Investigating convergence of the reaction $\gamma p \rightarrow \pi^+\Delta$ and tensor meson $a_2$ exchange at high energy

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A Regge approach to the reaction processes $\gamma p \rightarrow \pi^-\Delta^{++}$ and $\gamma p \rightarrow \pi^+\Delta^0$ is presented for the description of existing data up to $E_\gamma = 16$ GeV. The model consists of the $t$-channel $\pi(139) + \rho(775) + a_2(1320)$ exchanges which are reggeized from the relevant Born amplitude. Discussion is given on the minimal gauge prescription for the $\pi$ exchange to render convergent the divergence of the $u$-channel $\Delta$-pole in the former process. A new Lagrangian is constructed for the $a_2N\Delta$ exchange in this work and applied to the process for the first time with the coupling constant deduced from the duality plus vector dominance. It is shown that, while the $\pi$ exchange dominates over the process, the role of the $a_2$ exchange is crucial rather than the $\rho$ in reproducing the cross sections for total, differential, and photon polarization asymmetry to agree with data at high energy.

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Photoproduction of $\Delta$-baryon is an example of the hadron reaction to study the formation of a composite particle from the $\pi N$ interaction. Efforts in existing theories and experiments on this reaction process have been concentrated mainly on understanding of the dynamical and static properties of $\Delta$-baryon around the $\Delta$-resonance region \cite{1,3}. But, it could also be of value to question how the production mechanism would proceed over the region, and it is, therefore, a challenging issue to establish a model for the $\gamma p \rightarrow \pi^-\Delta^{++}$ process which is valid at high energy, because the $\Delta$-propagation in the process would be highly divergent there.

In experiments evidences are clear for the formation of the $\Delta$-baryon through the reaction $\gamma N \rightarrow \pi\pi N$ in the photon energy below the threshold of $\rho N$ production. At high energies the reaction cross sections for the $\gamma p \rightarrow \pi^-\Delta^{++}$ process were measured for the differential, spin observables for the photon beam and density matrix elements up to photon energy $E_\gamma = 16$ GeV \cite{4,5,6}. Only recently the total and differential cross sections for $\gamma p \rightarrow \pi^+\Delta^{++}$ were obtained from threshold up to $\sqrt{s} = 2.6$ GeV at the ELSA \cite{7}. In particular, the total cross section for $\gamma p \rightarrow \pi^-\Delta^{++}$ at the ELSA shows a sharp peak of $\sigma_{\text{max}} \approx 70$ mb in size around $E_\gamma \approx 1.6$ GeV with the steep decrease following over the resonance region, and, hence, exhibits a typical feature of the nondiffractive two-body process.

In this work we will analyze the production mechanism of the reactions $\gamma p \rightarrow \pi^-\Delta^{++}$ and $\gamma p \rightarrow \pi^+\Delta^0$ at high energies with a focus on the convergence of the reaction processes there. From a theoretical point of view only the $\pi$ exchange in the $t$-channel peripheral subprocess is expected to dominate at high energies and small momentum transfer. Hence the production amplitude should be $M \propto q \cdot \epsilon / (t - m_\pi^2)$, where $\epsilon$ is photon polarization, and $q$ and $m_\pi$ are pion momentum and mass. However, since the $t$-channel $\pi$ exchange itself is not gauge invariant, an extension of the production amplitude is needed for gauge invariance. Furthermore this should be a specialized one for the extended amplitude has to be convergent at high energy, even if it includes highly divergent $\Delta$ propagation for gauge invariance. For this requirement a theoretical speculation was suggested in Ref. \cite{8} that the amplitude, thus extended, contain only the charge couplings of the $s$-channel proton-pole and $u$-channel $\Delta$-pole coupling to photon field in the $\gamma p \rightarrow \pi^-\Delta^{++}$ process. In other words, the transverse components in these $s$ and $u$-channel poles should be removed in order for the convergence of the process to be ensured at high energy. This leads to the so-called the minimal gauge prescription in the sense that the proton-pole and $\Delta$-pole terms are minimally introduced for gauge invariance of the $t$-channel $\pi$ exchange. Moreover, such a scheme seems to be reasonable because the higher multipoles of the $\Delta$-baryon and proton electromagnetic moments are defined uniquely in the static limit and such a uniqueness can no longer be valid at high energy.

Application of the minimal gauge condition is found in Ref. \cite{9} in which case the dynamics of $\gamma N \rightarrow \pi^\pm \Delta$ was investigated in the kinematical region, $-t \leq m_\pi^2$ and $s \rightarrow \infty$ at forward angles. A more qualitative analysis of the reaction was made in Ref. \cite{10} by using the $\pi^+b_1 + \rho + a_2$ Regge-pole exchanges in the $t$-channel helicity amplitude with their residues and cuts considered to fit to data.

On the other hand, we note that the tensor-meson $a_2$ plays the role to significantly improve the cross sections for the differential and spin polarizations in the $\gamma N \rightarrow \pi^\pm N$ process at high energy \cite{11}. The significance of such a higher-spin interaction is confirmed in the cases of $\gamma p \rightarrow K^+\Lambda(\Sigma^0)$ as well by the role of the $K^+_2 \ (12)$. Nevertheless, there are no attempts at present, however, to investigate the role of the tensor meson $a_2$ in the $\pi\Delta$ photoproduction utilizing the effective Lagrangian except for the case of the Regge-pole fit to data discussed above.

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In this work our interest is to construct a model for the $\gamma p \rightarrow \pi^- \Delta^{++}$ process at high energy where the reaction cross sections can be described without either fit parameters or any counter terms included in ad hoc fashion. For this purpose we consider to incorporate the two basic ingredients with the model, i.e., the minimal gauge-invariance and the role of the spin-2 tensor-meson exchange.

For a heuristic introduction of the minimal gauge prescription, let us begin with the Born amplitude for the process,

$$\gamma(k) + p(p) \rightarrow \pi^\pm(q) + \Delta(p'),$$

(1)

where the production amplitude for the $\gamma p \rightarrow \pi^- \Delta^{++}$ process consists of the proton-pole in the $s$-channel, the $\Delta^{++}$-pole in the $u$-channel, and the $\pi$-exchange in the $t$-channel to respect the charge conservation, $e_N - e_\pi - e_\Delta = 0$, with the charges of nucleon, $\Delta$, and $\pi$ denoted by $e_N$, $e_\Delta$, and $e_\pi$, respectively. These are summarized in diagrams in Fig. 1.

With the contact term further the reggeized $\pi$ exchange which is gauge invariant is, thus, given by

$$M_\pi = [M_{s(N)} + M_{u(\Delta)} + M_{t(\pi)} + M_c] \times (t - m_\pi^2) R^\varphi(s, t),$$

(2)

where

$$iM_{s(N)} = \frac{f_{\pi \Delta}}{m_\pi} \bar{u}_{\nu}(p') q^\gamma (\not{p} + \not{k} + M_N) e_N \not{u}(p),$$

(3)

$$iM_{u(\Delta)} = -\frac{f_{\pi \Delta}}{m_\pi} \bar{u}_{\nu}(p') e_\Delta (g^{\gamma \alpha} \not{q} - e^\nu \gamma^\alpha) \times (\not{p}' - \not{k} + M_\Delta) \Pi^\Delta_{\alpha \beta} (p' - k) q^\beta u(p),$$

(4)

$$iM_{t(\pi)} = \frac{f_{\pi \Delta}}{m_\pi} \bar{u}_{\nu}(p') e_\pi (2 q - k) \cdot \epsilon (q - k) v u(p),$$

(5)

$$iM_c = - e_\pi \frac{f_{\pi \Delta}}{m_\pi} \bar{u}_{\nu}(p') v^{\nu} u(p),$$

(6)

with the masses of nucleon, $\Delta$, and $\pi$ denoted by $M_N$, $M_\Delta$, $m_\pi$, respectively. Here, the off-shell effect in the $\pi N$ vertex is neglected for simplicity.

For the charge coupling of the $\gamma \Delta$ vertex we use

$$e_\Delta e_{\pi} \Gamma_{\gamma \Delta\Delta} = - e_\Delta (g^{\nu \alpha} \not{q} - e^\nu \gamma^\alpha) (\gamma^\nu e^\alpha + \gamma^\nu f^\alpha),$$

(7)

which is obtained from the Ward identity at the $\gamma \Delta$ vertex

$$k_{\mu} \Gamma^\mu_{\gamma \Delta \Delta}(p, k) = (D^\nu)_{\alpha}^{-1}(p + k) - (D^\nu)_{\alpha}^{-1}(p),$$

(8)

by using the propagator

$$D^\alpha\beta(p) = \frac{(\not{p} + M_\Delta) \Pi^\alpha\beta(p)}{p^2 - M_\Delta^2},$$

(9)

and the spin projection for the spin-$3/2$ $\Delta$ baryon,

$$\Pi^\alpha\beta(p) = -g^{\alpha\beta} + \frac{1}{3} \gamma^\alpha \gamma^\beta + \frac{\gamma^\alpha p^\beta - \gamma^\beta p^\alpha}{3M_\Delta} + \frac{2p^\alpha p^\beta}{3M_\Delta^2},$$

(10)

written collectively for $\varphi = \pi, \rho, a_2$-meson of spin $J$ with $s_0 = 1$ GeV$^2$. For the phase of the Regge pole the canonical form of $\frac{1}{2}((-1)^J + e^{-i\pi \alpha_{\varphi}(t)})$ is generally assigned to the exchange non-degenerate meson $^{13}$. In the case of the exchange-degenerate (EXD) trajectories $\pi-b_1$ and $\rho-a_2$ pairs the determination of the phases will be discussed later.

The minimal gauge prescription for $\pi$ exchange

As discussed above the reaction amplitude converging at high energy should couple to the Coulomb component of photon field, and such a condition should be taken into account in the gauge invariant amplitude in Eq. (2).

We recall that the $u$-channel $\Delta$-pole as well as the $s$-channel proton-pole term is introduced merely to preserve gauge invariance for the $t$-channel $\pi$ exchange at high energy, as discussed in Ref. $^{[3]}$. We, then, consider only the charge couplings of the $s$, and $u$-channel amplitudes that are indispensable to restore gauge invariance, but remove all the transverse ones which are redundant by gauge invariance. In the proton-pole term in Eq. (3), for instance, only the $2 \not{p} \cdot \epsilon$ term has to be there, whereas such a gauge invariant term, $\not{p} \not{q}$ from the $(\not{p} + \not{k} + M_N) \not{q}$ as well as from the magnetic moment term is redundant and, hence, excluded.

Similarly, in the case of the $u$-channel amplitude in Eq.
where we use the interaction Lagrangian

\[ iM_{u(\Delta)} = \sum_{\alpha \beta} g_{\alpha \beta \lambda \sigma} \partial_\alpha a_{\lambda \sigma} u(p) \]

which is written in a fully expanded form as

\[
iM_{u(\Delta)} = \epsilon_\Delta \frac{f_{\pi N \Delta}}{m_\pi} u(p)^\prime \left[ q_\nu (2 \epsilon \cdot p^\prime - k^\prime \cdot k) + \frac{2}{3} (k_\nu \cdot k^\prime - q_\nu \cdot k) \right] + \frac{2}{3M_\Delta} (2k_\nu \cdot p^\prime - 2\epsilon \cdot p^\prime \cdot k - k_\nu \cdot k^\prime) \cdot q + \frac{1}{3M_\Delta} \left[ 2(k_\nu \cdot p^\prime - 2\epsilon \cdot p^\prime \cdot k - k_\nu \cdot k^\prime) \cdot q - \frac{2}{3M_\Delta} (2k_\nu \cdot p^\prime - 2\epsilon \cdot p^\prime \cdot k - k_\nu \cdot k^\prime) \right] \cdot \left( \epsilon^{\prime \prime} = \frac{1}{u - M_\Delta} \right),
\]

only the first term proportional to \(2 \epsilon \cdot p^\prime\) is not invariant and should be reserved, whereas all the others are excluded by redundancy. It should be noted that this simplification is possible only when the \(M_{u(\Delta)}\) term can be written in such an antisymmetric form as in Eq. 12 with respect to photon polarization \(\epsilon\) and momentum \(k\), and this can only be done by the benefit of the second term \(-\epsilon^{\prime \prime} \gamma^a\) in the \(\gamma \Delta \Delta\) coupling in Eq. 11. This signifies the validity of the Ward identity Eq. 9 at the photon coupling vertex.

The invariant amplitude \(M_{a(\pi)} + M_{u(\Delta)} + M_{l(\pi)} + M_c\) in Eq. 2 in this minimal gauge is, therefore, written as

\[
\frac{f_{\pi N \Delta}}{m_\pi} \sum_{\alpha \beta} g_{\alpha \beta \lambda \sigma} \partial_\alpha a_{\lambda \sigma} u(p)^\prime \left[ q_\nu (2 \epsilon \cdot p^\prime - k^\prime \cdot k) + \frac{2}{3} (k_\nu \cdot k^\prime - q_\nu \cdot k) \right] + \frac{2}{3M_\Delta} (2k_\nu \cdot p^\prime - 2\epsilon \cdot p^\prime \cdot k - k_\nu \cdot k^\prime) \cdot q + \frac{1}{3M_\Delta} \left[ 2(k_\nu \cdot p^\prime - 2\epsilon \cdot p^\prime \cdot k - k_\nu \cdot k^\prime) \cdot q - \frac{2}{3M_\Delta} (2k_\nu \cdot p^\prime - 2\epsilon \cdot p^\prime \cdot k - k_\nu \cdot k^\prime) \right] \cdot \left( \epsilon^{\prime \prime} = \frac{1}{u - M_\Delta} \right),
\]

In the numerical analysis, the effect of the minimal gauge on the cross section will be examined as the photon energy increases up to 16 GeV.

The value for the coupling constant \(f_{\pi - p \Delta^{++}}\) is scattered in various reactions, i.e., from the quark model prediction \(f_{\pi N \Delta} = \frac{2M_\pi}{\sqrt{2}} f_{\pi N N} \approx 1.7\) with \(f_{\pi N N} = 1\) for the NN interaction \(11\) to \(f_{\pi - p \Delta^{++}} = 2.16\) from the decay width \(\Gamma_{\Delta \rightarrow \pi N} = 120\) MeV for the \(\pi \Delta\) photoproduction \(1\). We consider the one within the range of \(1.7 \leq f_{\pi N \Delta} \leq 2.16\) that is better to agree with experimental data.

1. The interaction form of the Lagrangian in Eq. 11, of course, might not be unique but one of the possible couplings between \(a_2\) and \(N \Delta\) baryon transition-current, and one could also consider the interaction of form

\[ L_{a_2 N \Delta} = f_{a_2 N \Delta} \Delta_{\rho \gamma} \gamma_5 N a_2^{\mu \nu} \]

by replacing the \(\rho^{\mu \nu}\) with \(a_2^{\mu \nu}\) in Eq. 13, for instance, though unnatural to identify the \(\rho^{\mu \nu}\) with \(a_2^{\mu \nu}\). In this case, however, he(she) cannot use the identity in Eq. 13 to determine the \(f_{a_2 N \Delta}\), but has to consider it as a parameter to fit to data, because of the different mass dimensions between the \(f_{\rho N \Delta}\) and \(f_{a_2 N \Delta}\).
As the only unknown coupling constant $f_{a2N\Delta}$ is determined, once the $f_{\rho N\Delta}$ is given, there are, therefore, no free parameters in the present calculation. We choose the signs of the coupling constants $g_{\gamma\rho}$ and $g_{\gamma\pi a_2}$ to agree with photon polarization asymmetry $\Sigma$ of $\gamma p \to \pi^- \Delta^{++}$ and $\gamma p \to \pi^+ \Delta^0$.

The reggeized $a_2$ exchange is given by

$$iM_{a2} = -\frac{2g_{\gamma a_2 N\Delta}}{m_0^2 - m_{a2}^2} \alpha_\beta \mu \lambda \epsilon_\mu \epsilon_\lambda Q_\alpha Q_\rho \gamma_\nu \gamma_\lambda \Gamma_\rho \Gamma_\lambda, \quad \Pi^{\rho \sigma \xi}(Q) \equiv \frac{1}{2} \left( Q^{\rho \sigma} + Q^{\sigma \rho} - i \eta^{\rho \sigma} \right) \frac{1}{3} \eta^{\rho \sigma} \eta^{\rho ^\prime \sigma ^\prime}$$

(20)

where $P = (p + p')/2$ and the spin-2 projection is

$$\Pi^{\rho \sigma \xi}(Q) = \frac{1}{2} \left( Q^{\rho \sigma} + Q^{\sigma \rho} - i \eta^{\rho \sigma} \right) \frac{1}{3} \eta^{\rho \sigma} \eta^{\rho ^\prime \sigma ^\prime}$$

(21)

with $\eta^{\rho \rho} = -g^{\rho \rho} + Q^2 \eta^{\mu \nu} / m_0^2$.

In the Regge framework the predictions for the physical observables are strongly dependent on the phase and sensitive to the intercept of the trajectory as well. Therefore, to use the right phase and trajectory is of importance, though there is no rigorous theory for this purpose. One feasible scheme for this is the addition of the phases of the EXD pairs $\pi - b_1$ and $\rho - a_2$ as discussed in Ref. [13].

From the $G$-parity of the photon-meson coupling vertex and the $\pi N\Delta$ coupling constants related to the isospin,

$$f_{\pi^- \Delta^{++}} = -f_{\pi^+ \Delta^-} = -\sqrt{3} f_{\pi^0 \Delta^0} = \sqrt{3} f_{\pi^- \Delta^+},$$

(22)

the production amplitude is written symbolically as

$$\mathcal{M} = \left\{ 1 - \frac{1}{1/\sqrt{3}} \right\} \left( \pm \pi + b_1 \right) \left( \rho \pm a_2 \right),$$

(23)

for the $\gamma N \to \pi^\pm \Delta$, $\gamma p \to \pi^\pm \Delta^{++}$ (upper), and $\gamma p \to \pi^0 \Delta^0$, $\gamma n \to \pi^\pm \Delta^+$ processes (lower), respectively. The phases of the exchanged mesons, thus determined, are the same as those given in the $\gamma N \to \pi^\pm N$ process [11, 13].

**Results and discussion**

Given the trajectories for $\pi$, $\rho$, and $a_2$ Regge-poles as

$$\alpha_{\pi}(t) = 0.7 (t - m_\pi^2),$$

(24)

$$\alpha_{\rho}(t) = 0.8 (t + 0.55),$$

(25)

$$\alpha_{a2}(t) = 0.85 (t - m_{a2}^2) + 2,$$  

(26)

respectively, we calculate the total cross section for $\gamma p \to \pi^- \Delta^{++}$ and present the result in Fig. [2], where the blue dashed line denotes the total cross section from the phase of the $\pi$ exchange with the EXD phase, 1, as determined in Eq. (23), and the solid line is from the case of the canonical phase for the $\pi$ exchange, respectively.

For a better agreement with data as shown in the resonance region we choose the canonical phase for the dominating $\pi$ exchange in the absence of $b_1$ exchange in the present calculation.

A summary of the coupling constants and the phases of the exchanged mesons used for the present calculation is given in Table [I].

| Coupling const. | $^{(a)}$ Phase | $^{(b)}$ Phase |
|-----------------|----------------|----------------|
| $\pi$ | $f_{\rho N\Delta} = 2.0$ | $1/2\left(1 + e^{-i\pi\alpha_{\pi}(t)}\right)$ |
| $\gamma p$ | $g_{\gamma\pi \rho} = 0.224$ | $1/2\left(1 + e^{-i\pi\alpha_{\pi}(t)}\right)$ |
| $\gamma N\Delta$ | $f_{\rho N\Delta} = 8.57$ | $e^{-i\pi\alpha_{\rho}(t)}$ |
| $a_2$ | $g_{\gamma\pi a_2} = -0.276$ | $e^{-i\pi\alpha_{a2}(t)}$ |
| $f_{a2 N\Delta}$ | $f_{a2 N\Delta} = -3 f_{\rho N\Delta}$ | $1$ |

(24)

(25)

(26)

(27)

(28)

(29)

Table I. Meson-baryon coupling constants for $^{(a)}\gamma p \to \pi^- \Delta^{++}$ and $^{(b)}\gamma p \to \pi^+ \Delta^0$ processes. The superscript indicates the phase taken for the process denoted.
FIG. 3. Differential cross section and photon polarization asymmetry for $\gamma p \to \pi^- \Delta^{++}$ at $E_\gamma = 16$ GeV. The solid and dotted lines are from the $\rho + \pi$ exchanges in the minimal gauge with and without tensor meson $a_2$, respectively. The dashed line in the left panel depicts the $a_2$ contribution. Data are from Refs. [4, 6].

FIG. 4. Differential cross section and photon polarization asymmetry for $\gamma p \to \pi^+ \Delta^0$ at $E_\gamma = 16$ GeV. Notations for the curves are the same as in Fig. 3. Data are from Refs. [4, 6].

by using the minimal gauge as shown by the solid and the blue dashed lines. These findings confirm the validity of the minimal gauge for the high energy behavior of the $\pi \Delta$ photoproduction.

The role of the tensor meson $a_2$ in the reaction process is evident in the differential cross section $d\sigma/dt$ and the photon polarization asymmetry which is defined as

$$\Sigma = \frac{d\sigma^\perp - d\sigma^\parallel}{d\sigma^\perp + d\sigma^\parallel},$$

in the c.m. frame of the pion production plane.

We present the cross sections for the differential and the photon polarization asymmetry from the SLAC data for the $\gamma p \to \pi^- \Delta^{++}$ process up to $E_\gamma = 16$ GeV with our focus on the production mechanism of the reaction process at high energy. For this purpose we constructed a Born term model where the $\pi$ exchange is reggeized in the $t$-channel with the $u$-channel $\Delta$-pole included for gauge invariance in addition to the $s$-channel proton-pole and the contact term. In order to make convergent the energy-dependence of the reaction cross section against the divergence of the $\Delta$-pole at high energy we utilized the minimal gauge prescription to simplify the $\Delta$-pole, which is possible for the antisymmetric form of the charge coupling terms in the $\gamma \Delta \Delta$ vertex due to the Ward identity at the vertex.

We further showed that the tensor meson $a_2$ exchange plays the key role to agree with the existing data on the differential and photon polarization asymmetry for $\gamma p \to \pi^- \Delta^{++}$ and $\gamma p \to \pi^+ \Delta^0$ at high energy. For doing this we constructed a new effective Lagrangian for the tensor meson-nucleon-$\Delta$ coupling in this work and demonstrate its validity by obtaining quite improved differential cross section as well as photon polarization asymmetry with the coupling constant $\frac{f_{\pi N \Delta}}{m_{a_2}} = -3 \frac{g_{\pi N \Delta}}{m_\rho}$ which is deduced from the duality plus vector dominance.

While revealing the well-known approximation $\Pi_\Delta^{\mu \nu} \approx -g^{\mu \nu}$ to be valid only in the limited energy region near threshold, we understand the production mechanism in this minimal gauge as the dominance of the $\pi$ exchange incorporating with the $a_2$ exchange rather than the $\rho$.

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