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## Differential cross section measurement of $\eta$ photoproduction on the proton from threshold to 1100 MeV

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## Abstract

The differential cross section for the reaction  $p(\gamma, \eta p)$  has been measured from threshold to 1100 MeV photon laboratory energy. For the first time, the region of the S<sub>11</sub>(1535) resonance is fully covered in a photoproduction experiment and will allow a precise extraction of its parameters at the photon point. These high precision data together with the already measured beam asymmetry data will provide stringent constraints on the extraction of new couplings of baryon resonances to the  $\eta$  meson.

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The nucleon, like any composite object, shows a spectrum of excited states intimately connected to its internal structure. Precise measurements of the properties of these states offer a unique opportunity to test Quantum ChromoDynamics (QCD) in the nonperturbative regime and to approach the confinement problem. Historically, they have been first observed as baryon resonances in  $\pi$ -N scattering [1], with a rich spectrum typical of a few-body problem. Since the dominant decay channel of nucleon resonances is the strong decay through meson emission, photoproduction of light mesons ( $\pi$ ,  $\eta$ , K,...) gives a complementary way to access information about nucleon spectroscopy. Whereas elastic and inelastic  $\pi$  –N scattering have provided precise values for the masses and widths [2], meson photoproduction allows a measurement of the electromagnetic transitions, thus provides a stringent dynamical test for models of the nucleon.

Among the large variety of existing models [3], Constituent Quark Models (CQM) have been the most successful in accounting for the observed spectrum. These "QCD-inspired" models describe the nucleon as three massive constituent quarks ( $m_Q \approx 300 \text{ MeV}/c^2$ ) confined by a harmonic potential. The hyperfine interaction, essential to reproduce the spectrum, is derived from gluon exchange in the original approach, or meson exchange in the more recent chiral version of CQM [1]. Both versions also predict so far unobserved states ("missing resonances") whose absence has been interpreted, for instance, by a weak coupling to  $\pi$ -N channels [4].

Extraction of resonance properties in pion photoproduction is a difficult exercise since one needs to disentangle many overlapping contributions [5,6]. By contrast, eta photoproduction close to threshold is strongly dominated by a single resonance, the  $S_{11}(1535)$ , and thus is the ideal place to investigate this benchmark state for nucleon models. Analyzes of the available data base, including differential cross sections below 800 MeV [7], target asymmetries below 1000 MeV [8] and our beam asymmetry  $\Sigma$  measurements [9] have identified two other resonances: the  $D_{13}(1520)$  and the  $F_{15}(1680)$ . On the one hand,  $\Sigma$  was shown to be very sensitive to the  $D_{13}$  and allowed a precise extraction of its parameters [10–13]. On the other hand, the  $F_{15}(1680)$  was suggested to explain the forward peaking observed in  $\Sigma$  above 1000 MeV, but, in the absence of cross section data at this energy, no definite conclusion could be reached.

In this Letter, we report on measurements of the differential cross section and extraction of the total cross section for the reaction  $p(\gamma, \eta p)$  from threshold  $E_{\gamma} = 707 \text{ MeV} (W = 1485 \text{ MeV})$  to 1100 MeV (W = 1716 MeV), where *W* is the total CM energy.

These data have been obtained with the GRAAL facility, located at the ESRF (European Synchrotron Radiation Facility) in Grenoble. The polarized and tagged photon beam is created by Compton backscattering of laser light from the 6.04 GeV electrons circulating in the storage ring. The measurements presented here used the green line ( $\lambda = 514$  nm) of an Argon laser; the  $\gamma$ -ray energy spectrum extends from 500 MeV (geometrical limit of the tagging system) to the Compton edge at 1100 MeV. Detailed description of the beam,  $4\pi$  detector characteristics and acquisition system can be found in Refs. [9,14-17]. An energy deposition in the BGO calorimeter larger than 180 MeV in coincidence with an electron in the tagging system, triggers the data acquisition and allows simultaneous recording of the  $\pi^0 p$  and  $\eta p$  channels.

Complete detection of the reaction products is required in the event analysis. The photons from neutral  $\eta$  decays ( $\eta \rightarrow 2\gamma$  and  $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ ) are identified in the BGO calorimeter, while the recoil proton is tracked in wire chambers and characterized by time of flight (ToF) and dE/dx measurements. With the tagger providing the energy of the incoming photon, the kinematics is overdetermined and a clean event selection is easily achieved using kinematical cuts (6 in total). Two examples are given with the invariant mass of the  $\eta$  (Fig. 1(a)) and the missing mass calculated from the proton momentum (Fig. 1(b)). For both quantities, the simulated spectrum nicely reproduces the experimental shape, which indicates the reliability of the simulation program and the absence of any elec-



Fig. 1. (a) invariant mass spectrum for  $\eta \rightarrow 2\gamma$  decay; (b) missing mass spectrum, as calculated from the proton momentum. Data (full curve) and simulation (black dots) are presented with all kinematical cuts applied.

tromagnetic background. The average hadronic background has been estimated to be less than 1% [16].

The cross section normalization takes into account the target thickness, the photon beam intensity, the detection efficiency and the branching ratios of the *n*-meson decays taken from [2]  $(n \rightarrow 2\nu)$ : 39.21 ± 0.34%,  $\eta \rightarrow 3\pi^0$ : 32.2  $\pm$  0.4%). The thickness of the liquid hydrogen target is  $0.217 \pm 0.003$  g cm<sup>-2</sup>, which gives a contribution of 1.5% to the systematic errors. Empty target runs have indicated a contribution of the target walls of 0.9%, consistent with their thickness. The photon intensity is monitored by thin plastic scintillators located between the target and a total absorption calorimeter (Spacal) which serves as a beam dump. Both detectors are in coincidence with the tagging system and their ToF spectra are measured for correction of accidentals. The low efficiency of the thin monitor ( $\simeq 2.7\%$ ) prevents pile-up effects at high photon rate and is measured by comparison with the Spacal rate at low flux.

The detector efficiency (50% on average) is calculated with a complete Monte Carlo simulation of the apparatus, including the dependence of beam shape on energy and polarization, using a realistic event generator [18]. Apart from the geometrical acceptance, the main loss comes from the overlap of clusters associated with  $\gamma$ -rays in the BGO ball (4 crystals hit on average per photon). This effect is strongly correlated to the  $\gamma$ -ray multiplicity as well as the cluster threshold, and is, moreover, energy dependent. In order to test the reliability of our simulation code, the differential cross section has been calculated simultaneously for the two



Fig. 2. Differential cross section for the  $p(\gamma, \eta p)$  reaction at 800 MeV. Results for events with  $\eta \rightarrow 2\gamma$  (black dot) and  $\eta \rightarrow 3\pi^0$  (open triangles) decays are compared.

 $\eta$  decays:  $\eta \rightarrow 2\gamma$  and  $\eta \rightarrow 3\pi^0$ . The comparison at one energy (800 MeV) is displayed in Fig. 2 and illustrates the excellent agreement between both results. In addition, we have systematically used the high statistics reaction  $p(\gamma, \pi^0 p)$  to perform precise tests and comparisons with the world data base [16]. The error bars shown in the data correspond to the quadratic sum of all systematic and statistical errors except for those due to global normalization factors estimated to be  $\pm 3.0\%$ .

The total cross section has been obtained by integration of the differential cross section, using a polynomial fit in  $\cos \theta$  to extrapolate to the unmeasured region ( $\simeq 10\%$ ). A good reduced  $\chi^2$  is already achieved with a polynomial of degree two in agreement with the smooth behavior observed in our measurements. It should be noticed that this extrapolation procedure is a source of error that cannot be evaluated experimentally. The results calculated from threshold to 1100 MeV are plotted in Fig. 3. One can notice the nice agreement with previous measurements obtained at Mainz [7] except for a small discrepancy around 800 MeV.

As mentioned earlier, the  $S_{11}(1535)$  resonance strongly dominates  $\eta$  photoproduction up to 900 MeV and its parameters (mass, width and photocoupling amplitude) can be directly estimated from the shape of the total cross section. A fit with a single Breit-Wigner shape limited to energies less than 900 MeV gives  $M = 1543 \pm 2$  MeV and  $\Gamma_R = 174 \pm 8$  MeV for the mass and width of the resonance. Extending the fit



Fig. 3. Total cross section of the  $p(\gamma, \eta p)$  reaction. The GRAAL results (close circles) are compared with previous experimental results and to four different analyzes. See text for details.

to higher energies results in a much smaller width (for instance,  $\Gamma_R = 152 \pm 4$  MeV for  $E_{\gamma} \leq 950$  MeV) and underlines the presence of other contributions. Our extracted  $\Gamma_R$  is significantly smaller than the one obtained with the Mainz data ( $\geq 200 \text{ MeV}$ ) [7] but is in agreement with the PDG estimate (150 MeV) and also with two recent electroproduction experiments performed at JLab ( $\Gamma_R \approx 150$  MeV) [19,20]. The helicity amplitude  $A_{1/2}$  can be readily obtained from the maximum of the cross section. It shows less sensitivity to the energy range covered but is correlated to the branching ratio of the resonance to the  $\eta p$  channel,  $b_{\eta}$ . Taking  $b_{\eta} = 0.55$  for consistency with extractions from the two JLab electroproduction experiments, we obtain  $A_{1/2} = 102 \pm 2 \times 10^{-3} \text{ GeV}^{-1/2}$ . This value falls within the broad range of the PDG estimate (90  $\pm$  30), but, taking into account other contributions, especially the second  $S_{11}(1650)$ , might significantly change the result.

The differential cross section, plotted in Fig. 4 for a sample of photon energies as a function of  $\cos \theta$ where  $\theta$  is the  $\eta$  C.M. polar angle, was measured every 17 MeV between threshold and 1100 MeV (233 points). For the two lowest energies of the figure, data from Mainz are also shown and illustrate again the good agreement between both experiments. Thanks to the overwhelming dominance of the S<sub>11</sub>(1535) resonance, the differential cross section can be expanded in terms of the S-wave multipole and its interference with other multipoles. Limiting the expansion to P and D waves, an approximation valid at least up to 900 MeV, the following expression can be derived [12]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{q_{\eta}}{k} \{ a + b\cos\theta + c\cos^2\theta \},\tag{1}$$

where  $q_{\eta}$  and k are the  $\eta$  and  $\gamma$  C.M. momenta, and

$$a = |E_{0^+}|^2 - \operatorname{Re}\left[E_{0^+}^*(E_{2^-} - 3M_{2^-})\right],$$
  

$$b = 2\operatorname{Re}\left[E_{0^+}^*(3E_{1^+} + M_{1^+} - M_{1^-})\right],$$
  

$$c = 3\operatorname{Re}\left[E_{0^+}^*(E_{2^-} - 3M_{2^-})\right].$$

We have fitted our results with expression (1) and the extracted coefficients are plotted versus  $\gamma$ -ray energy on the right-hand side of Fig. 4. As expected, the D<sub>13</sub>(1520) contribution already seen in Ref. [7] close to threshold is observed in *c* (S–D interference). The *b* coefficient (S–P interference) exhibits small and negative values below 1000 MeV and then a sudden rise with a zero-crossing at  $E_{\gamma} = 1030$  MeV (W =1680 MeV), which indicates the onset of a P-wave. A similar trend has been observed in electroproduction at low  $Q^2$  [20] where this P-wave has been associated with the P<sub>11</sub>(1710) resonance. Above 1000 MeV, nevertheless, a simple interpretation of these coefficients becomes doubtful since S-wave dominance vanishes.

A multipole analysis has been performed by the GWU group [21]. They achieved a nice global fit to the cross section (dashed line, Figs. 3 and 4) and asymmetry (Fig. 5); for the latter, we have displayed the highest energy bin published in 1998 and a new measurement using a UV laser line that confirms the large values at forward angle. Only S. P and D multipoles are needed: this rules out a strong contribution from the  $F_{15}(1680)$ . Analysis of the individual multipoles confirms the previous qualitative conclusions and indicates strong P- and D-wave contributions above 900 MeV. These higher multipoles can indeed be associated with nucleon resonances ( $P_{11}(1710)$  or  $P_{13}(1720)$ ,  $D_{15}(1675)$  or  $D_{13}(1700)$ ), but additional contributions can originate from vector meson exchange as well as nucleon Born terms. In the following section, we present three recent theoretical interpretations which bring different answers to this question.

The first, from Waluyo and Bennhold, [22,23] is a coupled-channels calculation based on the Bethe-



Fig. 4. Differential cross section for the  $p(\gamma, \eta p)$  reaction. Legend as in Fig. 3. The coefficients *a*, *b* and *c* result from the fit to the data by expression (1).



Fig. 5. Beam asymmetry  $\Sigma$  for the  $p(\gamma, \eta p)$  reaction. Results published in 1998 (circles) are compared to new results obtained with a UV line (squares). Legend as in Fig. 3.

Salpeter equation in the K-matrix approximation. It includes all hadronic and electromagnetic reactions with  $\gamma N$ ,  $\pi N$ ,  $\pi \pi N$ ,  $\eta N$ ,  $K\Lambda$ ,  $K\Sigma$  and  $\eta' N$  asymptotic states. Nucleon resonances with spin  $J \leq 3/2$  are included up to M = 2 GeV. The results (Figs. 3–5 (dotted line)), based on a large data base, show a fair overall agreement. The unexpected conclusion is that above 900 MeV, the forward peaking of  $\Sigma$  is primarily due to intermediate vector meson exchange in the *t*-channel, although a contribution from the D<sub>13</sub>(1700) resonance appears necessary to fit the data.

The second, from Li and Saghai, [24] is based on a quark model and includes all known resonances. To avoid double counting, vector meson exchange in the *t*-channel is excluded, a valid approximation as long as resonant contributions dominate. A unique property of this approach is that it directly links data to the quark model, hence to quantities such as mixing angles of resonance configurations. Despite the presence of all known resonances, the initial model could not fit properly our set of data. Only the addition of a new S<sub>11</sub> resonance allowed to reproduce nicely the experiment as illustrated in Figs. 3–5 (solid line). According to the authors, this resonance, not predicted by the Constituent Quark Model, may have an exotic nature such as a  $\Sigma K$  or  $\Lambda K$  molecular state.

Most recently, a Taiwan–Mainz Collaboration has extended the MAID program to the  $\eta$  channel and developed the ETA-MAID model [25] (dashed-dotted line). This isobar model includes Born terms, vector meson exchange and nucleon resonances, and is compared to photoproduction [7–9] as well as electroproduction data [19,20]. A very good overall agreement is achieved with 8 well-established resonances (D<sub>13</sub>(1520), S<sub>11</sub>(1535), S<sub>11</sub>(1650), D<sub>15</sub>(1675), F<sub>15</sub>(1680), D<sub>13</sub>(1700), P<sub>11</sub>(1710), P<sub>13</sub>(1720)). This model leads to conclusions that are contradictory to the two previous ones: no strong contributions from meson exchange and no need for a third S<sub>11</sub> resonance.

More surprisingly, the three models also largely disagree on the total extracted width of the dominant  $S_{11}(1535)$  resonance: 252 MeV for Waluyo et al.,  $162 \pm 1$  MeV for Li-Saghai and 191 MeV for Chiang et al. Moreover, these values are much larger than the one obtained in an other recent coupled-channels calculation [1]: 112 MeV. These discrepancies originate from the influence of other contributions (in particular the  $S_{11}(1650)$  resonance) and underline the necessity to first clarify the reaction mechanism.

In summary, we have measured the differential cross section for the reaction  $p(\gamma, \eta p)$  from threshold to 1100 MeV photon lab. energy, completing our previous measurement of the beam asymmetry  $\Sigma$  over the same energy range. Despite the overwhelming dominance of the S<sub>11</sub>(1535) resonance, its parameters are not yet fixed. In particular, its width turns out to be very sensitive to other contributions and the present extracted values range from 112 to 252 MeV. We are looking forward to a common effort to clarify this situation.

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