Chiral quark model approach for the study of baryon resonances

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We report the chiral quark model approach for the study of baryon resonances in meson photoproduction and meson-nucleon scattering processes. Focusing on the $\pi N$ and $KN$ scatterings, we show that the cross sections near threshold can be well accounted for by the chiral quark model with only few parameters. The $S$-wave dominance in both $\pi^- p \rightarrow \eta n$ and $K^- p \rightarrow \Sigma^0 \pi^0$ can be well understood in the quark model framework. In particular, the quark model provides a constraint on the relative signs for resonance coupling form factors, which seems to be consistent with results from isobaric models.

§1. Introduction

The study of baryon resonances and search for so-called “missing resonances” in photo- and electroproduction, and meson-nucleon scatterings have been one of the physics goals at international hadron facilities. The increasing database gives access to more spin observables by which detailed information about the underlying dynamics can be extracted. Theoretical analyses are also making progresses on extracting baryon resonance parameters (see e.g. proceeding of NSTAR2009 on which recent analyses from EBAC, SAID, MAID, Bonn-Gatchina, and Juelich are reported). Meanwhile, it turns out to be urgent for theorists to communicate with each other and understand the approaches employed by different groups.

There is a clear need to treat all resonances consistently, and to understand the relation between the $s$- and $u$-channel resonances and $t$-channel meson exchanges. A recently developed quark model framework, augmented by an effective Lagrangian approach to reaction dynamics, provides a good starting point. The main feature of this model is the introduction of an effective chiral Lagrangian for the quark-pseudoscalar-meson coupling in a constituent quark model. In this framework, the tree level diagrams for pseudoscalar production reactions, such as in meson photoproduction and meson-nucleon scattering, can be explicitly calculated, and the quark model wavefunctions for the nucleons and baryon resonances, after convolution integrals, provide a form factor for the interaction vertices. Consequently, all the $s$- and $u$-channel resonances can be consistently included.

This model has the advantage of being able to describe a large photoproduction database, employing only a very limited number of parameters within a microscopic framework. Applications of this model to the $\eta$, $K$ and pion photoproduction have been quite successful. Recently, this approach has been extended to $\pi^- N$ and $K^- p$ scattering which provide some novel insights into the observables measured in these two channels.
As follows, we give a brief introduction to the effective chiral Lagrangian for quark-pseudoscalar-meson interactions in the SU(3) flavor symmetry limit. We present results for $\pi^- p \rightarrow \eta n$ reaction in Sec. 3, and for $K^- p \rightarrow \Sigma^0 \pi^0$ in Sec. 4. A summary is given in the last Section.

§2. The model

In the chiral quark model, the low energy quark-meson interactions are described by the effective Lagrangian[7], [11], [14]

$$\mathcal{L} = \bar{\psi} \gamma_\mu (i\partial^\mu + V^\mu + \gamma_5 A^\mu) - m |\psi + \cdots|,$$

(2.1)

where $V^\mu$ and $A^\mu$ correspond to vector and axial currents, respectively.

The quark-meson pseudovector coupling at tree level can be extracted from the leading order expansion of the Lagrangian

$$H_m = \sum_j \frac{1}{f_m} \bar{\psi}_j \gamma_\mu \gamma_5 \psi_j \vec{\tau} \cdot \partial^\mu \vec{\phi}_m,$$

(2.2)

where $\omega_a$ and $\omega_b$ are the energy of the initial and final state mesons, respectively. $H_m$ and $H^a_m$ represent the quark-meson couplings at tree level described by Eq. (2.2). $|N_i\rangle$, $|N_j\rangle$ and $|N_f\rangle$ stand for the initial, intermediate and final state baryons, respectively, and their corresponding energies are $E_i$, $E_j$ and $E_f$, which are the eigenvalues of the NRCQM Hamiltonian. The $s$ and $u$ channel transition amplitudes have been worked out in the harmonic oscillator basis in Refs. [12], [13].

There are a limited number of parameters introduced in this approach. Apart from the SU(6)$\otimes$O(3) quark model parameters, i.e. $m_q = 330$ MeV and $\alpha = 400$ MeV, the overall quark-pseudoscalar-meson coupling can be related to the hadronic couplings by axial-vector current conservation. Then, the relative strengths among $s$-channel baryon resonances will be determined by the quark model symmetry. At tree level, we adopt the resonance masses and widths from the Particle Data Group[15]. This treatment violates the unitarity constraints on the amplitudes. In principle, one should do coupled-channel calculations to restore the unitarity of the amplitudes, where the resonance masses and widths can also be calculated in the same framework. This is under development at this moment.

For the $t$-channel, we considered the scalar meson exchange (e.g. $a_0$ exchange in $\pi^- p \rightarrow \eta n$[12] and $\kappa$ exchange in $K^- p \rightarrow \Sigma^0 \pi^0$[13]), and vector meson exchange if
it is allowed. This will introduce additional parameters for the $t$-channel meson couplings. But they can be constrained by independent processes.

§3. $\pi^- p \to \eta n$

The $\pi^- p \to \eta n$ reaction should be an ideal channel for testing the chiral quark model approaches apart from photoproduction reactions. As it has been examined that the Goldberger-Treiman relation is respected well in the chiral quark model, this channel allows extraction of the $\eta NN$ coupling which can be compared with that determined in $\eta$ photoproduction. Furthermore, this channel is useful for investigating the $S$-wave resonance interferences, i.e. $S_{11}(1535)$ and $S_{11}(1650)$, by which the information about the nature of these two states can be obtained.

In Fig. 1 the differential cross sections near threshold are illustrated and compared with experimental data (see the solid curves). We also investigate effects arising from individual resonances as illustrated in Fig. 1. It shows that the interference between $D_{13}(1520)$ and $S_{11}(1535)$ are crucial for producing the correct shape for

![Fig. 1. The differential cross sections at various $W$. The data are from (open circles), (open up-triangles), (open down-triangles), (open squares), and the recent experiment (solid circles). The solid curves are for the full model differential cross sections. In (1a-12a), the dash-dotted and dashed curves are for the results switched off the contributions from nucleon pole and $D_{13}(1520)$, respectively. In (1b-12b), the dash-dotted and dashed curves correspond to the results without $S_{11}(1650)$ and without $t$-channel, respectively; the straight lines corresponds to the partial differential cross sections for $S_{11}(1535)$.](image)
Fig. 2. The cross section as a function of \( W \). The data are from \(^{17}\) (open circles), \(^{29}\) (open up-triangles), \(^{30}\) (open down-triangles), \(^{31}\) (open squares), and the recent experiment \(^{21}\) (solid triangles). The solid curves correspond to the full model result, while the other lines represent effects arising from individual resonances or single transition amplitudes.

The cross section around the \( \eta N \) threshold. This feature is mentioned in Refs. \(^{22}\)–\(^{24}\), and similar feature also appears in photoproduction reactions. \(^{8}, \)\(^{25}\)–\(^{27}\)

The results also show that the \( S \)-wave contributions play a dominant role near threshold. The enhanced cross sections after removing the \( S_{11}(1535) \) suggest that there exist cancellations between the \( S_{11}(1535) \) and other amplitudes. We shall see this point clearer in the total cross sections.

The total cross section turns out to be rather sensitive to the interferences between those two \( S \)-wave states, i.e. \( S_{11}(1535) \) and \( S_{11}(1650) \). As shown by Fig. 2, in the region of \( W < 1.6 \) GeV (i.e., \( p_{\pi} < 0.9 \) GeV), the major contributions to the cross sections are from the \( S_{11}(1535) \) and \( S_{11}(1650) \). The contributions of the \( S_{11}(1535) \) is about an order of magnitude larger than those from the \( P, D \) and \( F \) wave resonances. In particular, it shows that the exclusive cross section from \( S_{11}(1535) \) is even larger than the data. But the destructive interferences from the \( S_{11}(1650) \) bring down the cross sections, and as a consequence, a “second peak” around \( W \sim 1.7 \) GeV appears in the total cross section.

\[
\begin{array}{cccccc}
\langle H \rangle & \langle N, J_z = \frac{1}{2} | H | S_{17}^{15}(1535), J_z = \frac{1}{2} \rangle & \langle N, J_z = \frac{1}{2} | H | S_{17}^{15}(1650), J_z = \frac{1}{2} \rangle & AK^+ & p_{\eta}^n & n_{\pi}^+ & p_{\eta}^{\pi}^n & \Sigma^+ K^0 \\
\end{array}
\]

Table I. Spin-isospin factors for transition \( S_{11} \rightarrow MN \). The \( S_{11}(1535) \) is assigned to SU(6)⊗O(3) representation \([70, 28, 1, 1, 1/2^-] \), and \( S_{11}(1650) \) to \([70, 28, 1, 1, 1/2^-] \). Other charge conjugate channels can be obtained by multiplying a proper isospin Clebsch-Gordon (C-G) coefficient.

Such a destructive interference could be a natural consequence of non-relativistic constituent quark model (NRCQM) symmetry. In Ref. \(^{28}\), we show that based on the chiral Lagrangian, one can determine the relative signs among \( N^* NM \) couplings, where \( M \) and \( N \) stand for pseudoscalar meson and octet ground state baryon, respectively. The general form for the \( S_{11}NM \) coupling form factor can be expressed
as

\[ \mathcal{M}_{S_{11}\rightarrow N\pi} = \langle \hat{H} \rangle \left[ C_1 \alpha(q) + C_2 (\gamma(q) - \sqrt{2} \beta(q)) \right], \]

(3.1)

where \( C_1 \) and \( C_2 \) are kinematic factors, and \( \alpha(q) \), \( \gamma(q) \) and \( \beta(q) \) are functions of final-state meson momentum \( q \) and given by the spatial integrals. These are the common factors for \( S_{11}(1535) \) and \( S_{11}(1650) \) (if they are degenerate) in the symmetric NRCQM limit. The difference of the coupling form factor is given by the spin-isospin factor \( \langle \hat{H} \rangle \), which is listed in Table I for different coupling channels.

One notices that for \( \pi N \rightarrow S_{11} \rightarrow \eta N \), there is a sign different arises from the spin-isospin factor between \( S_{11}(1535) \) and \( S_{11}(1650) \) excitation amplitudes. Details about the state mixings of these two \( S_{11} \) states are discussed in Ref. 28).

For \( W > 1.6 \) GeV, the contributions of \( n = 2 \) resonances appear in the reaction. They play important roles around \( W = 1.7 \) GeV. Without the contributions from \( n = 2 \) shell, the “second peak” disappears. It is possible that the \( P \)-wave states in \( n = 2 \) shell have a dominant contribution. To know which resonance in \( n = 2 \) shell contributes to the “second peak”, we should rely on partial wave analysis, and more elaborate consideration of \( SU(6) \otimes O(3) \) symmetry breaking within individual resonances is needed.

§4. \( K^- p \rightarrow \Sigma^0 \pi^0 \)

The reaction \( K^- p \rightarrow \Sigma^0 \pi^0 \) is of particular interest in the study of baryon resonances and \( KN \) interaction since there are no isospin-1 baryons contributing here and it gives us a rather clean channel to study the \( \Lambda \) resonances, such as \( \Lambda(1405)S_{01} \), \( \Lambda(1670)S_{01} \), \( \Lambda(1520)D_{03} \) and \( \Lambda(1690)D_{03} \). On the other hand, the \( K^- p \rightarrow \Sigma^0 \pi^0 \) reaction serves another opportunity to examine the chiral quark model approach for the meson-nucleon scatterings. Note that in the \( s \)-channel process the allowed transitions will be via the processes that the initial and final state meson couple to different constituent quarks. Therefore, the \( s \)-channel will be qualitatively suppressed. This feature is reflected by the much predominant contributions from the \( u \)-channel amplitudes.\(^{13}\)

In Fig. 3, the differential cross sections are shown at different center mass energies (beam momenta) from \( W = 1536 \) MeV (\( P_K = 436 \) MeV/c) to \( W = 1687 \) MeV (\( P_K = 773 \) MeV/c) in comparison with experimental data.\(^{34}-^{39}\) The solid curves denote full calculations and appear to have an overall agreement with the data.

There are no data for the differential cross sections available near threshold, i.e. \( W = 1457 \sim 1532 \) MeV (or \( P_K = 200 \sim 425 \) MeV/c). Our calculation suggests that it is the region dominated by the low-lying \( \Lambda(1405)S_{01} \). In Ref. 13, exclusive cross sections by single resonance excitations or transitions are presented. We find that the exclusive cross section from \( \Lambda(1405)S_{01} \) even overshoots the data near threshold in the symmetric quark model limit. This feature is similar to the observation in \( \pi^- p \) scattering where the near-threshold region is also dominated by the \( S \)-wave resonance.
excitations. Such a large contribution from $\Lambda(1405)S_{01}$ would require a cancellation mechanism, and hence the $\Lambda(1405)S_{01}$ and $\Lambda(1670)S_{01}$ mixing is favored.\footnote{13} We note again the similarity with $\pi^-p \rightarrow \eta n$ reaction.

§5. Summary

The chiral quark model approach for the study of baryon resonances in meson photoproduction and meson-nucleon scattering turns out to have advantages for disentangling the s-channel resonances and providing an estimate of background contributions on an equal basis as the resonance amplitudes. In particular, the quark model provides a natural constraint on the relative signs for resonance coupling form factors, which can be compared with isobaric approaches. For the dominance of the $S$-wave resonances, we show that a cancellation appears between the first orbital excitation $S_{11}(1535)$ and $S_{11}(1650)$ in $\pi^-p \rightarrow \eta n$, and $\Lambda(1405)S_{01}$ and $\Lambda(1670)S_{01}$ in $K^-p \rightarrow \Sigma^0\pi^0$. Such an effect could be essential for our understanding of the constituent effective degrees of freedom within excited baryons.

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References

1) E. Klempt, C. Batty and J. M. Richard, Phys. Rept. 413 (2005) 197.
2) H. Kamano, Chinese Phys. C 33 (2009), 1077.
3) R.A. Arndt, W.J. Briscoe, M.W. Paris, I.I. Strakovsky, and R.L. Workman, Chinese Phys. C 33 (2009), 1063.
4) L. Tiator, D. Drechsel, S.S. Kamalov, M. Vanderhaeghen, Chinese Phys. C 33 (2009), 1069.
5) A. Sarantsev, Chinese Phys. C 33 (2009), 1085.
6) M. Döring, C. Hanhart, F. Huang, S. Krewald, and U.-G. Meissner, Chinese Phys. C 33 (2009), 1273.
7) Z. P. Li, H. X. Ye and M. H. Lu, Phys. Rev. C 56 (1997), 1099.
8) Z.-P. Li, Phys. Rev. C 52 (1995), 4961; Z.-P. Li and B. Saghai, Nucl. Phys. A 644 (1998), 345; Q. Zhao, B. Saghai and Z. P. Li, J. Phys. G 28 (2002), 1293; B. Saghai and Z.-P. Li, Eur. Phys. J. A 11 (2001), 217.
9) Z.-P. Li, Phys. Rev. C 52 (1995), 1648; Z.-P. Li, W. H. Ma and L. Zhang, Phys. Rev. C 54 (1996), 2171.
10) Z.-P. Li, Phys. Rev. D 50 (1994), 5639.
11) Q. Zhao, J. S. Al-Khalili, Z. P. Li and R. L. Workman, Phys. Rev. C 65 (2002), 065204.
12) X. H. Zhong, Q. Zhao, J. He and B. Saghai, Phys. Rev. C 76 (2007), 065205.
13) X. H. Zhong and Q. Zhao, Phys. Rev. C 79 (2009), 045202.
14) A. Manohar and H. Georgi, Nucl. Phys. B 234 (1984), 189.
15) C. Amsler et al. [Particle Data Group], Phys. Lett. B 667, 1 (2008).
16) M. L. Goldberger and S. B. Treiman, Phys. Rev. 110 (1958), 1178.
17) R. M. Brown et al., Nucl. Phys. B 153 (1979), 89.
18) W. Deinet et al., Nucl. Phys. B 11 (1969), 495.
19) J. Feltesse et al., Nucl. Phys. B 93 (1975), 242.
20) N. C. Debenham et al., Phys. Rev. D 12 (1975), 2545.
21) S. Prakhov et al., Phys. Rev. C 72 (2005), 015203.
22) A. M. Gasparyan, J. Haidenbauer, C. Hanhart, and J. Speth, Phys. Rev. C 68 (2003), 045207.
23) J. Durand, B. Julia-Diaz, T. S. Lee, B. Saghai and T. Sato, Phys. Rev. C 78 (2008), 025204.
24) R. A. Arndt et al., Phys. Rev C 72 (2005), 045202.
25) L. Tiator, C. Bennhold and S. S. Kamalov, Nucl. Phys. A 580 (1994), 455.
26) W. T. Chiang, S. N. Yang, L. Tiator and D. Drechsel, Nucl. Phys. A 700 (2002), 429.
27) L. Tiator, D. Drechsel, G. Knochlein and C. Bennhold, Phys. Rev. C 60 (1999), 035210.
28) X.-H. Liu and Q. Zhao, work in progress.
29) F. Bulos et al., Phys. Rev. 187 (1969), 1827.
30) W. D. Richards et al.: Phys. Rev. D 1 (1970), 10.
31) M. Clajus and B. M. K. Neffens, Pin Newslett. 7 (1992), 76.
32) V. Shklyar, H. Lenske, U. Mosel, nucl-th/0611036.
33) S. Ceci, A. Svarc and B. Zauner, Phys. Rev. Lett. 97 (2006), 062002.
34) R. Manweiler et al., Phys. Rev. C 77 (2008), 015205.
35) R. Armenteros et al., Nucl. Phys. B 21 (1970), 15.
36) G. W. London et al., Nucl. Phys. B 85 (1975), 289.
37) D. F. Baxter et al., Nucl. Phys. B 67 (1973), 125.
38) D. Berley et al., Phys. Rev. D 1 (1970), 1996 [Erratum-ibid. D 3 (1971), 2297].
39) T. S. Mast, M. Abston-Garnjost, R. O. Bangerter, A. S. Barbaro-Galtieri, F. T. Solmitz and R. D. Tripp, Phys. Rev. D 11 (1975), 3078.