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EXCHANGE CURRENTS IN PHOTOPRODUCTION OF THE $\Delta(1232)$ AND $N^*(1440)$ RESONANCES*

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We calculate the photoexcitation amplitudes for the $\gamma + N \to \Delta(1232)$ and $\gamma + N \to N^*(1440)$ transitions in the chiral quark model including two-body exchange currents. We show that the contributions from the various two-body currents are important. Compared with present experimental data we see a slight worsening for the $N - \Delta$ excitation but a small improvement for the transition to the Roper resonance ($N^*(1440)$) with respect to the impulse approximation.

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1. Introduction

Electromagnetic (e.m.) properties are of fundamental importance for our understanding of quark dynamics in the low-energy regime. In the past, most calculations have been made in the so-called impulse approximation, where the interaction between the quarks is neglected and consequently the total photon four-momentum is transferred to a single quark. However, two-body currents are necessary to conserve the electromagnetic current in an interacting quark-quark system. Here, we calculate the photoexcitation of the Δ and $N^*(1440)$ resonances including two-body exchange currents. For these transitions there are still large discrepancies between theoretical values calculated in impulse approximation and experimental data. In Section 2, we will shortly present our model including the Hamiltonian and the electromagnetic currents. In Section 3, we will give the definition of the helicity amplitudes and discuss the results, with special emphasis to the effect of the two-body currents.

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2. The chiral quark model

Constituent quarks are complicated objects consisting of a bare quark surrounded by a polarization cloud of quark-antiquark pairs which are continuously excited from the QCD-vacuum. This means that much of the complexity of QCD in the low-energy regime is already incorporated in the picture of constituent quarks as quasi-particles.

2.1. The Hamiltonian

The Hamiltonian of the Chiral Quark Model (χQM) is in the case of equal quark masses m_q given by

$$
\begin{aligned}
H = & \sum_{i=1}^{3}(m_q + \frac{\boldsymbol{p}_i^2}{2m_q}) - \frac{\boldsymbol{P}^2}{6m_q} + \sum_{i<j}(V^{\rm conf}(\boldsymbol{r}_i,\boldsymbol{r}_j) \\
& + V^{\rm OPEP}(\boldsymbol{r}_i,\boldsymbol{r}_j) + V^{\rm OSEP}(\boldsymbol{r}_i,\boldsymbol{r}_j) + V^{\rm OGEP}(\boldsymbol{r}_i,\boldsymbol{r}_j))\,. \qquad (1)
\end{aligned}
$$

Here, $\boldsymbol{p}_i(\boldsymbol{r}_i)$ describes the momentum (position) of the i-th quark and $\boldsymbol{P}$ the center of mass momentum, respectively. The interaction between the quarks consists of various terms, which model the main symmetries and the dynamical content in the low-energy regime. Chiral symmetry breaking leads to the appearance of the pion as Goldstone boson and its chiral partner, the sigma meson. The coupling of these mesons to the constituent quarks is described in lowest order by a one-pion- ($V^{\rm OPEP}$) and a one-sigma meson ($V^{\rm OSEP}$) exchange potential. Asymptotic freedom is simulated in our model by a one-gluon exchange potential ($V^{\rm OGEP}$), which dominates the quark dynamics in the short-distance range. Finally, we simulate the quark confinement by a phenomenological two-body harmonic oscillator potential ($V^{\rm conf}$). The free parameters of the χQM, listed in Table I, are taken from Ref. [1]

TABLE I

Quark model parameters

b [fm]	α_s	a_c [MeVfm^{-2}]	m_σ [MeV]	$g_\sigma^2/(4\pi)$	Λ [fm^{-1}]
0.613	1.093	20.20	675	0.554	4.2

2.2. The electromagnetic currents

In order to calculate electromagnetic properties of the baryons, we have to know the four-vector current density $J_\mu = (\rho(x), -\boldsymbol{J}(x))$ of the interacting quarks in the system. This current density is a coherent sum over one- and two-body terms, where the one-body current is given by the coupling of a photon to an elementary fermion, i.e. we assume that the constituent quarks have no anomalous magnetic moment. The two-body exchange currents are derived from the Feynman diagrams, shown in Fig. 1.

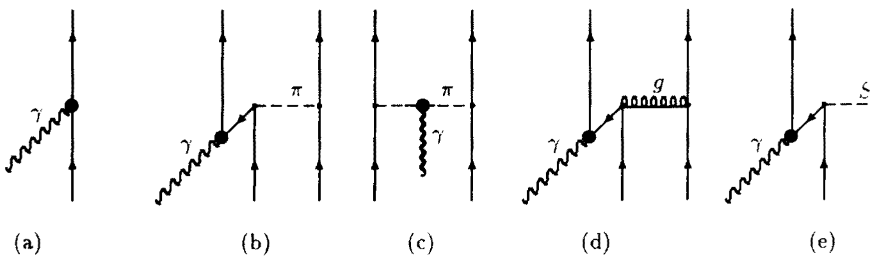

Fig. 1. One-body and two-body exchange currents between quarks: (a) — impulse, (b) — pion pair, (c) — pionic, (d) — gluon pair, (e) — scalar pair, *i.e.*σ meson or confinement pair.

From Fig. 1 the close interrelation between the electromagnetic current and the quark-quark interaction is evident. Note, that we have not introduced any further parameters and that the parameters are the same as for the calculation of the baryon spectrum. Explicit expressions for the one- and two-body operators may be found in Ref. [2].

3. Results

Photoproduction of excited nucleon states is determined by the photon-baryon interaction Hamiltonian

$$H_{\text{em}} = \int d^4x J_\mu(x) A^\mu(x) \,. \tag{2}$$

We define the helicity amplitudes [3] by

$$A_\lambda^N = \langle B^* \lambda \mid H_{\text{em}} \mid N, \lambda - 1 \rangle \,, \tag{3}$$

which describe the transition of the nucleon with total angular momentum projection $\lambda - 1$ to a resonance with projection λ. The relations between the magnetic (F_M) and quadrupole (F_Q) form factors defined in Ref. [1] and the helicity amplitudes are given by

$$A_{3/2}(\boldsymbol{q}^2) = -\sqrt{3\pi\omega}\left(\frac{e}{2M}\right)\left(F_M^{N\to\Delta}(\boldsymbol{q}^2) - \frac{M\omega}{6}F_Q^{N\to\Delta}(\boldsymbol{q}^2)\right) \tag{4}$$

$$A_{1/2}(\boldsymbol{q}^2) = -\sqrt{\pi\omega}\left(\frac{e}{2M}\right)\left(F_M^{N\to\Delta}(\boldsymbol{q}^2) + 3\frac{M\omega}{6}F_Q^{N\to\Delta}(\boldsymbol{q}^2)\right) \tag{5}$$

for the Δ-isobar and

$$A_{1/2} = \sqrt{\pi\omega}\frac{e}{M}F_M^{N\to N^*}(\boldsymbol{q}^2) \tag{6}$$

for the Roper resonance. Here $(\omega, \boldsymbol{q})$ is the four-momentum transfer of the photon in the center of mass frame and M is the nucleon mass.

In Tables II and III we show our results for the helicity amplitudes of the $N \to \Delta$ and $N \to N^*(1440)$ transitions. Note, that we here calculate the amplitudes at $\boldsymbol{q}^2 = \omega^2$ in contrast to Ref. [1], where the excitation amplitudes are calculated at $\boldsymbol{q}^2 = 0$.

TABLE II

Helicity amplitudes for the $p \to \Delta^+$ transitions at $\boldsymbol{q}^2 = \omega^2$ including two-body exchange currents; i=impulse, g=gluon, $\pi q\bar{q}$= pion pair, $\gamma\pi\pi$=pionic, $\sigma = \sigma$-meson, c=confinement. The helicity amplitudes for neutron targets are the same. All entries are in $[10^{-3}\text{GeV}^{-1/2}]$.

	A_i	A_g	$A_{\pi q\bar{q}}$	$A_{\gamma\pi\pi}$	A_σ	A_c	A_{total}	exp. [4]
$A^p_{1/2}$	-104	-4	+18	-22	-11	+40	-83	-141±5
$A^p_{3/2}$	-181	-22	+24	-37	-19	+70	-165	-257±8

TABLE III

Helicity amplitudes at $\boldsymbol{q}^2 = \omega^2$ for the $p, n \to N^*(1440)$ transitions. Same notation as in Table II.

	A_i	A_g	$A_{\pi q\bar{q}}$	$A_{\gamma\pi\pi}$	A_σ	A_c	A_{total}	exp. [4]
$A^p_{1/2}$	-38	-20	+6	-16	-18	-26	-112	-72±9
$A^n_{1/2}$	+25	+7	-10	+16	+12	+17	+67	+52±25

As can be seen from the tables, the two-body contributions are important for both the $N \to \Delta$ and $N \to N^*$ transitions. For the Δ-isobar, we observe large cancellations between the various exchange contributions. Our total result is slightly worse than the impulse approximation. For the excitation to the Roper resonance, however, the different exchange contributions reinforce each other and go in the right direction. However, the total effect of the various two-body contributions is even a little bit too large, at least for the excitation of the proton.

In this work, we have gone beyond the single-quark transition picture and demonstrated that two-quark transitions (exchange currents) are equally important. In the future, it will be very interesting to study the e.m. transitions to other excited nucleon and Δ-states, especially with respect to planned experiments at CEBAF, MAMI and ELSA.

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