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Precise measurement of Σ beam asymmetry for positive pion photoproduction on the proton from 800 to 1500 MeV

GRAAL Collaboration

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Abstract

The Σ beam asymmetry for positive pion photoproduction on the proton has been measured over an angular range of 40–170° at photon energies from 0.8 to 1.5 GeV. The resulting data set includes 237 accurate points, 136 of these belonging to an almost unexplored domain above 1.05 GeV. Data of such high precision provide severe constraints for partial wave analyses. The influence of this experiment on the GW multipole analysis is demonstrated. Significant changes are found in multipoles connected to the $S_{31}(1620)$ and $P_{13}(1720)$ resonances. Comparisons using the MAID analysis are also presented.

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The spectrum of baryon resonances contains important information regarding the internal structure of the nucleon. Precise determinations of resonance properties (masses, widths, and electromagnetic couplings) provide vital benchmarks for the development of quark models. Much of our present knowledge has been obtained through pion–nucleon scattering. The existence of many resonances has been established and some properties have been determined with reasonable precision [1]. However, many features of the baryon spectrum remain a mystery. Among 43 nucleon and delta resonances predicted by QCD-inspired models [2], only 24 have been well established ("four-star" or "three-star" resonances [1]). The remaining (existing) resonances are either masked by overlapping states or are weakly excited in reactions coupled to the single-pion–nucleon channel.

Meson photoproduction offers a complementary approach to the baryon spectroscopy. The photoproduction of mesons other than pions allows access to states which could be suppressed in the pion–nucleon scattering. Here, and also in the case of pion photoproduction, the beam asymmetry observable Σ has proven to be particularly sensitive to resonance properties [3].

Properties of resonances are extracted from the photoproduction data by means of partial wave analysis and multipole decomposition in the framework of different approaches [4,5]. The comparison of calculated observables to experimental data constrains theoretical models [6,7] and determines the role and properties of the included resonances. The quality of this procedure is directly related to the quality of the data base. The extraction of resonance parameters clearly requires both the unpolarized cross section and polarization observables [8,9]. While the cross section is a source of information on dominating components of the scattering amplitude, the polarization observables, in particular the polarized-photon beam-asymmetry Σ, are much more sensitive to the non-dominant contributions.

The high yield and kinematic simplicity of single-pion photoproduction offers an opportunity to produce high precision experimental data. Several recent attempts have been made to study the nucleon and Delta resonances using single-pion photoproduction data, from which parameters of the dominant resonances have been extracted [4,5,7]. Uncertainties for other resonances remain large, due both to the quality of available data and model-dependence inherent in the extraction process.

The world data base is rather extensive, containing 20 000 data points for a single-pion photoproduction [4] below 2 GeV. However, this count includes many old unpolarized cross sections measured with bremsstrahlung beams in the first and second resonance regions. There is a clear lack of polarized data above 1 GeV. Only a few tens of beam asymmetry points, of low accuracy and dated before 1980, are available for the $\pi^+ n$ final state. In this Letter, we report a new measurement of the beam asymmetry Σ for positive-pion photoproduction on the proton over the energy range of 0.8–1.5 GeV. We shall see that, by adding a significant number of precise points to the data base, an important constraint is placed on the existing partial wave analyses.

The present data have been obtained at the GRAAL facility. The polarized and tagged photon beam is produced by backscattering of laser light on 6.04 GeV electrons which circulate in the storage ring of the ESRF (Grenoble, France). Through the use of green 514 nm laser light, the tagged spectrum covers an energy range of 0.55–1.1 GeV. Alternately, the UV 351 nm line can be employed, resulting in an energy range of 0.8–1.5 GeV. The linear beam polarization varies from ~0.45 at the lower energy limits to 0.98 at the upper limits. The detection system includes three main parts.

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- At forward angles $\theta_{\mathrm{lab}} \leqslant 25^{\circ}$ there are two planar wire chambers, a thin time-of-flight (TOF) hodoscope made up of 26 horizontal and 26 vertical plastic scintillator strips, each 3 cm thick, and a TOF shower wall [10]. The latter is an assembly of 16 modules, each being a sandwich of four converter-plus-scintillator layers.
- At central angles from 25 to 155°, the target is surrounded by two cylindrical wire chambers, a 5 mm thick scintillator ΔE barrel, and a BGO ball made up of 480 crystals, each of 21 radiation lengths [11].
- At backward angles $\theta_{\mathrm{lab}} \geqslant 155^{\circ}$ there are two plastic scintillator disks separated by a 1 cm lead converter.

The apparatus provides the detection and identification of all types of final state particles in an almost 4π solid angle and has cylindrical symmetry, making it suitable for measurements of the beam asymmetry Σ. The detailed description of the GRAAL facility and the procedure used in deriving Σ from experimental data may be found in [10–13].

The present measurement is a high energy extension of the previous one, performed at GRAAL in the energy range of 0.6–1.1 GeV by using the green laser line [13]. One important advantage of this measurement is the use of the high resolution cylindrical chambers, in coincidence with the scintillator barrel and BGO ball, to detect pions and to reconstruct their trajectories. As a result, the determination of the scattering angle Θ_{cm} is made possible with an average accuracy of 2.5° (FWHM). This feature allows a reduction in the widths of angular bins and decreases systematic uncertainties related to the granularity of the BGO ball. Furthermore, an improved background rejection is achieved by requesting this triple coincidence between the chambers, the barrel, and the BGO ball.

Neutrons at forward angles, corresponding to backward pions, were detected in the forward shower wall. Their discrimination from other types of particles is made possible by means of the anticoincidence of the wall with the preceding planar chambers and scintillator hodoscope, and by using a ΔE–TOF relation [10]. Neutrons emitted at central angles above 25° were detected in the BGO ball. The wire chambers and the scintillator barrel surrounding the target allow a discrimination between neutral and charged particles. Further separation between photons and neutrons is possible, considering the number of BGO crystals in the cluster which correspond to a neutral particle hit. As found in GEANT simulations, neutron clusters normally do not contain more than 3 crystals. Photons, however, produce larger clusters of a size depending on the deposited energy, and usually include 4–10 crystals. The identification of charged pions and their discrimination from protons is achieved by using $\Delta E - E$ relations between the energy ΔE deposited by a charged particle in the thin scintillator barrel and the corresponding energy deposition E in the BGO ball.

The TOF resolution for neutrons in the shower wall is 700 ps (FWHM) [10]. For fast neutrons in the forward direction, this results in a poor energy resolution of about 30% depending on the neutron kinetic energy. The response of the BGO ball for both neutrons and pions is not uniquely related to the kinetic energy due to the complicated interaction of these particles in the detector volume [11]. By contrast, the angles of outgoing particles are measured with good resolution: 3° (FWHM) for pions, 2.5–3° (FWHM) for neutrons in the forward direction and 6–8° (FWHM) for neutrons at central angles. For this reason, only the angular quantities have been exploited for the identification of the $\pi^{+}n$ final state. For those events which have generated two hits in the detection system, associated with a pion and a neutron, the correlation between the pion and neutron Θ angles and the coplanarity have been used to select the $\pi^{+}n$ events. After this selection, the spectrum of the reaction coplanarity $(\phi_n - \phi_\pi)$ exhibited a narrow peak (Fig. 1) lying on the broad background originating mostly from multipion production. The contribution of this background, which never exceeded 3%, was evaluated from the tails in $(\phi_n - \phi_\pi)$ distributions and subtracted separately in each $\Delta E \Delta\Theta \Delta\phi$ bin, in order to account for the possible azimuthal anisotropy of this background.

The beam asymmetry Σ was extracted from the azimuthal distribution of selected events for the linearly polarized beam, normalized to the azimuthal distribution corresponding to an unpolarized beam, as it is described in details in [13]. This procedure reduces significantly systematic errors of the extracted asymmetries. The remaining systematic errors, estimated as not more than 0.02, originate from the unsignificant

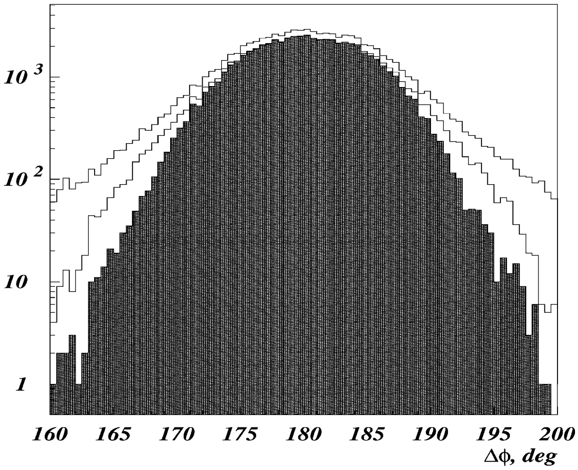

Fig. 1. Spectrum of the coplanarity ($\phi_n - \phi_\pi$). Upper curve corresponds to the selection of one neutral and one charged hit in the detector; medium curve is after the identification of a neutron and a pion; black area indicates finally selected events.

uncertainties in the background subtraction and from the slight variations of the beam profile on the target. Another source of the systematic uncertainty is the possible deterioration of the laser light polarization on the mirrors, lenses and the window of the laser focusing system. This factor adds the relative error of 1%.

The present set of 237 Σ beam asymmetries, measured over the energy and angular ranges of 800–1500 MeV and 40–160°, is an extension of a previous GRAAL data set consisting of 92 data points from 600 to 1050 MeV. The two sets of points are shown at overlapping energies in Fig. 2. The new data have been measured using the UV laser, producing a different beam spectrum and a different polarization for each beam energy [12]. Some improvements in the apparatus and the analysis procedure have also been implemented. Given these differences, the reproducibility of our results is excellent and supports the quality of both data sets.

The major part of our new results is shown in Fig. 3, along with results from the most accurate older experiments [14–16]. In general, our values are in agreement with the previous measurements. However, above 950 MeV, we do not confirm four points from [14] at 75°. 136 data points were produced in an almost unexplored domain above 1050 MeV, where only 45 old points of lower accuracy were available. The new results also cover backward angles above

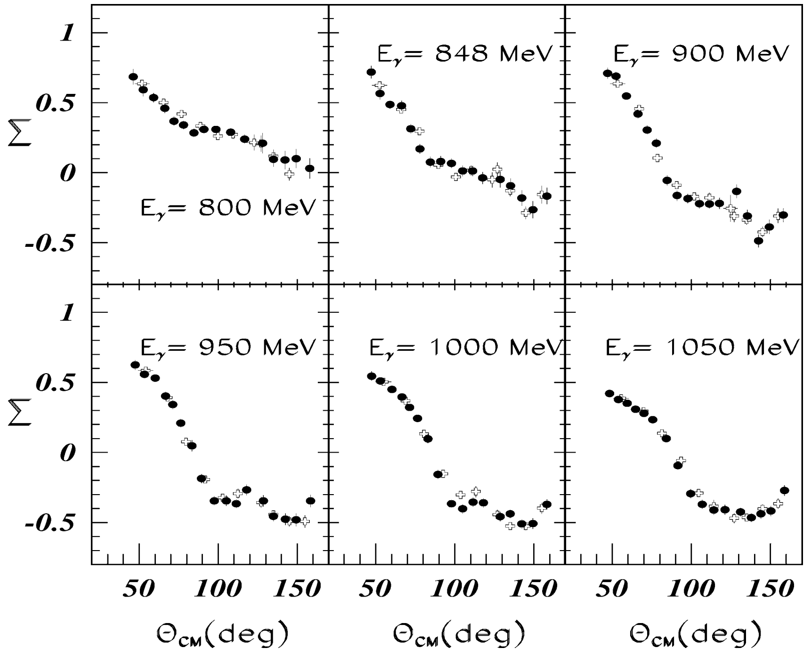

Fig. 2. Comparison of new and previous GRAAL results. Black circles are the new points, crosses are the results of the previous measurement [13].

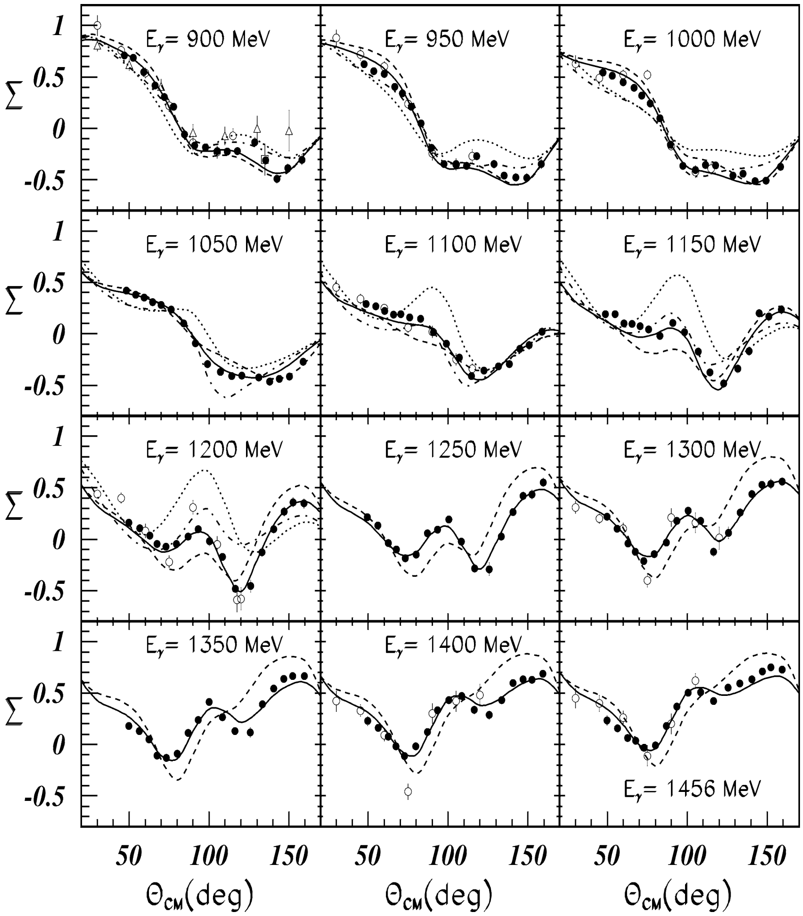

Fig. 3. Σ beam asymmetry at different energies. Black circles indicate our results (error bars are the quadratutes of the statistic and systematic errors); open circles indicate the results of the Daresbury group [14]; open triangles and squares indicate the results from SLAC [15,16]. The solid and dashed lines indicate the FA01 and WI00 solutions of [4], respectively; the dotted line is the prediction of MAID2000 [5]; the dashed line is MAID2000 after fitting the benchmark database [17].

120°, where no previous measurements exist. Due to improved angular resolution, these results have been obtained with narrow angular bins of 6–10°, which reveal a complicated angular variation in the Σ asymmetry.

We have compared our results with the prediction of a unitary isobar model of Drechsel et al. [5]. This model, known as MAID2000, in addition to Born terms and vector meson exchange, includes all 3- and 4-star resonances to a CM energy of 1800 MeV, apart from the $P_{33}(1600)$ and $D_{15}(1675)$. The latest version of these calculations [17], which includes resonance parameters obtained from a fit to the restricted benchmark data base [18], in general reproduces our data up to 1200 MeV, though in some regions discrepancies are still significant.

In order to assess the impact of our new data, we employed the partial wave analysis of the Data Analysis Center of The George Washington University (SAID) [4]. Two solutions of the SAID analysis are shown in Fig. 3: WI00, which was produced prior to this measurement, however using our previous results [13], and FA01, a solution developed after adding our new polarized data and cross section points [19] to the data base. At the lower energies between 900 and 1050 MeV, the WI00 solution is found to be in agreement with the new data, although differing slightly at angles less than 70°. At the higher energies, differences become more apparent and only a qualitative agreement is available. The FA01 solution fits our data reasonably well, with $\chi^2/$data of 555/237, compared to an overall $\chi^2/$data ~ 2 for the full data base (in both WI00 and FA01).

In order to illustrate the effect of new data in the SAID analysis, we compare ${}_pE_{0+}^{1/2}$, ${}_pE_{0+}^{3/2}$, and ${}_pE_{1+}^{1/2}$ multipoles of the WI00 and FA01 solutions. Partial cross section contributions from these multipoles are shown in Fig. 4.

${}_pE_{0+}^{1/2}$ *multipole.* Two distinct peaks correspond to the $S_{11}(1535)$ and $S_{11}(1650)$ resonances. The possibility of a third S_{11} resonance, near 1750 MeV, has been considered in several recent studies [6,20,21]. The effect of this resonance was found to be particularly significant in a study of eta photoproduction data [6]. In Fig. 3, this state would be hidden in the shoulder of the second S_{11} peak of the FA01 solution. Another candidate has been suggested at higher energy (the $S_{11}(2090)$). The "one-star" $S_{11}(2090)$ included in Refs. [22,23] has an estimated mass nearer to 1900 MeV. A further indication for this state stems from the analysis of low-statistics η' photoproduction data [23].

Differences appearing in the ${}_pE_{0+}^{1/2}$ wave may be indications of such states, which have not been included in either of the displayed fits (WI00 and FA01). However, the signals are weak. New data at higher energies (π^0 data from GRAAL) are required before any conclusion is possible. These states, if they exist, can only be weakly coupled to πN (as is evident in the low cross section). Clearer results may come from other channels, such as ηN, through studies such as the one reported in Ref. [6]. Forthcoming GRAAL and CLAS η photoproduction data are clearly of great importance to this issue.

${}_pE_{0+}^{3/2}$ *multipole.* The peak existing in the WI00 solution corresponds to the $S_{31}(1620)$ resonance. This structure nearly vanishes in the FA01 solutions.

${}_pE_{1+}^{1/2}$ *multipole.* An opposite trend is found in this multipole. Here a much more pronounced structure,

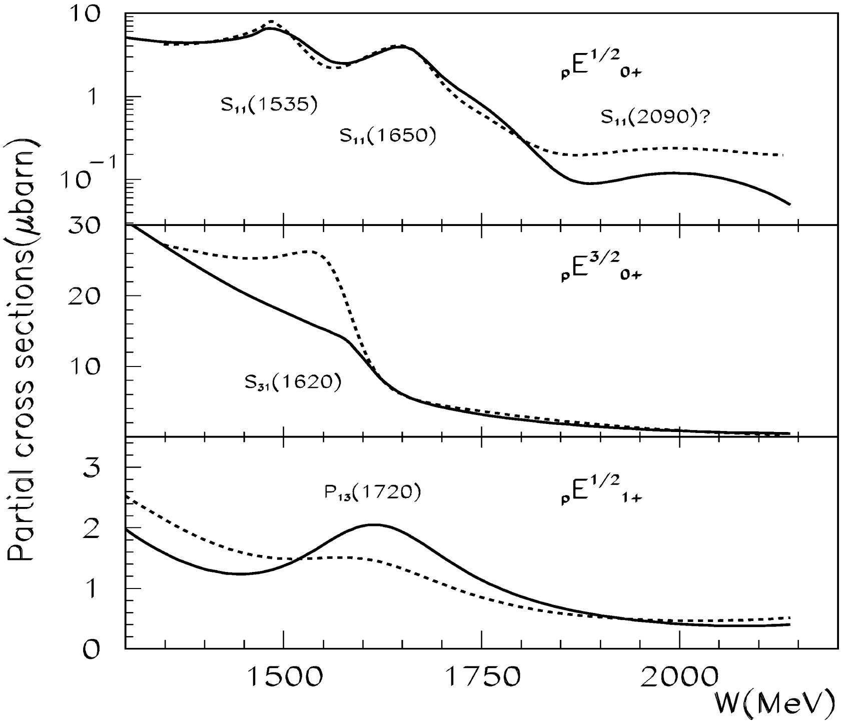

Fig. 4. ${}_pE_{0+}^{1/2}$, ${}_pE_{0+}^{3/2}$, and ${}_pE_{1+}^{1/2}$ multipoles of the SAID analysis. Solid line gives the FA01 solution, and the dashed line is from WI00.

corresponding to the $P_{13}(1720)$, is seen in the revised fit.

At present, the $P_{13}(1720)$ and $S_{31}(1620)$ resonances have poorly determined photo-decay amplitudes. Neither state can be identified through the "canonical" resonance behavior of its associated multipoles. A similar problem is seen in the analysis of elastic pion–nucleon scattering data [20]. Both states have nearby pole-zero pairs in the complex energy plane. As a result, resonance properties are difficult to determine.

The ambiguous situation surrounding the $S_{31}(1620)$ has been pointed out in [24]. The Particle Data Group estimates the photo-decay coupling of the $S_{31}(1620)$ to be $A_{1/2} = (0.027 \pm 0.011)\ \mathrm{GeV}^{-1/2}$ [1]. This value was obtained as a weighted average of contradicting results from [4,25], which range from (-0.026 ± 0.008) to $(0.126 \pm 0.021)\ \mathrm{GeV}^{-1/2}$. In a recent multichannel fit [7] this quantity was found to be near zero. Our results also suggest a small value.

We have studied the sensitivity of observables in the WI00 and FA01 solutions to the $S_{31}(1620)$ resonance. For $W = 1620$ MeV, we found an essential difference (10–15%) between two solutions for the Σ, T, and P observables in $\pi^+ n$ photoproduction, and Σ observable in $\pi^0 p$ photoproduction (Σ, T, P denote beam, target, and recoil asymmetries respectively). For $\pi^0 p$ T and P observables the difference reaches 30–40%. New polarized data from modern photon factories are clearly needed to place more constraints on determination of properties of this and other resonances.

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