Beam Asymmetries in π^0 Photoproduction on the Proton

Nathan Sparks on behalf of the CBELSA/TAPS Collaboration

Florida State University, Tallahassee, FL, 32306,USA

Abstract. Polarization observables, such as the beam asymmetry Σ, are vital to the study of the many N^* and Δ resonances that decay to the $p\pi^0$ final state. Beam asymmetries in π^0 photoproduction off the proton have been determined using the Crystal Barrel CsI(Tl) calorimeter at ELSA, University of Bonn in Germany, in the energy range E_γ = 920 to 1680 MeV by analyzing the neutral decay mode $\pi^0 \to \gamma\gamma$. In this experiment, the BaF_2 spectrometer TAPS was placed in the forward direction increasing the solid angle coverage to nearly 4π and serving as a fast trigger. For the first time, these measurements include the most forward angles in $\theta_{\pi^0}^{\mathrm{c.m.}}$. Additionally, this analysis provides new data points in the energy range E_γ = 1510 to 1680 MeV where few measurements have previously been made.

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INTRODUCTION

Quantum Chromodynamics (QCD) in a perturbative approximation is successful at describing the dynamics and structure of hadrons at high energies where the quark and gluon constituents are relatively weakly interacting. As the energy of the probe is lowered, the strong coupling constant increases such that an energy regime is reached where the perturbative expansion is no longer useful. This is the bound state energy regime of QCD. Much can be learned about hadrons in this energy regime experimentally. By mapping out the excitation spectrum of a hadron, information is gained about the effective number of constituents of the hadron and the forces that bind these constituents within the hadron.

A particularly challenging task is understanding the spectra of the excited baryons. Although constituent quark models are good at predicting properties of the ground state baryons, there is a large discrepancy between the number of excited states predicted by these models and the number that has been observed. Is there a physical mechanism that can account for this discrepancy? Attempts at answering this question have not thus far yielded a satisfactory answer. Can these differences be explained by the fact that the higher mass regions of the excitation spectra remain largely unexplored and/or a limited number of production mechanisms have been pursued? (Most known baryon resonances have a mass less than 2 GeV and were discovered in elastic πN scattering.) These are questions that are currently being addressed experimentally.

Current efforts at the CBELSA/TAPS experiment in Bonn, Germany are using the photoproduction mechanism to study baryon resonances. The experimental setup is optimized for photon detection, allowing for the study of excited baryons that decay to a nucleon and one or multiple neutral meson(s) that decay(s) into photons. As well as measuring differential and total cross sections, polarization observables, which allow for a more complete description of the decay amplitude of the resonance [1], are extracted. The baryon resonances have large widths and tend to overlap so that this information, which includes the interference terms of the amplitude, is often required for the identification of excited baryons.

It is important to confirm baryon resonances in photoproduction that were previously identified in πN scattering and even more important to find any resonances that were overlooked there. For this reason, π^0 photoproduction on the proton is an ideal channel to work with.

There are still some angular regions where observables have not been determined in π^0 photoproduction off the proton. In particular, π^0 beam asymmetry measurements are missing at forward polar angles of the pion in the center-of-mass system $\theta_{\pi^0}^{\mathrm{c.m.}} < 60^\circ$. Also, measurements are sparse above photon energies E_γ = 1500 MeV (see [2]). Observables measured over the full angular range reduce the need for model dependent extrapolations in a PWA. This means that model dependence is minimized in the subsequent interpretation of the data.

Beam asymmetries are sensitive to interference terms in the decay amplitudes of resonances [1]. Hence, they are important in the discovery of resonances that couple weakly to $p\pi^0$.

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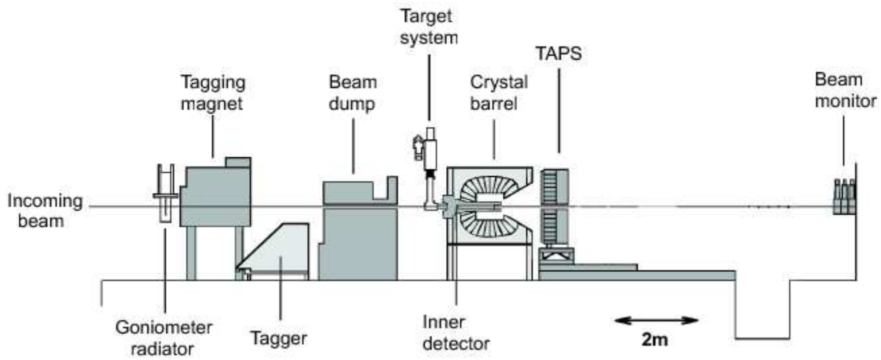

FIGURE 1. Experimental setup of CBELSA/TAPS in Bonn. The electron beam delivered by the accelerator ELSA enters from the left side and hits the diamond crystal of the goniometer.

In the following, the extraction of the beam asymmetry Σ in π^0 photoproduction will be described. First, the experimental setup will be overviewed before moving on to the procedures used in event reconstruction and the observable extraction. Lastly, the experimental results will be discussed.

EXPERIMENTAL SETUP

A 3.175 GeV electron beam was provided by the ELectron Stretcher Accelerator ELSA, in Bonn, Germany, by slow resonant extraction. It was incident on a 500 micron diamond radiator. Careful orientation of this radiator with a 5-axis goniometer allowed the entire lattice to recoil when an electron underwent bremsstrahlung. This fixed the plane that these electrons were deflected in and resulted in the emission of plane polarized photons. This process is known as coherent bremsstrahlung. Electrons were deflected by a dipole magnet into the tagging system where their detection by scintillating fibers or counters allowed each photon energy to be determined by taking the difference between the incoming electron energy and the electron energy after bremsstrahlung. Electrons that did not undergo bremsstrahlung were deflected at small angles into a beam dump located behind the tagger.

The linearly polarized photons continued along the beam line toward an unpolarized (liquid hydrogen) target located at the center of the Crystal Barrel (see Figure 1). Some of these photons interacted with protons within the target to produce a proton and multiple photons in the final state, the photons resulting from the decay of neutral mesons. The photons were detected by the two EM calorimeters that together covered almost the full solid angle. The Crystal Barrel consisted of 1290 CsI(Tl) crystals and covered the polar angles from 30° to 170° while TAPS consisted of 528 hexagonal BaF_2 crystals and covered the polar angles from 5° to 30°. Both covered the full azimuthal circle. Forward going protons were detected by plastic scintillators located in front of each TAPS module, the other protons were detected by a 3-layer scintillating fiber detector surrounding the target.

EVENT RECONSTRUCTION

The data were taken during two separate run periods: March and May 2003. The position of the coherent bremsstrahlung peak was at 1305 MeV in March, it was at 1610 MeV in May. The maximum degree of polarization was about 50% in March and 40% in May. A total number of $\sim 1.06 \times 10^6$ π^0 events has been included in this analysis.

The first level trigger was formed by the fast response of the TAPS modules. The second level trigger determined the number of clusters in the Crystal Barrel using a cellular logic (FACE). Data were recorded when at least two hits were found in TAPS each above a low energy threshold, or when at least one hit was found in TAPS above a high energy threshold in combination with at least two hits detected in the Crystal Barrel.

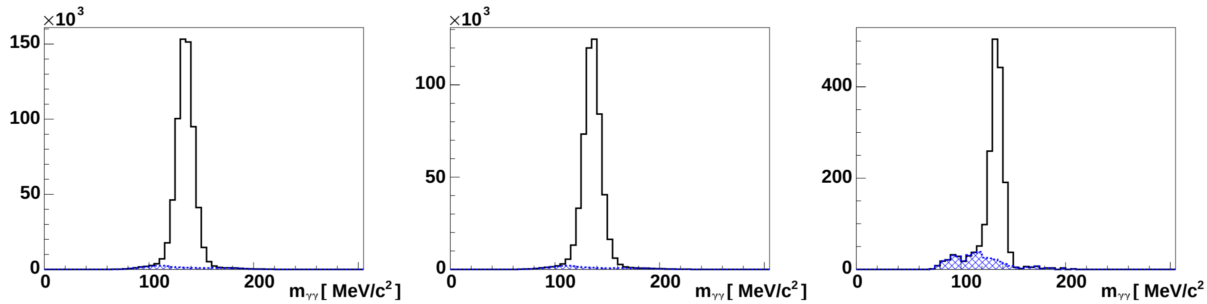

FIGURE 2. Invariant $\gamma\gamma$-mass spectra for the reaction $\gamma p \rightarrow p\gamma\gamma$ using data with the coherent peak at 1305 MeV (left) and at 1610 MeV (center); confidence level cuts were applied at 10^{-2}. The π^0 mesons are observed with very little background. On the right, a mass spectrum for a forward bin is shown at $E_\gamma = 1097$ MeV (bin width 33 MeV) and $\theta_{\text{c.m.}} = 25^\circ \pm 5^\circ$. The colored area indicates the background.

Events were analyzed for which only the two final state photons (from $\pi^0 \rightarrow \gamma\gamma$) or all final state particles ($p\gamma\gamma$) were detected. Prompt coincidence between an electron in the tagger and a particle in TAPS was required to reduce time accidental background. Proton clusters in the EM calorimeters are on average much smaller than photon clusters and do not provide sufficient resolution for proton identification. A missing proton kinematic fit allowed the identification of particles in the event. This fit was performed for each possible unique particle combination by shifting the initial state photon tag through the initial state photon list and proton tag through the final state particle list. The combination with the largest confidence level was selected. Finally, only events with a confidence level greater than 1% were taken. The invariant $\gamma\gamma$-mass of the two detected photons was required to be between 30 to 240 MeV/c^2 to remove η mesons from the event sample without losing knowledge of the background shape.

Before obtaining the physical observable one must carefully remove all events that are not $p\gamma\gamma$ final states (background) from the event sample. Usually this is done by interpolating the shape of the background in the signal region based on the distribution of events outside the signal region, and is known as side-band subtraction.

We decided to gain experience using a generalization of the side-band subtraction known as the Q-factor method so that we can use it as a tool in an event based analysis (PWA) in the future. This method consists of finding a quality factor (Q-factor) or signal 'probability' for each event. The background can then be removed from any distribution by simply weighting it with the Q-factors. The sample mass spectra in Figure 2 illustrate background subtraction by the Q-factor method. A complete presentation of the Q-factor method can be found in [3].

BEAM ASYMMETRY EXTRACTION

The azimuthal symmetry of the final state particles is broken by the linear polarization of the photon beam such that the differential cross section of pseudoscalar mesons has the form

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left(1 - P_\gamma \Sigma \cos\left(2\varphi\right)\right), \qquad (1)$$

where $(d\sigma/d\Omega)_0$ denotes the unpolarized differential cross section, P_γ is the degree of linear polarization, and φ is the azimuthal angle between the photon polarization vector and the pion. Notice that this angle is related to the azimuthal angle of the pion ϕ by $\varphi = \alpha - \phi$ where α is the angle to the polarization vector from lab x axis. $\alpha = 0$ corresponds to photons polarized in a plane parallel to the floor of the experimental hall (xz plane), whereas for $\alpha = \frac{\pi}{2}$ the photons are polarized in a plane perpendicular to the floor (yz plane). Because of poor horizontal beam emittance, these

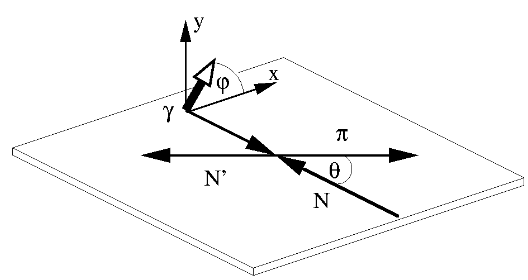

FIGURE 3: Sketch of the $\gamma p \rightarrow p\pi^0$ reaction in the center-of-mass system; the open (white) arrow indicates the linearly polarized photon.

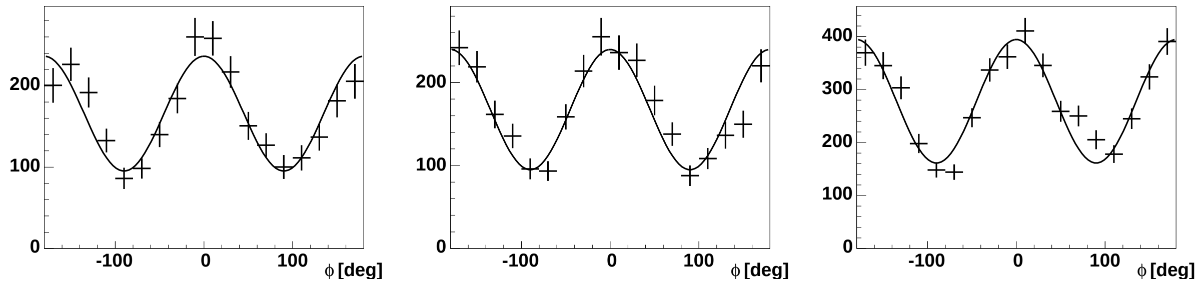

FIGURE 4. Typical ϕ distributions for forward-angle bins at $\theta_{\mathrm{c.m.}} = 35^{\circ}$ and E_{γ} = 1229 MeV (left), 1295 MeV (middle), and 1625 MeV (right). We have chosen 18 bins in the azimuthal angle ϕ corresponding to a bin width of 20°.

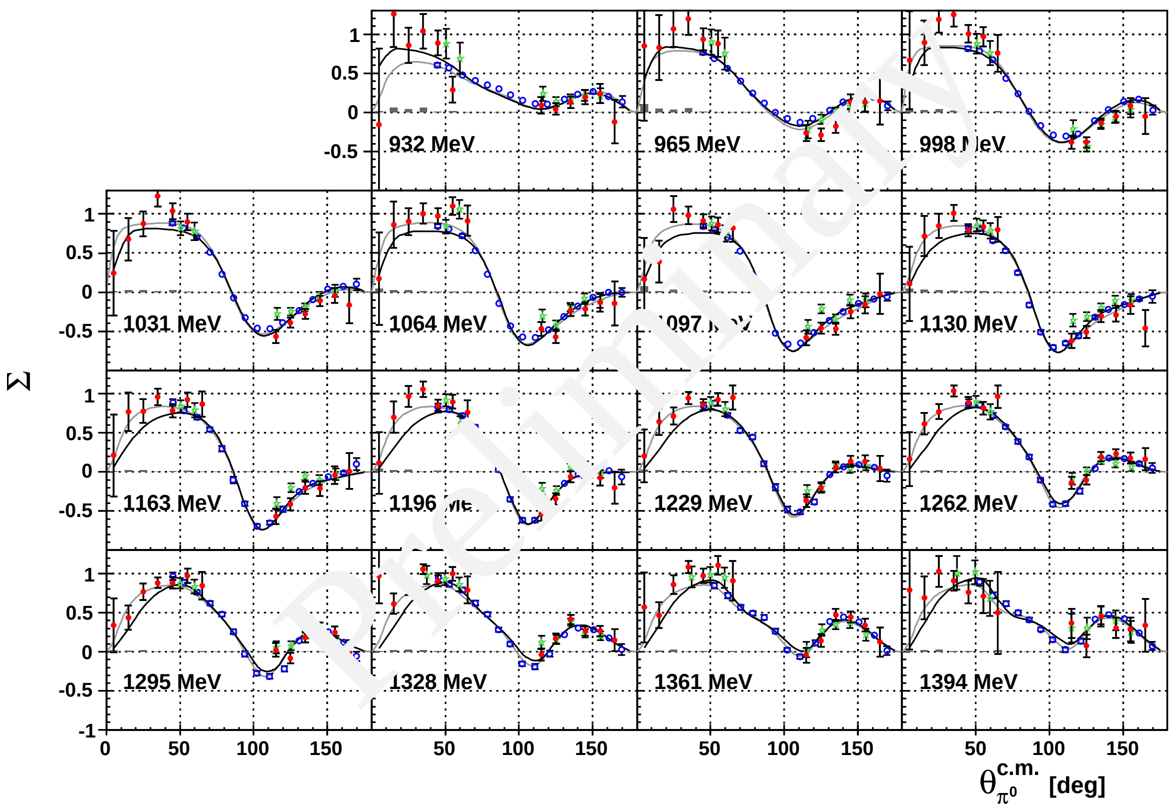

FIGURE 5. The photon beam asymmetries extracted from the data set with a coherent peak position at 1305 MeV. The filled (red) circles (•) denote this preliminary analysis, the (green) stars ($*$) our previous CBELSA/TAPS analysis [4], and the open (blue) circles (∘) the GRAAL results [5]. The black solid line shows the recent solution of the Bonn-Gatchina partial wave analysis [6] and the grey solid line shows the SAID SP09 prediction [2, 7]. The width of the energy bins is 33 MeV, consistent with the published earlier results. The energy of the bin centers is given in each distribution.

data only include photons with the perpendicular orientation, hence $\varphi = \frac{\pi}{2} - \phi$. The form of the differential cross section allows us to obtain Σ by fitting the azimuthal distribution of the pions to

$$N(\phi) = A + B\cos(2\phi), \tag{2}$$

where $P_{\gamma}\Sigma$ is given by the ratio B/A for each (E_{γ},$\theta_{\pi^0}^{\mathrm{c.m.}}$) bin. Some sample ϕ distributions are shown in Figure 4.

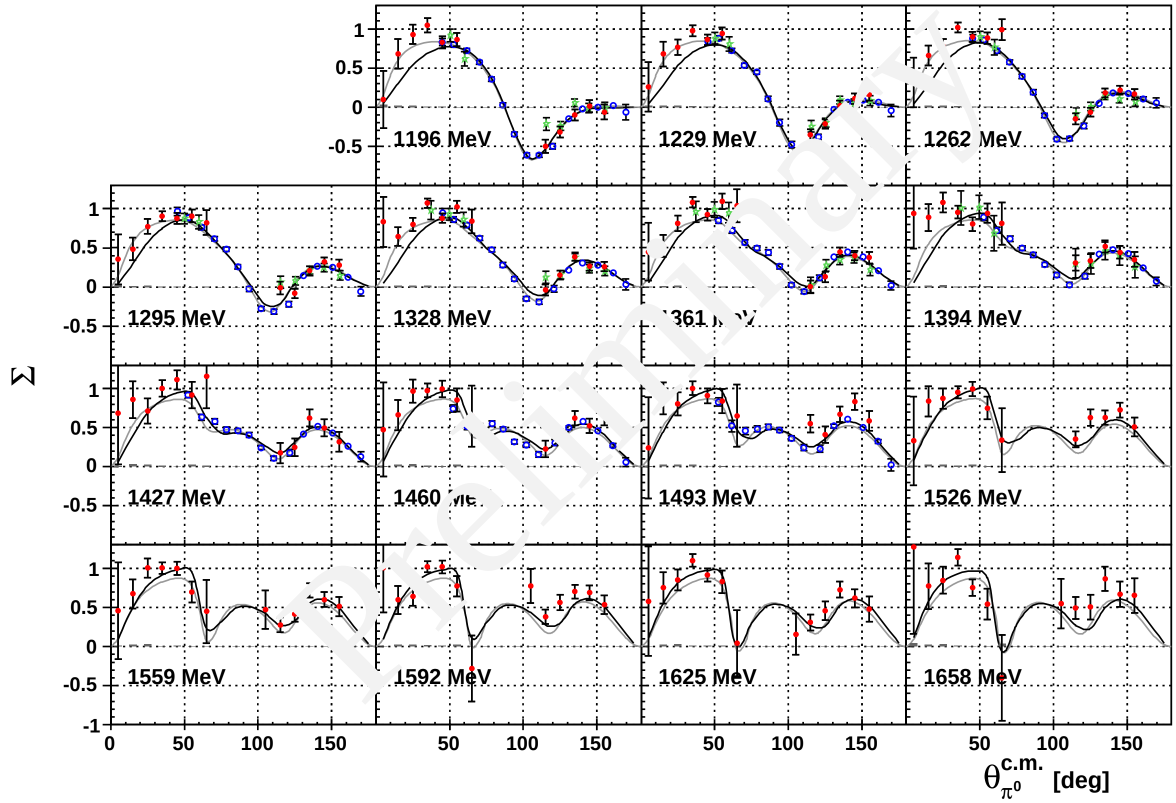

FIGURE 6. The photon beam asymmetries extracted from the data set with a coherent peak position at 1610 MeV. The filled (red) circles (•) denote this preliminary analysis, the (green) stars (∗) our previous CBELSA/TAPS analysis [4], and the open (blue) circles (◦) the GRAAL results [5]. The black solid line shows the recent solution of the Bonn-Gatchina partial wave analysis [6] and the grey solid line shows the SAID SP09 prediction [2, 7]. The width of the energy bins is 33 MeV, consistent with the published earlier results. The energy of the bin centers is given in each distribution. For energies below 1400 MeV, we have averaged the results from both data samples.

EXPERIMENTAL RESULTS

Figure 5 and Figure 6 show the beam asymmetry as a function of $\theta_{\pi^0}^{c.m.}$ with 33 MeV wide E_γ bins. This photon energy bin width was chosen to facilitate a comparison with the GRAAL [5] and previous CBELSA/TAPS [4] results. Small energy shifts between the different data sets are still present for some of the bins. The coherent bremsstrahlung peak position is at 1305 MeV for the data in Figure 5. Notice that the first seven energy bins of Figure 6 ($\approx$ 1200 MeV to 1400 MeV) overlap with energy bins in Figure 5. Based on their good agreement, the beam asymmetries for these energy bins in Figure 6 are an average of the 1305 Mev and 1610 MeV coherent peak position data sets. The remainder of the incoming photon energy bins in Figure 6 include data with the coherent peak position at 1610 MeV.

The statistical errors of the beam asymmetries are very large in the most forward angle bins because the differential cross sections vanish at zero degrees. Additionally, for incoming photon energies below 1 GeV the data have low statistics and the degrees of polarization are very small. Thus, the statistical errors are also large for these data points. The acceptance of π^0 mesons is very small in the middle $\theta_{\pi^0}^{c.m.}$ angle region ($\approx 65^\circ$ to 115°) because the trigger conditions during data taking were optimized for η mesons. An acceptance cut of 8% was applied to remove these points.

The results from this analysis have an overall good agreement with previous measurements and the model predictions. The SAID model SP09 predictions [2, 7] describe our data very well. However, at larger E_γ ($E_\gamma \geq 1400$ MeV) and in the forward region the SAID predictions are slightly smaller than our measurements. The Bonn-Gatchina partial wave solution [6] also has a nice overall agreement with our data, but for photon energies between about 1000 MeV to 1400 MeV it significantly underestimates the data in the forward region.

SUMMARY

CBELSA/TAPS results for the beam asymmetries in neutral pion photoproduction off the proton have been presented. These measurements cover the very forward angles for the first time and increase the granularity of the measured photon beam asymmetries at higher energies. The continuous beam from the ELSA accelerator and the goniometer setup of the experiment provided a plane polarized tagged-photon beam for the coherent peak positions at 1305 MeV and 1610 MeV. The results are in excellent agreement with the earlier measurements at ELSA and also with previous results from other facilities. The SAID model SP09 predictions describe the data better than the Bonn-Gatchina partial wave analysis results do at forward angles for the incoming photon energy range 1000 MeV to 1400 MeV.

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