MULTIPOLE ANALYSIS FOR PION PHOTOPRODUCTION WITH MAID AND A DYNAMICAL MODELS

S. S. KAMALOV¹, D. DRECHSEL², L. TIATOR² AND S. N. YANG³

¹Laboratory of Theoretical Physics, JINR, 141980 Dubna, Russia
²Institut für Kernphysik, Universität Mainz, 55099 Mainz, Germany
³Department of Physics, National Taiwan University, Taipei, Taiwan

We present results of new analysis of pion photoproduction data obtained with Dynamical and MAID models.

During the last few years we have developed and extended two models for the analysis of pion photo and electroproduction, the Dynamical Model (hereafter called Dubna-Mainz-Taipei (DMT) model) and the Unitary Isobar Model (hereafter called MAID). The final aim of such an analysis is to shed more light on the dynamics involved in nucleon resonance excitations and to extract $N^*$ resonance properties in an unambiguous way. For this purpose as a testing ground we will use benchmark data bases recently created and distributed among different theoretical groups.

The crucial point in a study of $N^*$ resonance properties is the separation of the total amplitude (in partial channel $\alpha = \{l, j\}$)

$$t^\alpha_{\gamma\pi} = t^{B,\alpha}_{\gamma\pi} + t^{R,\alpha}_{\gamma\pi}$$

in background $t^{B,\alpha}_{\gamma\pi}$ and resonance $t^{R,\alpha}_{\gamma\pi}$ contributions. In different theoretical approaches this procedure is different, and consequently this could lead to different treatment of the dynamics of $N^*$ resonance excitation. As an example we will consider the two different models: DMT and MAID.

In accordance with Ref.[1], in the DMT model the $t^{B,\alpha}_{\gamma\pi}$ amplitude is defined as

$$t^{B,\alpha}_{\gamma\pi}(DMT) = e^{i\delta_\alpha} \cos \delta_\alpha \left[ v^{B,\alpha}_{\gamma\pi} + P \int_0^\infty dq' q'^2 R^{(\alpha)}_{\pi N}(q_E, q') v^{R,\alpha}_{\gamma\pi}(q') \right]$$

where $\delta_\alpha(q_E)$ and $R^{(\alpha)}_{\pi N}$ are the $\pi N$ scattering phase shift and full $\pi N$ scattering reaction matrix, in channel $\alpha$, respectively, $q_E$ is the pion on-shell momentum. The pion photoproduction potential $v^{B,\alpha}_{\gamma\pi}$ is constructed in the same way as in Ref.[1] and contains contributions from the Born terms with an energy dependent mixing of pseudovector-pseudoscalar (PV-PS) $\pi N N$ coupling and t-channel vector meson exchanges. In the DMT model $v^{B,\alpha}_{\gamma\pi}$ depends on 7 parameters: The PV-PS mixing parameter $\Lambda_m$ (see Eq.(12) of Ref.[1], 4
coupling constants and 2 cut-off parameters for the vector mesons exchange contributions.

In the extended version of MAID, the $S$, $P$, $D$ and $F$ waves of the background amplitudes $t^{B,\alpha}_{\gamma\pi}$ are defined in accordance with the K-matrix approximation

$$t^{B,\alpha}_{\gamma\pi}({\text{MAID}}) = \exp (i\delta_\alpha) \cos \delta_\alpha t^{B,\alpha}_{\gamma\pi}(q, W, Q^2), \quad (3)$$

where $W \equiv E$ is the total $\pi N$ c.m. energy and $Q^2 = -k^2 > 0$ is the square of the virtual photon 4-momentum. Note that in actual calculations, in order to take account of inelastic effects, the factor $\exp (i\delta_\alpha) \cos \delta_\alpha$ in Eqs.(2-3) is replaced by $\frac{1}{2}[\eta_\alpha \exp (2i\delta_\alpha) + 1]$, where both the $\pi N$ phase shifts $\delta_\alpha$ and inelasticity parameters $\eta_\alpha$ are taken from the analysis of the SAID group.

From Eqs. (2) and (3), one finds that the difference between the background terms of MAID and of the DMT model is that pion off-shell rescattering contributions (principal value integral) are not included in the background of MAID. From our previous studies of the $P$ wave multipoles in the $(3,3)$ channel it follows that they are effectively included in the resonance sector leading to the dressing of the $\gamma N\Delta$ vertex. However, in the case of $S$ waves the DMT results show that off-shell rescattering contributions are very important for the $E_{0^+}$ multipole in the $\pi^0 p$ channel. In this case they have to be taken into account explicitly. Therefore, in the extended version of MAID we have introduced a new phenomenological term in order to improve the description of the $\pi^0$ photoproduction at low energies,

$$E_{\text{corr}}(\text{MAID}) = \frac{\Delta E}{(1 + B^2 q_E^2)^2} F_D(Q^2), \quad (4)$$

where $F_D$ is the standard nucleon dipole form factor, $B = 0.71$ fm and $\Delta E$ is a free parameter which can be fixed by fitting the low energy $\pi^0$ photoproduction data. Thus the background contribution in MAID finally depends on 8 parameters. Below $\pi^+ n$ threshold for both models we also take into account the cusp effect due to unitarity, as it was described in Ref. 4, i.e.

$$E_{\text{cusp}} = -a_{\pi N} \omega_c \Re E_{0^+} \sqrt{1 - \frac{\omega^2}{\omega_c^2}}, \quad (5)$$

where $\omega$ and $\omega_c = 140$ MeV are the $\pi^+$ c.m. energies corresponding to $W = E_p + E_\gamma$ and $W_c = m_n + m_{\pi^+}$, respectively, and $a_{\pi N} = 0.124/m_{\pi^+}$ is the pion charge exchange amplitude.
For the resonance contributions, following Ref. 2, in both models the Breit-Wigner form is assumed, i.e.

\[
\gamma^{R\alpha}(W,Q^2) = \frac{\bar{A}_R^{\alpha}(Q^2) f_{\pi R}(W) \Gamma_{R} M_{R} f_{\pi R}(W)}{M_{R}^2 - W^2 - i M_{R} \Gamma_{R}} e^{i \phi_R},
\]

(6)

where \(f_{\pi R}\) is the usual Breit-Wigner factor describing the decay of a resonance \(R\) with total width \(\Gamma_{R}(W)\) and physical mass \(M_{R}\). The phase \(\phi_R(W)\) in Eq. (6) is introduced to adjust the phase of the total multipole to equal the corresponding \(\pi N\) phase shift \(\delta_{\alpha}\).

The main subject of our study in the resonance sector is the determination of the strengths of the electromagnetic transitions described by the amplitudes \(\bar{A}_R^{\alpha}(Q^2)\). In general, they are considered as free parameters which have to be extracted from the analysis of the experimental data. In our two models we have included contributions from the 8 most important resonances, listed in the Table 1. The total number of \(\bar{A}_R^{\alpha}\) amplitudes is 12 and they can be expressed also in terms of the 12 standard helicity elements \(A_{1/2}\) and \(A_{3/2}\). Thus, to analyze experimental data we have a total of 19 parameters in DMT

| \(N^*\)     | MAID current | MAID HE fit | DMT HE fit | PDG2000 |
|-------------|--------------|-------------|------------|---------|
| \(P_{33}(1232)\) | A\(_{1/2}\)  | -138        | -143       | —       | -135±6  |
|             | A\(_{3/2}\)  | -256        | -264       | —       | -255±8  |
| \(P_{11}(1440)\) | A\(_{1/2}\)  | -71         | -81        | -77     | -65±4   |
|             | A\(_{3/2}\)  | -17         | -6         | -7      | -24±9   |
| \(D_{13}(1520)\) | A\(_{1/2}\)  | 164         | 160        | 165     | 166±5   |
|             | A\(_{3/2}\)  | 67          | 81         | 102     | 90±30   |
| \(S_{11}(1650)\) | A\(_{1/2}\)  | 39          | 32         | 34      | 53±16   |
|             | A\(_{3/2}\)  | 10          | 5          | 10      | -15±6   |
| \(P_{15}(1680)\) | A\(_{1/2}\)  | 138         | 137        | 132     | 133±12  |
|             | A\(_{3/2}\)  | 10          | 5          | 10      | -15±6   |
| \(D_{33}(1700)\) | A\(_{1/2}\)  | 86          | 119        | 107     | 104±15  |
|             | A\(_{3/2}\)  | 85          | 82         | 74      | 85±22   |
| PV-PS mixing: | \(\Lambda_m\) | 450         | 406        | 302     |         |
| \(\Delta E\) | 2.01         | 1.73        | —          |         |
| \(\chi^2/d.o.f.\) | 11.5         | 6.10        | 6.10       |         |

Table 1. Proton helicity amplitudes (in \(10^{-3} \text{GeV}^{-1/2}\)), values of the PV-PS mixing parameter \(\Lambda_m\) (in MeV) and low-energy correction parameter \(\Delta E\) (in \(10^{-3}/m_{\pi^+}\)) obtained after the high-energy (HE) fit.
and 20 parameters in MAID. The final results obtained after the fitting of the high-energy (HE) benchmark data base with 3270 data points in the photon energy range $180 < E_\gamma < 1200$ MeV are given in Table 1.

For the analysis of the low-energy (LE) data base with 1287 data points in the photon energy range $180 < E_\gamma < 450$ MeV in the DMT model we used only 4 parameters: The PV-PS mixing parameter and 3 parameters for the $P_{33}(1232)$ and $P_{11}(1440)$ resonances. In MAID we have one more parameter due to the low energy correction given by Eq. (4). The final results for the helicity elements and the E2/M1 ratio (REM) are given in Table 2. In Table 3 we summarize our results and show the $\chi^2$ obtained for different channels and different observables after fitting the LE and HE data bases. Note that the largest $\chi^2$ in the LE fit we get for

| Observables | LE | HE |
|-------------|----|----|
| $d\sigma/d\Omega(\gamma, \pi^+)$ | 317 | 871 |
| $d\sigma/d\Omega(\gamma, \pi^0)$ | 354 | 859 |
| $\Sigma(\gamma, \pi^+)$ | 245 | 546 |
| $\Sigma(\gamma, \pi^0)$ | 192 | 488 |
| $T(\gamma, \pi^+)$ | 107 | 265 |
| $T(\gamma, \pi^0)$ | 72 | 241 |
| Total | 1287 | 3270 |

Table 2. Proton helicity elements (in $10^{-3}$ GeV$^{-1/2}$) and REM=E2/M1 ratio (in %) obtained from the LE fit.

| N* | MAID current | MAID LE fit | DMT LE fit | PDG2000 |
|----|--------------|-------------|------------|---------|
| $P_{33}(1232)$ | $A_{1/2}$ | -138 | -142 | — | -135±6 |
| | $A_{3/2}$ | -256 | -265 | — | -255±8 |
| $P_{11}(1440)$ | $A_{1/2}$ | -71 | -81 | -93 | -65±4 |
| | REM(%) | -2.2 | -1.9 | -2.1 | -2.5±0.5 |
| $\chi^2$/d.o.f. | 4.76 | 4.56 | 3.59 |

Table 3. $\chi^2/N$ for the cross sections ($d\sigma/d\Omega$), photon ($\Sigma$) and target ($T$) asymmetries in ($\gamma, \pi^+$) and ($\gamma, \pi^0$) channels obtained after LE and HE fit. N is the number of data points obtained practically in all other analyses. A detailed compari-
son with the results of different theoretical groups is given on the website [http://gwdac.phys.gwu.edu/analysis/pr_benchmark.html]. Below, in Fig. 1 we show only one interesting example, the $E_{0+}$ multipole in the channel with total isospin 1/2. In this channel contributions from the $S_{11}(1535)$ and $S_{11}(1620)$ resonances are very important. At $E_\gamma > 750$ MeV our values for the real part of the $E_{0+}$ amplitude are mostly negative and lower than the results of the SAID multipole analysis. The only possibility to remove such a discrepancy in our two models would be to introduce a third $S_{11}$ resonance. Another interesting result is related to the imaginary part of the $E_{0+}$ amplitude and, consequently, to the value of the helicity elements given in Table 1. Within the DMT model for the $S_{11}(1535)$ we obtain $A_{1/2} = 102$ for a total width of 120 MeV, which is more consistent with the results obtained in $\eta$ photoproduction, than with previous pion photoproduction results obtained by the SAID and MAID groups.

References

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