Λ resonances studied in $K^-p \to \Sigma^0\pi^0$ in a chiral quark model*

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Abstract A chiral quark-model approach is extended to the study of the $\bar{K}N$ scattering at low energies. The process of $K^-p \to \Sigma^0\pi^0$ at $P_K \lesssim 800$ MeV/c (i.e. the center mass energy $W \lesssim 1.7$ GeV) is investigated. The $\Lambda(1405)S_{01}$ dominates the reactions over the energy region considered here. Around $P_K \simeq 400$ MeV/c, the $\Lambda(1520)D_{03}$ is responsible for a strong resonant peak in the cross section. Our analysis suggests that there exist configuration mixings within the $\Lambda(1405)S_{01}$ and $\Lambda(1670)S_{01}$ as admixtures of the $[\mathbf{70},{}^2\mathbf{1},1/2]$ and $[\mathbf{70},{}^2\mathbf{8},1/2]$ configurations. The $\Lambda(1405)S_{01}$ is dominated by $[\mathbf{70},{}^2\mathbf{1},1/2]$, and $\Lambda(1670)S_{01}$ by $[\mathbf{70},{}^2\mathbf{8},1/2]$. The non-resonant background contributions, i.e. u-channel and t-channel, also play important roles in the explanation of the angular distributions due to amplitude interferences.

Key words strange resonance, quark model, meson-baryon interaction

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1 Introduction

In the literature, many experimental and theoretical efforts have been devoted to understanding the nature of the low-lying Λ resonances. However, their properties are still controversial. For example, in the naive quark model the $\Lambda(1405)$ is classified as the lowest $L=1$ orbital excited qqq state as an $SU(3)$ flavor singlet[1—3]. Meanwhile, it is also proposed to be a dynamically generated resonance emerging from the interaction of the $\bar{K}N$ and $\pi\Sigma$ with a multi-quark structure[4—9]. How to clarify these issues and make a contact with experimental observables are still an open question.

Recently, the higher precision data of the reaction $K^-p \to \Sigma^0\pi^0$ at eight momentum beams between 514 and 750 MeV/c were reported[10], which provides us a good opportunity to study the properties of these low-lying Λ resonances. In this work, we make an investigation of the $K^-p \to \Sigma^0\pi^0$ reaction in a chiral quark model. In this model an effective chiral Lagrangian is introduced to account for the quark-pseudoscalar-meson coupling. Since the quark-meson coupling is invariant under the chiral transformation, some of the low-energy properties of QCD are retained. The chiral quark model has been well developed and widely applied to meson photoproduction reactions[11—19]. Its recent extension to describe the process of πN scattering[20] and investigate the strong decays of charmed hadrons[21] also turns out to be successful and inspiring.

2 Framework

In the chiral quark model, the quark-pseudoscalar-meson coupling at the tree level is described by[18, 19]

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

where ψ_j represents the j-th quark field in a hadron. f_m is the meson's decay constant. The pseudoscalar-

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meson octet ϕ_m is written as

$$\phi_m = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & \mathrm{K}^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \mathrm{K}^0 \\ \mathrm{K}^- & \bar{\mathrm{K}}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}. \quad (2)$$

The s and u channel transition amplitudes are determined by

$$\mathcal{M}_s = \sum_j \langle N_f|H_\pi|N_j\rangle\langle N_j|\frac{1}{E_i+\omega_{\mathrm{K}}-E_j}H_{\mathrm{K}}|N_i\rangle, \quad (3)$$

$$\mathcal{M}_u = \sum_j \langle N_f|H_{\mathrm{K}}\frac{1}{E_i-\omega_\pi-E_j}|N_j\rangle\langle N_j|H_\pi|N_i\rangle, \quad (4)$$

where ω_{K} is the energy of the incoming K^--meson. H_{K} and H_π are the standard quark-meson couplings at tree level described by Eq. (1). $|N_i\rangle$, $|N_j\rangle$ 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 $\hat{H}$[1, 22]. The s and u channel transition amplitudes have been worked out in the harmonic oscillator basis in Refs. [20, 23]

For the t-channel, we considered the vector meson K^* and scalar meson κ exchange in the reactions. The amplitudes are obtained in Ref. [22].

The amplitudes in terms of the harmonic oscillator principle quantum number n are the sum of a set of $SU(6)$ multiplets with the same n. In the $n = 1$ shell, there are four resonances $\Lambda(1405)S_{01}$, $\Lambda(1520)D_{03}$, $\Lambda(1670)S_{01}$ and $\Lambda(1690)D_{03}$ contributing here. To see the contributions of individual resonances, we need to separate out the single-resonance-excitation amplitudes within each principle number n in the s-channel. Taking into account the width effects of the resonances, the resonance transition amplitudes of the s-channel can be generally expressed as[19, 20]

$$\mathcal{M}^s_R = \frac{2M_R}{s-M_R^2+\mathrm{i}M_R\Gamma_R}\mathcal{O}_R\mathrm{e}^{-(\boldsymbol{k}^2+\boldsymbol{q}^2)/6\alpha^2}, \quad (5)$$

In Eq. (5), $\mathcal{O}_R$ is the separated operators for individual resonances in the s-channel. The detail of extracting $\mathcal{O}_R$ can be found in our recent work[22].

3 Results

The resonance parameters used in present work are listed in Table 1. They are fitted to the differential cross sections[10], and roughly agree with the PDG values[24]. The preferred Breit-Wigner mass of the $\Lambda(1405)S_{01}$ is 1420 MeV, which is about 10 MeV larger than the upper limit of the PDG suggestion[24].

To fit the total cross section, we find the widths of $\Lambda(1520)D_{03}$ should have a narrower width $\Gamma\simeq 8$ MeV, which is only half of the PDG value. The fitted mass and width for $\Lambda(1670)S_{01}$ are $M = 1697$ and $\Gamma = 65$ MeV, respectively, which are slightly larger than the PDG suggestions.

Table 1. Breit-Wigner masses M_R (in MeV) and widths Γ_R (in MeV) for the resonances in the s-channel. States in the $n=2$ shell are treated as degenerate to n.

resonance	M_R	Γ_R	M_R (PDG)	Γ_R (PDG)
$S_{01}(1405)$	1420	48	1406 ± 4	50 ± 2
$S_{01}(1670)$	1697	65	1670 ± 10	$25\sim50$
$D_{03}(1520)$	1520	8	1520 ± 1	16 ± 1
$D_{03}(1690)$	1685	63	1690 ± 5	60 ± 10
$n=2$	1850	100		

In the u-channel, the intermediate states are the nucleon and its resonances. We find that contributions from the $n\geq 1$ shell are negligibly small near threshold, and are insensitive to the degenerate masses and widths for these shells.

The relative strength $g_{S_{01}(1405)}/g_{S_{01}(1670)}$ turns to be crucial for reproducing the angular distributions in the differential cross sections. With no configuration mixing, i.e. $g_{S_{01}(1405)}/g_{S_{01}(1670)} = -3$, the data can not be well explained as shown by the dashed curves in Fig. 1. We empirically introduce a mixing angle between $[\mathbf{70},{}^2\mathbf{1}]$ and $[\mathbf{70},{}^2\mathbf{8}]$ for the physical states $S_{01}(1405)$ and $S_{01}(1670)$, i.e.

$$|S_{01}(1405)\rangle = \cos(\theta)|\mathbf{70},{}^2\mathbf{1}\rangle - \sin(\theta)|\mathbf{70},{}^2\mathbf{8}\rangle, \quad (6)$$

$$|S_{01}(1670)\rangle = \sin(\theta)|\mathbf{70},{}^2\mathbf{1}\rangle + \cos(\theta)|\mathbf{70},{}^2\mathbf{8}\rangle. \quad (7)$$

The relative strength $g_{S_{01}(1405)}/g_{S_{01}(1670)}$ can be related to the mixing angle by

$$\frac{g_{S_{01}(1405)}}{g_{S_{01}(1670)}} = \frac{[3\cos(\theta)-\sin(\theta)][\cos(\theta)+\sin(\theta)]}{[3\sin(\theta)+\cos(\theta)][\sin(\theta)-\cos(\theta)]}. \quad (8)$$

It is found that with the ratio $g_{S_{01}(1405)}/g_{S_{01}(1670)} = -9$, the data can be described well (see the solid curves in Fig. 1). Thus, two mixing angles, $\theta\simeq 41^\circ$ and 165°, satisfy the condition. It is interesting to note that this feature that the $\Lambda(1405)$ and $\Lambda(1670)$ as mixed states dominated by the singlet and octet, respectively, is also obtained by the coupled channel studies based on UχPT[7].

As shown by Figs. 1 and 2, both the differential cross sections and total cross section are in good agreement with the experimental data. To see the role of resonances, we plot their partial cross sections in Fig. 3 as well. It shows that in the low energy region, i.e., $P_{\mathrm{K}} < 800$ MeV/c, the resonances

$\Lambda(1405)S_{01}$, $\Lambda(1520)D_{03}$ and $\Lambda(1670)S_{01}$ in the $n=1$ shell play important roles in the reactions, while the $n \geqslant 2$ shell resonance contributions are negligible small.

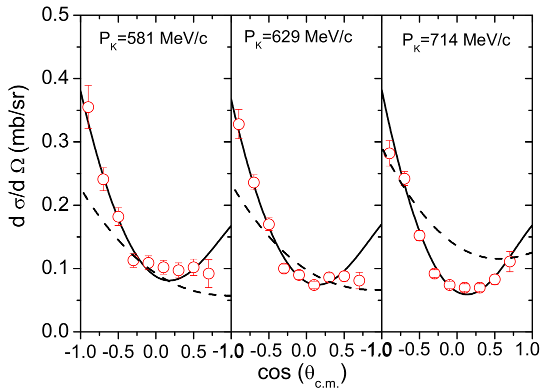

Fig. 1. Differential cross sections with (solid curves) and without configuration mixings (dashed curves) between the $\Lambda(1405)$ and $\Lambda(1670)$.

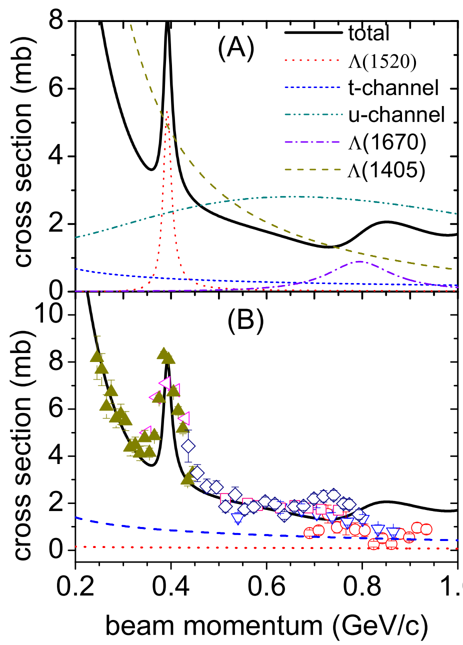

Fig. 2. Total cross section as a function of the beam momentum P_K. The solid curves are the full model calculations. Data are from Refs. [29] (open circles), [31] (up-triangles), [27] (open diamonds), [30](left-triangles), [28] (down-triangles), and [10] (squares). In (A), exclusive cross sections for the $\Lambda(1405)S_{01}$, $\Lambda(1670)S_{01}$, $\Lambda(1520)D_{03}$, t-channel, and u-channel are indicated by different lines, respectively. In (B), the dotted and dashed curves correspond to the exclusive cross sections for the t-channel κ and K^* -exchange, respectively.

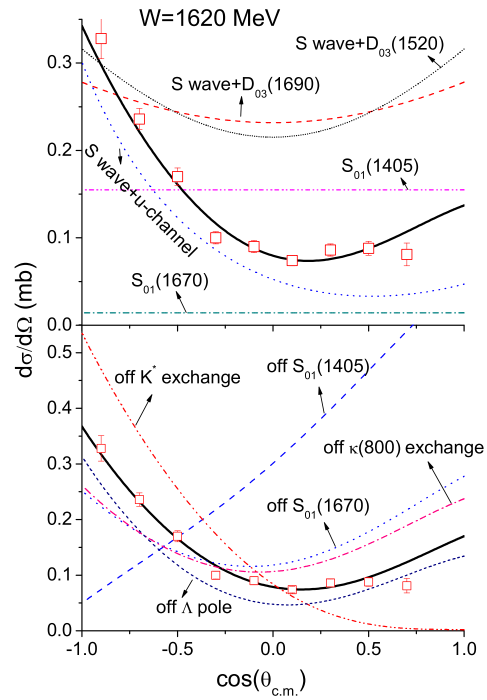

Fig. 3. Cross sections of exclusive channels or individual resonances at $W=1620$ MeV.

The $\Lambda(1405)S_{01}$ is the major contributor of the S-wave amplitude in the low-energy region. In particular, in the region of $P_K \lesssim 300$ MeV/c, $\Lambda(1405)S_{01}$ is dominant and contributions from the other resonances are nearly invisible in the total cross section. Around $P_K=400$ MeV/c, the $\Lambda(1520)D_{03}$ is responsible for the strong resonant peak in the total cross section. Around $P_K = 800$ MeV/c, the differential cross sections are sensitive to the $\Lambda(1670)S_{01}$. In this energy region the $\Lambda(1690)D_{03}$ is visible, but less important than $\Lambda(1670)S_{01}$.

The non-resonant backgrounds, u- and t-channel, also play important roles in the reaction. In the t-channel, the K^*-exchange has larger cross sections than the κ. It enhances the cross section obviously at the forward angles, and has some destructive interferences at the backward angles. There can be seen a small contribution of the s-channel Λ-pole, which slightly enhances the cross section.

The u-channel significantly suppresses the differential cross section at the forward angles, and produces the characteristic backward enhancement. The significant contributions of the u-channel agree with the results of UχPT[25, 26]. In the quark model framework, the u-channel allows transitions that the initial and final state mesons can be coupled to the same quark or different quarks, while the s-channel can only occur via transitions that the initial and final state mesons are coupled to different quarks. This explains the importance of the u-channel contributions as a unique feature in $K^-p \to \Sigma^0\pi^0$. In comparison with the UχPT, the agreement implies some similarity of the coupling structure at leading order.

4 Summary

The chiral quark model provides an ideal framework to include the s and u-channel resonances in meson production reactions. In the threshold region the quark model imposes a natural constraint on the relative phases between different resonance excitation amplitudes. With a small number of parameters, the calculation results can be regarded as encouraging and inspiring. This model can be compared with hadronic approaches to extract meson-baryon coupling form factors as a probe of baryon internal effective constituent degrees of freedom. It would be interesting to learn by such studies where the non-relativistic constituent scenario would fail and how far such a prescription can be extended to. With the availabilities of more and more precise measurements of meson production channels at hadron facilities, we expect that a coherent treatment for multi-channels will help clarify some complexities of strong QCD phenomena at low energies.

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