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 could be met in the $g14$ (2012) run of the CLAS experiment at Jefferson Lab.

1 Introduction and motivation

The study of the 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 of differential cross sections. Since the polarization observables can be expressed through bilinear forms of the partial amplitudes, they can be more sensitive to possible interference effects, hence to relatively small resonant contributions. Both in 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" of energies, the baryon mass range beyond the $P_{33}(1232)$ ($\Delta(1232)$) peak. 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; they 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 expected fom the theory, starting from the Constituent Quark Model, but they have never been observed so far – or for a few of them just very elusive hints exist. They are commonly known as “missing resonances".

The photoproduction reaction is a good tool to investigate the formation of possibly missing baryonic states. So far, most of the information had been obtained exploiting πN or KN interactions, but it is likely that the strength of the coupling of some states is larger in photon induced reaction rather than in mesonic production. However, the former were never studied extensively in the past due to their small cross sections and the limited photon energy and resolution, as well as the available beam intensities.

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. Fig. 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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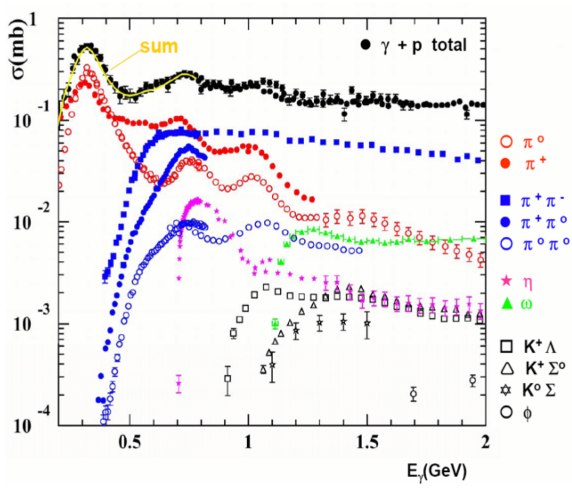

Figure 1. Collection of several photoproduction total cross-sections.

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, and 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 $g14$ run, that featured both a circularly polarized photon beam and a longitudinally polarized cryogenic target made of deuteron hydride (HD), containing by both polarizable protons and deuterons. In this case, it is possible to determine two out of the three possible polarizations states of the particles involved in the reaction, those related to the polarization of the beam and the target (the recoiling nucleon polarization not being measured), and measure the following spin polarization asymmetries: $I^{\odot}$, which describes the beam asymmetry for an unpolarized target and a circularly-polarized photon beam, and is related to the beam helicity, the target asymmetry $\vec{P}$ which arises only when the target nucleon is polarized, and the double polarization $\vec{P}^{\odot}$, occurring when both the target and the beam are polarized and depending 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) [1], and by MAMI-Crystal Ball, TAPS and A2 [2, 3]. The GDH and A2 experiment also published results on the variable $P_z^{\odot}$ [4]. No measurements whatsoever exist, so far, for reactions induced on neutrons.

In general, the three mentioned polarization observables are related to asymmetries in the differential cross sections obtained when comparing different combinations of spins for both the incoming photon ($\leftarrow$ or $\rightarrow$) and the polarized target nucleon ($\Leftarrow$ or $\Rightarrow$). Being $\sigma_0 = \sigma_{\leftarrow\Leftarrow} + \sigma_{\leftarrow\Rightarrow} + \sigma_{\rightarrow\Leftarrow} + \sigma_{\rightarrow\Rightarrow}$ the unpolarized γN cross section, and σ_b, σ_t, σ_{bt} the partial contributions to the total cross section for different combination of beam or/and target polarizations, the following holds:

- if just the beam is polarized, with a $\delta_{\odot}$ degree, the relationship between the beam asymmetry and the $I^{\odot}$ polarization variable is $A_{beam} = \dfrac{\sigma_b}{\sigma_0} = \dfrac{-\sigma_{\leftarrow\Leftarrow} + \sigma_{\rightarrow\Rightarrow} - \sigma_{\leftarrow\Rightarrow} + \sigma_{\rightarrow\Leftarrow}}{\sigma_0} = \delta_{\odot} I^{\odot}$;

- if the target only is polarized along the beam axis (which is identified along the z direction, by convention), with a Λ_z degree, the target-polarization P_z is related to the target-beam experimental asymmetry by $A_{target} = \dfrac{\sigma_t}{\sigma_0} = \dfrac{-\sigma_{\leftarrow\Leftarrow} - \sigma_{\rightarrow\Leftarrow} + \sigma_{\leftarrow\Rightarrow} + \sigma_{\rightarrow\Rightarrow}}{\sigma_0} = \Lambda_z P_z$;
- when both the beam and the target are polarized, the double target-beam polarization $P_z^{\odot}$ is related to the experimental target-beam asymmetry by
$A_{target+beam} = \dfrac{\sigma_{bt}}{\sigma^0} = \dfrac{\sigma_{\leftarrow\Leftarrow} - \sigma_{\rightarrow\Leftarrow} - \sigma_{\leftarrow\Rightarrow} + \sigma_{\rightarrow\Rightarrow}}{\sigma_0} = \delta_{\odot}\Lambda_z P_z^{\odot}$.

We recall that the spin combinations ($\leftarrow\Leftarrow$) and ($\rightarrow\Rightarrow$) correspond to a total spin 3/2 (third component $\pm3/2$, triplet configuration) of the system (beam+target), while when the directions of the spins are opposite (($\leftarrow\Rightarrow$) or ($\rightarrow\Leftarrow$)) (third component $\pm1/2$, 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

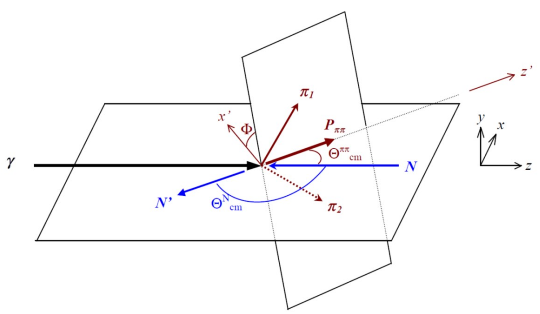

Figure 2. Reaction and production planes in the $\gamma N \to \pi^+\pi^- N$ reaction.

planes can be identified:

- the production plane, which contains the incoming photon and the nucleon momenta;
- the reaction plane, which contains all the particles produced in the final state, in the present case a nucleon recoiling back-to-back to a pair of charged pions. The direction of the recoiling nucleon is chosen along the negative z' axis, while the sum of the pions momenta, named henceforth dipion in short, is directed along the positive z' direction. With these choice of axes, the center of mass of the dipion is called *helicity* system; the extraction of the polarization variables is usually performed in this system.

The angle formed by the two planes is called Φ_{hel} and is used as the analyser for the studied reaction. The transformation of reference system from the laboratory to the helicity frame requires first a Lorentz boost to the reaction center-of-mass, and two rotations. After these transformations, ϕ_{hel} results as the angle between the incoming beam direction in the new system and the direction of the positive pion momentum. For more information on the treatment of three-body reactions in the helicity reference system see Ref. [5–7].

The final purpose 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_{hel} in discrete W energy ranges, where W is the total energy available in the center of mass of the reaction depending, event by event, on the incoming photon momentum.

The circularly polarized photons available in the $g14$ run were produced, together with unpolarized photons, via bremsstrahlung of a longitudinally polarized beam through an amorphous radiator, a 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 δ_{e^-}, 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 [8]. 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 [9]. The polarization of the target was obtained through the "brute force method". 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. 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

Denoting by x_i the set of independent observables necessary to describe the i-th phase-space volume of a given reaction, induced by circularly polarized photons, the differential cross section in a x_i bin is expressed by [10]:

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

being Λ is the degree of target polarization and $\delta_\odot$ that of the beam; $\vec{P}$ is the single polarization observable in case of unpolarized beam, and $\vec{P}^\odot$ is the double polarization observable in case of circularly polarized beam. Only the z component of these vector is considered given the initial choice for the z axis orientation.

The differential cross section, by definition, is proportional to the number of events of the reaction under study measured in the kinematic bin Δx_i. Indicating generically with c the target constant, with the already introduced notations for the target and beam polarizations, one can expand eq. (1) according to 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 equation, Λ_z stands for the absolute value of the z component of the target polarization, the sign for the parallel/antiparallel case having been explicited 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).

Eq. (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 the helicity angle (formed by the π^+ in the dipion reference system) 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 in ref. [6, 10]), Φ is defined as the angle between the normal vectors to the reaction and the production plane, on which the three outcoming particles lie, and it can be evaluated through

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

The orientation of the cross product of the two normal vectors sets the sign of $\sin\Phi$.

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

Being the data analysis and the extraction of the final results still underway, as an example of the expected distributions the already published results from CLAS on the experimental beam-asymmetry $I^{\odot}$ can be reported. These results were obtained about 20 years ago with the data collected in the $g1c$ CLAS run [1], 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

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

having expanded the target constant c mentioned above introducing the target density ρ, the Avogadro number N_{Av}, the target mass number A, the detection efficiency ϵ and the photon flux F, assumed to be the same for photons with different helicities. From eq. (4) one gets:

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

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

Fig. 3 shows the trend of $I^{\odot}$ in several ranges of available energy W, superimposed with the expectations from some models [11, 12] (see ref. [1] for further details and references therein). The trend of $I^{\odot}$ exhibits the expected odd symmetry as a function of Φ_{hel}; the models used to reproduce the trends are not completely satisfactory especially in some of the W ranges, indicating that the theoretical description still needed substantial improvement. The results of the ongoing analysis on $g14$ data, presented preliminarly at this Conference, are in good agreement with this first assessment and are going to be published shortly, together with the other polarization observables.

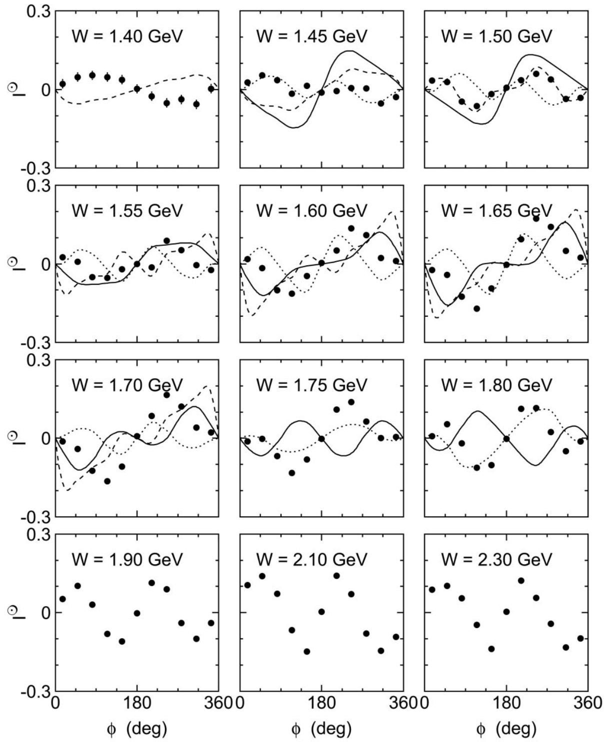

Figure 3. $I^{\odot}$ first published results for the $\vec{\gamma}p \to \pi^+\pi^- p$ reaction with CLAS *g*1*c* data [1]. The superimposed curves from model calculations are from ref. [11] (solid and dotted curves) and [12] (dashed curves).

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