Eur. Phys. J. A **31**, 441–445 (2007)
DOI 10.1140/epja/i2006-10272-8

THE EUROPEAN PHYSICAL JOURNAL A

Special Article – QNP 2006

Meson photoproduction on the nucleon with polarized photons

The GRAAL Collaboration

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Received: 8 December 2006
Published online: 20 March 2007 –

Abstract. Meson photoproduction with polarized photons has proved to be a powerful tool to identify contributions of baryon resonances that are not evident in the differential cross-sections. It provides information that are complementary to those extracted using pion-nucleon scattering data. Extensive results have been produced in the past on beam asymmetries by the Graal collaboration for η and π^0 on the proton. New results are now available for the same reactions on the quasi-free neutron and for the K^+ photoproduction on the proton. Contributions from hitherto undetected baryon resonances may be important to understand the results.

PACS. 13.60.Le Meson production – 13.88.+e Polarization in interactions and scattering – 25.20.Lj Photoproduction reactions

1 Introduction

The determination of baryon resonances properties, such as masses, widths, helicity amplitudes and partial decay widths in nucleon-meson channels, is fundamental to improve our understanding of the internal structure of the nucleons. Most of our knowledge of resonance parameters come from πN scattering data, however recent precise data on photonuclear reactions have provided complementary information such as resonance photocouplings [1]. Quark model calculations are presently able to reproduce most of the properties of the excited states of the nucleon [2–4], but several issues still remain open. The number of observed states is smaller than the predicted one: the hitherto undetected resonances are called *missing resonances* and the search of experimental evidence of their existence is presently of great interest. One possible explanation is that the *missing resonances* weakly couple to the πN channels and their contribution to πN scattering and π photoproduction reactions is negligible. The study of different reactions such as K, η and ω photoproduction,

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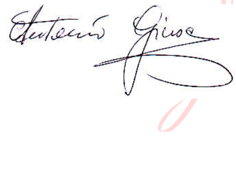

where the resonant state couples to different meson-N decay channel, may provide new information on the subject.

The access to polarization observables, which are sensitive to the interference between different multipoles, has the potential to reveal small resonance contributions which remain hidden in the differential cross-section under the dominant terms.

The Graal Collaboration has extensively studied η photoproduction on the proton using polarized photons, providing new important constraints to models that extract resonance properties from multipole analysis of the reaction amplitudes. The helicity amplitude $A^p_{1/2}$ of the $S_{11}(1535)$-resonance, which dominates the reaction at lower energies, has been extracted from η photoproduction data and the result obtained ($(100\pm3)\ 10^{-3}\,\mathrm{GeV}^{-1/2}$) is higher than the one obtained from πN scattering data ($(78\pm4)10^{-3}\,\mathrm{GeV}^{-1/2}$). (See [5] for a review.) More experimental information is necessary to clarify the situation, since quark models predict a much higher value for the $A^p_{1/2}$ parameter than the experimental ones.

Complementary information may be provided by the neutron helicity amplitudes, which are related to those of the proton by isospin decomposition relations: $A^p = A^{IS} + A^{IV}$ and $A^n = A^{IS} - A^{IV}$, where A^{IS} and A^{IV} are the isoscalar and the isovector components of the electromagnetic excitation of the resonance. However, experimental results on the neutron are scarce and must be extracted from bound nucleons in light nuclei.

We present samples of the first measurements obtained for the beam asymmetry Σ on quasi-free protons and quasi-free neutrons for the η and π^0 photoproduction reactions on a deuteron target. Comparison of results of the same channels from free protons are also presented to evaluate the contribution from the nucleon binding effects. Some recent results on the $K^+\Lambda$ and $K^+\Sigma^0$ photoproduction beam asymmetries have also been obtained on a proton target, being the first world result on the subject.

2 The GRAAL experimental setup

Present results are obtained at the GRAAL facility, which consists of a tagged and polarized Compton backscattering photon beam, located at the European Synchrotron Radiation Facility in Grenoble, complemented by a large-solid-angle detector (Laγrange). The tagged photon energy spectrum extends from 600 MeV to 1500 MeV, and the beam may be linearly polarized to a degree higher than 75% on the whole tagged range. The central part of the Laγrange detector (see [6] for details) consists of a BGO calorimeter, complemented by a plastic scintillator barrel and an internal tracker made of two cylindrical multi-wire proportional chambers (MWPC), covering all azimuthal angles corresponding to polar angles in the interval 25°–155°; forward polar angles, lower than 25°, are covered by two couples of tracking planar MWPCs, a double wall of plastic scintillators and a shower wall, consisting of four layers of lead and plastic scintillators.

The BGO calorimeter has excellent energy resolution for electrons and photons detection (3% FWHM at 1 GeV energy), and good response to protons for energies up to 300 MeV. Charged particles are tracked with high spatial resolution by the MWPCs (from 1.5° to 3.5° FWHM) and their energy is well determined by time-of-flight (TOF) measurements by the forward walls. Neutrons may be detected either in the BGO calorimeter, with no information on their energy, or in the forward shower wall, the energy being given by TOF measurements.

The whole apparatus is optimized for the detection of mesons that decay into photons, but it is also able to detect with reasonable performances final states having multiple charged particles.

A cryogenic target of 6 cm length may be filled either with liquid hydrogen or liquid deuterium, so that reactions on the free proton or bound protons and neutrons may be studied, respectively.

During data taking the beam polarization direction is periodically rotated to be either horizontal or vertical. Data analysis selects photonuclear events, in both polarization conditions. By constructing the ratio

$$\frac{N_{||}/F_{||}}{N_{||}/F_{||} + N_{\perp}/F_{\perp}} = \frac{1}{2}(1 - P\Sigma\cos(2\varphi)), \qquad (1)$$

where $N_{||}$ ($N_{\perp}$) is the number of reaction events and $F_{||}$ ($F_{\perp}$) is the corresponding photon flux for horizontal (vertical) beam polarization, the Σ beam polarization observable may be extracted from the fit of the azimuthal dependence of the ratio, P being the known degree of beam polarization. We observe that the value of Σ may be determined without knowing the absolute efficiency of the event selection procedure.

3 η photoproduction from quasi-free neutrons

η-meson photoproduction events are selected requiring that two photons, having an invariant mass in the interval 0.35–0.7 GeV, are detected by the BGO calorimeter. When a deuterium target is used, data are analyzed to select quasi-free kinematic conditions on the bound nucleons: $\gamma d \to N\eta(spectator)$. The η-meson is produced by the photon interaction with one of the nucleons whose momentum is given by the Fermi distribution, while the other nucleon acts as a spectator and most of the times does not escape the target. By detecting a proton or a neutron in the BGO calorimeter or in the forward walls, in coincidence with the η-meson and satisfying two-body kinematics constraints, slightly smeared by Fermi motion effects, it is possible to select an η photoproduction event on the quasi-free proton or neutron, respectively.

The Σ beam polarization observable has been determined from eq. (1) for the η photoproduction reaction on both bound nucleons, for eleven incoming beam energy bins from reaction threshold to 1.5 GeV, and nine angular bins from 30° to 170° for the meson polar angle in the centre-of-mass reference.

Applying the same selection criteria on data taken using a proton target, the Σ beam asymmetry have been

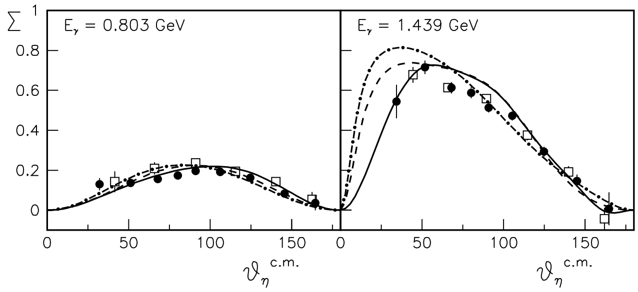

Fig. 1. Comparison of Σ beam asymmetry for η photoproduction on free (open squares) and bound (full circles) protons. Predictions from SAID multipole analysis are plotted as solid curves. MAID(2001) and MAID(2003) isobar models are shown as dashed and dot-dashed curves, respectively.

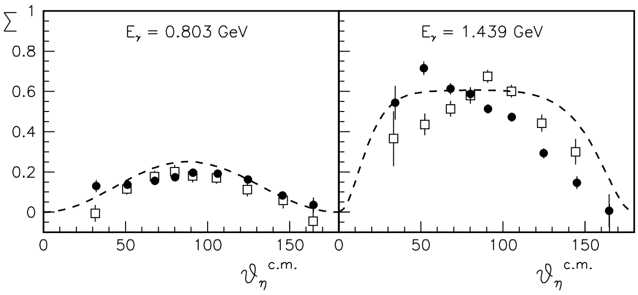

Fig. 2. Comparison of Σ beam asymmetry results for η photoproduction from quasi-free neutrons (open squares) and quasi-free protons (full circles). Predictions from MAID(2001) isobar model are shown as dashed curves.

obtained also for the free proton. Figure 1 shows the comparison of the results obtained on the free and the bound proton for two energy bin values, close to threshold and in the higher-energy range, respectively. We find that the behaviour is very similar for the free and the bound nucleon for almost all energies and angles and we deduce that the binding effects in deuteron are almost negligible when the beam asymmetry is considered.

Data are also compared with existing predictions from SAID partial wave analysis [7] (solid curve), η-MAID(2001) [8] isobar model (dashed curve) and the new reggized version of the same model η-MAID(2003) [9] (dot-dashed curve). A general good agreement is obtained between both models and our results, the SAID prediction being closer to our data for the higher-energy values.

Results for the Σ beam asymmetry for the η photoproduction from quasi-free neutrons (open squares) are shown in fig. 2, compared with results from quasi-free protons (full circles) and MAID(2001) predictions from the free neutron (dashed curve), which is presently the only available model for the neutron target. We note that the behaviour of the beam asymmetry is quite similar for the two nucleons, the neutron presenting a more backward-forward symmetrical peak at higher energies. Comparison with MAID model is generally not satisfactory, being too high at energies close to 1 GeV, and showing an angular distribution which is flat compared to data. The present

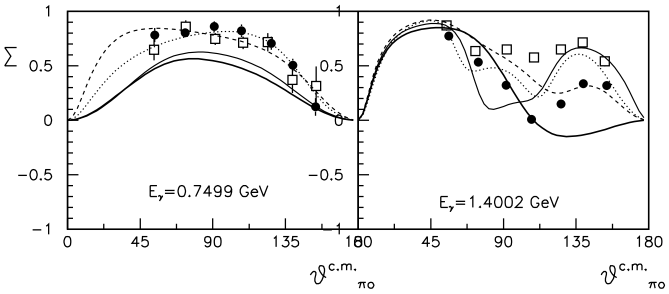

Fig. 3. Comparison of Σ beam asymmetry for π^0 photoproduction from quasi-free neutrons (open squares) and quasi-free protons (full circles). Predictions from SAID multipole analysis are plotted as dotted and thin solid curves for π^0 production on the proton and the neutron, respectively. MAID(2003) isobar models are shown as dashed and thick solid curves for π^0 production on the proton and the neutron, respectively.

data, being the first ones from quasi-free neutrons are expected to be useful for a better understanding of the isospin dependence of the η-nucleon photoproduction.

4 π^0 photoproduction from quasi-free neutrons

Extensive results have been obtained by the GRAAL collaboration also on the π^0 photoproduction on the proton [6]. The main difference with respect to the η photoproduction channel is due to the fact that pions have isospin $I = 1$ while η-mesons are iso-singlets. This implies that both Δ and N^* resonances may be excited in pion photoproduction reactions, while only N^* baryon resonances are involved in the η photoproduction channel. This makes the multipole analysis of pion photoproduction more complicated, but due to the higher cross-section the existing experimental database is much wider and very precise data are available.

Starting from the same data set to which we refer in sect. 3 and using the same events selection criteria described therein, imposing that the invariant mass of the two detected photons falls into the interval 90–175 MeV we obtained results on the Σ beam asymmetry for the π^0 photoproduction from quasi-free protons and quasi-free neutrons, using the deuteron target and from the free proton using the hydrogen target. The behaviour of the beam asymmetry for the free and the quasi-free proton is identical within the experimental errors showing also for the π^0 channel that binding and/or rescattering effects are negligible.

Results for π^0 photoproduction beam asymmetry off the quasi-free neutron are shown in fig. 3 (open squares) together with those off the quasi-free proton (closed circles), for two energy bins. While the trend for the two nucleons is similar at lower energies, the Σ beam asymmetry is sensibly higher for the quasi-free neutron than for the proton. Comparison with MAID(2003) [10] isobar model and SAID partial-wave amplitude predictions are also plotted as dashed and dotted curves, respectively, for

π^0 photoproduction from the proton and thick and thin solid curves, respectively, for the same reaction from the neutron.

We observe that prediction for the π^0p channel are not in agreement with our experimental results and revised versions of both SAID and MAID solutions have been created including Graal data on the proton in the experimental database. Moreover predictions for the π^0 production off the neutron show more complicated structure than our results. After several decades of results on the pion photoproduction channels, constraints from polarization observables are still able to add new information on the reaction mechanism.

5 K^+ photoproduction from the proton

Using the hydrogen target and taking advantage of the high resolution for angular information from the tracking detectors, it has been possible to analyze events from the K^+ photoproduction on the proton; both $\gamma p \to K^+\Lambda$ and $\gamma p \to K^+\Sigma^0 \to K^+\Lambda\gamma$ reactions could be studied, considering the charged decay channel of the Λ ($\Lambda \to p\pi^-$).

Events with three charged particles in the final state have been analyzed; particle identification and momentum calculation was performed using two different kinematics procedures, the former starting from a three-body kinematics approach, the latter treating the reactions as a cascade of two-body reactions ($K\Lambda$ production followed by the Λ decay in $p\pi^-$). The detection of the photon from the Σ^0 decay, which has 76.96 MeV energy in the reference frame where Σ^0 is at rest, was used to discriminate among the two reactions.

The Λ decay, being governed by weak interactions, allows for the measurement of the Λ degree of polarization, so that both the recoil polarization P and the Σ beam polarization observables could be measured.

Results for the first observables have been found in agreement with data from SAPHIR [11] and CLAS [12]. Those for the Σ beam polarization are the first available in the energy range from reaction threshold to 1.5 GeV incoming photon energies.

Figure 4 shows the angular distribution of the beam asymmetry for three incoming photon energies, compared with presently available model predictions: kaon-MAID(2000) isobar model [13] (dotted line), Saclay-Argonne-Pittsburgh dynamical coupled-channel model [14] (dashed line), Ghent isobar and Regge plus Resonance models [15] (dot-dashed lines) and Bonn coupled-channel partial-wave analysis [16] (solid line).

The kaon-MAID(2000) model includes a *missing* resonance: the $D_{13}(1900)$. It may well reproduce the angular distribution of the unpolarized differential cross-section from SAPHIR, but it over estimates the present measurements of the Σ beam asymmetry.

The Saclay-Argonne-Pittsburgh dynamical coupled-channel model includes resonances in the frame of a chiral constituent-quark model and finds the necessity to include three new resonances: $S_{11}(1806)$, $P_{13}(1893)$ and $D_{13}(1954)$, the last one being the most evident. Its ability to reproduce the new beam asymmetry data is scarce at backward angles.

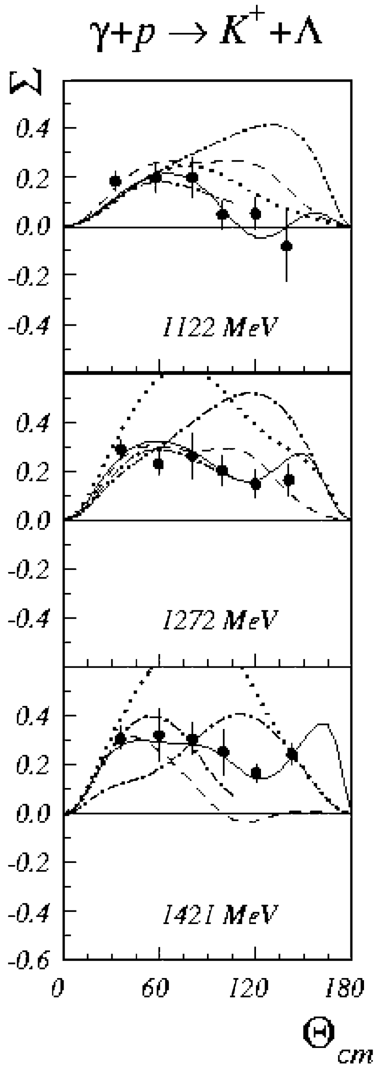

Fig. 4. Angular distributions for the beam asymmetry for the $\gamma p \to K^+\Lambda$ reaction. Data are compared with kaon-MAID(2000) isobar model (dotted line), Saclay-Argonne-Pittsburgh dynamical coupled-channel model (dashed line), Ghent isobar and Regge plus Resonance models (dot-dashed lines) and Bonn coupled-channel partial-wave analysis (solid line).

The Ghent isobar model includes a *missing* $D_{13}(1900)$ state, in addition to standard Born, background and resonance terms; its reggized version, plotted only for forward angles, better agrees with present beam asymmetry results.

Finally the Bonn coupled-channel partial-wave model finds the necessity of including several new N^*-resonances above 1800 MeV and it strongly demands the presence of a new $D_{13}(1875)$ state. Its ability to reproduce the Graal results on the beam asymmetry is remarkable.

We conclude that most models confirm the need of including a *missing* D_{13}-resonance of mass around 1900 MeV, the Bonn model being able to well reproduce

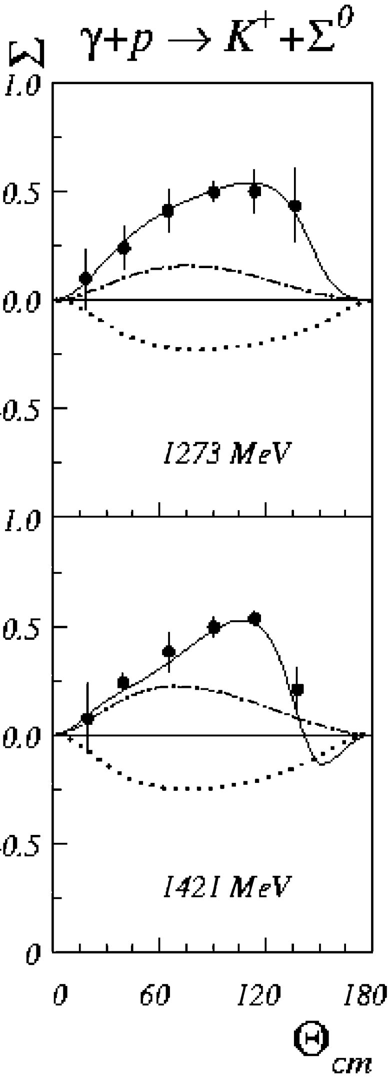

Fig. 5. Angular distributions for the beam asymmetry for the $\gamma p \to K^+\Sigma^0$ reaction. Data are compared with kaon-MAID(2000) isobar model (dotted line), Ghent isobar (dot-dashed line) and Bonn coupled-channel partial-wave analysis (solid line).

all the new Graal results on the Σ beam asymmetry for the $\gamma p \to K^+\Lambda$ channel.

Similar results for the $\gamma p \to K^+\Sigma^0$ channel are shown in fig. 5 for two energy bins. Also these data are the first available for the beam polarization asymmetry at low energies. They are compared with kaon-MAID(2000) isobar model (dotted line), Ghent isobar model (dot-dashed line) and the Bonn coupled-channel partial-wave analysis (solid line). Again the Bonn model has the impressing ability to fully reproduce our results.

6 Summary

First results on the Σ beam asymmetry observable have been obtained for incoming photon energies up to 1500 MeV for the η-meson and the π^0 photoproduction from the quasi-free neutron. The data are not reproduced by the presently available model predictions and may contribute to a better understanding of the isospin dependence of the reaction mechanisms. First new data are also available for the K^+ photoproduction from the proton for both $K^+\Lambda$ and $K^+\Sigma^0$ channels. Comparison with existing predictions show a very good agreement with the Bonn coupled-channel partial-wave analysis, which supports the need for the introduction of a new $D_{13}(1900)$-resonance.

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