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Measurement of polarization observables in multi-meson photoproduction off the proton with the CBELSA/TAPS experiment

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The reaction $\gamma p \rightarrow p\pi^0\pi^0$ was analyzed using data of the CBELSA/TAPS experiment where linearly polarized photons impinged on a transversely polarized butanol target. Single and double polarization observables were extracted. Within the BnGa-PWA resonance parameters were determined. N^* and Δ^* resonances demonstrated systematic differences in their decay branching ratios via excited hadrons which hint at the internal structure of these states.

Keywords: BnGa-PWA resonance.

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1. Introduction

The excited states of QCD in the non-perturbative regime are observed as broad and overlapping states in the experimental data. A partial wave analysis (PWA) is needed to extract resonance parameters. Here, polarization observables complement the (unpolarized) cross sections and are essential in resolving ambiguities in the PWA solutions. Multi-meson final states are of increasing importance in photoproduction experiments at higher energies since their cross section does not decrease as fast as that of single-meson final states. The double neutral pion final state is characterized by a low amount of non-resonant contributions compared to the charged double pion photoproduction channel: no diffractive ρ production or direct $\Delta\pi$ production (Kroll-Ruderman term) occurs and t-channel processes are less important. Thus, the $p\pi^0\pi^0$ final state is very sensitive to resonance contributions.

2. Experimental Setup

The CBELSA/TAPS experiment is located at the electron stretcher accelerator ELSA [1] at the University of Bonn. The accelerator provided an electron beam of 3.2 GeV energy. The electrons produced linearly polarized photons via coherent bremsstrahlung on a diamond crystal [2]. The crystal was oriented such, that the maximal degree of polarization of 66 % was reached at a photon energy of 850 MeV. The polarized photons hit the transversely polarized frozen-spin butanol (C_4H_9OH) target [3]. Here an average polarization degree of 74 % was reached. The target was surrounded by the Crystal Barrel calorimeter [4] and the Forward Plug, consisting of 1320 CsI(Tl) crystals. The very forward direction was covered by the TAPS calorimeter [5] with its 216 BaF_2 crystals. Together, the calorimeters covered nearly the full solid angle.

Charged particles could be identified by a scintillating fiber detector [6] surrounding the target and plastic scintillator counters in front of the Forward Plug and TAPS crystals.

3. Analysis

The final state $p\pi^0\pi^0 \rightarrow p4\gamma$ is selected by requiring four neutral hits in the calorimeters (*i.e.* no matching hit in the charge-sensitive detectors) and one charged hit. For the latter, no corresponding hit in the calorimeters was necessary. Cuts on the direction of the proton candidate relative to the sum of the momenta of the four photons ensured that the proton and the sum of photon momenta were back-to-back in the center of mass system. The invariant masses of the photon pairs are shown in Fig. 1, where a clear peak from the $p\pi^0\pi^0$ final state is seen. Peaks from the $p\pi^0\rho$ final state are visible as well.

A kinematic fit of the final state $p_{miss}\pi^0\pi^0$ allowed to eliminate combinatorial background. In addition, a cut to remove the competing final state $p_{miss}\pi^0\rho$ was performed. Here, p_{miss} indicates that the final state proton is calculated from energy and momentum conservation using the measured photons. A cut on the confidence level of the fit is effectively serving as cuts on the proton and pion masses.

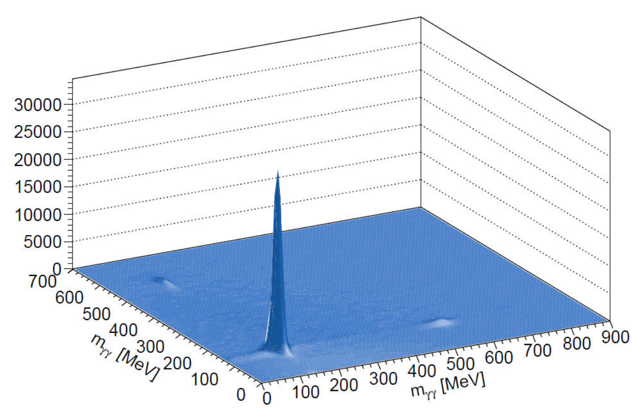

FIGURE 1. Invariant mass of one $\gamma\gamma$ pair versus the other.

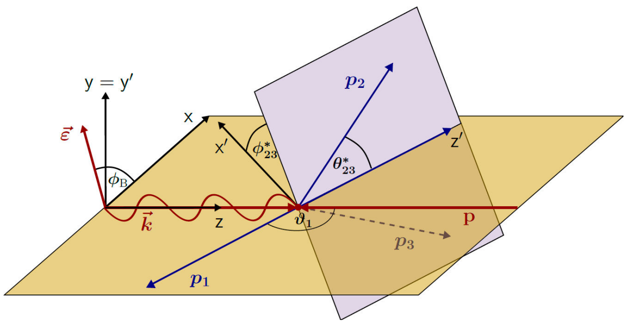

FIGURE 2. Definition of kinematic variables of the 3-body final state. The reaction plane is defined by the incoming photon and one of the out-going particles (p_1), the decay plane by the two remaining final state particles (p_2 and p_3).

After all cuts, the final data sample contained about 1.5 % background globally, varying from below 1 % to about 5 % in certain kinematic regions.

Butanol also contains nucleons bound in the carbon and oxygen nuclei. Those bound protons cannot be polarized, thus effectively reducing the polarization degree. The so-called dilution factor gives the ratio of polarizable protons. Due to the Fermi-motion of the bound nucleons and kinematically dependent cuts, the dilution factor also depends on the kinematics. The dilution factor had to be determined experimentally with a dedicated measurement employing a carbon foam target of about the same area density as the bound nucleons in the butanol target. Especially for energies below 1100 MeV, the dilution factor reaches values of about 90 %, while for the higher energies it still stays above 70 %.

The polarized cross section of double pseudoscalar meson photoproduction (only taking linear beam polarization and transverse target polarization into account) reads as follows [7]:

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma_0}{\mathrm{d}\Omega} \cdot \Big\{ & 1 + \Lambda_x \cdot P_x + \Lambda_y \cdot P_y \\ & + \delta_\ell \sin(2\phi_\mathrm{B}) \cdot I^s_\mathrm{eff} + \delta_\ell \cos(2\phi_\mathrm{B}) \cdot I^c_\mathrm{eff} \\ & + \Lambda_x\, \delta_\ell \sin(2\phi_\mathrm{B}) \cdot P^s_x + \Lambda_y\, \delta_\ell \sin(2\phi_\mathrm{B}) \cdot P^s_y \\ & + \Lambda_x\, \delta_\ell \cos(2\phi_\mathrm{B}) \cdot P^c_x + \Lambda_y\, \delta_\ell \cos(2\phi_\mathrm{B}) \cdot P^c_y \Big\}.\end{aligned}$$

Here Λ_x (Λ_y) is the target polarization in (perpendicular to) the reaction plane, and δ_ℓ is the beam polarization (with angle ϕ_B to the reaction plane). I^s_eff and I^c_eff are the beam polarization observables. These still contain contributions from the bound nucleons in the carbon and oxygen nuclei in the butanol. P_x and P_y are the target asymmetries, P^s_x, P^s_y, P^c_x and P^c_y the double polarization observables.

The kinematics of the 3-body final state $\mathrm{p}\pi^0\pi^0$ is fully described by five kinematic variables (cf. Fig. 2). Used here are the energy of the incoming photon, E_γ, the scattering angle $\cos\vartheta_1$, the invariant mass of the two particles spanning the decay plane, m_{23} and two angles, ϕ^*_{23} and θ^*_{23}.

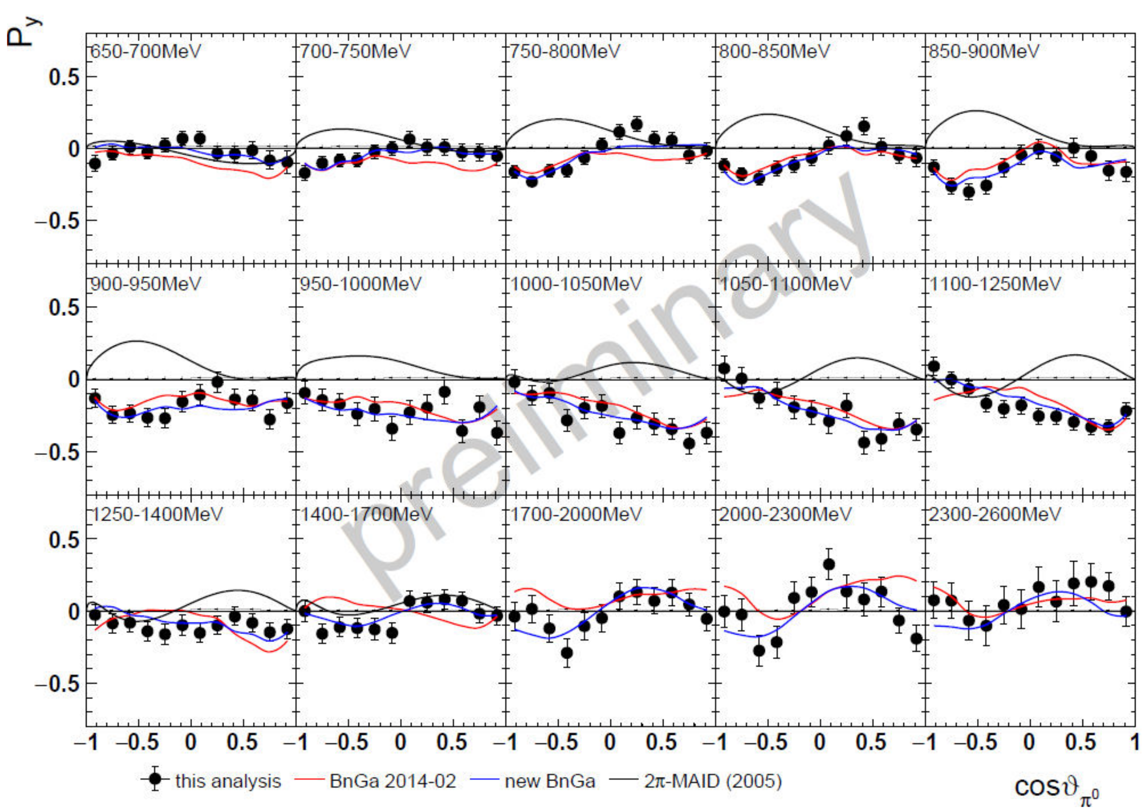

FIGURE 3. Target asymmetry P_y as a function of beam energy E_γ and $\cos\vartheta_{\pi^0}$.

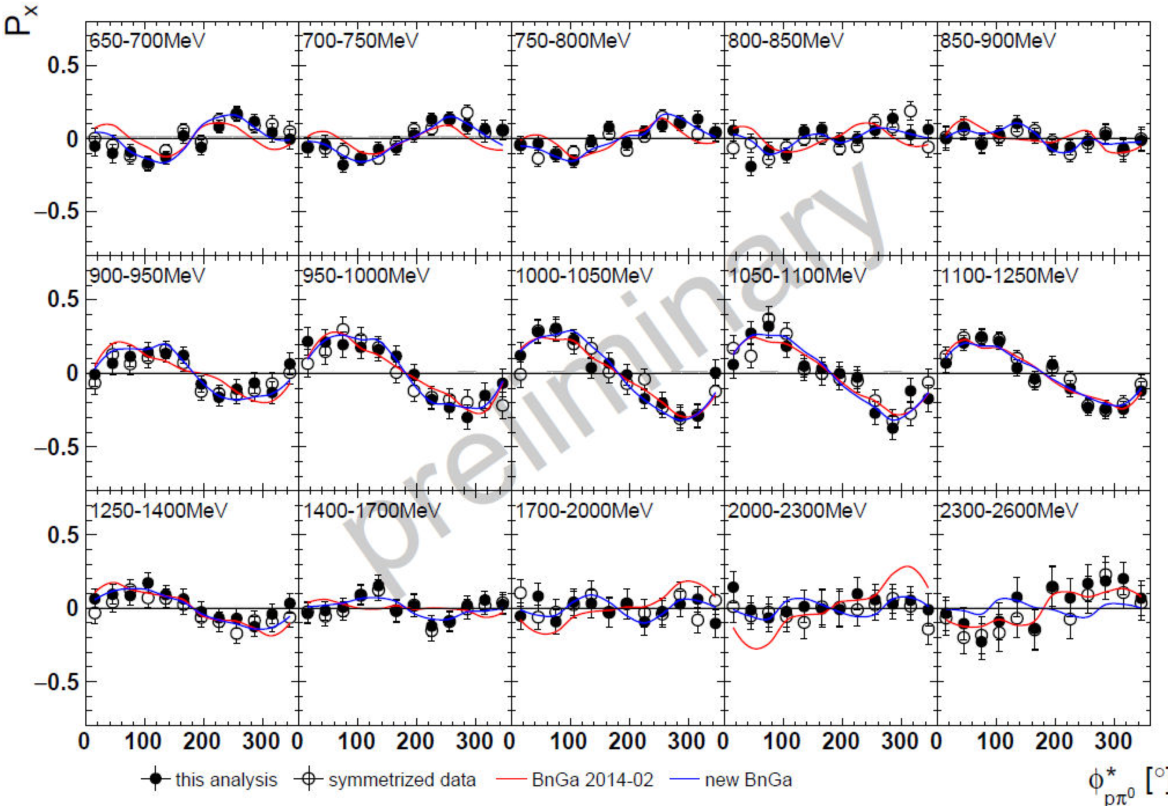

FIGURE 4. Target asymmetry P_x as a function of beam energy E_γ and $\phi^*_{p\pi^0}$.

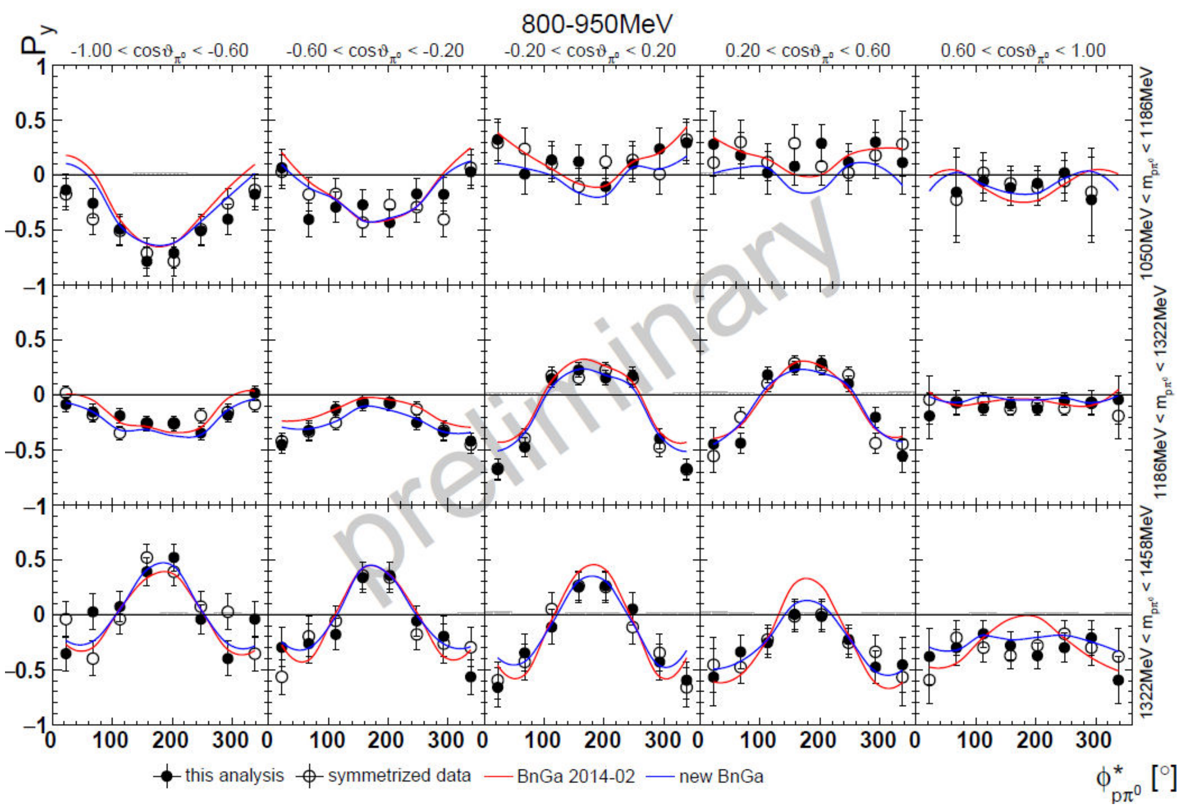

FIGURE 5. Four dimensional target asymmetry P_y as a function of $\phi^*_{p\pi^0}$ in the energy bin $(800 - 950)$ MeV. Within a row $\cos\vartheta_{\pi^0}$ is varied, within a column $m_{p\pi^0}$.

An (in the azimuthal angle) unbinned maximum-likelihood fit was employed to determine the polarization observables in each kinematic bin [8, 9]. Detector asymmetries were expanded in a Fourier series up to the highest order which could interfere with the observables.

Examplary results for the target asymmetry P_y are shown in Fig. 3 as a function of $\cos\vartheta_{\pi^0}$, and P_x in Fig. 4 as a function of $\phi^*_{p\pi^0}$. The latter is only accessible in the full 3-body kinematics of the final state. P_x is odd in ϕ^*. This is fulfilled well in the data as can be seen from the open symbols which make use of this symmetry property. In addition to the data, partial wave analysis solutions are shown: the 2π-MAID [10] (black curve), the BnGa-PWA [11] (red curve), and the new BnGa solution (blue curve). The latter already includes the presented data. Especially the 2π-MAID solution shows large deviations to the data. While the 2014 solution of the BnGa-PWA describes the data fairly well at lower energies, above $E_\gamma \approx 1700$ MeV larger discrepancies become apparent.

For beam energies below 1250 MeV it was possible to determine the target asymmetries depending simultaneously on four variables. An example is shown in Fig. 5 where one energy bin of the target asymmetry P_y plotted versus $\phi^*_{p\pi^0}$ is shown. Here, $\cos\vartheta_{\pi^0}$ is varied within a row and $m_{p\pi^0}$ within a column. From the (sometimes large) variations from bin to bin, it is obvious that a partially integrated analysis does not contain the full information.

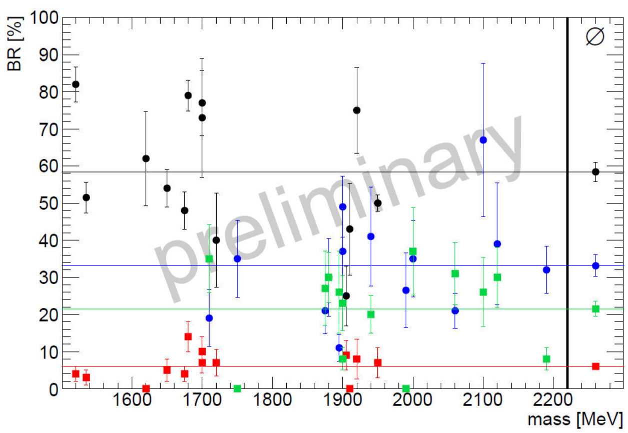

FIGURE 6. Branching ratios of resonances included in the BnGa-PWA are illustrated. Resonances with a single oscillator excitation decaying into the ground states (Nπ or $\Delta\pi$) are shown as black dots, decays into excited resonances (N$(1520)\pi$, N$(1535)\pi$, N$(1680)\pi$, or Nσ) as red squares. Resonances with a mixture of oscillator excitations decaying into the ground states are shown as blue dots, decays into the excited states as green squares. The average branching ratios are shown as colored lines in addition to the symbols on the right.

4. PWA

The observables extracted in this analysis were incorporated in the BnGa-PWA, which is a coupled-channel analysis of all major data on pion- or photo-induced reactions off nucleons [12]. In the decay modes of the excited states systematic differences emerged. In one group of excited states the branching ratios for decays into excited hadron states are significant, while in the other group these decays are negligible compared to the dominant decays into the N or Δ ground states ($\ell = 0$ in the quark model). This might be explained by the structure of the baryon wave function.

In a quark model picture, the spatial wave function can be expanded in a harmonic oscillator basis with two oscillators, λ and ϱ. The excited baryons can now belong to one of three classes: either only one of the harmonic oscillators is in an excited state but not the other, both oscillators are excited simultaneously, or a mixture of the first two classes.

Baryons belonging to the first class have a dominant decay to the ground states Nπ or $\Delta\pi$, the average branching ratio here is nearly 60 % (black dots in Fig. 6), while the decay into excited hadrons (N$(1520)\pi$, N$(1535)\pi$, N$(1680)\pi$, or Nσ) is small, 6 % on average (red squares).

For the third class (mixture of only one excited oscillator and both oscillators excited), the branching ratio into the ground states (blue dots) and the aforementioned excited states (green squares) is rather similar, on average 33 % and 22 % respectively. The second class of baryons with both oscillators simultaneously excited, belongs to the antisymmetric SU(6) 20-plet. No baryons of this multiplet have been identified experimentally yet.

5. Summary

Results of single and double polarization observables in the photoproduction of two neutral pions with the CBELSA/TAPS experiment were reported. For the analyzed data a linearly polarized photon beam produced the pions off a transversely polarized butanol target. Within the framework of the BnGa coupled-channel partial wave analysis the data allowed the determination of resonance parameters. The decay branching ratios of excited nucleon and delta states revealed systematic differences. Using a quark model picture, resonances whose wave function have only one excited oscillator dominantly decay into ground state ($\ell = 0$) baryons while the decay into an excited baryon or meson is suppressed compared to those N*- and Δ^*-resonances which have both oscillators excited.

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