Chiral Dynamics and Dubna-Mainz-Taipei Dynamical Model for Pion-Photoproduction Reaction

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We demonstrate that the Dubna-Mainz-Taipei (DMT) meson-exchange dynamical model, which starts from an effective chiral Lagrangian, for pion photoproduction provides an excellent and economic framework to describe both the \( \pi^0 \) threshold production and the \( \Delta \) deformation, two features dictated by chiral dynamics.

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An important feature of the low-energy QCD is the chiral symmetry. Chiral symmetry is expected to show up in the parity doubling of all hadronic states (Winer-Weyl mode), e.g., the proton with \( J^P = 1/2^+ \) would have a \( 1/2^- \) partner. This is not observed experimentally. Instead the symmetry is broken spontaneously (Nambu-Goldstone mode) which leads to the appearance of massless pseudoscalar mesons. The opposite parity partner of the proton is a proton plus a "massless pion".

Spontaneous chiral symmetry breaking (SCSB) has led to the development of chiral perturbation theory (ChPT), a low-energy effective field theory of QCD. It utilizes the concept of SCSB and replaces the quark and gluon fields by a set of fields describing the degrees of freedom of the observed hadrons. There is generally good agreement between the ChPT predictions and experiments\(^1\), including the \( \pi^0 \) photoproduction near threshold where very precise measurements have been performed and the ChPT calculation to one loop \( O(p^4) \) has been carried out in the heavy-baryon formulation\(^2\).

The fact that opposite parity partner of the proton is a proton plus a pion leads to the consequence that the \( \pi N \) interaction in momentum space takes the form\(^1\)

\[
V_{\pi N} = g_{\pi N} \vec{\sigma} \cdot \vec{q},
\]

where \( \vec{\sigma} \) and \( \vec{q} \) are the nucleon spin and pion momentum, respectively. This strong \( p \)-wave \( \pi N \) interaction gives rise to the \( \Delta \) resonance and its deformation\(^3\) which has been observed in pion photoproduction.

In this contribution, I will present a meson-exchange dynamical model for pion photoproduction we recently developed in a collaboration between groups at Dubna, Mainz, and Taipei (DMT)\(^4\) which can describe well the pion-photoproduction data from threshold to the first resonance region, including the \( \pi^0 \) threshold production.
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and $\Delta$ deformation. The DMT dynamical model also starts from an effective chiral Lagrangian. The effective Lagrangian is then used to construct a potential for use in the scattering equation. The solutions of the scattering equation will include rescattering effects to all orders and thereby unitarity is ensured.

In a dynamical model for pion photoproduction, the $t$-matrix is given as

$$t_{\gamma\pi}(E) = v_{\gamma\pi} + v_{\gamma\pi}g_0(E) t_{\pi N}(E),$$

where $v_{\gamma\pi}$ is the $\gamma\pi$ transition potential, $g_0$ and $t_{\pi N}$ are the $\pi N$ free propagator and $t$ matrix, respectively, and $E$ is the total energy in the c.m. frame. Physical multipole amplitude in channel $\alpha$ then reads as

$$t_{\gamma\pi}(\alpha; E + i\varepsilon) = e^{i\delta_{\alpha}} \cos \delta_{\alpha} |v_{\gamma\pi}(\alpha)| + P \int_0^\infty dq q^2 R_{\pi N}^{(\alpha)}(q E, q'; E) v_{\gamma\pi}(\alpha, q, k_E) (E - E_{\pi N}(q')) \] (1)

where $\delta_{\alpha}, R_{\pi N}^{(\alpha)}, E_{\pi N}(q)$ and $P$ denote the $\pi N$ phase shift, reaction matrix in channel $\alpha$, total CM energy of momentum $q$, and principal value integral, respectively; $k_E = |k|$ is the photon momentum and $q_E$ the pion on-shell momentum. The amplitudes $t_{\pi N}$ are obtained in a meson-exchange $\pi N$ model constructed in the Bethe-Salpeter formalism and solved within Cooper-Jennings reduction scheme. At low energies where resonances play little role, only background part, $v_{\pi N}^B$ and $v_{\gamma\pi}^B$, which are derived from an effective Lagrangian containing Born terms and $\rho$ and $\omega$ exchanges in the $t$ channel, contribute.

For $\pi^0$ photoproduction from proton, we calculate the multipole $E_{0+}$ near threshold by solving the following coupled channels equation within a basis with physical pion and nucleon masses. It leads to the following expression in $\pi^0 p$ channel:

$$t_{\gamma\pi^0}(E) = v_{\gamma\pi^0}(E) + v_{\gamma\pi^0}(E) g_{\pi^0 p}(E) t_{\pi^0 p\to\pi^0 p}(E) + v_{\gamma\pi^0}(E) g_{\pi^0 n}(E) t_{\pi^0 n\to\pi^0 p}(E).$$

(2)

The $\pi N$ $t$-matrices are obtained by solving the coupled channels equation for $\pi N$ scattering using the meson-exchange model. In Fig. 1, the prediction of DMT model for $Re E_{0+}$ obtained without and with isospin symmetry assumption, are shown in dashed and solid curves, respectively, and compared with heavy-baryon ChPT results (dash-dotted curve). Agreement of DMT prediction with the data...
and ChPT results are excellent.

The polarized linear photon asymmetry $\Sigma$ has been found to be very sensitive to small $p$-wave multipoles\[\text{[\textsuperscript{7}]}\] DMT model (solid curve) is not able to reproduce the data at 159.5 MeV, of Ref.\[\text{[\textsuperscript{8}]}\] as shown in Fig. 2, while ChPT calculation of $O(p^4)$ with six low-energy constants (dashed curve) is seen to be able to describe the experiment reasonably well. However, preliminary analysis of a new measurement at Mainz\[\text{[\textsuperscript{9}]}\] seems to agree with DMT’s prediction.

We now turn to the issue of the $\Delta(1232)$ deformation. In a symmetric SU(6) quark model, $\Delta$ is in $S$ state and spherical. The photo-excitation of the $\Delta$ could then proceed only via $M1$ transition. The existence of a $D$ state in the $\Delta$ has the consequence that the $\Delta$ is deformed and the photon can excite a nucleon through electric $E2$ quadrupole transition. In pion photoproduction, $E2$ excitation would give rise to nonvanishing $E^{(3/2)}_1$ multipoles amplitude. Recent experiments give $R_{EM} = E^{(3/2)}_1/M^{(3/2)}_1 = -(2.5 \pm 0.5)\%$ a clear indication of $\Delta$ deformation.

In the (3,3) channel where $\Delta$ excitation plays an important role, the transition potential $v_{\gamma\pi}$ consists of two terms

$$v_{\gamma\pi}(E) = v_{\gamma\pi}^B + v_{\gamma\pi}^D(E),$$  

where second term of Eq. \text{[\textsuperscript{3}]} corresponds to the contribution of bare $\Delta$, namely, $\gamma N \rightarrow \Delta \rightarrow \pi N$. We may then write

$$t_{\gamma\pi} = t_{\gamma\pi}^B + t_{\gamma\pi}^\Delta,$$  

where $t_{\gamma\pi}^B(E) = v_{\gamma\pi}^B + v_{\gamma\pi}^D g_0(E) t_{\pi N}(E)$ and $t_{\gamma\pi}^\Delta(E) = v_{\gamma\pi}^\Delta + v_{\gamma\pi}^D g_0(E) t_{\pi N}(E)$.  

By combining the contributions of $t_{\gamma\pi}^B$ and $t_{\gamma\pi}^\Delta$ and using the bare $\gamma N \Delta$ coupling constants $G_{M1}$ and $G_{E2}$ for $M1$ and $E2$ transitions as free parameters, results of
our best fit to the resonant multipoles $M^{(3/2)}_{1+}$ and $E^{(3/2)}_{1+}$ obtained in the analyses of Mainz\cite{11} and VPI group\cite{12} are shown in Fig. 3 by solid curves. The dashed curves denote the contribution from $t^B_{\gamma\pi}$ only. The dotted curves represented the $K$-matrix approximation to $t^B_{\gamma\pi}$, namely, without the principal value integral term of Eq. (1) included.

For $M^{(3/2)}_{1+}$, one sees a large effect of the pion off-shell rescattering (difference between dotted and dashed curves), which results from the principal value integral part of Eq. (1). The total pion rescattering (dashed curves) contributes for half of the $M^{(3/2)}_{1+}$ as seen in Fig. 3 while the remaining half originates from the bare $\gamma N\Delta$ excitation. Furthermore, one sees that almost all of the $E2$ strength is generated by the $\pi N$ rescattering.

At the resonance position $t^B_{\gamma\pi}$ vanishes within $K$-matrix approximation and only principal value integral term survives. The latter corresponds to the contribution where $\Delta$ is excited by the pion produced via $v^B_{\gamma\pi}$. Consequently the addition of this contribution to $t^\Delta_{\gamma\pi}$ can be considered as a dressing of the $\gamma N\Delta$ vertex. For $E^{(3/2)}_{1+}$, the dominance of background and pion rescattering contributions leads to a very small bare value for electric transition. We hence conclude that bare $\Delta$ is almost spherical and the deformation observed experimentally arises mostly from the long-range effect of the pion cloud, a manifestation of chiral dynamics.

In summary, we have demonstrated that the DMT meson-exchange dynamical model for pion photoproduction, which starts from an chiral effective Lagrangian, provides an excellent and economical framework in describing threshold $\pi^0$ production and $\Delta$ deformation, two key consequences of chiral dynamics.

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