# New Measurement of $\Sigma$ Beam Asymmetry for $\eta$ Meson Photoproduction on the Proton

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We present new $\Sigma$ beam asymmetry data for $\eta$ meson photoproduction on the proton, using a novel tagged, laser backscattered, linearly polarized photon beam up to 1.1 GeV. The data show large, positive asymmetries, at all incident photon energies. In addition to the $S_{11}(1535)$ and $D_{13}(1520)$ resonances necessary to reproduce the cross sections, $P_{13}(1720)$ and $D_{15}(1675)$ "four stars" resonances contribute to the $\Sigma$ observable, but cannot reproduce the strong forward asymmetries measured at energies higher than 900 MeV. [S0031-9007(98)06957-9]

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The underlying substructure of the nucleon gives rise to a rich spectrum of excited states, many of which have been associated with the baryon resonances seen in $\pi N$ scattering [1] and $\pi$ photoproduction. These baryon resonances and their associated $\gamma NN^*$ electromagnetic couplings form bench marks for models of hadron structure. Quark models have been quite successful in accounting for the masses of most observed resonances, although in some cases the electromagnetic couplings have presented more of a challenge [2].

At energies above the first excited state of the nucleon [the $P_{33}(1232)$ resonance], the baryon spectrum is severely complicated by the presence of many broad overlapping states, and this has limited the constraints that can be placed upon theory. Several "missing resonances" have also been predicted which have so far escaped experimental identification, these being either unresolved or only weakly coupled to the $\pi N$ channel [3]. The $\pi$ meson carries isospin $I = 1$, and as a result can couple to both isospin $1/2$ and $3/2$ channels. However, since the $\eta$ meson has $I = 0$, the $(\gamma, \eta)$ process offers the very attractive possibility of being completely insensitive to all $I = 3/2$ resonances. In addition, comparatively few baryon resonances have a significant decay branch into the $\eta N$ channel. This reduces the complexity of the spectrum considerably. Moreover, the comparison between amplitudes for resonances seen in $(\gamma, \eta)$ and $(\gamma, \pi)$ would significantly reduce the model dependence in the separation of the entrance channel electromagnetic couplings from the strong meson-decay modes.

Multipole analyses of meson photoproduction are necessary to extract resonance properties. These require a minimum of eight observables to avoid ambiguities: the cross section, the three single-polarization observables (polarized beam, target, and nucleon recoil) and four appropriately chosen double-polarization observables [4]. Such complete information is not available and the extraction of resonance parameters is necessarily model dependent. Polarization observables provide important constraints on this extraction. For this, one of the most important is the beam asymmetry $\Sigma$, i.e., the beam polarization analyzing power of a photoproduction reaction induced by linearly polarized photons. This asymmetry is very sensitive to interfering multipoles of opposite parity and has frequently been used to separate electric and magnetic excitations. In this Letter, we present the first measurements of the $\Sigma$ observable for the $\eta$ meson photoproduction on the proton from threshold up to 1.1 GeV.

Below 1 GeV, the $S_{11}(1535)$ resonance which has a branching ratio to $\eta N$ much larger than the other neighboring resonances, plays a highly dominant role for the cross section observable [5], while the Roper $P_{11}(1440)$, the $D_{13}(1520)$, and the $D_{15}(1675)$ resonances give minor contributions. Other $P$ and $D$ wave resonances can be ignored [6,7]. As will be shown in this paper, all $P$ and $D$ wave resonances contribute significantly to the $\Sigma$ observable, mainly through interferences with the $S_{11}(1535)$. Accordingly, it should be possible to better evaluate the contribution of individual resonances as well as to understand nonresonant mechanisms (Born terms including vector meson exchange). Approaches as those of Ref. [7], where the determination of the $S_{11}(1535)$ electromagnetic coupling strengths from the available $\eta$ photoproduction data was attempted, will therefore provide more reliable results.

For the photoproduction of the $\pi$ meson, the experimental situation is extensive [8], while for the $\eta$ meson, only differential cross section data [9] and four polarization points, corresponding to the recoil proton polarization [10], all measured before 1974 using untagged photon beams, are available. The recently published results concerning the differential and total cross sections are devoted either to the study of the threshold behavior [11] or to the investigation at energies above the $S_{11}(1535)$ region [12]. For the $\Sigma$ beam asymmetry observable, a few points exist above 1.39 GeV [13], but no measurement has been done near threshold. Our present $\Sigma$ data complement the differential cross sections on the proton [11,14], on the neutron [15], and the recent target asymmetry data on polarized protons from Bonn [16], all measured from threshold to above 1 GeV, to provide new information on the $\gamma\eta$ process in the $S_{11}(1535)$ region.

Our measurements have used the GRAAL [17] polarized and tagged photon beam obtained by the backscattering of laser light on the high energy electrons circulating in the 6.04 GeV storage ring of the ESRF (European Synchrotron Radiation Facility) in Grenoble. The linear polarization of the beam results from the conservation of the laser polarization in the Compton backscattering. The energy dependence of the polarization can be calculated by QED, from the laser light polarization at the collision point, and has been estimated by computer simulation, taking into account laser and electron beams emittances. It varies from 0.98 at the maximum photon energy to 0.69 at the $\eta$ threshold. In the measurements presented here, using a green line at 514 nm, the $\gamma$-ray energy spectrum extended from the maximum energy of 1.1 GeV to the lowest tagged energy of 550 MeV, well below the $\eta$ photoproduction threshold. The tagging detector provides an energy resolution of 16 MeV (FWHM) which is limited by the emittance and the energy spread of the electron beam. The $\gamma$ tagging rate was up to $2 \times 10^6$ photons per second for the integrated spectrum. It was continuously monitored on line using a set of three thin plastic scintillators and a total absorption detector [18]. The liquid hydrogen target was contained in a Mylar cell of 3 cm length and 4 cm diameter.

The $4\pi$ detector, for the detection of neutral and charged particles, consists of a cylindrical central part and a forward detector. The particles emitted into the central part at angles between 25° and 155° with respect to the beam axis, pass through two coaxial cylindrical wire chambers, a barrel made of 32 plastic scintillators, that provides $\Delta E$ information for particle identification, and the BGO ball made of 480 $Bi_4Ge_3O_{12}$ crystals each of 21 radiation lengths. The BGO has cylindrical symmetry around the beam axis with 15 segments in the axial plane and 32 in the transverse one [19]. The energy resolution for $\gamma$ ray detection is 3% at 1 GeV [20].

The particles emitted in the forward direction at polar angles less than 25° pass two plane wire chambers that provide tracking angular resolution of 0.5° and a double wall of plastic scintillators covering an area of $3 \times 3$ m$^2$ and located 3 m away from the target. This detector gives an angular resolution of 2°, a measurement of the time of flight (TOF) with a resolution of 600 ps (FWHM) and a $\Delta E$ information. It is followed by a shower detector consisting of 16 vertical modules (lead/scintillator sandwiches) covering the same area as the double plastic wall, having similar time and angular specifications and a limited energy resolution for photons.

An energy deposition in the BGO larger than 200 MeV in coincidence with an electron in the tagging detector, triggers the data acquisition. We have collected data on the photoproduction of $\pi^0$, $\pi^+$, $2\pi^0$, and $\eta$. For the reaction $p(\gamma, \eta p)$, events corresponding to two or six photons from $\eta \rightarrow 2\gamma$ or the $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ decay channels in the BGO, or one photon in the BGO and one photon in the forward shower detector were collected and analyzed. Recoil protons were detected either in the BGO or in the forward detectors.

Figure 1 shows the invariant mass spectrum for $2\gamma$ events, reconstructed from the energy and angles of each decay photon hitting the BGO. With the tagger providing the energy of the incoming $\gamma$ and all particles detected in the final state, the reaction is overdetermined and the events from $\eta$ photoproduction are easily identified using kinematical constraints. The events for which one of the photons is detected by the shower detector have been analyzed using a global kinematical fit. These events provide a statistically independent set of data. Empty target runs have indicated a contribution of the order of 1%, consistent with the target walls thickness.

For a photon linearly polarized in the vertical direction, the differential cross section for $\eta$ photoproduction is

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{\mathrm{unp}}}[1 + P\Sigma\cos(2\varphi)], \qquad (1)$$

where $P$ is the polarization degree of the photon and $\varphi$ is the angle between the reaction plane and the horizontal plane. The cylindrical symmetry of the GRAAL detector allows this $\cos(2\varphi)$ dependence to be observed directly in the azimuthal distribution of events. By switching the polarization alternatively between horizontal and vertical states, two independent sets of data were collected. The sum of the two yields normalized by the respective fluxes

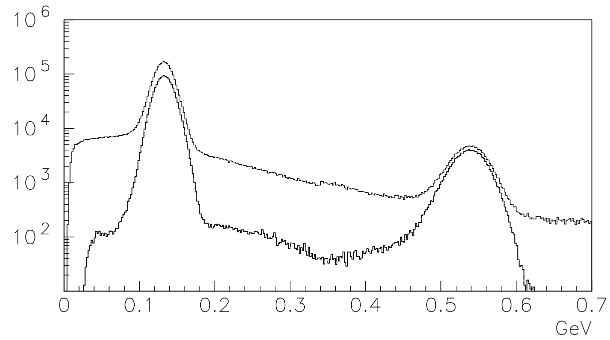


FIG. 1. Upper curve: invariant mass for $2\gamma$ events calculated from the BGO response. Two peaks are clearly visible at the $\pi^0$ and $\eta$ masses before kinematical cuts. Lower curve: invariant mass for $2\gamma$ after kinematical cuts. The resolution on the $\eta$ mass is 50 MeV FWHM.

$N_{\mathrm{hor}}$ and $N_{\mathrm{ver}}$ provides the unpolarized cross section $d\sigma_{\mathrm{unp}}$ and the possibility to correct for small anisotropies in the azimuthal response of the detector. Figure 2 shows the ratio:

$$\frac{d\sigma}{d\sigma_{\mathrm{unp}}} = \frac{2N_{\mathrm{ver}}}{N_{\mathrm{ver}} + N_{\mathrm{hor}}} = 1 + P\Sigma\cos(2\varphi). \quad (2)$$

The values of $\Sigma(E_\gamma, \theta)$, where $E_\gamma$ is the photon energy and $\theta$ the polar angle of the outgoing $\eta$, result from a fit to the distributions obtained in this way. The results are shown in Fig. 3. The asymmetries are large and positive. Below 900 MeV, the angular distribution is fairly symmetric around 90°, but at the highest $\gamma$ incident energies, there is a marked forward peaking, with large asymmetries, reaching values as high as 70%. The small polarization loss of the fully polarized laser light, by mirror reflections and window transmissions along the beam optics, is the main source of a $\pm 2\%$ systematic error on the data points.

Several predictions for the $\Sigma$ asymmetries can be derived from the existing models that fit the differential cross sections. The authors of Ref. [6] use a coupled channel analysis based on $\gamma\pi$, $\pi\pi$, and $\pi\eta$ data to predict the $\gamma\eta$ channel. They include in their model, only the first $N^*$ resonances: Roper $P_{11}(1440)$, $S_{11}(1535)$, and $D_{13}(1520)$. The corresponding predictions are shown by the dotted curves. Although positive asymmetries result from this approach, the agreement is poor, except at 808 MeV. In Ref. [21], an effective Lagrangian formalism, that contains Born terms and both vector meson and nucleon resonance contributions [$P_{11}(1440)$, $S_{11}(1535)$, $D_{13}(1520)$, and $D_{15}(1675)$], has been developed and fitted to recent $\gamma\eta$ cross section data. The corresponding predictions for the $\Sigma$ observable follow the dashed curves. The agreement is quite good at energies below 900 MeV, but the large asymmetries observed at higher energies are not reproduced.

In an attempt to reproduce the large forward asymmetries, the "nodal approach" developed by the authors of Ref. [22] was used. In this framework, the angular structure of spin observables provides a powerful tool to find out which angular momentum quantum numbers, corresponding to excited intermediate resonances, must play a role in pseudoscalar meson photoproduction processes [23]. Such an analysis, limited to resonances with intrinsic angular momenta $L \leq 2$, has been carried out for the target asymmetry observable $T$ [16] and has shown that all "four stars" $S$, $P$, and $D$ resonances must be taken into account [24]. A similar nodal analysis including our $\Sigma$ data points, shows that $S_{11}$, $P_{13}$, $D_{13}$, and

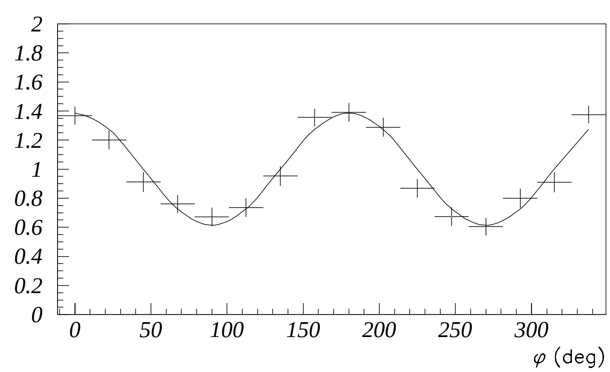


FIG. 2. Azimuthal distribution at $E_\gamma = 990$ MeV and $\theta = 90°$. The fitted curve $[1 + P\Sigma\cos(2\varphi)]$ provides the value for $\Sigma = \Sigma(E_\gamma, \theta)$.

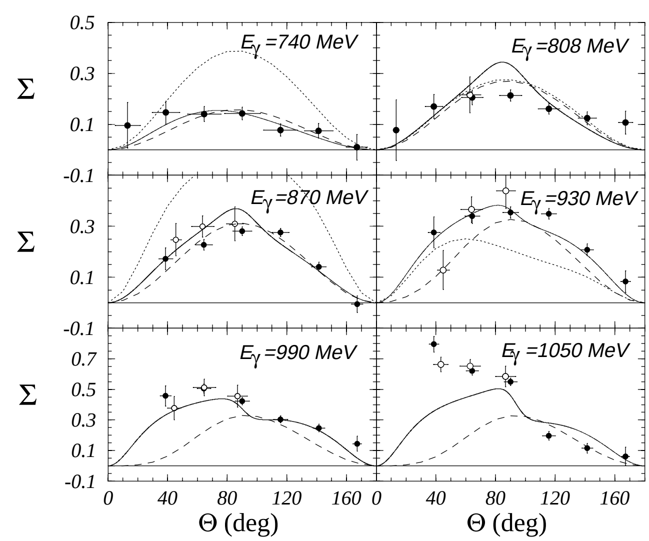


FIG. 3. $\Sigma$ observable, at different incident $\gamma$ energies, corresponding to the photoproduction of the $\eta$ meson on the proton as a function of the $\eta$ angle $\Theta$ in the c.m. The full circles are the results when the 2 or 6 decay photons are all detected in the BGO ball. The open circles are the results for one photon in the BGO and the other one in the shower detector. The error bars include statistical and systematic errors. The horizontal bars indicate the angular resolution. Predictions from already published approaches are dotted curves, Ref. [6]; dashed curves, Ref. [21]. Full curves, fit to our data resulting from the nodal approach, Ref. [25].

$D_{15}$ resonances are needed, with no evidence for $P_{11}$ [25]. The fit obtained with the inclusion in the dynamical model [26] of the established $S_{11}(1535)$, $D_{13}(1520)$, $P_{13}(1720)$, and $D_{15}(1675)$ resonances and a "missing" $P_{13}$ ($M = 1880$ MeV, $\Gamma = 150$ MeV) resonance is shown by the full curve in Fig. 3. There is a significant improvement towards fitting the large forward asymmetries at the highest energies. It is worth noting that it is the inclusion of a missing $P_{13}$ resonance, predicted by quark model calculations [3], but not yet observed experimentally, which generates significant forward peaking as observed experimentally in our $\Sigma$ data [25]. The inclusion of this resonance also produces the best fit to the $T$ observable [24].

However, in spite of the contribution of a significant number of low multipole ($L \leq 2$) resonances, the large forward asymmetries cannot be reproduced. Large forward asymmetries were also observed on earlier data above 1.39 GeV [13]. Therefore, it is likely that the contribution of higher multipoles is needed. In particular, the $F_{15}(1680)$ resonance which is strongly excited in the initial channel, should play an important role. More comprehensive theoretical investigations, including higher multipole resonances, are expected using the available formalisms quoted above [7,21] as well as a recent quark-based approach [27], with the task to provide a simultaneous description of the cross section and of the asymmetry data.

In summary, we have presented new $\Sigma$ beam asymmetry data for the photoproduction of $\eta$ meson on the proton. Existing theoretical predictions, based on differential cross section data, cannot reproduce the large forward asymmetries showing up above 900 MeV. A fit of our data within the nodal approach shows the sensitivity of polarization observables to $P$ and $D$ resonances ignored in the differential cross sections fit, but fails to give a good account of the experimental results, in spite of the tentative inclusion of a missing $P_{13}$ resonance. It is argued that definite conclusions must await a global analysis of the existing data and the inclusion of higher multipole resonances, in particular the $F_{15}(1680)$.

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