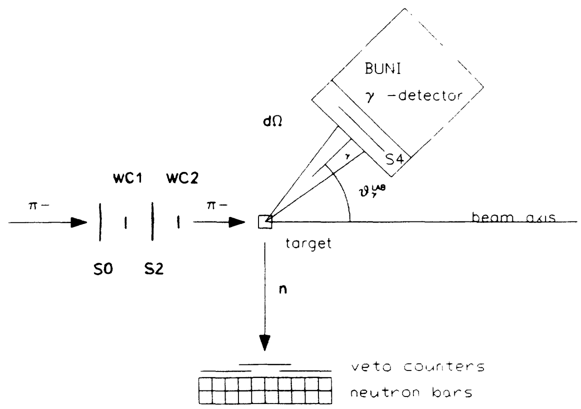

FIG. 1. Experimental setup.

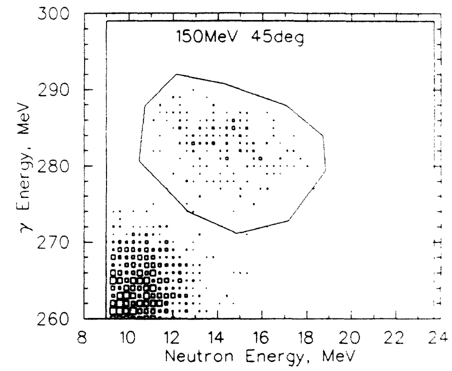

FIG. 2. A scatterplot of E_γ versus T_n for a run from the 150 MeV 45° point. The radiative capture events are delineated with a cut. The events to the lower left of the radiative capture events are charge exchange events.

butanol beads cooled to about 60 mK, and doped with EHBA(CrV). The target was polarized in a 2.5 T superconducting solenoid. For data taking, the solenoid was removed and the polarization was maintained with a 0.33 T water-cooled Helmholtz coil. The target polarization was measured using NMR, with typical polarizations of 0.75. In order to minimize systematic uncertainties between spin up and spin down the target polarization was flipped and measured regularly. In addition, the target temperature was recorded continuously, thereby allowing minute-by-minute calculation of the polarization.

Gamma rays were detected in BUNI, the Boston University NaI spectrometer [7], with an energy resolution of about 1.7% FWHM at 129.4 MeV [8]. A 17.5 cm diam lead collimator was used in front of BUNI. The resolution of the γ spectrometer was critical in separating the RC events from the CEX background. BUNI is composed of a 55.9 cm long×26.7 cm diam NaI core surrounded by an annulus of four quadrants of NaI, which brought the detector to a diameter of 48.3 cm. The energy response of the BUNI core was calibrated with the RC events. The quadrants were calibrated with the 2.6 MeV line from ^{228}Th. A plastic scintillator, S4, between BUNI's collimator and the detector itself, was used to reject charged particles.

Neutrons with energies from about 9 to 113 MeV were detected in a double array of twenty vertical 10 cm×10 cm×100 cm plastic scintillator bars positioned about 400 cm from the target and equipped with RCA 8575 photomultiplier tubes at both ends. The two layers formed a 1 m×1 m×20 cm wall of scintillator. The intrinsic mean-time resolution of these detectors was measured with cosmic rays to be about 200 psec (σ), allowing neutron events to be localized with a position resolution of about 10 cm × 10 cm. The neutron kinetic energy, T_n, was calculated from the measured time of flight between S0 and the neutron hit. A set of four veto counters in front of the neutron bars was used to reject charged particles. The analyzing power is calculated from

$$A_N = \frac{Y_u - Y_d}{P_d Y_u + P_u Y_d},$$

where Y_i represents the yields for the RC events (normalized to the incident pion flux), and P_i the up/down target polarizations. Most effects due to solid angles and efficiencies cancel in this expression. However, A_N remains sensitive to neutron detection efficiency because of the potential for neutron detector gain drifts between target spin up and down configurations. Therefore it was necessary to track the gain of the photomultipliers. An absolute calibration of the pulse heights was performed using cosmic rays. Drifts were monitored with a highly stable 2 Hz light-emitting diode light source, which illuminated all neutron detectors. Gain drifts were evaluated hourly, and a calibration correction was applied. The neutron bar pulse height was calculated from a geometric average of the top and bottom photomultipliers.

In the data analysis time of flight between the various scintillators was used to select pions in the beam, gammas into BUNI, and neutrons into the neutron array. In addition, charged particles in the final state were rejected via pulse height in S4 and in the neutron veto counters. Only events with a single hit in the neutron array were considered in the analysis, multiple hit events comprising only about 6% of the events. The data were analyzed with different neutron pulse height thresholds, and therefore different neutron efficiencies, in order to check for consistent A_N results. There was very good agreement between the number of counts obtained with different neutron pulse height thresholds and DEMONS Monte Carlo results [9]. Figure 2 shows a typical example of E_γ versus T_n for the accepted events. This figure also exhibits the excellent separation of radiative capture from charge exchange events. The final number of events was extracted from a two-dimensional cut, as shown in Fig. 2. More details of the data analysis can be found in Ref. [10].

The wire chamber information enabled us to track the beam pions through the known magnetic field of the Helmholtz coil to the target. This was used as a diagnostic tool to ensure that the center of the small target cell

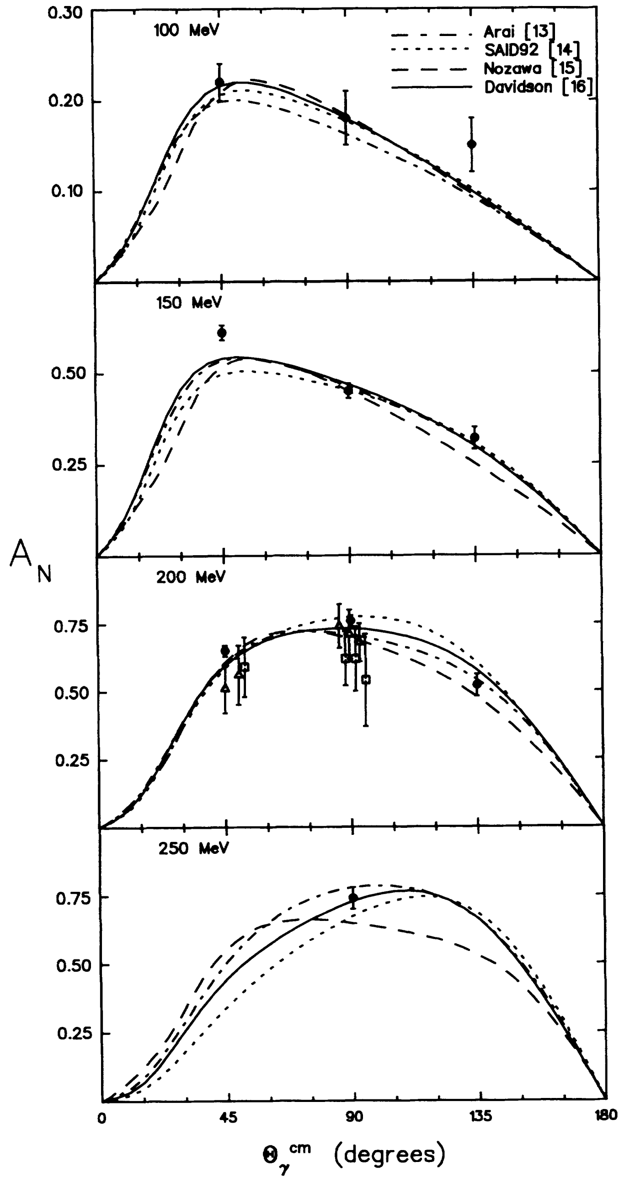

FIG. 3. Radiative capture analyzing powers from this experiment (solid circles) versus $\theta_\gamma^{\mathrm{c.m.}}$. Only statistical errors are shown. The data from Kim *et al.* [4] at 192 MeV (open squares) and 205 MeV (open triangles) are shown for comparison. Theoretical curves from different calculations are also plotted.

was hit, thus minimizing background from the aluminum shielding and other apparatus around the target cell. In the final analysis the RC events were so well constrained by kinematics and resolution that the tracking made no statistically significant difference in A_N. As mentioned earlier, the principal background was pion CEX on the free protons in the target, $\pi^- \vec{p} \rightarrow \pi^0 n$, which occurs at a much higher rate than RC. The combination of very high E_γ resolution and moderately good T_n resolution allowed a complete separation of these events, as shown earlier. This represents one of the distinguishing features of our

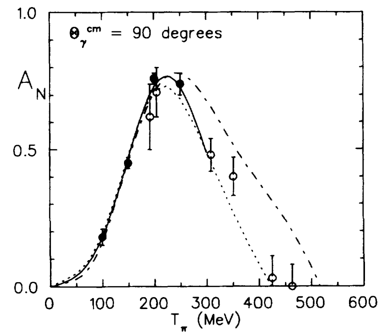

FIG. 4. A plot of RC data for $\theta_\gamma^{\mathrm{c.m.}} = 90°$. Analyzing powers are plotted against T_{π^-}. The legend for the theoretical curves is the same as for Fig. 3.

experiment from previous work. In addition, contamination due to reactions on nonhydrogen components of the target was eliminated by tight kinematic constraints placed upon the data. Because of the different Q value, such contamination leaves hits in the neutron-array outside the kinematically correct area for true RC events. Very few such hits were observed in the final data sample.

As a cross-check for target polarization and for analysis technique, the CEX analyzing powers were analyzed, and compared to πN phase shift calculations, like SAID [11]. These new data represent a significant contribution to the existing CEX data set and will be published separately [12].

The greatest source of systematic error is in the uncertainty of the target polarization. Extensive study of this target [5] indicates a 4% (absolute) uncertainty. Other sources of error include nonhydrogen contamination, which turned out to be negligible, and neutron detector gain drift. Systematic errors from neutron detector gain drift were evaluated by changing the pulse height threshold and by removing this cut altogether. These changes did not significantly affect the resulting A_N. Since the overall systematic error is completely dominated by the target polarization uncertainty, a conservative estimate of the total systematic error was made by evaluating the error due to polarization uncertainty and rounding up to the nearest 0.01.

Recent theoretical efforts, to be compared with our data, include the following: an energy-dependent partial-wave analysis using fixed-t dispersion relations by the Tokyo group [13]; the latest energy-dependent and -independent partial-wave analysis of the VPI group [14]; a dynamical model involving a model Hamiltonian plus unitary and gauge invariant photoproduction amplitudes [15]; and an effective Lagrangian incorporating chiral symmetry [16].

Our results are shown in Figs. 3 and 4, and are enumerated in Table I. Data reported in Table I correspond to a 3 MeV pulse height threshold in the neutron bars. With the exception of a few of the small and large angle points, we find satisfactory agreement with the mentioned theo-

TABLE I. Analyzing power results A_N for radiative capture $\pi^- \vec{p} \to \gamma n$.

T_{π^-} Energy (MeV)	$\theta_\gamma^{\text{c.m.}}$ Angle (deg)	A_N	Stat. Err.	Syst. Err.
100	45	0.22	±0.02	±0.01
100	90	0.18	±0.03	±0.01
100	135	0.15	±0.03	±0.01
150	45	0.61	±0.02	±0.02
150	90	0.45	±0.03	±0.02
150	135	0.32	±0.03	±0.01
200	45	0.65	±0.02	±0.03
200	90	0.76	±0.02	±0.03
200	135	0.52	±0.04	±0.02
250	90	0.74	±0.04	±0.03

retical calculations.

Figure 4 shows the large analyzing powers obtained at 90° c.m. as a function of pion energy. Included are the LAMPF data of Kim *et al.* [4]. Our results are in good agreement with their two lowest energy data points. The SAID92 solution [14], and, in particular, the calculation of Davidson *et al.* [16] are in very good agreement with our four data points at this angle. We conclude that the E_{0+}/M_{1+} interference term is well understood, and that the $M1$ transition for $\Delta^0 \to \gamma n$ is consistent with the $M1$ transition for $\Delta^+ \to \gamma p$ [17]. Accurate knowledge of this $M1$ multipole is clearly important before more subtle effects, like a resonant $E2$ contribution, can be determined. Our data should make an important contribution here. In addition, since A_N is very sensitive to the higher multipoles, small discrepancies at forward and backward angles between our data and theoretical models may indicate that these higher multipoles are not given simply by the usual nucleon Born terms, in particular the t-channel pion exchange [17].

In summary, by using high-resolution, coincident γ–n detection, it was possible to obtain cleaner and higher precision data for the analyzing power $A_N(\pi^- \vec{p} \to \gamma n)$ than available so far. An important gap in polarization variables for pion photoproduction reactions has been filled, without the need for a deuterium target and the associated corrections. Because our data span the Δ resonance, they can provide a good basis for developing an energy-dependent analysis. The angular distributions then test elements of the dynamical description of the pion photoproduction reaction, which one must necessarily understand if the radiative decay of the Δ is to be studied in this way.

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