Resonances with Dubna-Mainz-Taipei Dynamical Model for $\pi N$ Scattering and Pion Electromagnetic Production

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Abstract. We present the results on $P_{11}$ resonances obtained with Dubna-Mainz-Taipei (DMT) dynamical model for pion-nucleon scattering and pion electromagnetic production. The extracted values agree well, in general, with PDG values. One pole is found corresponding to the Roper resonance and two more resonances are definitely needed in DMT model. We further find indication for a narrow $P_{11}$ resonance at around 1700 MeV with a width $\sim 50$ MeV in both $\pi N$ and $\gamma\pi$ reactions.

Keywords: pion-nucleon interaction, pion photo- and electroproduction, baryon resonances

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One of the most important tasks in the study of baryon structure is to extract their properties like, mass, width, and helicity amplitudes etc. from $\pi N$ scattering and pion electromagnetic (EM) production. There are several approaches to extract properties of nucleon resonances ($N^*$) from $\pi N$ data, like speed plot, regularization method, dispersion relation, and meson-exchange model etc.

Interest on the properties of $P_{11}$ resonances has recently intensified considerably [1, 2] after the properties of $\Delta(1232)$ is well studied [3]. In this contribution, we present results on $P_{11}$ resonances obtained from analyzing data of $\pi N$ scattering and pion EM production with Dubna-Mainz-Taipei (DMT) meson-exchange model which we have constructed in [4, 5].

The DMT $\pi N$ meson-exchange model was developed on the basis of the Taipei-Argonne $\pi N$ meson-exchange model [6] which describes pion-nucleon scattering up to 400 MeV pion laboratory energy. It starts from an effective chiral Lagrangian. The effective Lagrangian is then used to construct a potential for use in the scattering equation

$$t_{\pi N} = v_{\pi N} + v_{\pi N} g_0 t_{\pi N}.$$  \hspace{1cm} (1)

The Taipei-Argonne $\pi N$ model was extended up to c.m. energies $W = 2.0$ GeV [5] by inclusion of higher resonances and the $\eta N$ channel, namely,

$$t_{ij}(W) = v_{ij}(W) + \sum_k v_{ik}(W) g_k(W) t_{kj}(W),$$  \hspace{1cm} (2)
with $i$ and $j$ denoting the $\pi$ and $\eta$ channels and $W$ is the total c.m. energy. The potential $v_{ij}$ is a sum of background $v^B_{ij}$ and bare resonance $v^R_{ij}$ terms,

$$v_{ij}(W) = v^B_{ij}(W) + v^R_{ij}(W),$$

where

$$v^R_{ij}(W) = \sum_{k=1}^{n} v^R_{kj}(W),$$

if there are $n$ resonances in any specific channel. The background term $v^B_{\pi\pi}$ for the $\pi N$ elastic channel is taken as obtained in [6]. The model describes well both $\pi N$ phase shifts and inelasticity parameters in all the channels up to the $F$ waves and $W = 2$ GeV, except for the $F_{17}$ partial wave.

The DMT $\pi N$ model is also a main ingredient of the DMT dynamical model describing the photo- and electroproduction of pions [7] up to 2 GeV, which can be expressed, in analogy to Eq. (1), as

$$t_{\gamma\pi} = v_{\gamma\pi} + v_{\gamma\pi} g_{0f\pi N},$$

where $v_{\gamma\pi}$ is the transition potential which describes the production of a pion by an incident photon and is a sum of background and resonance terms. The background term $v^B_{\gamma\pi}$ is obtained from the same effective chiral Lagrangian for $\pi N$ with the use of minimal substitution. The resonance term $v^R_{\gamma\pi}$ also contains contribution from the $n$ resonances as appeared in Eq. (4) since all of them can be excited by a photon. The details can be found in [4, 7]. This model gives excellent agreement with pion production data from threshold to the first resonance region [8, 9]. For details, we refer readers to [4, 5, 6].

From Eqs. (1-5), it is seen that the resonance parameters extracted would be affected by the choice of background terms $v^B_{ij}$ and $v^B_{\gamma\pi}$, which can best be tested in the low-energy region where the resonance contributions are expected to be negligible. It has been shown that the DMT model describes well the $\pi^0$ photo- and electroproduction at threshold [9], namely, the $s$-wave multipoles $E_{0+}(\pi^0 p)$ and $L_{0+}(\pi^0 p)$, and the recent measurement of electroproduction differential cross section at threshold with $Q^2 = 0.05$ (GeV/c)$^2$ [10]. A new measurement on the polarized linear photon asymmetry [11] which is found to be very sensitive to the small $p$-wave multipoles, and the extracted multipole $pM_{1-}$ [12] also agree well with the DMT predictions. This nice agreement between data and DMT predictions in the case of $p$-wave multipoles validates, to some extent, the reasonableness of the choice of $v_{ij}^B$ and $v_{\gamma\pi}^B$ used in the extraction of the properties of $P_{11}$ resonances from $\pi N$ scattering and pion EM production data with DMT model.

The model parameters, including bare resonance masses, coupling constants, and cut-off parameters for each resonance are then fitted to $\pi N$ phase shifts and inelasticity parameters in all channels up to $F$ waves and for energies less than 2 GeV [13]. The results for the $P_{11}$ channel is shown in Fig. 1. The solid, dashed, and dash-dotted curves in Fig. 1 correspond to the predictions of full DMT model, without the 2nd and 3rd resonances, and with the removal only second resonance, respectively. The indication for need of three resonances in order to reach a reasonable description of the data within DMT model seems stronger than what was found by the EBAC group [2].
Our predictions for $t_{\pi N}(P_{11})$. The solid, dashed, and dash-dotted curves correspond to the predictions of full DMT model, without the 2nd and 3rd resonances, and with the removal only second resonance, respectively. The data are from [13].

The bare masses, Breit-Wigner physical masses and widths, and the pole positions extracted, all in units of MeV, are presented in Table 1. The pole positions are determined by analytic continuation and agree well with those obtained by speed plot and regularization method [14]. We find only one pole corresponding to the Roper resonance, in contrast to the two poles found in [1]. This is because we do not consider explicitly $\pi \Delta$ channel and hence do not have a complex branch cut associated with it. We did not try to look for poles beyond 2 GeV.

| $N^*$         | $M_R^{(0)}$ | $M_R$  | $\Gamma$ | Re$W_p$ | -Im$W_p$ |
|---------------|-------------|--------|----------|---------|---------|
| $P_{11}(1440)$| 1612        | 1418   | 436      | 1371    | 95      |
| PDG ****      |             |        |          |         |         |
| $P_{11}(1710)$| 1798        | 1803   | 508      | 1746    | 184     |
| PDG ***       |             |        |          |         |         |
| $P_{11}(2100)$| 2196        | 2247   | 1020     | 2120 ± 240 | 240 ± 80 |
| PDG *         |             |        |          |         |         |

With the inclusion of the three $P_{11}$ resonances determined from $\pi N$ data as explained above, we are able to obtain a description of the multipoles $\mu M_{1-}(1/2)$ and $\nu M_{1-}(1/2)$ in the range of photon energy $E_\gamma$ between 150-1650 MeV of comparable quality obtained in the case $\pi N$ data as shown in Fig. 1, except in the neighborhood of $E_\gamma \sim 1050$ MeV where a peak and a bump are seen in the imaginary and real part of $\mu M_{1-}(1/2)$, respectively. If a narrow $P_{11}$ resonance of mass 1700 MeV and width of 47 MeV is included within MAID2007 [15], then the peak and bump mentioned above can be very nicely described, as shown in Fig. 2.

In summary, we find, with the use of the DMT dynamical model for analyzing the $\pi N$ scattering and pion EM production data, we find three $P_{11}$ resonances at energies of 1418, 1803, and 2247 MeV, all with rather broad widths. We further find that, within MAID 2007, the inclusion of a narrow $P_{11}$ resonance at $W = 1700$ MeV with...
\( \Gamma = 47 \text{ MeV} \) can greatly improve the agreement with \( pM_{1-}(1/2) \) data in the vicinity of \( E_\gamma \sim 1050 \text{ MeV} \).

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