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PION-NUCLEON CHARGE EXCHANGE MEASUREMENTS IN THE REGION OF THE Δ(1232) RESONANCE

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Measurements of differential cross sections for pion-nucleon scattering, $\pi^- \mathrm{p} \to \pi^0 \mathrm{n}$, in the region of the $\Delta(1232)$ resonance are presented. These data were obtained as part of the baryon spectroscopy program using the Crystal Ball detector in the C6 beam line of the Alternating Gradient Synchrocyclotron at Brookhaven National Laboratory. The results reported here are limited to the momenta at which the beam contaminations could be deduced by TOF. Data at higher momenta require the use of special normalization runs completed in 2002 and are still under analysis.

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1. *Introduction*

Data taken in 1998 by the new Crystal Ball Collaboration have resulted in nine publications [1 − 9] six Ph.D. dissertations [10 − 16] and dozens of papers in the proceedings of international conferences. This experimental program was conducted at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL). The motivation is to improve the determination of the masses, widths and decay modes of N*, Δ*, Λ* and Σ* resonances, to determine the ηn, $\eta\Lambda$ and $\eta\Sigma$ scattering lengths, and to measure branching ratios for η decays.

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AGS experiments E913 [16] and E914 [17], measurements of $\pi^- p \to$ neutrals and $K^- p \to$ neutrals, respectively, pertained to baryon and hyperon spectroscopy. Differential cross sections for pion-nucleon charge exchange, $\pi^- p \to \pi^0 n$, are presented here at π^- momenta of 148, 174, 189, 213, 238, 271, 298, and 323 MeV/c, a region dominated by the $\Delta(1232)$ resonance. Data at lower momenta (to 113 MeV/c) and at higher momenta (up to 750 MeV/c) will eventually be available as results from our 2002 run are analyzed. Preliminary results of these measurements are included in three other presentations at this conference [18].

2. *The Crystal Ball and experimental setup*

The Crystal Ball (CB) detector, designed and built at SLAC, is a highly-segmented, total-energy electromagnetic calorimeter and spectrometer that covers $\approx$93% of 4π steradians. A schematic is shown in Fig. 1. The ball proper is a sphere with an entrance and exit opening for the beam and an inside cavity with diameter of 50 cm for the target. It is constructed of 672 optically isolated NaI(Tl) crystals that detect individual γ's. Electromagnetic showers in the CB are measured with an energy resolution of 3 − 5% for gamma rays of 400 − 100 MeV. Directions of the γ rays are measured with a resolution of 2 − 3° in the polar angle. An electromagnetic

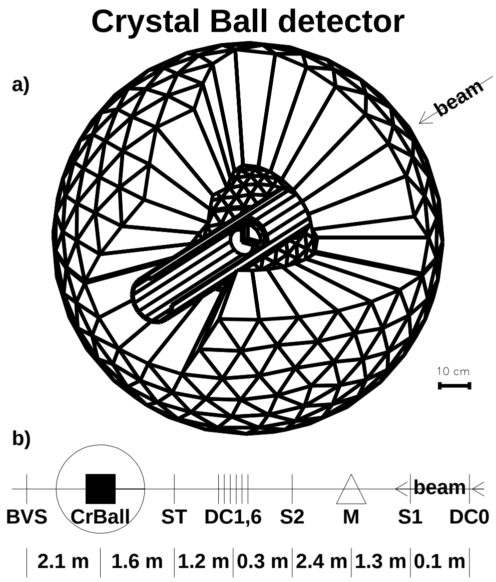

Fig. 1. a) The Crystal Ball detector with 1/4 of the crystals in the top hemisphere removed to show the veto barrel and the target, and b) schematic picture of the beam line showing the positions of scintillators S1, ST and BVS and the six downstream drift chambers (DC1,6). An upstream drift chamber (DC0) was located just before S1. Between S1 and S2 were a bending magnet (M) and two quadrupoles (not shown).

shower from a single γ ray deposits energy in several crystals, called a cluster. The cluster algorithm sums the energy from the crystal with the highest energy with that from its nearest neighbors. More detail on the CB is given in Ref. [5].

The cavity in the center of the CB housed a liquid hydrogen (LH_2) target. The target geometry was a 10-cm diameter cylinder with spherical endcaps. The target length was 10.6 cm along the central beam axis. The target vacuum was maintained inside a cylindrical aluminum beam pipe. A veto barrel (VB) was installed to reject events that had charged particles in the final state. It was constructed of four curved plastic scintillators that formed a cylindrical shell around the beam pipe. ST was the primary beam-defining scintillator and was placed just upstream of the entrance to the beam pipe.

3. Data analysis

The $\pi^-\mathrm{p} \to \pi^0\mathrm{n}$ reaction was identified by measuring the energy and direction of the two photons from $\pi^0 \to \gamma\gamma$ decay ($BR = 98.8\%$). Each photon produces an electromagnetic shower in the NaI that spreads over several crystals around a central one. The cluster algorithm finds the crystal with maximum deposited energy and identifies it as the central one. A cluster was defined to be the central crystal and its nearest neighbors. Clusters with a central crystal energy greater than 7 MeV and an energy sum over all crystals in the cluster of at least 17.5 MeV were standard in this analysis.

The direction of the photon is determined by calculating the trajectory from the target center to the weighted average of the crystal positions, where the weighting factor is the square root of the deposited energy. The remaining crystals are searched to find the one with maximum energy to form the next cluster using the same criteria. The process is repeated until all the clusters are found.

With the assumption that the clusters originated from photons at target center, the invariant mass of photon pairs was found and compared to the π^0 mass. Two-cluster events that had an invariant mass between 97 and 181 MeV/c^2 were selected in the analysis. The recoil neutron can also give a cluster. Three-cluster events were included if two of the clusters reconstructed to the π^0 mass within the same interval and if the location of the third cluster was consistent with the direction of the neutron. In principle, this procedure eliminates the need to determine the detection efficiency for neutrons in the NaI since the events are included in the yield regardless of whether the neutron is detected. The efficiency depends strongly on the threshold and increases with the neutron energy [4].

The missing mass for producing the two clusters was calculated using the beam momentum information provided by the drift chambers. The missing mass was required to be within 110 MeV of the neutron mass. If this test was passed, the c.m. scattering angle of the π^0 was calculated and the data were histogrammed into 20 bins of $\cos\theta_{\mathrm{cm}}$. Runs with an empty target were taken at each momentum and yields were subtracted from the data taken with the full target.

The acceptance of the Crystal Ball for detecting π^0's from $\pi^-\mathrm{p} \to \pi^0\mathrm{n}$ was calculated using a Monte Carlo program based on GEANT [19]. All 672 crystals, the CB enclosure, the target assembly, the beam pipe, and all scintillation counters in the trigger were included in the simulation. Outgoing π^0's from a given angular distribution were passed to the GEANT simulation program. The two photons from $\pi^0 \to \gamma\gamma$ and the neutron were tracked through all elements on which they were incident and the deposited energy was recorded. The Monte Carlo events were then analyzed in the same way as the real data. The average acceptance for a given angle bin was the ratio of the number of events that passed the cuts divided by the number thrown.

The two photons and neutron traversed the LH_2 target, the containment vessel, beam pipe and veto barrel scintillator before reaching the Crystal Ball. The photons could convert to e^+e^- or the neutrons could interact hadronically in any of these materials. The veto barrel rejected these events if the energy deposited exceeded the signal threshold. This threshold was low in order to reject minimum ionizing charged particles, so this correction was significant. It was evaluated as part of the Monte Carlo simulation.

4. *Results*

The obtained values of $\pi^- p \to \pi^0 n$ differential cross sections are plotted in Fig. 2 and Fig. 3 together with the results of the FA02 partial-wave analysis (PWA) of the

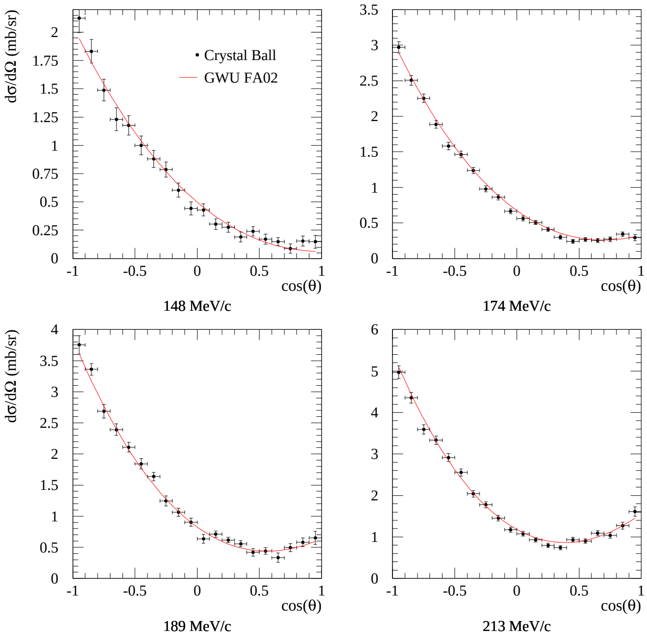

Fig. 2. Differential cross sections of reaction $\pi^- p \to \pi^0 n$. *Black circles are the values obtained in this experiment. The curves show the results of the FA02 partial-wave analysis of the George Washington group [20] based on experiments made earlier by other groups.*

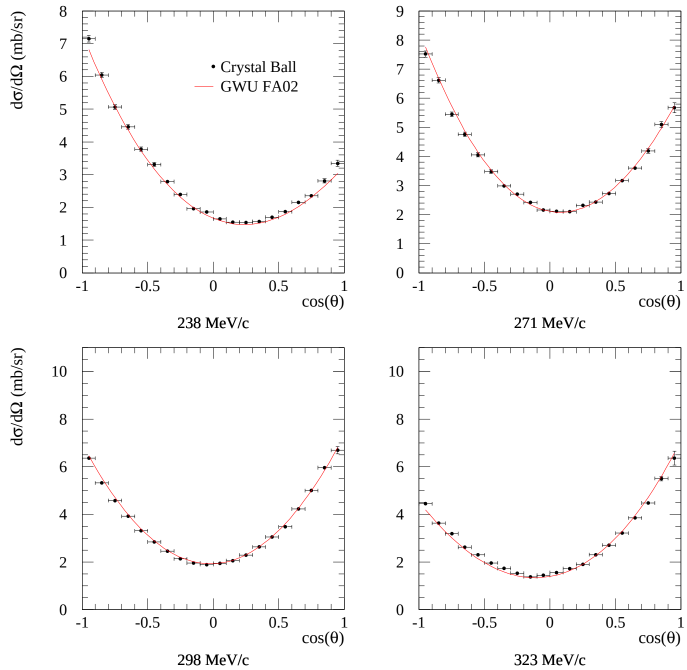

Fig. 3. Differential cross sections of reaction $\pi^- \mathrm{p} \to \pi^0 \mathrm{n}$. Black circles are the values obtained in this experiment. The curves show the results of the FA02 partial-wave analysis of the George Washington group [20] based on experiments made earlier by other groups.

George Washington group [20]. The statistical errors of the differential cross section are typically 2 − 6%, except at the lowest momentum and the forward-angle points at the three lowest momenta where the cross sections decrease to a few tenths of a mb. The present results exhibit excellent agreement with the FA02 PWA that is based on previous data.

The 160 data points in Figs. 2 and 3 double the existing database [21 − 28] in this momentum interval. The previous data were taken using either neutron counters or γ-ray spectrometers with small solid angle acceptance. The normalization uncertainties inherent in neutron detection are eliminated and the acceptance corrections associated with smaller detectors are reduced. The Crystal Ball also provides unmatched angular coverage at these momenta.

The results presented in Figs. 2 and 3 were selected because the electron and muon contamination of the beam can be deduced from time-of-flight (TOF) measurements at these momenta. Data were taken at momenta up to 750 MeV/c but the normalization is uncertain because a Cherenkov counter used to monitor the electron contamination was unreliable. Data from the 2002 run were taken to improve the normalization.

A minimum systematic uncertiainty of 2.0% was applied at all momenta to account for the calibration of the veto barrel, the uncertainty of determining the probability of vetoing legitimate events in the veto scintillators. An additional 1.5% was added at all momenta to account for the uncertainties in effective target length, hydrogen density, and the residual gas in the target for the empty runs. The following systematics were evaluated to obtain the overall uncertainties: 1) the uncertainties in the fits of the pion peak in the TOF spectra ($\approx 1\%$), 2) the statistical uncertainty for the counts in the pion peak in the TOF spectra (0.5 – 1.4%), and 3) 20% of the multiple scattering losses to the pion beam (1.1 – 5.9%). The quadrature summation of these factors gives total systematic uncertainties of 3.1% to 6.5%, increasing as the beam momentum decreases.

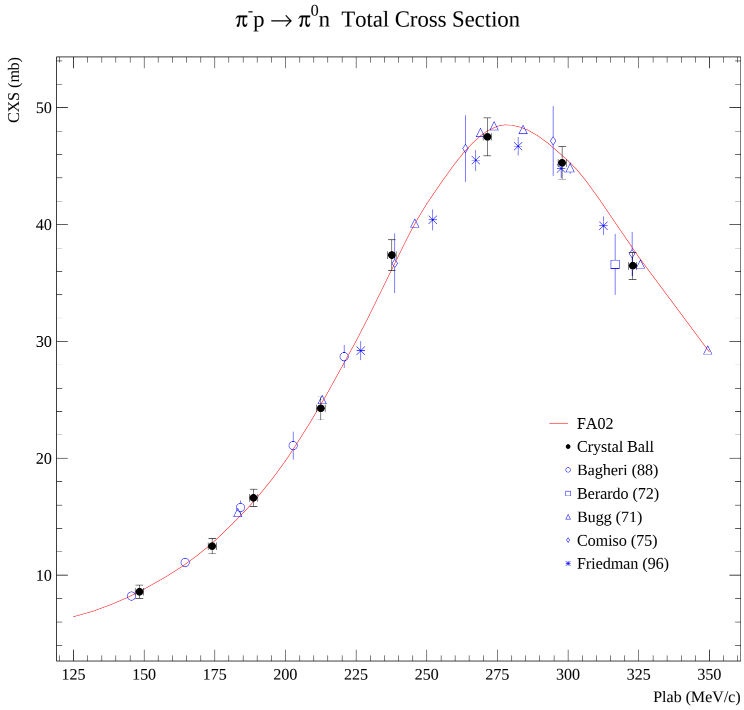

Fig. 4. The total charge exchange cross section obtained from integrating the differential cross sections. The errors unclude the systematic uncertainties. The results are compared to the GWU FA02 partial wave analysis [20] and to previous data [21, 24, 27, 29, 30] .

The differential cross sections were integrated to obtain the total charge exchange cross sections at the eight momenta. The systematic uncertainty was added in quadrature to the statistical uncertainty of the sum. The results are shown in Fig. 4. As with the differential cross sections, the general agreement with the GWU FA02 partial wave analysis is good. The most accurate data on which the partial wave analysis is based are Ref. [29, 30]. These experiments measured the fraction of beam pions that converted to neutral final states in a hydrogen target and made corrections for small effects such as $\pi^-p \to \gamma n$.

5. *Conclusions and future plans*

Measurements presented here are a small subset of the data obtained at BNL in 1998 and 2002. These results are the first that evaluated the systematic uncertainties at the few percent level.

The obvious extension of this program is to use the Crystal Ball to measure $\pi^-p \to$ neutrals and $K^-p \to$ neutrals with higher-momentum meson beams. An endcap would be needed to improve the acceptance at forward angles. Beam momenta of 2 GeV/c are needed to produce N* or Δ^* at W = 2.1 GeV and Λ^* or Σ^* at 2.2 GeV. These data are needed to complete the original goals of our BNL proposals and to complement the N* program at Jefferson Laboratory.

The Crystal Ball is presently at Mainz for experiments with photon beams. If an opportunity to utilize higher-momentum meson beams with the CB becomes available, we plan to be ready to take advantage of it.

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MJERENJA IZMJENE NABOJA PION-NUKLEON U PODRUČJU $\Delta(1232)$ REZONANCIJE

Opisujemo mjerenja diferencijalnih udarnih presjeka za raspršenje pion-nukleon, $\pi^- p \to \pi^0 n$, u području $\Delta(1232)$ rezonancije. Podatke smo dobili u okviru programa barionske spektroskopije s detektorom Crystal Ball na snopu C6 sinkrociklotrona s izmjeničnim gradijentom u Nacionalnom laboratoriju u Brookhavenu. Podaci su ograničeni na impulse za koje se onečišćenje u snopu moglo razlučiti vremenom proleta. Podaci za više impulse zahtijevaju posebna normalizacijska mjerenja koja su izvršena u 2002. godini, ali analize još nisu dovršene.