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Study of η and η' photoproduction at MAMI

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The reactions γp → ηp and γp → η′p have been measured from their thresholds up to the center-of-mass energy W = 1.96 GeV with the tagged-photon facilities at the Mainz Microtron, MAMI. Differential cross sections were obtained with unprecedented accuracy, providing fine energy binning and full production-angle coverage. A strong cusp is observed in the total cross section and excitation functions for η photoproduction at the energies in vicinity of the η′ threshold, W = 1896 MeV (Eγ = 1447 MeV). This behavior is explained in a revised η′MAID isobar model by a significant branching of the N(1895)1/2− nucleon resonance to both, ηp and η′p, confirming the existence and constraining the properties of this poorly known state.

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The photo-induced production of η and η' mesons is a selective probe to study excitations of the nucleon. The η and the η' represent the isoscalar members of the fundamental pseudoscalar-meson nonet and, in contrast to the isovector π, excitations with isospin I = 3/2 (Δ resonances) do not decay into ηN and η′N final states. Several single and double-spin observables of the γp → ηp reaction have recently been measured [1,2]. A review of the experimental and phenomenological progress can be found in Ref. [7]. All model calculations [8,13] agree in the dominance of the E9,4(JP = 1/2−) multipole amplitude, which is populated by the well established N(1535)1/2− and N(1650)1/2− resonances. The existence of a third 1/2− nucleon resonance, however, is still under discussion. The N(1895)1/2− is presently listed by the PDG with only two stars [14]. The experimental data for η′ production is much more scarce. The most recent measurements by CLAS [4,15] and CBELSA/TAPS [5] decreased uncertainties in the γp → η′p differential cross sections, leaving, however, the near-threshold region still unexplored. Recently, this threshold region attracted additional attention, after the first results for the beam asymmetry Σ were presented by GRAAL [16] which, although limited in statistics, could not be reproduced by any of the existing models describing η′ photoproduction [17–21]. The threshold for the γp → η′p reaction at
$W = 1896$ MeV is located in a mass region that plays a key role for our understanding of the nucleon spectrum. Presently, there are no well-established (four stars) states between $W = 1800 - 2100$ MeV. However, there are many state candidates and an even larger number of states predicted by quark-models or lattice QCD.

This work contributes to the study of $\eta$ and $\eta'$ photoproduction by presenting new, high-statistics measurements of the $\gamma p \rightarrow \eta p$ and $\gamma p \rightarrow \eta' p$ differential cross sections from reaction thresholds up to $E_\gamma = 1577$ MeV ($W = 1960$ MeV). The data were obtained with a fine binning in $E_\gamma$ and cover the full range of the production angles.

The experiments were conducted using the Crystal Ball (CB) as a central calorimeter and TAPS as a forward calorimeter. These detectors were installed at the energy-tagged bremsstrahlung-photon beam produced from the electron beam of the Mainz Microtron (MAMI). The beam photons were incident on a liquid hydrogen target located in the center of the CB. The energies of bremsstrahlung photons, $E_\gamma$, produced by the electrons in a $10 \mu$m copper radiator, were analyzed by detecting postbremsstrahlung electrons in tagging spectrometers (taggers). The Glasgow-Mainz tagger was used in the major part of the experiments. In order to tag the high-energy part of the bremsstrahlung spectrum, a dedicated end-point tagging spectrometer (EPT) was used, especially designed for $\eta'$ measurements.

In this letter, we present the analysis of three independent data sets from different periods of data taking. The first data set (Run-I) was taken in 2007 with the 1508-MeV electron beam and the bremsstrahlung photons analyzed by the Glasgow-Mainz tagger up to an energy of 1402 MeV. All details on the experimental resolution of the detectors and other conditions during these measurements are given in Refs. and references therein. In Ref. the total and differential cross sections for the $\gamma p \rightarrow \eta p$ reaction were obtained by identifying the $\eta$ meson via its $3\pi^0$ decay mode. This analysis was repeated with an improved cluster algorithm, better separating electromagnetic showers partially overlapping in the calorimeters. The second important neutral decay mode $\eta \rightarrow \gamma \gamma$ was analyzed as well. The second data set (Run-II) was taken in 2009 with the 1557-MeV electron beam and the bremsstrahlung photons analyzed up to 1448 MeV. The trigger conditions for this run required more than two clusters to be detected in the CB, which suppressed severely the detection of $\eta \rightarrow \gamma \gamma$ decays, and only $\eta \rightarrow 3\pi^0$ decays were reconstructed in the analysis. More details on the Run-II conditions can be found in Ref. The third data set (Run-III) was taken in 2014 with the 1604-MeV electron beam and the bremsstrahlung photons analyzed by the EPT spectrometer from 1426 MeV up to 1576 MeV. In this run, the energy of the $\eta'$ production threshold was covered, and both neutral $\eta$ decay modes as well as the $\eta' \rightarrow \gamma \gamma$ and $\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$ decays were reconstructed. More details on the Run-III conditions can be found in Ref. The selection of event candidates and the reconstruction of the outgoing particles was based on the kinematic-fit technique. Details on the kinematic-fit parametrization of the detector information and resolutions are given in Ref. The determination of the experimental acceptance for each decay mode of $\eta$ and $\eta'$ was based on a Monte Carlo (MC) simulation of all processes $\gamma p \rightarrow \eta(p)$. The generated events were propagated through a GEANT simulation of the experimental setup. To reproduce resolutions of the experimental data, the GEANT output was subject to additional smearing, thus allowing both the simulated and experimental data to be analyzed in the same way.

![FIG. 1: $m(\pi^0\pi^0\eta \rightarrow 6\gamma)$ invariant-mass distributions obtained for $E_\gamma = 1558$ MeV and $\cos \theta = 0.1 \pm 0.01$: (a) MC simulation of $\gamma p \rightarrow \eta' p \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$ with a Gaussian; (b) experimental spectrum fitted with the sum of a Gaussian and a polynomial of order four.](image-url)
calculation of the detection efficiency and the photon-beam flux was estimated similar to our previous analyses [2, 3] as 4\% for the data taken in Run-I and Run-II, and as 5\% for the data taken in Run-III. Similar systematic uncertainty for the $\eta'$ cross sections from Run-III is also 5\%.

In Fig. 2 the results from Run-I for both decay modes are compared to the previous analysis of Ref. [3]. A comparison of the differential cross sections from Run-I and Run-II for two selected energy bins, where the largest discrepancies are observed, is illustrated in Fig. 3. Finally, Fig. 4 checks Run-II against Run-III, which used a different tagging spectrometer. In general, the different data sets are in agreement within the given uncertainties. To reflect small discrepancies, which can be observed in particular regions with larger background, an additional 3\% systematic uncertainty reflecting uncertainties in the angular dependence of the reconstruction efficiency was added in quadrature to all statistical uncertainties in the $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow 3\pi^0$ results from Run-I and Run-II above $E_\gamma = 1.25$ GeV, and 5\% for Run III. These uncertainties were then used to combine the $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow 3\pi^0$ results together. Similar systematic uncertainties were estimated as 5\% for $\eta' \rightarrow \gamma\gamma$ and 6\% for $\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$.

The agreement of our $\gamma p \rightarrow \eta p$ differential cross section measurements with previous data was already demonstrated in [3]. At high energies, the results from CLAS [4] are in a better agreement with our present data than those from CBELSA/TAPS [5]. The new results for the $\gamma p \rightarrow \eta' p$ differential cross sections are illustrated in Fig. 5 for four energy bins which overlap with the data from CLAS [4] and CBELSA/TAPS [5] and to the new $\eta$MAID2016 solution (black solid line).

Besides the distinct dip at $W = 1670$ MeV [8], our new data for the $\gamma p \rightarrow \eta p$ reaction show another pronounced feature at higher energies. At the position of the $\eta'$ threshold at $W = 1896$ MeV, marked by the vertical line in Fig. 6 a clear cusp is observed. The sharpness of this cusp is strongly dependent on the polar angle of the $\eta$ meson, as shown in Fig. 8. While the dip at $W = 1670$ MeV is more pronounced at forward angles, the cusp effect is stronger around $90^\circ$.

One of the first dedicated models for photoproduction of $\eta$ and $\eta'$ mesons was the Mainz isobar model $\eta$MAID [13, 19], which was fitted to data available in...
The data are compared to the model calculations \(^{[5]}\) CBELSA/TAPS, SAPHIR \(^{[32]}\), ABBHHM \(^{[33]}\), and N1 \(^{[4]}\) as well as the sum of background and the contributions from N1/2\(^{-}\)-resonances (dashed-dotted) are shown separately.

![Figure 6](image1.png)

**FIG. 6:** (Color online) Total cross section obtained for the \(\gamma p \rightarrow \eta p\) reaction along with previous measurements by CBELSA/TAPS \(^{[2]}\), SAPHIR \(^{[32]}\), ABBHHM \(^{[33]}\), and AHHM \(^{[34]}\). The data are compared to the model calculations \(\eta\)MAID-2003 \(^{[15]}\) (black dotted line), SAID-GE09 \(^{[9]}\) (blue long dashed-dotted line), and BG2014-2 \(^{[8]}\) (magenta long dashed line). The new \(\eta\)MAID2016 solution is shown as a black solid line. The Regge-background (dashed) as well as the sum of background and the contributions from N1/2\(^{-}\)-resonances (dashed-dotted) are shown separately.

![Figure 7](image2.png)

**FIG. 7:** (Color online) Total cross section obtained for the \(\gamma p \rightarrow \eta p\) reaction along with previous measurements by CBELSA/TAPS \(^{[2]}\), SAPHIR \(^{[32]}\), ABBHHM \(^{[33]}\), and AHHM \(^{[34]}\). The data are compared to the model calculations \(\eta\)MAID-Regge-2003 \(^{[19]}\) (black dotted line) and to the new \(\eta\)MAID2016 solution (black solid line). Furthermore, the background (black dashed) as well as the main resonance contributions \(N(1895)1/2^{-}\) (red dashed-dotted), \(N(1990)1/2^{+}\) (green long dashed), and \(N(2020)3/2^{-}\) (blue long dashed-dotted) are shown separately.

These fits are shown as dotted lines in Figs. 6 and 7 and there is no surprise that they fail to reproduce the current measurements. However, even the more recent analyses by SAID-GE09 \(^{[9]}\) and BG2014-2 \(^{[8]}\), are still far from agreement with the new precision data.

To interpret the new data we have developed a model based on the ideas of \(\eta\)MAID \(^{[13, 19]}\). This new \(\eta\)MAID2016 model includes a non-resonant background, which consists of the vector (\(\rho\) and \(\omega\)) and axial-vector (\(b_{1}\)) exchange in the \(t\) channel, and s-channel resonance excitations. Regge trajectories for the meson exchange in the \(t\) channel were used to provide correct asymptotic behavior at high energies. In addition to the Regge trajectories, Regge cuts with natural and un-natural parities were included according to the ideas developed in Ref. 35 for pion photoproduction. Nucleon resonances in the s channel were parameterized with Breit-Wigner shapes. The new model was fitted to data from both \(\eta\) and \(\eta'\) photoproduction on protons. In addition to the new cross sections presented in this letter, data from \(^{[1, 2, 4, 6, 10]}\) were used. A detailed publication of the model including a quantitative comparison to all available data is in preparation. Here we concentrate on the comparison to the new cross section data. A key role for the description is played by the three s-wave resonances, N(1535)1/2\(^{-}\), N(1650)1/2\(^{-}\), and N(1895)1/2\(^{-}\). The importance of the first two resonances in \(\eta\) photoproduction is well known from previous analyses. In our model, the third resonance, N(1895)1/2\(^{-}\), is crucial in order to describe the cusp observed in \(\eta\) photoproduction around \(W = 1896\) MeV as well as the fast rise of the total cross section of the \(\gamma p \rightarrow \eta' p\) reaction near the threshold. Presently, this resonance has only an overall two-star status according to the PDG review \(^{[14]}\). The present data and our analysis clearly confirm the existence of this state. We find a mass slightly below the \(\eta'\) threshold and a significant coupling to both, \(\eta p\) and \(\eta' p\). The parameters of all s-wave resonances are presented in Table I. As the N(1895)1/2\(^{-}\) mass is below \(\eta' N\) threshold, an effective branching ratio of \(\beta_{\eta' N} = (38 \pm 20)\%\) was determined by integrating the decay spectrum above \(\eta' N\) threshold according to \(^{[36]}\). The contributions of this and the other two important resonances, the N(1990)1/2\(^{+}\) and the N(2020)3/2\(^{-}\), are shown in Fig. 7.

**TABLE I:** Fit results for \(J^P = 1/2^{-}\) resonances. Breit-Wigner parameters: mass \(M_{BW}\), width \(\Gamma_{BW}\), branching ratio to \(\eta N\) channel \(\beta_{\eta N} := \Gamma_{\eta N}(M_{BW})/\Gamma_{BW}\), and helicity amplitude \(A_{1/2}\) in \([10^{-3}\text{GeV}^{-1/2}]\). Stars in the first column indicate an overall status of the resonance. The first row for each resonance gives a parameter set of the new \(\eta\)MAID solution. The second row lists the corresponding numbers given by the PDG review \(^{[14]}\). The parameters indicated without errors were fixed during the fit.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>(J^P)</th>
<th>(M_{BW} [\text{MeV}])</th>
<th>(\Gamma_{BW} [\text{MeV}])</th>
<th>(\beta_{\eta N} [%])</th>
<th>(A_{1/2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1535)1/2(^{-})</td>
<td>****</td>
<td>1528 \pm 6</td>
<td>163 \pm 25</td>
<td>41 \pm 4</td>
<td>+115</td>
</tr>
<tr>
<td>N(1650)1/2(^{-})</td>
<td>****</td>
<td>1535 \pm 10</td>
<td>150 \pm 25</td>
<td>42 \pm 10</td>
<td>+115 \pm 15</td>
</tr>
<tr>
<td>N(1895)1/2(^{-})</td>
<td>**</td>
<td>1890 \pm 9</td>
<td>150 \pm 57</td>
<td>20 \pm 6</td>
<td>-30</td>
</tr>
</tbody>
</table>
FIG. 8: (Color online) Excitation function of $\eta$ photoproduction for selected angular bins. Black circles are the present data, the magenta line is the new $\eta$MAID2016 solution, the vertical line corresponds to the $\eta'$ threshold.

Differential cross sections were obtained with unprecedented statistical accuracy, providing fine energy binning and full production-angle coverage. The total cross section and the excitation functions for $\eta$ photoproduction demonstrate a strong cusp in the vicinity of the $\eta'$ threshold, $W = 1896$ MeV. The analysis of the present data with the revised $\eta$MAID model explains such a behavior by the strong coupling of the $N(1895)/2^{-}$ resonance to both channels. The new data and our analysis clearly confirm the existence of this two-star state and allow significant improvements in the determination of its parameters.

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