Photoproduction of $\eta$ and $\eta'$ Mesons on Proton

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New high-precision total and differential cross sections for $\eta$ and $\eta'$ photoproduction on the proton obtained by the A2 Collaboration at the Mainz Microtron are presented. The data for $\eta$ photoproduction demonstrate a cusp at the energy $W \sim 1.9$ GeV. Furthermore, we present a new version of the $\eta$MAID model for $\eta$ and $\eta'$ photoproduction. The model includes 23 nucleon resonances parametrized with Breit-Wigner shapes. The background is described by vector and axial-vector meson exchanges in the $t$ channel using the Regge phenomenology. Parameters of the resonances were obtained from a fit to preliminary data of the A2 Collaboration at MAMI and available data from other collaborations. The cusp is explained as a threshold effect due to the opening $\eta'p$ decay channel of the $N(1895)1/2^-$ resonance.

KEYWORDS: meson photoproduction, baryon spectroscopy, partial wave analysis

1. Introduction

The isobar model $\eta$MAID [1] was developed in 2002 for $\eta$ photo- and electroproduction on nucleons. The model includes a nonresonant background, which consists of nucleon Born terms, the vector meson exchange in the $t$ channel, and $s$-channel resonance excitations. The vector meson contribution is obtained by the $\rho$ and $\omega$ meson exchange in the $t$ channel with pole-like Feynman propagators. The resonance contribution is parametrized by the Breit-Wigner function with energy-dependent width. The $\eta$MAID-2003 version describes well the experimental data available in 2002, however fails to reproduce the new polarization data obtained in Mainz [2]. An updated version $\eta$MAID-2015 [3] extended the $\eta$MAID-2003 to higher energies, improved a description of the new polarization data, and included the $\eta'$ photoproduction channel. In the presented version $\eta$MAID-2016, the background contribution is calculated using Regge phenomenology. It allowed to describe well the high-energy data.

2. Review of experimental data

The revised model $\eta$MAID-2016 is used for a phenomenological analysis of the data. Data set includes the latest results for the $\gamma p \rightarrow \eta p$ reaction: CBELSA/TAPS [4] and CLAS [5] for differential cross sections, A2MAMI [2] for T and F, CLAS [6] for E, GRAAL [7] for $\Sigma$, and preliminary high statistics data from A2 Collaboration at MAMI for the differential cross sections. Energy dependencies of the new differential cross section for selected angular bins are shown in Fig. 1. The data demonstrate cusp effect, especially at polar angles of $\eta$ meson around 90°. The differential cross sections cover the energy region from threshold up to $W=2.8$ GeV. Polarization observables are from threshold up to $W=1.85$ GeV for T and F, 2.13 GeV for E, and 1.91 GeV for $\Sigma$. We used also old high energy data [9] to determine Regge background contributions.
Data set for the $\gamma p \to \eta'p$ reaction is much more scarce than for $\gamma p \to \eta p$: preliminary data from A2 Collaboration at MAMI, CBELSA/TAPS [4], and CLAS [5] for differential cross sections; GRAAL [8] for $\Sigma$. The differential cross sections cover the energy region from threshold up to $W=2.8$ GeV. For beam asymmetry $\Sigma$, data exist only for two energy bins close to threshold.

3. $\eta$MAID-2016

For new $\eta$MAID version, the background from Born terms was excluded because of very small contribution. The pole-like Feynman propagators are replaced by the Regge propagators for each vector meson $V$ in the $t$-channel:

$$\frac{1}{t - m_V^2} \Rightarrow p_V^{\text{Regge}} = \left( \frac{s}{s_0} \right)^{\alpha_V(t)-1} \frac{\pi\alpha_V}{\sin(\pi\alpha_V(t))} S + e^{-i\pi\alpha_V(t)} \frac{1}{\Gamma(\alpha_V(t))},$$

where the parameter $s_0$ is a mass scale taken as $s_0 = 1$ GeV$^2$. The gamma function $\Gamma(\alpha(t))$ suppresses poles of the propagator in the unphysical region. The $S$ is the signature of the trajectory: $S = (-1)^J$ for bosons, so $S = 1$ for vector mesons. In this case, a differential cross section goes to zero if $\alpha(t) = 0$ for each trajectory, see red lines in Fig. 2. Using Regge cut phenomenology, Donachie and Kalashnikova [10] excluded this anomaly for $\pi^0$ photoproduction.

Regge cuts arise from photoproduction rescattering of two Reggeons. Following Ref. [10], we used Pomeron with quantum numbers of the vacuum and tensor meson $f_2$ to produce four cut trajectories: $\rho P, \rho f_2, \omega P$, and $\omega f_2$. This is enough to get good description of the differential cross sections at high energies. Additional exchange by axial-vector meson $b_1$ is needed to describe polarization observables. All four Regge cuts contribute also to axial-vector exchanges [10]. Unknown coefficients for natural and unnatural parity cuts were obtained by a fit to the data. Fit result for high energy data for $\gamma p \to \eta p$ reaction is presented in Fig. 2 by the black lines. The obtained solution describes well the old data [9], but is not consistent with data from CLAS [5]. Background fixed by this way was extrapolated to the resonance region. We used the same fit parameters to determine background contribution for the $\gamma p \to \eta'p$ reaction.

Nucleon resonances in the $s$ channel were parametrized with Breit-Wigner shapes. The new model allows the use of 23 resonances to fit experimental data. The Breit-Wigner mass, total width, branching ratios to $\eta$ and $\eta'$ decays, photoexcitation helicity couplings $A_{1/2}$ and $A_{3/2}$ are model variable parameters. Branching ratios to further decay channels, namely $K\Lambda$, $K\Sigma$, $\omega N$, were fixed from PDG [11] or BnGa analysis [12]. The new model was fitted to published data of both $\eta$ and $\eta'$ photoproduction on the proton [2,4–8] and to the preliminary
Fig. 2. Differential cross sections and polarization observables $\Sigma$ and $T$ for the $\gamma p \rightarrow \eta p$ reaction described by Regge contributions. The red lines are the contribution by only $\rho$ and $\omega$ exchange, the black lines show the total Regge contribution with the cuts. The black squares are data from CLAS [5], and the other data are given in Ref. [9].

A2MAMI data.

Fig. 3. Total cross sections for $\gamma p \rightarrow \eta p$ (a) and $\gamma p \rightarrow \eta' p$ (b). The new $\eta$MAID solution is shown in the black solid lines, the black dashed lines are $\eta$MAID-2003 [1] (a) and $\eta$MAIDregge-2003 [14] (b) predictions. Other predictions: SAID-GE09 [13] (blue) and BG2014-2 [12] (magenta).

In Fig. 3(a), the total $\gamma p \rightarrow \eta p$ cross sections are shown for the most interesting energy region, where differences between the model calculations are especially visible. The new $\eta$MAID solution is compared to $\eta$MAID-2003 [1], SAID-GE09 [13], and BG2014-2 [12] predictions. The new data demonstrate a strong cusp at an energy corresponding to $\eta'$ threshold (vertical line in Fig. 3(a)). In Fig. 3(b) the new $\eta$MAID solution for the total cross section of the $\gamma p \rightarrow \eta' p$ reaction is compared to $\eta$MAIDregge-2003 [14] calculation, which was obtained with a fit to the old data (SAPHIR-98, ABBHHM-68, AHHM-76) [15]. The total cross sections for the CLAS Collaboration, we obtained from differential cross sections [5] using the Legendre fit and are shown for a qualitative comparison. The total cross sections themselves were not fitted, we show the result of the partial wave analysis.

A key role in the description of the investigated reactions is played by three $s$-wave
resonances $N(1535)1/2^-$, $N(1650)1/2^-$, and $N(1895)1/2^-$. The first two give the main contribution to the total cross section and are known very well. The third of them has only 2-star overall status according to the PDG review [11]. But we have found that namely this resonance is responsible for the cusp effect in the $\gamma p \rightarrow \eta' p$ reaction near the threshold.

![Fig. 4. New $\eta$MAID solution for the selected energy bins of the $\gamma p \rightarrow \eta' p$ differential cross section. Data: preliminary A2MAMI (red), CLAS [5] (black), and CBELSA/TAPS [4] (open circles).](image1)

![Fig. 5. New $\eta$MAID solution for the $\gamma p \rightarrow \eta' p$ beam asymmetry. Data: GRAAL [8].](image2)

The results for the $\gamma p \rightarrow \eta' p$ reaction are shown for differential cross sections in Fig. 4 for selected energy bins and the beam asymmetry $\Sigma$ in Fig. 3. The new $\eta$MAID solution very well describes the new data for the differential cross sections. The beam asymmetry $\Sigma$ is reproduced in its shape of the angular dependence. However, the energy dependence is inverted.

4. Summary

A new reggetized model for $\eta$ and $\eta'$ photoproduction on nucleons was presented. At energies below $W=2.5$ GeV nucleon resonance excitation dominate. To describe the data in this region we increased the number of $N^*$ resonances from 8 to 23, where 5 of them give only small contributions. At high energies Regge trajectories of $\rho, \omega, b_1$ and Regge cuts of $\rho$-$P$, $\omega$-$P$, $\rho$-$f_2$, $\omega$-$f_2$ were used. The obtained solution describes the data very well up to $E_\gamma=8$ GeV. The cusp in the total cross section of $\gamma p \rightarrow \eta p$ is explained as a threshold effect due to the opening of the $\eta' p$ decay channel of the $N(1895)1/2^-$ resonance.

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