Double polarisation observables $G$ and $E$ and helicity dependent cross section for single $\pi^0$ photoproduction off proton and neutron at MAMI

S Costanza for the A2 Collaboration
Dipartimento di Fisica, Università degli Studi di Pavia, I-27100 Pavia, Italy
E-mail: susanna.costanza@pv.infn.it

Abstract. Meson photoproduction, like other photon-induced reactions, allow to study the excitation spectra of the nucleons and, in combination with the use of polarised beam and/or target, allow to determine the properties of the nucleon resonances by accessing many different polarisation observables with great accuracy. The A2 Collaboration, located at the MAMI facility in Mainz, used elliptically polarised photons on longitudinally polarised proton and deuteron targets, for energies up to 1.6 GeV. From the experimental data, it was possible to extract the double polarisation observables $E$ and $G$ on single $\pi^0$ photoproduction off the proton and the neutron. New precise results on the helicity-dependent total and differential cross sections on the deuteron were collected too.

1. Introduction
In 1961, Hofstadter was awarded with the Nobel prize for discovering that the proton is not a point-like object but has an inner structure. Nowadays, almost 60 years after that discovery, despite the extensive research both from the theoretical and the experimental point of view, there are still fundamental properties of the proton (nucleon, in general), i.e. the proton radius or spin or its excited states, that are not understood.

Studying the excited states of the nucleon could provide an insight on fundamental properties of the strong interaction. At this energy scale, Quantum Chromodynamics is non-perturbative, therefore experimental results can be interpreted only by relying on phenomenological quark models. Nevertheless, even these models fail to provide a complete description of the nucleon excitation spectra. While the experimental findings are quite in agreement with the theoretical predictions in the low energy mass region, this is not the case for higher lying states: there are lots of “missing resonances” which are predicted by theories but not yet observed.

The reason for this mismatch could be found, experimentally, in the fact that data analysis was relying mostly on pion scattering; therefore, if there are higher lying states which decay preferentially via intermediate excited states or couple to decay channels involving heavier mesons, they will be missed [1].

To avoid this problem, it is possible to use electromagnetic reactions like meson photoproduction as an alternative: in this way, it is possible to explore states with multiple meson production, like $\pi\pi$, $\eta\pi$, ... and access resonances which decay preferentially via intermediate excited states.
If photoreaction experiments are performed with the use of polarised beam and/or targets, it is possible to access polarisation observables that allow to investigate the properties of nucleon resonances.

To be precise, a set of 16 polarisation observables can be defined, for every fixed value of energy $W$ and angle $\theta$, and classified depending on the beam, target and/or recoil nucleon polarisation: together with the unpolarised cross section $\sigma$, there are 3 single polarisation observables and 12 double polarisation observables (table 1).

The measurement of 7 (8) properly chosen observables leads to a model-independent analysis [2,3].

Table 1. Polarisation observables.

| Photon polarisation | Target polarisation | Recoil nucleon polarisation | Target and recoil polarisation |
|---------------------|---------------------|-----------------------------|-------------------------------|
|                     | X Y Z (beam)        | X' Y' Z'                    | X' X' Z' Z'                  |
| unpolarised         | $\sigma$ - T -     | - P -                       | $T_{X'}$ $L_{X'}$ $T_{Z'}$ $L_{Z'}$ |
| linear              | - $\Sigma$ H - P - G | $O_{X'}$ (-T) $O_{Z'}$ (-L$Z'$) $T_{Z'}$ $T_{X'}$ $L_{X'}$ $(T_{Z'}) (L_{X'}) (-T_{X'})$ |
| circular            | - F - E -           | $C_{X'}$ - $C_{Z'}$ -      | - - - -                      |

2. The experimental setup

In order to achieve a complete understanding of the nucleon and its excited states, not only measurements of meson photoproduction off the proton are required, but also off the neutron.

The A2 Collaboration has the possibility to carry out a broad and systematic study on these topics, thanks to the availability of polarised photon beams and polarised proton, deuteron and $^3$He targets.

The experimental apparatus of the A2 Collaboration is located in Mainz, at the MAMI tagged photon beam facility, that produces a photon beam via bremsstrahlung of a 1557 MeV electron beam. While the electrons are deflected in the magnetic field of the Glasgow-Mainz magnetic spectrometer, the photon beam is collimated and hit the target which is placed at the heart of the central detector system. The target cell is surrounded by the Particle Identification detector (PID), used to discriminate charged and neutral particles and enclosed in two cylindrical Multi-Wire Proportional Chambers (MWPCs), which are devoted to the tracking of charged particles. The outer detector is the Crystall Ball (CB), a large solid angle highly segmented photon and hadron spectrometer. Precise angular and energy measurements, together with particle identification from 0° to 360° in $\phi$ and from 21° to 159° in $\theta$, are achieved by combining the information of all three mentioned detectors (figure 1). The data discussed in the following were collected with an elliptically polarised photon beam, with both a linear and circular polarisation components, produced with longitudinally polarised electrons in combination with a diamond radiator. Concerning the target, a frozen-spin butanol (C$_4$H$_9$OH) and deuterated butanol (C$_4$OD$_{10}$) targets were used. The targets were polarised via Dynamic Nuclear Polarisation (DNP) to an initial polarisation degree up to 90% and 70% for butanol and d-butanol targets, respectively. Very long relaxation times (~ 2000 h for C$_4$H$_9$OH and ~ 200 h for C$_4$OD$_{10}$) were ensured.
3. Analysis results

3.1. Helicity dependent cross section for single $\pi^0$ photoproduction

The helicity dependent total cross section $\Delta \sigma = (\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow})$ and differential cross section $d\sigma/d\Omega(E_{\pi}) = d\sigma^{\uparrow\downarrow}/d\Omega(E_{\pi}) - d\sigma^{\uparrow\uparrow}/d\Omega(E_{\pi})$ on the deuteron for the semi-exclusive channel $\gamma d \rightarrow \pi^0 X$ are shown in figures 2 and 3, respectively. The subscripts $\uparrow\downarrow$ and $\uparrow\uparrow$ indicate the relative alignment between the photon and baryon spins.

The plot in figure 2 shows a good agreement between the A2 data (blue circles) [8] and the results of the GDH Collaboration (red circles) [9], available only in the $\Delta(1232)$ resonance region. Therefore, it is clear that the A2 data can contribute in an energy region where there are no other data available.

In addition, our experimental data are compared to two different versions of the MAID multipole analysis. The red line [6] is simply the sum of the free proton and free neutron contributions: hence, since it does not include the nuclear effects of the nucleons bound inside the deuteron target, which are not negligible, the agreement between the data and this model is poor. If the MAID predictions are corrected (green line) to include a contribution that accounts

![Figure 1. A2 experimental setup.](image)

![Figure 2. Helicity dependent total cross section for the semi-exclusive channel $\gamma d \rightarrow \pi^0 X$. The A2 data (blue circles) are compared to the GDH Collaboration results (red circles), to the MAID multipole analysis without (red line) and with (green line) the Impulse Approximation correction based on [7].](image)
Figure 3. Helicity dependent differential cross section for the semi-exclusive channel $\gamma d \rightarrow \pi^0 X$. The A2 data (blues circles) [8] are compared to the MAID multipole analysis without (red line) [6] and with (green line) the Impulse Approximation correction based on [7].

for the Fermi motion of the bound nucleons (Impulse Approximation) [7], the agreement improves for $E_\gamma > 500$ MeV but the model still fails to describe the $\Delta-$resonance region. This is due to the high Final State Interaction (FSI) contribution, that is not taken into account.

3.2. Double polarisation observables $E$ and $G$

In addition to the study of the helicity dependent cross sections, the frozen-spin butanol and deuterated butanol target data collected by the A2 Collaboration were used to extract the double polarisation observables $E$ and $G$ in the photoproduction reactions $\gamma p \rightarrow \pi^0 p$ and $\gamma n \rightarrow \pi^0 n$ (the latter only in the d-butanol target case).

The $G$ and $E$ observables require both the polarisation of the beam and of the target (table 1). $E$ is obtained by integrating over $\phi$ the differential cross section for pseudo-scalar meson photoproduction. In case of elliptically polarised photons hitting a longitudinally polarised target, the cross section is given by:

$$
\frac{d\sigma}{d\Omega}(\theta, \phi) = \frac{d\sigma}{d\Omega_0}(\theta)[1 - P_{lin}\Sigma \cos(2(\alpha - \phi)) - P_z(-P_{lin} G \sin(2(\alpha - \phi)) + P_{circ} E)].
$$

Hence:

$$
N_B^{\pm P_z}_{\pm \alpha}(\theta) = N_B(\theta) \cdot [1 - P_{circ} P_z E] \rightarrow E = \frac{(\sigma^{1/2} - \sigma^{3/2})}{\sigma^{1/2} + \sigma^{3/2}} = \frac{N_B^{1/2} - N_B^{3/2}}{N_B^{1/2} + N_B^{3/2}} \cdot \frac{1}{d} \cdot \frac{1}{P_{circ} P_z}, \quad (2)
$$

where $N_B^{1/2}$ and $N_B^{3/2}$ are the helicity-dependent count rates and $P_{circ} P_z$ are the degrees of target and beam polarisation. $d$ is the dilution factor $d = N_{free}/(N_{free} + N_{bound})$, that expresses the amount of polarisable free protons in the data, given that the count rates account also for the unpolarised bound nucleons in carbon and oxygen nuclei [8][10].

Like for the $E$ observable, $G$ is obtained by integrating equation [1] over all possible helicity states:

$$
N_B^{\pm P_z}_{\pm \alpha}(\theta, \phi) = N_B(\theta) \cdot [1 - P_{lin}\Sigma B \cos(2(\alpha - \phi)) + dP_{lin} P_z G \sin(2(\alpha - \phi))].
$$

Figure 4 shows the A2 results for the $E$ observable for the photoproduction channel $\gamma p \rightarrow \pi^0 p$ in selected energy bins (from 1270 MeV to 1630 MeV) for quasi-free protons (blue circles), as a
Figure 4. Results for the double polarisation observable $E$ for the photoproduction channel $\gamma p \rightarrow \pi^0 p$, as a function of $\cos \theta^C_{\pi^0}$ for selected 30 MeV energy bins, for quasi-free (blue circles) protons. The results are compared to the Bonn-Gatchina 2014-02 [12] (red line), SAID-CM12 [13] (black line), MAID [6] (magenta line), MAID + IA (cyan line), MAID + IA + FSI [7] (green line) partial wave solutions.

The energy and angular dependence of the polarisation observable $E$ can be described by a combination of multipoles and the associated Legendre polynomials. In order to do that, let’s introduce the profile function $\hat{E}$:

$$\hat{E}(W, \theta) = E(W, \theta) \cdot \frac{d\sigma}{d\Omega}(W, \theta) = \rho \sum_{l=0}^{2L_{\text{max}}}(a_{L_{\text{max}}})^{\hat{E}}(W)P_l(\cos \theta)$$

where the differential cross section is provided by the Bonn-Gatchina 2014-02 PWA solution, $\rho$ is a phase space factor, $(a_{L_{\text{max}}})^{\hat{E}}(W)$ are the Legendre coefficients for a given truncation at $L_{\text{max}}$ and $P_l(\cos \theta)$ are the associated Legendre polynomials of order zero.

Figure 5 shows six angular distributions of $\hat{E}$ for the $\pi^0 p$ channel, together with the performed fit functions using the associated Legendre polynomials, as in equation 4. The partial wave expansion has been truncated at different $L_{\text{max}}$ values, up to $L_{\text{max}} = 4$.

At $W = 1281$ MeV, the angular distribution is well described truncating at $L_{\text{max}} = 1$: this is expected, since in this energy region the $\Delta(1232)3/2^+(P33)$ resonance, which has $l = 1$ and contributes to the P-wave, provides the largest contributions to the $\pi^0 p$ final state.

At higher energies, a truncation at $L_{\text{max}} = 1$ is not good enough, since the contributions of $D$
and $F$ waves become dominant in the second and third resonance regions, respectively. This is mirrored in the angular distributions, which can be well described only by $L_{\text{max}} = 2$ and 3-fits.

![Figure 5. Samples of $\hat{E}$ for the $\pi^0p$ channel, fitted with the associated Legendre polynomials, truncated at $L_{\text{max}} = 1$ (green), 2 (blue), 3 (red) and 4 (black).](image)

4. Conclusions
The A2 Collaboration has performed double polarised pion photoproduction experiments to investigate the nucleon excitation spectra. By using an elliptically polarised photon beam on frozen-spin butanol and d-butanol targets, A2 could perform a simultaneous measurement of the double polarisation observables $E$ and $G$.

The experimental data provide new precise results on the total and differential cross sections for the semi-exclusive $\gamma N \rightarrow \pi^0X$ channels on the proton and the neutron, and allow the extraction of the $E$ asymmetry for quasi-free protons and quasi-free neutrons.

These new data increase the available statistics, in particular on the neutron, provide a contribution in energy regions where no other data are available and represent a valuable constraint on partial wave analysis models.

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