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Multi-meson photoproduction off the proton: Recent results from the CBELSA/TAPS experiment

Tobias Seifen for the CBELSA/TAPS Collaboration

Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn - Nussallee 14-16, 53111 Bonn, Germany

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Summary. — The final state $\mathrm{p}\pi^0\pi^0$ was analysed in photoproduction data of the CBELSA/TAPS experiment. Measurement with linearly polarized photons and a transversely polarized butanol target allowed the extraction of single and double polarization observables. The observables entered the BnGa-PWA, where branching ratios of resonances were determined. Systematic differences in the decay branching ratios of N^* and Δ^* resonances via excited hadrons hint at the internal structure of these states.

1. – Introduction

The excited states of QCD in the non-perturbative regime are measured as broad and overlapping states. Only with the help of a partial-wave analysis (PWA) resonance parameters can be extracted. Polarization observables are essential in resolving ambiguities in the PWA solutions, thus complementing unpolarized cross-sections. Multi-meson final states play an important role at higher energies as the single-meson cross-sections decrease more rapidly and cascading decays become important. In contrast to charged double pion photoproduction, the neutral double pion channel suffers less from non-resonant backgrounds (no diffractive ρ production, supressed direct $\Delta\pi$ production, t-channel processes less important) and is especially sensitive to resonance contributions.

2. – Experimental setup

The electron stretcher accelerator ELSA [1], located at the University of Bonn, delivered an electron beam of 3.2 GeV energy to the CBELSA/TAPS experiment. Via coherent bremsstrahlung, linearly polarized photons (maximal polarization degree of 66% at a photon energy of 850 MeV) were produced on a diamond crystal [2]. The photons impinged on the transversely polarized frozen-spin butanol target [3] (average polarization degree of 74%). The Crystal Barrel calorimeter [4], consisting of 1320 CsI(Tl)

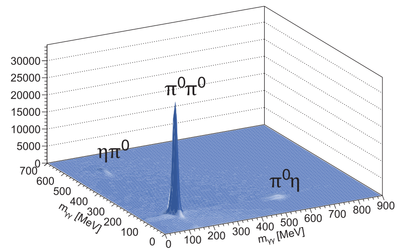

Fig. 1. – Invariant mass of one $\gamma\gamma$ pair *vs.* the other.

crystals, surrounded the target while the forward direction was covered by the TAPS calorimeter [5], a wall of 216 BaF_2 crystals. Nearly the full solid angle was covered by the calorimeters.

A scintillating fiber detector [6] between target and Crystal Barrel detector, in addition to plastic scintillator counters in front of the three most forward Crystal Barrel rings, as well as the TAPS crystals identified charged particles.

For further details on the experimental setup see ref. [7].

3. – Analysis

To select the final state $\gamma \mathrm{p} \rightarrow \mathrm{p}\pi^0\pi^0 \rightarrow \mathrm{p}4\gamma$ four hits in the calorimeters without a matching hit in the charge-sensitive detectors, and one hit in the charge-sensitive detectors (optionally with a matching calorimeter hit) was required. Cuts on the direction of the latter (the proton candidate) with respect to the sum of four-momenta of the four photon candidates ensured that proton and the sum of the photons were back to back in the center-of-mass system. Figure 1 shows the invariant mass of one photon pair plotted against the other. Clear peaks from the double pion final state, as well as the $\pi^0\eta$ final state are visible.

The combinatorial background in fig. 1 is eliminated by a kinematic fit of the final state $\mathrm{p}_{\mathrm{miss}}\pi^0\pi^0$. Here, the proton is calculated from energy and momentum conservation together with the measured photon four-vectors. In addition, the final state $\mathrm{p}_{\mathrm{miss}}\pi^0\eta$ was fitted and removed by an anti-cut.

The final event sample contained a global background of about 1.5%, which varied depending on the kinematic region from below 1% to about 5%.

In addition to the quasi-free protons in the hydrogen nuclei, butanol also contains bound protons in the carbon and oxygen nuclei. The bound protons cannot be polarized, effectivley reducing the polarization degree. This dilution of the polarizable protons was determined experimentally with a carbon foam target of approximately the same area density as the bound nucleons in the butanol target. The dilution factor reached about 90% for beam energies below 1100 MeV.

Five kinematic variables are needed to describe the kinematics of the 3-body final state $\mathrm{p}\pi^0\pi^0$ at a given energy E_γ of the incoming photon. Used here are the scattering angle $\cos\vartheta_1$, the invariant mass of the two particles spanning the decay plane, m_{23}, the two angles ϕ^*_{23} and θ^*_{23}, and the angle ϕ_{B} (cf. fig. 2).

The polarized cross-section of double pseudoscalar meson photoproduction (with only

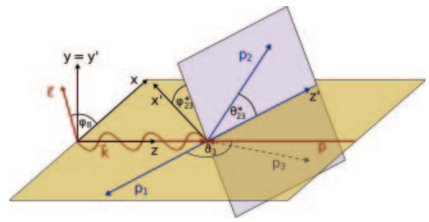

Fig. 2. – Kinematics of the 3-body final state. The reaction plane is defined by the incoming photon and one of the out-going particles (p_1), the decay plane by the two remaining final state particles (p_2 and p_3).

linearly polarized beam and transversely polarized target) can be written in the form [8]

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

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 which 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 polarization observables were determined in each kinematic bin by an unbinned (in the angle ϕ_B) maximum-likelihood fit [9, 10]. Possible detector asymmetries were expanded in a Fourier series up to the highest order which could interfere with the observables.

In addition to the polarization observables as a function of beam energy and one other kinematic variable, the observables were also extracted depending on the beam energy and three kinematic variables at once. An example of such a three-dimensional determination is shown in fig. 3, where one energy bin of the target asymmetry P_y is plotted depending on $\phi^*_{\mathrm{p}\pi^0}$ (x-axis), $\cos\vartheta_{\pi^0}$ (rows), and $m_{\mathrm{p}\pi^0}$ (columns). The sometimes large variations from bin to bin clearly reveal additional information not contained in the partially integrated observables. In addition to the data, results from the BnGa-PWA are shown: BnGa2014 solution [11] in red, new solution [10] which includes this data in blue.

4. – PWA

The extracted polarization observables entered the BnGa coupled-channel partial-wave analysis which includes all major data on pion- or photon-induced reactions off nucleons [12]. Systematic differences in the branching ratios of the excited states became apparent. One group of excited states decayed dominantly into the ground state nucleon or delta while another group has a significant branching ratio for decays into excited hadrons. This might be explained by the structure of the baryon wave function.

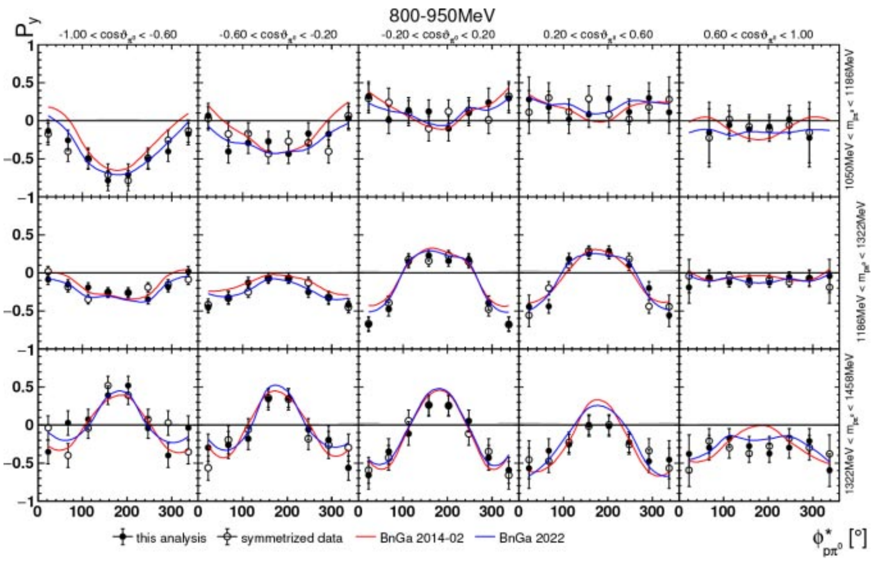

Fig. 3. – (Color online) Four-dimensional target asymmetry P_y as a function of $\phi^*_{\mathrm{p}\pi^0}$ in the energy bin (800–950) MeV. Within a row $\cos\vartheta_{\pi^0}$ is varied, within a column $m_{\mathrm{p}\pi^0}$ [10].

Within the quark model picture, the spatial wave function is expanded in two harmonic oscillators, λ and ϱ. There are then three classes of excited baryons: those with only one oscillator excited but not the other, those with both oscillators excited at the same time, and a mixture of the previous two classes [13].

Baryons belonging to the first class decay dominantly to the ground states $N\pi$ or $\Delta\pi$. The average branching ratio is about 60% (the black dots in fig. 4) while their average

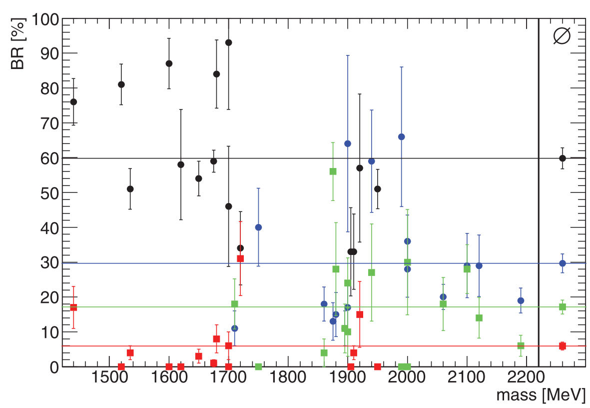

Fig. 4. – (Color online) Branching ratios of resonances included in the BnGa-PWA are illustrated. The black dots show resonances with a single oscillator excitation decaying into the ground states ($N\pi$ or $\Delta\pi$), red squares their decay branching ratio into excited resonances ($N(1520)\pi$, $N(1535)\pi$, or $N\sigma$). 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 [10].

branching ratio into excited states ($N(1520)\pi$, $N(1535)\pi$, or $N\sigma$) is a comparably low 6% (red squares). For those baryons which have the additional part with both excited oscillators in their wave function, the branching ratios into the ground states (blue dots in fig. 4) and the aforementioned excited states (green squares) are of much more similar size: on average 30% and 17% respectively. The second class of baryons which only have the part of the wave function 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

The double neutral pion final state was analyzed in data from the CBELSA/TAPS experiment taken with linearly polarized beam and transversely polarized target. The single and double polarization observables were included in the BnGa coupled-channel partial-wave analysis. The determination of resonance parameters revealed systematic differences in the decay branching ratios of excited non-strange baryons. N^*- and Δ^*-states which in a simple quark model picture have only one excited oscillator dominantly decay into ground state baryons. Resonances whose wave functions have parts with both oscillators in an excited state, have a significantly higher branching ratio in excited states with $\ell = 1$ followed by a subsequent decay into the three-particle final state.

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