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Precise measurement of Σ beam asymmetry for positive pion photoproduction on the proton from 550 to 1100 MeV

GRAAL Collaboration

J. Ajaka [a], O. Bartalini [b], M. Battaglieri [c], V. Bellini [d], J.P. Bocquet [e], P.M. Calvat [e], M. Capogni [a,b,1], M. Castoldi [c], L. Ciciani [b], A. D'Angelo [b], J.-P. Didelez [a], R. Di Salvo [a,b], M.-A. Duval [a], C. Gaulard [f], G. Gervino [g], F. Ghio [h], B. Girolami [h], M. Guidal [a], E. Guinault [a], E. Hourany [a], A. Jejcic [a], I. Kilvington [i], V. Kouznetsov [j,2], A. Lapik [j], P. Levi Sandri [f], A. Lleres [e], D. Morriciani [b,k], V. Nedorezov [j], L. Nicoletti [b,e], D. Rebreyend [e], F. Renard [e], M. Ripani [c], N. Rudnev [l], C. Schaerf [b], A. Turinge [m], A. Zucchiatti [c]

[a] *IN2P3, Institut de Physique Nucléaire, 91406 Orsay, France*
[b] *INFN sezione di Roma II and Università di Roma "Tor Vergata", 00133 Roma, Italy*
[c] *INFN Genova and Università di Genova, 16146 Genova, Italy*
[d] *INFN Laboratori Nazionali del Sud and Università di Catania, 95123 Catania, Italy*
[e] *IN2P3, Institut des Sciences Nucléaires, 38026 Grenoble, France*
[f] *INFN Laboratori Nazionali di Frascati, 00044 Frascati, Italy*
[g] *INFN sezione di Torino and Università di Torino, 10125 Torino, Italy*
[h] *INFN sezione Sanità and Istituto Superiore di Sanità, 00161 Roma, Italy*
[i] *European Synchrotron Radiation Facility, 38026 Grenoble, France*
[j] *Institute for Nuclear Research, 117312 Moscow, Russia*
[k] *Centro Siciliano di Fisica Nucleare e Struttura della Materia, 95125 Catania, Italy*
[l] *Institute of Theoretical and Experimental Physics, Moscow, Russia*
[m] *RRC "Kurchatov Institute", Moscow, Russia*

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Abstract

Σ beam asymmetries for π^+ photoproduction on the proton have been measured in the energy range 550–1100 MeV over a wide angular range. The statistical and systematic errors of the data are much lower than in previous measurements, due to the high polarization of the photon beam and the cylindrical geometry of the 4π detector. Our results confirm the

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[1] E-mail address: Capogni@ginevra.roma2.infn.it
[2] E-mail address: Slava@cpc.inr.ac.ru, Slava@gravax2.in2p3.fr

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predictions WI98 and SM95 of the VPI partial-wave analysis at the energies below 850 MeV and at 1050 MeV while, between these two regions, they differ at backward angles. It may indicate the smaller contribution of $S_{11}(1650)$ resonance, than it was quoted previously by the VPI and PDG groups. A newly developed unitary isobar model reproduces our data up to 950 MeV.

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The study of the baryon resonances spectrum is a very important task in intermediate energy nuclear physics. It provides information on the excited states of the three-quark-plus-gluons system. Our knowledge of resonance properties, initially obtained in the πN scattering, is now improved by the analysis of precise photonucleon data.

Photon-nucleon interaction below 2.0 GeV, is dominated by the excitation of baryon resonances, which then decay into πN final states. The detailed description of this mechanism requires a complete data base comprising at least eight independent observables: the differential cross sections, the three single-polarization observables (polarized beam, target and recoil nucleon) and four, appropriately chosen, double-polarization observables [1]. Such a complete set of data is not yet available and the extraction of resonance parameters from photoproduction data is necessarily model dependent [2,3]. It is done by means of partial-wave analysis and multipole decomposition in the framework of different theoretical approaches [4–9] which usually include, in addition to resonant contributions, non-resonant ones due to meson exchange and Born terms. The comparison of the calculated observables with experimental data constrains the theoretical models and determines the role and properties of the resonances included.

In another phenomenological approach [10–13], the contributions of partial waves, and the corresponding electric and magnetic multipoles for single-pion photoproduction are extracted from fits to the existing experimental data. This last approach is used by the Virginia Polytechnic Institute (VPI) group [12,13]. The corresponding amplitudes are now widely used [4,5,14,15]. Parameters of 16 nucleon and delta resonances have been determined using a Breit–Wigner-plus-background parametrization of the amplitudes [12].

The quality of these procedures is directly related to the quality of the existing experimental data base, which is mainly composed of cross-section points [12], obtained with bremsstrahlung untagged photons. While the cross section is a source of information about the general structure of the scattering amplitude, polarization observables depend much more on its details since they are given by the interference among different helicity amplitudes [4–6].

Σ, the beam asymmetry in a reaction induced by linearly polarized photons, is one of the single-polarization observables. For $\pi^+ n$ photoproduction it was measured in six previous experiments, all dated before 1980, with untagged bremsstrahlung [16,17,19–21] and laser backscattering [18] beams. Only two of them [18,19] cover simultaneously a wide range of energies and angles. A few points with large error bars and significant disagreement, exist at backward ($> 125°$) angles [16,18]. In this Letter, we present new accurate Σ data for the $\pi^+ n$ channel, measured from 550 to 1100 MeV, on a wide angular range including backward angles and compare them to existing predictions. We shall see that at angles $< 90°$ the experimental data are reasonably well reproduced, while at higher momentum transfers the situation is not so clear [4,8,13].

The novel GRAAL facility is described in [22]. It was designed to measure polarization observables in photon-induced reactions. It uses the polarized and tagged photon beam obtained by backscattering laser light on the 6.04 GeV electrons of the storage ring of the European Synchrotron Radiation Facility (ESRF). With the green 514 nm laser line, used in the present measurement, the tagged spectrum covers the energy range of 550–1100 MeV. It has an energy resolution of 16 MeV Full Width at Half Maximum (FWHM). The linear beam polarization varies from 0.43 at the lower energy limit to 0.98 at the upper one. The

GRAAL detector is made of a cylindrically symmetrical central part, for particles emitted at θ_{lab} angles of 25–155°, a forward part for angles smaller than 25°, and a backward part for angles larger than 155°. Together they cover a solid angle very close to 4π.

The central part consists of two coaxial cylindrical wire chambers, a 5 mm thick scintillator barrel, which provides ΔE information for particle identification, and the BGO ball made of 480 crystals [23]. The forward part consists of two planar wire chambers, a TOF (Time-Of-Flight) hodoscope counter made of two planes of 3 cm thick plastic scintillator bars, and a shower wall. The backward part consists of two plastic-scintillator disks separated by 1 cm of lead.

Neutrons, emitted at forward (less than 25°) angles, were identified by a signal in the shower wall and no signal in the preceding detectors. The shower detector is an assembly of 16 modules, covering together an area of 3×3 m^2 located at 3.3 m from the target. Each module is a sandwich of 4 layers of plastic scintillator (each 40 mm thick) separated by a lead converter. The shower wall is used for the detection of forward photons and neutrons as well as charged particles. Further particle identification in the shower wall is possible by means of the relation between their energy deposition and time of flight. The wall provides the detection of particles with an angular resolution of 2.5–3° (FWHM). The TOF resolution is 600 ps for photons and charged particles and 700–800 ps (FWHM) for neutrons. In Fig. 1, the energy deposition for neutral particles is plotted versus their time of flight. The well-separated line of photons is located at 11 ns, while neutron events start at a TOF of 13.3 ns, corresponding to the maximum of their kinetic energy at 1100 MeV.

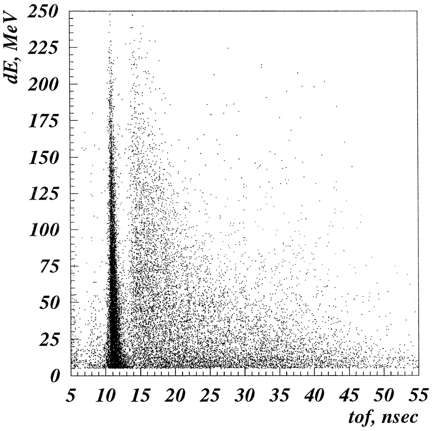

Fig. 1. Energy deposition in the shower wall versus time of flight for neutral particles.

Pions, corresponding to neutrons at forward angles, were detected by the BGO ball. The barrel separates charged and neutral particles. This assembly provides an angular resolution of about 8° (FWHM). Pions loose their energy in the BGO through ionization and hadronic interactions [24]. Pions with a kinetic energy larger than 300 MeV escape from the crystals unless they undergo a deep hadronic interaction with the BGO. Stopped pions decay mostly into neutrinos and muons. Also muons decay inside the detector and the energy of the electron can be detected in total or in part. The average energy deposited by the pions, in the kinematical range of this measurement, was found from a GEANT simulation to be 20–40 MeV higher than their kinetic energy. After corrections the determination of the pion kinetic energy became possible, however, with a rather poor resolution: 15–30% (FWHM). With the energy of the incoming gamma provided by the tagger and the energies and angles of the pion and neutron measured by our detector, the kinematics of the reaction is overdetermined. Therefore this process can be well identified using kinematical constraints.

At the first step of the analysis, the events were selected by the relation of missing masses, calculated from the energy of the incoming photon and the measured momenta of the other particles. After that, a global kinematical fit was applied. The center of mass angles of the pion and the ϕ-angles of the reaction plane were determined by a χ^2 minimization procedure comparing the calculated energies and angles in the laboratory system with the measured ones and their estimated errors. The value of χ^2 was used for further selection of events. This procedure eliminated the rest of the background and provided an improved determination of the $\theta_{\rm cm}$ and ϕ angles.

For π^+ emitted at medium angles in the CM, both outgoing particles, the π^+ and the neutron interact with the BGO ball. The identification of the corresponding final state was achieved in successive steps. First, from the response of the segmented scintillating barrel surrounding the target, the events generating two clusters in the BGO, one corresponding to a neutral and the other to a charged particle, were selected. Corresponding events could still be polluted by partially detected events coming from the $\gamma p \to p\pi^0$ reaction, when one γ from the π^0 decay escapes the BGO. Therefore, a second selection was performed using the energy balance calculated with the assumption of either a $\gamma p \to n\pi^+$ or a $\gamma p \to p\pi^0$ reaction. The corresponding energy spectrum displays well separated peaks and allows the selection of the $\gamma p \to n\pi^+$ events. Finally it was considered the variable θ_{sum} for the two clusters $\theta_{\text{sum}} = 0_{\text{neutral}} + \theta_{\text{charged}}$, where θ is the polar angle in the laboratory system. A narrow peak in the distribution of the difference $\theta_{\text{sum}}^{\text{exp}} - \theta_{\text{sum}}^{\text{calc}}$, corresponding to the two-body $\gamma p \to n\pi^+$ reaction, was obtained around zero, standing on top of a flat background. This background, coming from multipion final states, never exceeded 10% and was subtracted from the ϕ distributions of selected events.

For photons linearly polarized in the vertical plane with a polarization degree P, the cross section can be written as

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{pol}}(\phi) = \left(\frac{d\sigma}{d\Omega}\right)_{\text{unpol}}(1 + P\Sigma\cos(2\phi)),$$

where ϕ is the angle between the reaction plane and the horizontal plane and Σ is the beam asymmetry. The cylindrical symmetry of the detector provides the distributions of selected events over the entire range 0–360° of ϕ angles. Measurements were carried out with two alternated orthogonal states of the beam polarization.

The asymmetry is extracted (Fig. 2) from the azimuthal distribution of events for one of the polarization states, normalized to the azimuthal distribution corresponding to an unpolarized beam

$$\begin{aligned}\left(\frac{d\sigma}{d\Omega}\right)_{\text{pol}}(\phi) / \left(\frac{d\sigma}{d\Omega}\right)_{\text{unpol}} &= 1 + P\Sigma\cos(2\phi) \\ &= 2F_{\text{ver}}(\phi)/(F_{\text{ver}}(\phi) + \alpha F_{\text{hor}}(\phi)),\end{aligned}$$

F_{hor} and F_{ver} are the measured azimuthal distributions of events for each polarization state, α is the ratio of the beam fluxes corresponding to the vertical and horizontal polarizations. This procedure decreases significantly the systematic errors of the extracted asymmetries. The remaining systematic error, estimated as not more than 0.02, is due to the uncertainties originating from the possible deterioration of the laser light polarization on the mirrors, lenses and the window of the laser focusing system, from slightly different beam profiles on the target for each polarization state and from insignificant uncertainties in the background subtraction.

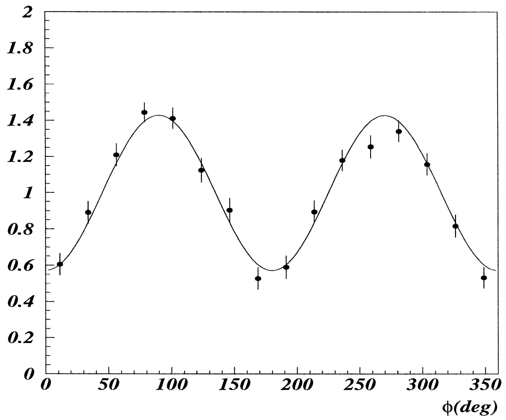

Fig. 2. $2F_{\text{ver}}(\phi)/(F_{\text{ver}}(\phi) + \alpha F_{\text{hor}}(\phi))$. Normalized azimuthal distribution at $E_\gamma = 950$ MeV and $\theta_{\text{cm}} = 135°$. The fitted curve $(1 + P\Sigma\cos(2\phi))$ makes it possible to extract the beam asymmetry $\Sigma = \Sigma(E_\gamma, \theta_{\text{cm}})$.

Our results, shown in Fig. 3 together with the most accurate previous results [16,18,19], are in good agreement with the other experiments. New data points are produced in the almost unmeasured region of backward angles up to 160°. There is a discrepancy in these angles with two existing points at 900 MeV from Ref. [18] which are also in contradiction with the results of Ref. [16].

At energies below 750 MeV and above 1050 MeV, the results of the VPI analysis are confirmed. Between 800 and 1000 MeV the SM95 solution is rather lower at backward angles. The recent WI98 solution is a significant step toward our results. However, it still differs in the region of 850–1000 MeV at backward angles and seems to be slightly worse below 700 MeV.

We have compared our results also with the predictions of Drechsel et al. [4]. This newly developed

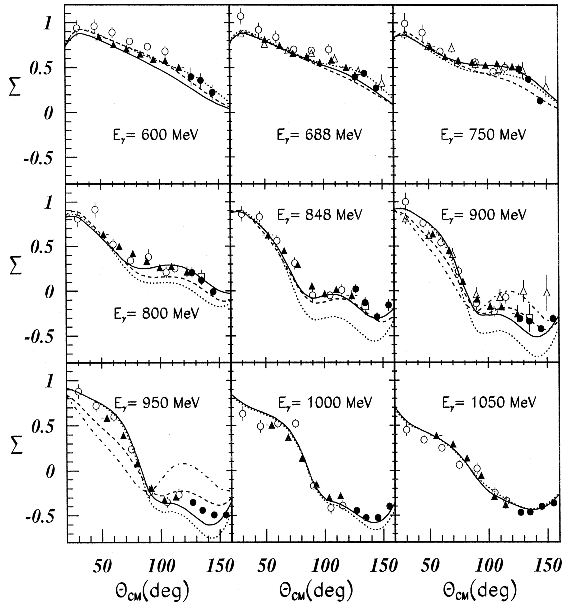

Fig. 3. Σ-asymmetry for positive pion photoproduction at different incident γ energies. Black triangles are our results for both outgoing particles (π^+ and neutron) detected by the BGO ball, black circles are our results for the neutrons emitted at forward angles: open circles are the results of the Daresbury group [19], open triangles and squares are from SLAC [18,16]. The solid and dotted lines are the WI98 and SM95 solutions of the VPI partial-wave analysis, respectively [13], and the dashed and dash-dotted lines are the predictions from [4] with and without $S_{11}(1650)$.

unitary isobar model for pion photo- and electroproduction includes all the main resonances. Resonances properties were determined from the fit to pion photoproduction data, initially starting from the VPI parameters set. While a reasonable agreement with the previous analyses was achieved, the extracted $S_{11}(1650)$ helicity coupling $A^p_{1/2} = 39 \times 10^{-3}$ GeV$^{-1/2}$ was essentially smaller, than it was quoted by two groups: the VPI ($A^p_{1/2} = (69 \pm 5) \times 10^{-3}$ GeV$^{-1/2}$ [12]) and the PDG ($A^p_{1/2} = (53 \pm 16) \times 10^{-3}$ GeV$^{-1/2}$ [25]). This model seems to reproduce our data up to 950 MeV, with a minor deviation in the region of 750 MeV. The important role of $S_{11}(1650)$ at backward angles is illustrated in Fig. 3. Four curves are plotted: two corresponding to calculations [4] with and without $S_{11}(1650)$ contributions (respectively $A^p_{1/2} = 39 \times 10^{-3}$ GeV$^{-1/2}$ and $A^p_{1/2} = 0$) and two with the VPI solutions SM95 ($A^p_{1/2} = (69 \pm 5) \times 10^{-3}$ GeV$^{-1/2}$) and WI98 ($A^p_{1/2}$ is not yet available [26]).

A similar result was obtained in [5], where the effective Lagrangian approach was applied for both meson scattering and photoproduction. In order to fit properly the kaon-photoproduction data, authors reduced the helicity coupling of the $S_{11}(1650)$ resonance. The overall fit reasonably reproduced the whole data base, including previous pion photoproduction data, with the couplings $A^p_{1/2} = 31$, 33, or 45×10^{-3} GeV$^{-1/2}$ for three variations of the fitting procedure.

This Σ data at backward angles, together with the results of [4,5], suggest a smaller contribution of the $S_{11}(1650)$ resonance, than it was previously assumed. It is likely, that the coupling strengths of another resonances should be also re-evaluated. However, definite conclusions should be the subject of a careful analysis, now carried out by the VPI group [26].

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