Extraction of polarization observables in two pion photoproduction reactions

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Abstract. The relevance of the study of polarization observable to gather insight on the features of baryonic resonances, and the procedure applied for the extraction of this information from the data, are illustrated. The reference reaction is the photoproduction of two charged pions with both polarized beam and target, experimental conditions that were met in the $g14$ (2012) run of the CLAS experiment at Jefferson Lab. The method for the determination of the $I^{\odot}$ observable is discussed and illustrated utilizing previously published data.

1 Introduction and motivation

The study of polarization observables, in reactions where the projectiles and/or the targets are polarized, is a relatively novel approach for the investigation of the dynamics of baryon formation and production, alternative to the measurement of total or differential cross sections. Since polarization observables can be expressed through bilinear forms of the partial amplitudes [1], they can be more sensitive to possible interference effects, and hence reactive to small resonant contributions. In both total and differential cross sections these contributions can be very difficult to disentangle, because of the broad width of the excited resonances, especially in the so-called "second resonance region" with baryon energies beyond the $P_{33}(1232)$ ($\Delta(1232)$). Indeed, this region is populated by many overlapping nucleonic N^* and Δ^* resonances, for instance the $P_{11}(1440)$, the $D_{13}(1520)$ and the $S_{11}(1535)$ states; these can be excited by several different reactions and have been observed in various decay modes. In addition, in this mass region and beyond, several states are predicted by the theory, but they have never been observed so far – or just weak indications for the existence of few of them was found. Such states are commonly known as “missing resonances".

Photoproduction reactions provide the essential tool to investigate the formation of possibly missing baryonic states. So far, most of the information has been obtained exploiting πN or KN interactions, but it is likely that the strength of the coupling of some states is larger in photo-induced reactions rather than in mesonic production. However, the former reactions were never studied extensively in the past due to their small cross sections and the limited photon energy and resolution.

Above 1.5 GeV center-of-mass energy the largest contribution to the γp cross section is given by the three body $N\pi\pi$ final state. This is the most common final state following the decay of possible intermediate resonances. Figure 1 reports a collection of the measured photoproduction cross-sections in several channels, where the two pion production dominance appears in full evidence.

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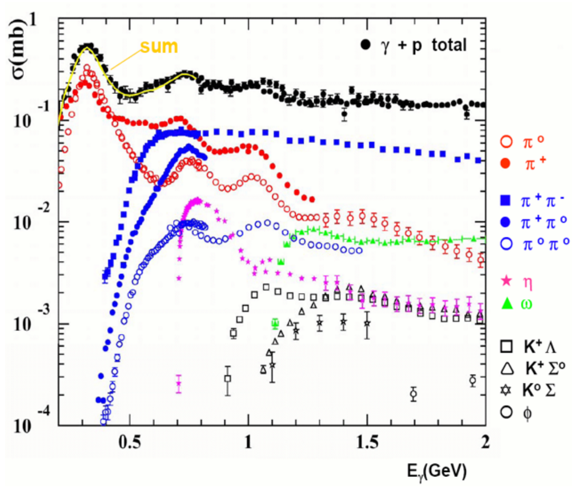

Figure 1. Collection of several photoproduction total cross-sections.

Polarization observables for such a reaction may be derived theoretically on account of different hypotheses for the baryonic spectrum composition and the interference pattern among intermediate resonant states. The comparison with experimental data can help constraining models in a more powerful way as compared to the simple investigation of cross sections.

In one of the analyses of the CLAS photoproduction data currently underway, the double-pion production on nucleons has been studied exploiting the data collected about one decade ago in the E06-101 experiment (CLAS $g14$ run). It featured both a circularly polarized photon beam and a longitudinally polarized cryogenic target made of deuteron hydride (HD), containing both polarizable protons and deuterons. In this analysis, it is possible to determine two out of the three possible polarizations states of the particles involved in the reaction, particularly those related to the polarization of the beam and of the target (the recoiling nucleon polarization not being measured). The polarization variable $I^{\odot}$ describes the beam asymmetry for an unpolarized target and a circularly-polarized photon beam, and is thence related to the beam helicity. On the other hand, the $\vec{P}$ polarization vector arises only when the target nucleon is polarized, while the double polarization one $\vec{P}^{\odot}$ appears when both the target and the beam are polarized and depends on the helicity difference. The $I^{\odot}$ observable in double-pion photoproduction on the proton was already published in earlier analyses performed by CLAS ($g1c$ run) [2], and by MAMI-Crystal Ball, TAPS and A2 [3, 4]. The GDH and A2 experiment also published results on the variable $P_z^{\odot}$ [5]. No measurements whatsoever exist, so far, for reactions induced on neutrons.

Denoting by x_i the set of independent observables necessary to describe the i-th phase-space volume of a given reaction, the differential cross section induced by circularly polarized photons in the x_i kinematic bin is expressed via the polarization variables by [1, 6]:

$$\frac{d\sigma}{dx_i} = \sigma_0 \left\{ (1 + \Lambda P_z) + \delta_{\odot}(I^{\odot} + \Lambda P_z^{\odot}) \right\} \tag{1}$$

being Λ the degree of target polarization and $\delta_{\odot}$ that of the beam. Only the z component of the $\vec{P}$ and $\vec{P}^{\odot}$ polarization vectors is considered, based on the choice for the z axis orientation (along the incoming photon direction). σ_0 is the unpolarized cross section.

In general, the three mentioned polarization observables can be expressed through experimental asymmetries, obtained when comparing different combinations of helicity/spin for both the incoming photon (← or →) and the polarized target nucleon (⇐ or ⇒). In particular one has the following relationships between experimental asymmetries and polarization variables:

- if just the beam is polarized, with a $\delta_\odot$ degree: $A_{beam} = (-\sigma_{\leftarrow\Leftarrow} + \sigma_{\rightarrow\Rightarrow} - \sigma_{\leftarrow\Rightarrow} + \sigma_{\rightarrow\Leftarrow})/\sigma_0 = \delta_\odot I^\odot$;
- if only the target is polarized (by convention, along the beam axis), with a Λ_z degree: $A_{target} = (-\sigma_{\leftarrow\Leftarrow} - \sigma_{\rightarrow\Leftarrow} + \sigma_{\leftarrow\Rightarrow} + \sigma_{\rightarrow\Rightarrow})/\sigma_0 = \Lambda_z P_z$;
- when both the beam and the target are polarized: $A_{target+beam} = (\sigma_{\leftarrow\Leftarrow} - \sigma_{\rightarrow\Leftarrow} - \sigma_{\leftarrow\Rightarrow} + \sigma_{\rightarrow\Rightarrow})/\sigma_0 = \delta_\odot \Lambda_z P_z^\odot$.

We recall that the spin combinations (←⇐) and (→⇒) correspond to a total spin 3/2 (third component ±3/2, triplet configuration) of the system (beam+target), while when the directions of the spins are opposite ((←⇒) or (→⇐)) (third component ±1/2, singlet configuration) the total spin can be 3/2 or 1/2.

2 The $\vec{\gamma}\vec{N} \to \pi^+\pi^- N$ reaction with polarized beam and target

Figure 2 shows the $\vec{\gamma}\vec{N} \to \pi^+\pi^- N$ reaction kinematics on a nucleon target. N denotes, in general, both a proton or a neutron. As shown in Fig. 2, in the reaction center-of-mass two

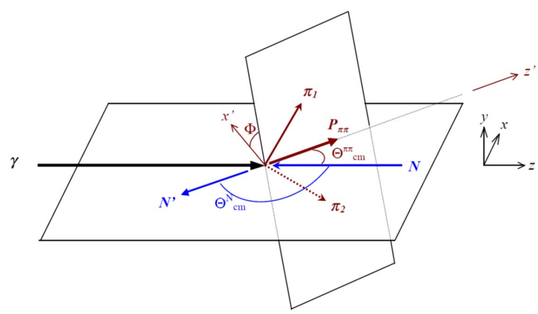

Figure 2. Reaction and production planes in the $\gamma N \to \pi^+\pi^- N$ reaction.

planes can be identified:

- the production plane, which contains the incoming photon and the final-state nucleon momenta;
- the reaction plane, which in the present reaction contains the two charged pions produced in the final state, that recoil back-to-back against the nucleon. The sum of the pions momenta define the "dipion" vector. The reference frame in which the dipion is at rest, and the z axis is taken along the direction of flight the dipion has in the reaction center-of-mass, is called *helicity* system.

In the helicity reference system the angle ϕ between the incoming photon and the direction of the positive pion, together with the available energy in the center of mass W, is particularly sensitive to the resonant contributions to the amplitude. By construction, ϕ coincides with the angle formed between the production and the reaction planes, Φ in Fig. 2. For more information on the treatment of three-body reactions in the helicity reference system see Ref. [7–9].

The main goal of these analyses is to study the dependence of the polarization observables $I^{\odot}$, $\vec{P}$ and $\vec{P}^{\odot}$ as a function of ϕ in discrete W energy ranges.

Concerning the experimental details of the data taking, the $g14$ run employed a circularly polarized photon beam produced via bremsstrahlung by impinging longitudinally polarised electrons on an amorphous radiator (gold plated thin carbon foil). The photon energy depends linearly on the energy of the incoming electron beam, with the spectrum featuring a $1/E_\gamma$ distribution typical of the brehmsstrahlung process. The degree of circularly polarized photons $\delta_{\odot}$, that in the $g14$ data taking varied in the range (20–85)%, depends on the electron beam longitudinal polarization and is also a monotonically rising function of the primary beam energy [10]. Photons with both helicities were produced, as a consequence of the electron beam longitudinal polarization flipping with a frequency of 960.015 Hz.

The polarized target, "HD-ice” in short, was a cryogenic frozen-spin solid state target consisting of HD molecules with 99% purity, in which both hydrogen and deuterium were polarized [11]. The polarization of the target was obtained through the "brute force method" [12]. The HD-ice target, being composed of free protons and deuterons only, could in principle be polarized to a higher degree compared to other targets such as ammonia or butanol, which contained non-polarizable N, C and O atoms. The degree of polarization of protons in hydrogen and deuterium was periodically determined through Nuclear Magnetic Resonance measurements [13]. The effective value of the proton polarization in the target is obtained by an average of the proton polarizations measured in H and D; the latter defines also the amount of neutron polarization in the HD target.

3 Extraction method

The differential cross section in Eq. (1), by definition, is proportional to the number of events of the reaction under study measured in the kinematic bin Δx_i. Being $c = \epsilon \cdot F \cdot \rho \cdot \mathcal{N}_{Av}/A$ a shorthand factor, collecting the information about the target density ρ, its atomic number A, the photon flux F and the detector and reconstruction efficiency ϵ, one can expand Eq. (1) in four possible combinations of beam/target polarizations:

$$\begin{aligned}
\Lambda(\Rightarrow) > 0, \delta_{\odot}^{\rightarrow} > 0 &: \frac{N_{events}^{\rightarrow\Rightarrow}}{c^{\rightarrow\Rightarrow}} = (1 + \Lambda_z P_z) + \delta_{\odot}(I^{\odot} + \Lambda_z P_z^{\odot}) \\
\Lambda(\Rightarrow) > 0, \delta_{\odot}^{\leftarrow} < 0 &: \frac{N_{events}^{\leftarrow\Rightarrow}}{c^{\leftarrow\Rightarrow}} = (1 + \Lambda_z P_z) - \delta_{\odot}(I^{\odot} + \Lambda_z P_z^{\odot}) \\
\Lambda(\Leftarrow) < 0, \delta_{\odot}^{\rightarrow} > 0 &: \frac{N_{events}^{\rightarrow\Leftarrow}}{c^{\rightarrow\Leftarrow}} = (1 - \Lambda_z P_z) + \delta_{\odot}(I^{\odot} - \Lambda_z P_z^{\odot}) \\
\Lambda(\Leftarrow) < 0, \delta_{\odot}^{\leftarrow} < 0 &: \frac{N_{events}^{\leftarrow\Leftarrow}}{c^{\leftarrow\Leftarrow}} = (1 - \Lambda_z P_z) - \delta_{\odot}(I^{\odot} - \Lambda_z P_z^{\odot}).
\end{aligned} \tag{2}$$

In this set of equations, Λ_z stands for the absolute value of the z component of the target polarization, the sign for the parallel/antiparallel case having been made explicit in the formulas. The same holds for the beam polarization factor $\delta_{\odot}$ (assuming $\delta_{\odot}^{\rightarrow} = \delta_{\odot}^{\leftarrow} \equiv \delta_{\odot}$ for short).

Equation (2) provides a linear system of four equations in the four unknown quantities $I^{\odot}$, P_z, $P_z^{\odot}$ and the unpolarized cross section. Since the target polarization was fixed along relatively long time periods, appropriate data-sets taken in different experimental conditions must be chosen and combined to provide the necessary information for the solution of the system.

The equations are valid in the reference system shown in Fig. 2. However, the sign of Φ, that coincides by definition with the helicity angle, is related to the relative orientation of the production and decay planes, that is to the hemisphere of emission of the π^+, and this affects the signs of the z component of the target polarization vector and the beam helicity which enter in the equations. With reference to Fig. 2, in the reaction center-of-mass (as specified in Ref. [1, 8]), Φ can be expressed also through the normal vectors to the reaction and the production plane, as

$$\cos\Phi = \frac{(\vec{\gamma}\times\vec{N})\cdot(\vec{\pi}_1\times\vec{\pi}_2)}{\left|\vec{\gamma}\times\vec{N}\right|\left|\vec{\pi}_1\times\vec{\pi}_2\right|}, \quad \sin\Phi = \frac{\left((\vec{\gamma}\times\vec{N})\times\vec{N}\right)\cdot(\vec{\pi}_1\times\vec{\pi}_2)}{\left|\vec{\gamma}\times\vec{N}\right|\left|\vec{\pi}_1\times\vec{\pi}_2\right|}. \tag{3}$$

The orientation of the cross product of the two normal vectors sets the sign of $\sin\Phi$ and, consequently, the orientation of the polarization vectors $\vec{P}$ and $\vec{P}^{\odot}$.

4 The experimental beam-asymmetry $I^{\odot}$

Here we utilize the already published results from CLAS on the experimental beam-asymmetry $I^{\odot}$ measured in the $\gamma p \to \pi^+\pi^- p$ reaction as an example, since the work carried out on the polarised HD target is currently underway. These results were obtained about 20 years ago with the data collected in the $g1c$ CLAS run [2], in which the photon beam was circularly polarized, but the target was unpolarized, so the experimental conditions were partially different as compared to $g14$. Differently from the polarization variables discussed so far, a single data-set can be used to extract $I^{\odot}$. In this case the relationships simplify and one gets

$$\begin{aligned} N^{\rightarrow} + N^{\leftarrow} &= \sigma_0 \cdot \epsilon \cdot F \cdot \rho \cdot \mathcal{N}_{Av}/A \cdot \Delta x_i \\ N^{\rightarrow} - N^{\leftarrow} &= \sigma_0 \cdot \epsilon \cdot F \cdot \rho \cdot \mathcal{N}_{Av}/A \cdot \Delta x_i \cdot \delta_{\odot} I^{\odot}. \end{aligned} \tag{4}$$

Equation (4) expands the quantity c mentioned above. Assuming the photon flux F to be the same for photons with different helicities, from eq. (4) one gets:

$$I^{\odot} = \frac{1}{\delta_{\odot}} \frac{N^{\rightarrow} - N^{\leftarrow}}{N^{\rightarrow} + N^{\leftarrow}}. \tag{5}$$

Therefore, $I^{\odot}$ is only dependent on the beam polarization and the number of events with a given helicity.

Figure 3 shows the distributions of $I^{\odot}$ in several ranges of available energy W [2], together with some models predictions [14, 15], based on fits of the unpolarized cross sections. In both these models, amplitudes for intermediate $\pi\Delta^*$ and πN^* states have been included, up to the $\Delta(1600)$ and the $N(1720)$ excitations (that is, up to $W \simeq 1.8$ GeV). The trend of $I^{\odot}$ exhibits the expected odd symmetry as a function of ϕ; the models used to reproduce the $I^{\odot}$ trends, however successful for the unpolarized cross sections, are not satisfactory especially in some of the W ranges. This indicates that the theoretical description still need substantial improvement, for instance taking into better account the interference effects among amplitudes, to which the beam asymmetry is sensitive.

The preliminary results of the ongoing analysis on $g14$ data, presented at this Conference, are in good agreement with this first assessment and are going to be published shortly, together with the other polarization observables.

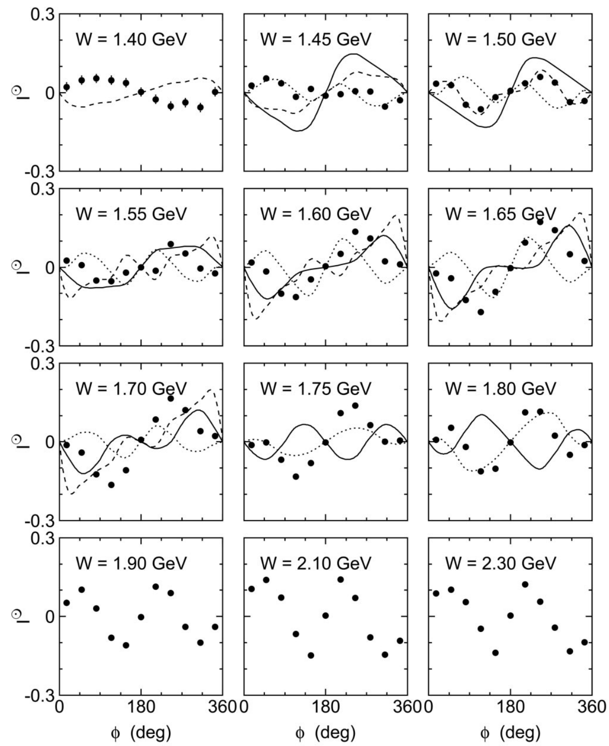

Figure 3. $I^{\odot}$ first published results for the $\vec{\gamma}p \rightarrow \pi^{+}\pi^{-}p$ reaction with CLAS $g1c$ data [2]. The superimposed curves from model calculations are from Ref. [14] (solid and dotted curves) and [15] (dashed curves).

References

[1] W. Roberts and T. Oed, Phys. Rev. **C71**, 055201 (2005)

[2] CLAS Collaboration, S. Strauch *et al.*, Phys. Rev. Lett.**95** (2005), 162003

[3] Crystal Ball at MAMI, TAPS and A2 Collaboration, D. Krambrich *et al.*, Phys. Rev. Lett.**103**, 052002

[4] M. Oberle *et al.*, Phys. Lett. **B721** (2013), 237; Eur. Phys. J. **A50** (2014), 54

[5] GDH and A2 Collaboration, J. Ahrens *et al.*, Eur. Phys. J. **A34** (2007), 11; GDH and A2 Collaboration, J. Ahrens *et al.*, Phys. Lett.**B551** (2003), 49

[6] D. Ireland, E. Pasyuk, I, Strakovsky, Prog. Part. Nucl. Phys. **111** (2020), 103752

[7] S. M. Berman and M. Jacob, Phys. Rev. **139** (1965), B1023

[8] K. Schilling *et al.*, Nucl. Phys. **B15** (1970), 397

[9] I.S. Barker *et al.*, Nucl. Phys. **B95** (1975), 347

[10] H. Olsen and L.C. Maximon, Phys. Rev. **114** (1959), 887

[11] M.M. Lowry *et al.*, Proceedings of Science (PSTP 2013), 015

[12] A. Honig, Phys. Rev. Lett. **119** (1967), 1009

[13] S. Goertz *et al.*, Prog. Part. Nucl. Phys. **49** (2002), 403

[14] V. Mokeev *et al.*, Phys. At. Nuclei **64**, 1292 (2001)

[15] A. Fix and H. Arenhövel, Eur. Phys. J. **A25** (2005), 115