ISSN 1330–0016
CODEN FIZBE7

PRODUCTION OF PSEUDOSCALAR MESONS

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Received 18 September 2003; Accepted 26 April 2004
Online 16 July 2004

Experiments that study the hadronic and electromagnetic production of the pseudoscalar mesons – pions, etas and kaons, contribute to our knowledge of the properties of baryon and hyperon resonances. Fixed-target programs at hadronic facilities, such as BNL-AGS, have been phased out. However, the availability of modern experimental facilities with pseudo-monochromatic or tagged medium-energy photon beams at GRAAL, SPring-8, Bonn, Mainz, and Jefferson Lab, together with LEGS, Max-Lab, and HIGS at lower energies, are beginning to produce high-quality results. These new data have smaller statistical uncertainties and better understood systematic uncertainties, than those obtained at the older bremsstrahlung facilities, for measurements of differential and integrated cross sections, as well as polarization and asymmetry. Experimental results are compared with the predictions of QCD-based approaches, such as the lattice-gauge calculations of baryon properties, and chiral perturbation theory applied to threshold photoproduction, and are essential to the performance of partial-wave analyses (PWA). These PWA studies are less model dependent than in the past, and are used in coupled-channels calculations that incorporate unitarity dynamically, and combine results from hadronic reaction channels with electromagnetic processes. This approach is necessary to extract resonance properties and may lead to the discovery of the "missing resonances" predicted by a number of different QCD-inspired calculations. We discuss recent experimental and phenomenological results for single and double pseudoscalar meson hadronic and photoproduction channels with emphasis on the JLab Hall B and the BNL/AGS Crystal Ball programs.

PACS numbers: 14.20.Gk, 13.75.Gx, 11.80.Et, 25.20.Lj UDC 539.126

Keywords: single-pion photoproduction, πN elastic scattering, baryon and hyperon resonances, electromagnetic and hadronic probes

1. *Introduction*

In the following, we review a set of experiments, utilizing both electromagnetic and hadronic probes, designed to enhance our understanding of the baryon and hyperon resonances. These programs are complementary, since hadronic information (mass, width, and branching fraction) is required in the extraction of photo-decay amplitudes. The overall program is quite broad, aiming not only to improve upon existing estimates (obtained mainly from single-pion photoproduction and πN elastic scattering), but also including the production of other mesons (such and the η and K), and including multi-particle final states [1]. These processes are more difficult to analyze, but must be included if we are to solve the missing resonance problem and provide stringent constraints for QCD-inspired models and lattice calculations [2].

2. Photoproduction of pseudoscalar mesons at JLab

The first round of real-photon experiments using the Tagged Photon Facility [3] and CLAS [4] at the Thomas Jefferson National Accelerator Laboratory in Newport News Virginia (JLab) was divided into several running groups, each of which included experiments that used the same target nucleus and had similar technical needs. The G1 Running Group combined several approved experiments that involved the interaction of real photons with the proton. Besides the PAC approved experiments [5–10], there was one independent analysis [11] that is relevant to this paper. The G2 running group had many of the same goals as the G1 running group, but used the deuteron as a neutron target [5, 12, 13]. The G3 running group used ^{3}He and ^{4}He targets to study coherent and incoherent production of mesons and hyperon formation in nucleus [14–16]. The G6 running group measured the photoproduction of vector mesons at high t in order to study the region below which vector dominance is important and in which hard processes are thought to dominate [17].

2.1. Single-meson photoproduction

Figure 1 shows a sample of the differential cross sections obtained (2% of the G1B data). The evolution of this set of differential cross sections is well reproduced by SAID in the region where there is sufficient experimental data to constrain the fit (up to 1.2 GeV). Even up to 1.7 GeV, the agreement is quite good.

Single-pion photoproduction yields that were obtained from the G1C data run for $\gamma p \to \pi^\circ p$ and $\gamma p \to \pi^+ n$ are shown in Fig. 2. While normalization is still being discussed within the collaboration, one is again comforted by the apparent good agreement between data and SAID. Additionally, results for the reaction $\gamma p \to \eta p$ have been obtained and are shown in Fig. 3. Here also phenomenology appears to be capable of reproducing general features in the data.

Significant improvement in the stability of PWA solutions, over a wider range of energies, is expected with the polarized beam and target experiments planned for Hall B of JLab [20]. At present, double polarization measurements are few and have little weight in a fit to the full database.

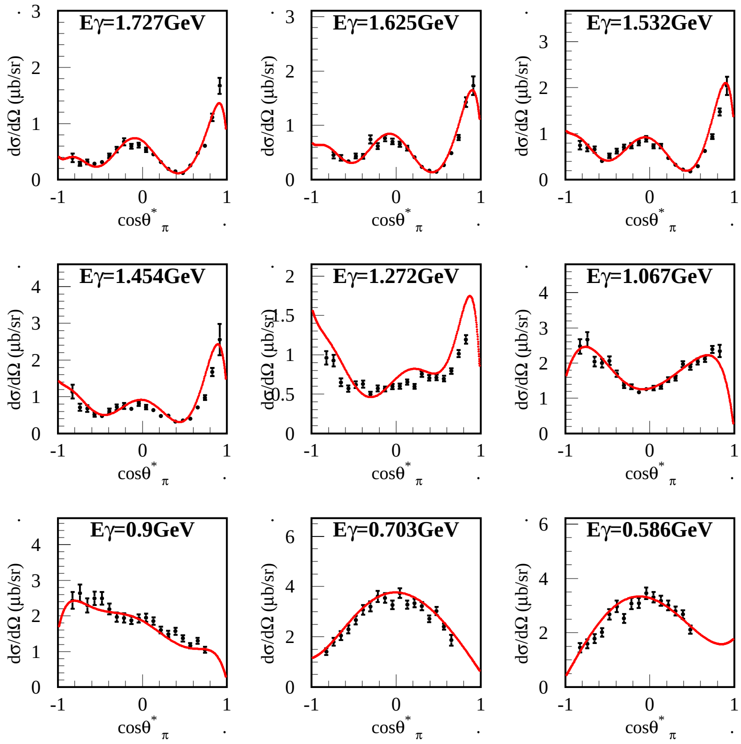

Fig. 1. Preliminary differential cross sections from the CLAS G1B run group for $\gamma p \to \pi^\circ p$ angular distributions – arbitrary scale (solid circles) [18]. These data are compared to SAID [1] (solid line) predictions.

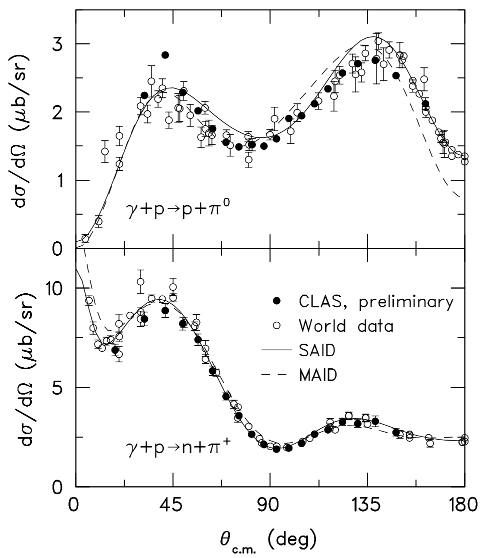

Fig. 2. Preliminary differential cross section data at E_γ = 1000 MeV from the CLAS G1C run group (solid circles). These data are compared to other world data (open circles), along with SAID [1] (solid line) and MAID [19] (dashed line) predictions.

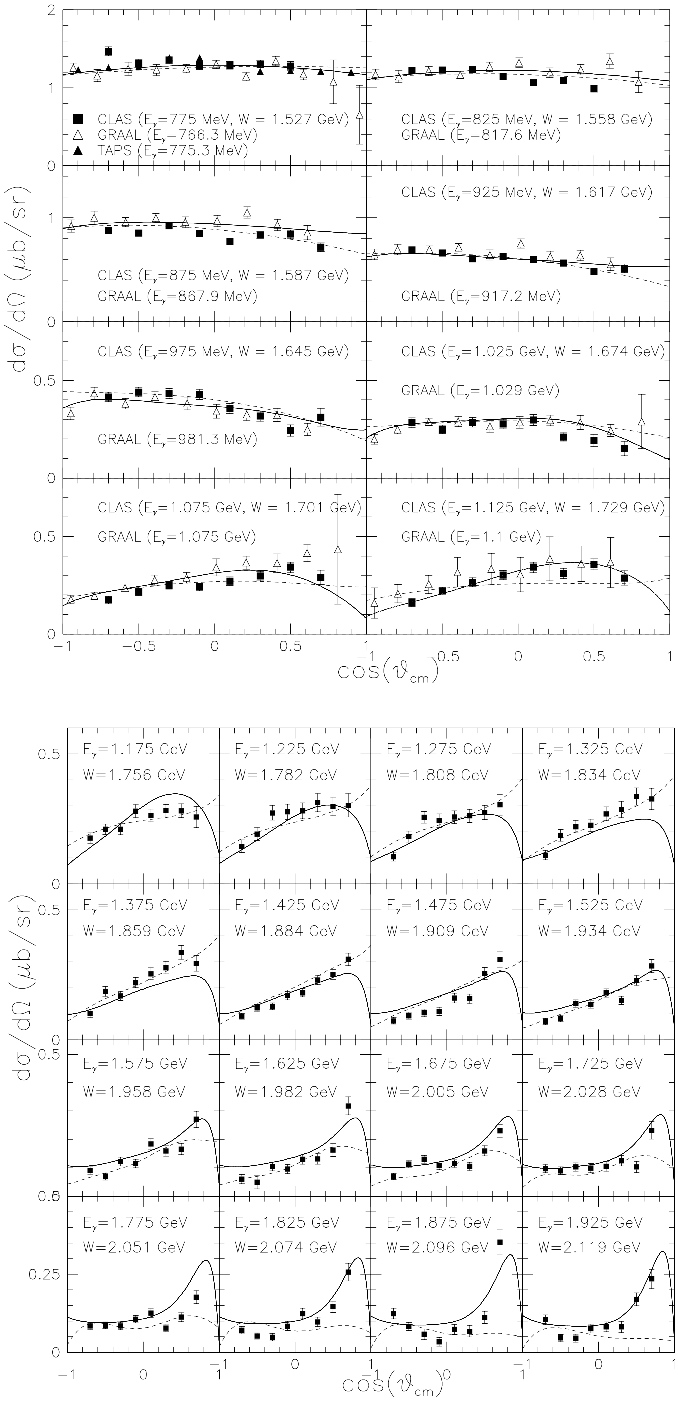

Fig. 3. Differential cross sections for γp $\to$ ηp angular distributions, 750 to 1150 MeV *(upper panel) and 1200 to 1950* MeV *(lower panel). CLAS JLab data (solid squares) [21] are shown vs. previous TAPS [22] and GRAAL [23] measurements for comparison. Also shown are results from REM (solid lines) [24] and χQM (dashed lines) [25] approaches.*

The $\gamma n \to K^+\Sigma^-$ channel has been measured as part of a study of kaon photoproduction on deuterium. The photon-energy range covered was from 0.50 to 2.95 GeV. In the present analysis, the reaction $\gamma n \to K^+\Sigma^-$ was selected by detecting the K^+ and the decay products of the Σ^-. The π^- was detected using the time-of-flight counters and the drift chambers, while the neutron was detected in the electromagnetic calorimeter. The neutron momentum was determined from time-of-flight. Preliminary differential cross sections are shown in Fig. 4 as a function of the invariant energy W and the kaon polar angle in the center-of-mass system. Here the data shows significant deviation from a model based mainly on fits to proton-target data. These fits are far less constrained, by both data and theory, than those associated with the single-pion photoproduction process.

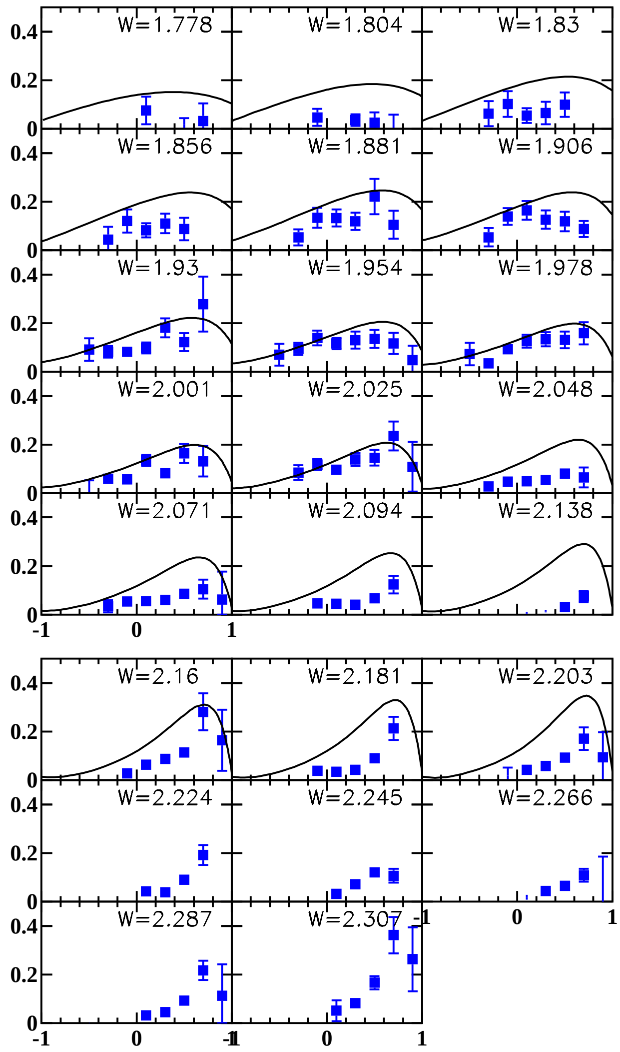

Fig. 4. Preliminary differential cross sections for $\gamma n \to K^+\Sigma^-$. These CLAS JLab data [26] are compared to [27] (solid line) predictions.

2.2. Double-meson photoproduction

Double-pion photoproduction cross sections (for the γp $\rightarrow$ p$\pi^{\circ}\pi^{\circ}$ reaction channels) extend the study of nucleon resonances beyond previous works based upon pion-nucleon scattering and with single-pion production. The $\pi\pi$N channel will be used to extract information on the electromagnetic excitation and decay mechanisms of resonances at higher excitation energies, and may be essential for disentangling the broad, overlapping resonances that do not couple strongly to the πN channel. Two-π^0 production, in particular, is not contaminated with background events from the Born terms. Moreover, intermediate $\rho^o(770)$ processes are forbidden since ρ^o cannot decay into two neutral pions.

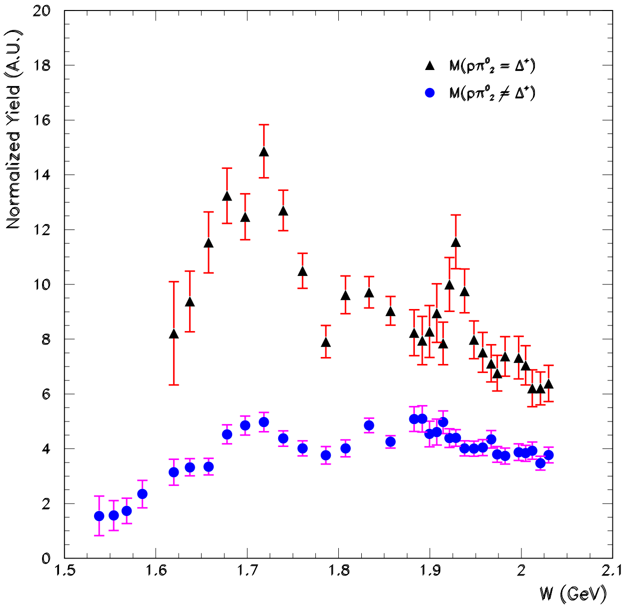

Fig. 5. CLAS Jlab preliminary cross sections for the reaction γp $\rightarrow$ p$\pi^{\circ}\pi^{\circ}$ [11].

Figure 5 shows the preliminary cross sections for the reaction γp $\rightarrow$ p$\pi^{\circ}\pi^{\circ}$ extracted from the two earliest G1 running periods, at photon energies between 500 and 1700 MeV. This analysis extends the total cross section measurements beyond E_{γ} = 800 MeV. A prominent peak at E = 1.1 GeV corresponds to a center-of-mass energy of W = 1.715 GeV; and another at E = 1.4 GeV corresponds to W = 1.9 GeV). The cross section up to 800 MeV agrees very well with the earlier work done at Mainz; the peak at 1.1 has been recently reported by GRAAL but the one at 1.4 GeV has not been seen before. The general shape of the cross section agrees with the DAPHNE measurement. It is particularly interesting that at higher photon energies there is evidence of some structure in the cross section, as these data are the first of their kind in this energy region. Angular distributions of all three final state particles will be available once a more detailed analysis is complete. These results should foster new theoretical work at these higher energies.

2.3. The Crystal Ball program at BNL/AGS

The SLAC Crystal Ball Spectrometer was used to make measurements at the C6 line at the Brookhaven National Laboratory, BNL, Alternating Gradient Synchrotron, AGS, with pion momenta from 147 MeV/c to 760 MeV/c. This series of experiments studied all neutral final states of π^-p and K^-p induced reactions. New results for the radiative capture reaction $\pi^-\mathrm{p} \to \gamma\mathrm{n}$, charge exchange $\pi^-\mathrm{p} \to \pi^\circ\mathrm{n}$, two π° production $\pi^-\mathrm{p} \to \pi^\circ\pi^\circ\mathrm{n}$, and η production $\pi^-\mathrm{p} \to \eta\mathrm{n}$, reactions have recently been reported. Data were taken simultaneously on all reactions, which ensures that background events were accurately subtracted. Data taking using the Crystal Ball began in July 1998 and continued until late November 1998. An additional two-week run was completed in May 2002, just before disassembling the Crystal Ball for shipment to Mainz.

The Crystal Ball is a segmented, electromagnetic calorimetric spectrometer, covering 94% of 4π steradians. It was built at SLAC and used for meson spectroscopy measurements there for three years. It was then used at DESY for five years of experiments and put in storage at SLAC from 1987 until 1996 when it was moved to BNL by our collaboration. The Crystal Ball is constructed of 672 hygroscopic NaI crystals, hermetically sealed inside two mechanically separate stainless steel hemispheres. Each crystal is viewed by a photomultiplier tube (PMT). There is an entrance and exit tunnel for the beam, LH_2 target plumbing, and veto counters. Each crystal is shaped like a truncated triangular pyramid, points toward the interaction point, is optically isolated, and is viewed by a PMT which is separated from the crystal by a glass window. The beam pipe is surrounded by 4 scintillators covering 98% of the target tunnel and form the veto-barrel. Electromagnetic showers are measured with an energy resolution of $\Delta\mathrm{E/E} = 0.02/[\mathrm{E(GeV)}]^{0.36}$, and an angular resolution for θ of $2^\circ - 3^\circ$, for energies in the range 50 – 500 MeV, and a resolution in ϕ of $2^\circ/\sin\theta$. The energy calibration is done *in situ* using the reactions: i) $\pi^-\mathrm{p} \to \gamma\mathrm{n}$ at rest, yielding an isotropic, monochromatic γ flux of 129.4 MeV; ii) $\pi^-\mathrm{p} \to \pi^\circ\mathrm{n}$ at rest, yielding a pair of photons in the energy range 54.3 – 80 MeV, almost back to back; and iii) $\pi^-\mathrm{p} \to \eta\mathrm{n}$ at threshold, yielding two photons, about 300 MeV each, in coincidence almost back to back. Scintillators surround the LH2 target to provide a charged particle veto and a beam veto scintillator is located downstream of the target as is a Cerenkov counter to monitor electron contamination in the beam. The trigger consists of: a beam coincidence trigger, no downstream beam veto, and a total energy-over-threshold signal from the Crystal Ball. A trigger based on the distribution of the energy in different regions of the Crystal Ball was also used to provide a more restrictive trigger in certain cases.

2.3.1. **The radiative decay of nucleon resonances**

The radiative decay of a resonance provides an excellent laboratory for testing theories of the strong interaction, allowing us to probe the structure of the nucleon itself. In particular, radiative-capture data are important in the study of the poorly understood neutral Roper resonance. They can be combined with the recent JLab Hall B data for the reactions $\gamma\mathrm{p} \to \pi^+\mathrm{n}$ and $\gamma\mathrm{p} \to \pi^\circ\mathrm{p}$, which have contributions from mesonic decays of the charged Roper, excited by incident photons with energies from 400 to 700 MeV. In addition, comparison of radiative capture data to the new JLab data taken in the inverse reaction $\gamma\mathrm{n} \to \pi^-\mathrm{p}$, using a deuteron target, tests extrapolation techniques for the deuteron correction and allows one to study medium effects within the deuteron. Figure 6 shows the results of our radiative capture measurements at the equivalent $E_\gamma = 285$ MeV compared the latest SAID [1] and MAID [19] differential cross section predictions. On average, over all 18 energies measured at BNL, the new data favor the SAID predictions. Very little change in the cross sections are seen when our data are included in the SAID fit. However, there are some hints of significant changes in the electric and especially the magnetic multipoles.

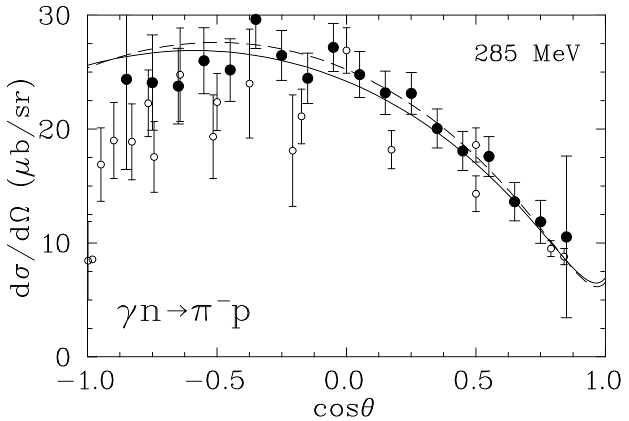

Fig. 6. Preliminary differential cross section data for $\gamma\mathrm{n} \to \pi^-\mathrm{p}$ at $E_\gamma = 285$ MeV from the Crystal Ball (solid circles) [28]. These data are compared to other world data (open circles), along with SAID [1] (solid line) and MAID [19] (dashed line) predictions.

The primary reason that so few data are available for the radiative capture reaction is the difficulty in separating its contribution from other reactions. This is mainly due to the significant background from $\pi^-\mathrm{p} \to \pi^\circ\mathrm{n}$ whose cross-section is about 50 – 100 times larger. The geometry of the Crystal Ball provides the capability of discriminating against multiple γ-rays that arise from the decay of π°s and ηs. However, because of the large entrance and exit tunnels, there is a 20% chance that one of the two γ's from say π° decay is missed, resulting in a false one-photon event. The separation of signal for $\pi^-\mathrm{p} \to \gamma\mathrm{n}$ from "background" was investigated using GEANT and EHS. Our Monte-Carlo includes such subtleties as secondaries from photon and pion breakup of a nucleus in the NaI, photon split-offs (a single photon cluster split into two) and backward Compton scattering. It reproduces and improves upon the photon energy and angular resolution that were measured in the course of the Crystal Ball's eight-year tenure at SLAC and DESY. The large solid angle acceptance of the Crystal Ball leads to a rejection factor of about 40 – 150 for the background events from $\pi^-\mathrm{p} \to \pi^\circ\mathrm{n}$.

2.3.2. **Charge exchange**

The charge-exchange process has been the weakest link in πN partial-wave and coupled-channel studies. The accurate data that we have obtained in this momentum region will help in improving the determinations of the isospin-odd s-wave scattering length, the πNN coupling constant, and the π-N σ term. In addition, better charge exchange data helps in evaluating the mass splitting of the Δ resonance and may result in new values for the $P_{11}(1440)$ mass and width. Figure 7 shows the charge exchange data used in the evaluation of background in our crystal ball measurements. A full reanalysis using these data is in progress. The solid line representing the current SAID fit does not include these data.

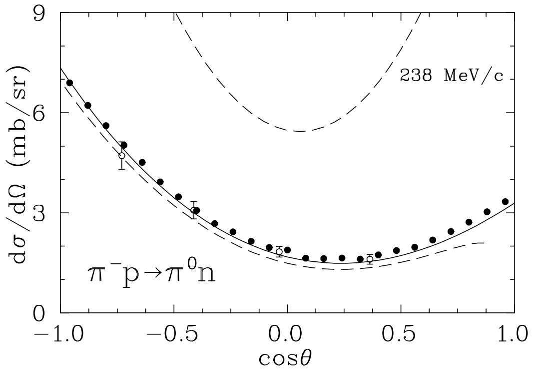

Fig. 7. Preliminary differential cross section data for π^-p $\rightarrow$ π°n at E_γ = 238 MeV/c from the Crystal Ball (solid circles). These data are compared to other world data (open circles), along with SAID [29] (solid line) predictions. Dashed lines associated with the triangle inequality.

2.3.3. **Near-threshold eta production**

Near-threshold η-production measurements provide data useful in verifying models of η-meson production and are necessary for an extraction of the η-N scattering length. They will also be necessary to resolve ambiguities in the resonance properties of the $S_{11}(1535)$ and in the η photoproduction helicity amplitudes. In Fig. 8, low-energy data are compared to a recent GW coupled-channel fit [29] to πN elastic and π^-p $\rightarrow$ ηp data. Here one can see the level of conflict between datasets, and the much improved statistical uncertainties associated with the Crystal Ball data [30]. It should be pointed out that the lowest energy points for the crystal ball data set are a few MeV higher than those of Morrison et al. [31] which were taken with a small acceptance detector previous to the arrival of the crystal ball at BNL. Accounting for the higher energy and the steep rise in cross section at threshold, one would expect a somewhat higher value that is still fairly flat indicating a mostly S-wave behavior very near threshold.

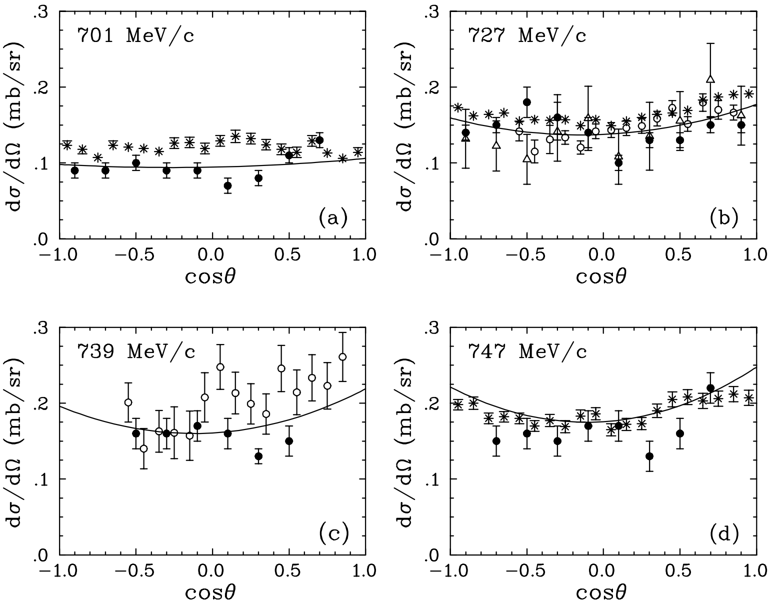

Fig. 8. Preliminary differential cross section data for π^-p $\to$ ηn at from E909 of BNL/AGS [31] (solid circles) and the Crystal Ball E913/914 BNL/AGS [30] (stars). These data are compared to other world data (open circles), along with SAID [29] (solid line) predictions.

3. Summary and conclusions

The baryon spectroscopy programs at JLab and BNL have produced a plethora of data points that enhance our ability to do new partial-wave analyses. Besides the single-channel analyses of the past, several coupled-channel analyses are being accomplished owing to the expansion of the data base. It is anticipated that final results of the experiments are eminent and that our new fits can be firmed up. With the apparent "discovery" of the pentaquark, a revival of "N-Star" physics seems very likely with even the most unlikely candidates jumping on the bandwagon. It is hoped that this resurgence of interest will allow those who have been long standing workers in the field to continue their efforts and reap the fruits of their labors. One word of caution - the analyses in progress must be fully and carefully completed as expeditiously as possible. Without these data the data base remains incomplete.

Acknowledgements

The author acknowledges the support of the United States Department of Energy (DOE), The Southeastern Universities Research Association (SURA), The Thomas Jefferson National Accelerator Facility (JLab), and the George Washington University Research Enhancement Fund.

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TVORBA PSEUDOSKALARNIH MEZONA

Mjerenja hadronske i elektromagnetske tvorbe pseudoskalarnih mezona, piona, eta i kaona, doprinose našem znanju o svojstvima barionskih i hiperonskih rezonancija. Programi s hadronskim snopovima i mirnom metom, kao BNL-AGS, su obustavljeni. Međutim, moderni eksperimentalni sustavi s približno monokromatskim ili s obilježenim fotonskim snopovima srednje energije u GRAALu, SPring-8, Bonnu, Mainzu i JLabu, zajedno s LEGS, Max-Lab i HIGSom na nižim energijama, započeli su davati odlične podatke. Ti podaci imaju manje statističke pogreške i manje sistematske neodređenosti od ranijih mjerenja s kočnim zračenjem, kako u određivanju diferencijalnih i totalnih udarnih presjeka, tako i za polarizaciju i asimetrije. Ovdje se eksperimentalni podaci uspoređuju s predviđanjima pristupa zasnovanih na QCDu, kao računi svojstava bariona metodom rešetka-baždarnost i primjena kiralne teorije smetnje za pragove fototvorbe, te su ključni za ishod analize po parcijalnim valovima (APV). Istraživanja APV manje ovise o modelima nego prije i primjenjuju se u računima vezanih kanala koji sadrže unitarnost dinamički i sjedinjuju ishode hadronskih reakcijskih kanala s elektromagnetskim procesima. Taj je pristup nužan da bi se izvela svojstva rezonancija, i on može dovesti do otkrića "manjka rezonancija" koje predviđaju razni računi nadahnuti QCDom. Raspravljamo nedavne eksperimentalne i fenomenološke ishode za hadronsku i fototvorbu pseuduskalarnih mezona, pojedinačno i u parovima, s naglaskom na programe JLab Hall B i BNL/AGS Crystal Ball.