Strange and Charmed Baryon Productions with an Instanton Interaction

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We study strange and charmed baryon productions, $\pi + p \rightarrow K(D) + Y(Y_c)$, where $Y(Y_c)$ is a strange(charmed) baryon of a ground or an excited state. We propose a new production mechanism where two quarks in the baryon participate in the reaction (two-quark process), which enables excitation of both $\lambda$- and $\rho$-modes of the baryons. To deal with the two-quark process, we consider the ’t Hooft six-quark interaction from the instanton model. We study production rates in relation with the structure of charmed baryons for the forward angle scattering.

Keywords: J-PARC, heavy baryon, production rates, diquark

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I. INTRODUCTION

Recently, as new hadrons including heavy quarks such as charm and bottom have been observed continuously, experimental and theoretical researches on them have been actively conducted [1]. It is necessary to fix their properties such as spin-parity, structure, and reaction mechanism of hadrons. In this context, a heavy baryon can be a good testing ground for a research. In a baryon containing one heavy quark, two types of excited states from the heavy quark-diquark description, the so-called λ- and ρ-modes, are distinguished, providing unique features for heavy baryon structure together with heavy quark symmetry [2].

Based on the above background, an experimental plan for charmed baryon productions, $\pi^- + p \rightarrow D^* + Y_c$, has been made at J-PARC [3] and the theoretical studies on this experiment have been carried out [4]. However, in the previous theoretical work, only the λ-modes are discussed among the two kinds of excited states of heavy baryons, a further theoretical study is required to investigate both λ- and ρ-mode excitations.

In the present work we propose a reaction mechanism for heavy baryon productions, $\pi^- + p \rightarrow K^0 + Y$ or $D^- + Y_c$, which can excite both λ- and ρ-modes. We calculate matrix elements for the reaction by using a non-relativistic constituent quark model with a three-quark interaction derived from the QCD instanton model. We also calculate the production rates of various heavy baryons.

II. FORMALISM

A. Two-quark process

In Fig. 1 a quark line representation for two-quark process is given. In the two-quark process, an antiquark in the pion interacts with two quarks in the proton. The two-quark process excites both λ- and ρ-modes. Here, λ-modes are excitations of relative motion between a diquark and a heavy quark and ρ-modes are excitations of diquark itself in the heavy baryon. One can also consider one-quark process in which one quark in the baryon interacts with an antiquark in the pion and possible excitations are only λ-modes [4].

In Fig. 1 various momentum fractions carried by various quarks are shown; the momenta of the initial and the final state baryons consist of the momenta of the three quarks inside of the baryons, $\vec{P}_N = \vec{p}_1 + \vec{p}_2 + \vec{p}_3$, $\vec{P}_Y = \vec{q}_1 + \vec{q}_2 + \vec{p}_3'$, where $\vec{p}_i$ and $\vec{q}_i = \vec{p}_i + \vec{q}_i$ ($i = 1, 2, 3$) are the quark momenta inside of the baryons and $\vec{q}_i$ is the transferred momentum from the initial pion to i-th quark in the heavy baryon. In the two quark process the momentum transfer $\vec{q}$ is shared by two quarks (2,3) such that $\vec{q} = \vec{P}_Y - \vec{P}_p = \vec{q}_2 + \vec{q}_3$ is the transferred momentum from the pion to the heavy baryon.

B. Three-quark interaction

For the description of two-quark processes we need a suitable interaction where three quarks participate in. Here we employ a point-like interaction of three quarks, the ’t Hooft interaction, as inspired by the instanton dynamics of...
QCD. The interaction works well for low-energy hadron properties including up, down and strange quarks. However, a naive extension to the charm sector may not be available, while some discussions have been made \[5\]. Thus, the present study is most likely to be applied to the strange sector, though some features may be discussed for the charm productions. Therefore, results will be shown both for strangeness and charm productions.

The use of the zero-range three-body interaction has a virtue that actual computations become simple. For a more realistic description, finite-range nature of the interaction may be included in terms of form factors.

The relevant ’tHooft interaction is given by \[6\].

\[
\mathcal{L}_{tH} = c \text{det}(\bar{q}(1 + \gamma_5)q) + H.c. = \begin{vmatrix} \bar{u}(1 + \gamma_5)u & \bar{d}(1 + \gamma_5)u & \bar{s}(1 + \gamma_5)u \\ \bar{d}(1 + \gamma_5)u & \bar{d}(1 + \gamma_5)u & \bar{s}(1 + \gamma_5)u \\ \bar{s}(1 + \gamma_5)u & \bar{s}(1 + \gamma_5)u & \bar{s}(1 + \gamma_5)u \end{vmatrix} + H.c.,
\]

where \(c\) is a coupling constant, which, however, is not important in the present study, since it is difficult to determine the absolute values of the reaction cross sections. Thus, we focus here only on relative production rates.

### III. MATRIX ELEMENTS AND PRODUCTION RATES

In a non-relativistic quark model, baryon wave functions can be written as a product of the plane wave for the center-of-mass motion and bound state wave functions in internal coordinates, Jacobi coordinates \(\lambda\) and \(\rho\). Then, the transition amplitudes for the reaction \(\pi^- p \to MY\) can be written as

\[
\langle Y M | \mathcal{L}_{tH} | N \pi^- \rangle 
\approx \delta^{(3)}(\vec{P}_Y - \vec{P}_N - \vec{q}) 
\times \int d^3q_2 d^3q_3 \delta^{(3)}(\vec{q} - \vec{q}_2 - \vec{q}_3) 
\int d^3\rho e^{i\vec{q}_2 \cdot \vec{\rho}} \psi^\ast_{\lambda}(\vec{\rho}) \psi^\ast_{\rho}(\vec{\rho}) 
\int d^3\lambda e^{i\vec{q}_3 \cdot \vec{\lambda}} \psi^\ast_{\lambda'}(\vec{\lambda}) \psi^\ast_{0}(\vec{\lambda}) 
+ (1 \leftrightarrow 2, \vec{\rho} \to -\vec{\rho})
\]

Having performed the integration with respect to \(q_2, q_3, \rho, \lambda\), we obtain the matrix elements for heavy baryon productions as

\[
\langle Y(l_\rho, l_\lambda) M | \mathcal{L}_{tH} | p \pi^- \rangle = C_{YM} I_l (2\pi)^3 \delta^{(3)}(\vec{P}_Y - \vec{P}_p - \vec{q})
\]

where \(I_l\) is given as

\[
I_{l=0} \equiv \left(\frac{16\pi\alpha^2\alpha_\lambda}{B^2}\right)^\frac{3}{4} e^{-\vec{q}_{eff}^2/(4B^2)},
\]

for \(l = 0\)

\[
I_{l=1} \equiv \frac{i\sqrt{2}\alpha_\lambda |\vec{q}_{eff}|}{2B^2} \left(\frac{16\pi\alpha^2\alpha_\lambda}{B^2}\right)^\frac{3}{4} e^{-\vec{q}_{eff}^2/(4B^2)}
\]

and

\[
I_{l=1} \equiv \frac{-i\sqrt{2}\alpha_\rho |\vec{q}_{eff}|}{2B^2} \left(\frac{16\pi\alpha^2\alpha_\lambda}{B^2}\right)^\frac{3}{4} e^{-\vec{q}_{eff}^2/(4B^2)}
\]

for \(l = 1\). The coefficients \(C_{YM}\) are the prefactors from spin and isospin calculations. The effective momentum transfer, \(\vec{q}_{eff}\) and \(B^2\) are defined as

\[
\vec{q}_{eff} \equiv \frac{m_d}{m_d + m_q} \vec{P}_N - \frac{m_d}{m_d + m_Q} \vec{P}_Y, \quad B^2 \equiv \frac{8\alpha^2 + \alpha_\lambda^2 + \alpha_\rho^2}{2}
\]

where \(m_d, m_q,\) and \(m_Q\) are the masses of a diquark, light quarks (\(u, d\) quark), and the heavy quark, respectively. \(\alpha_\rho, \alpha_\lambda,\) and \(\alpha_\lambda\) are the oscillator parameters for the \(\rho\)–modes, initial and final state \(\lambda\)–modes, respectively. Here, except for the delta function, the matrix elements Eq. \(\[\]\) depend on \(\vec{q}_{eff}\) instead of \(\vec{q}\) because of the so-called recoil effect due to the change in the masses of particles before and after the interaction.

In the center of mass frame, the differential cross sections for the heavy baryon productions can be written as

\[
\mathcal{R}(Y(J^P, J_z)) = \frac{1}{4|p_1|\sqrt{s}} |C_{YM}|^2 |I_l|^2 \frac{|\vec{p}_f|}{4\pi\sqrt{s}}.
\]

(8)
IV. DISCUSSION

The production rates of hyperons and charmed baryons are given in Table I. In the present work, we calculate the production rates of various heavy baryon productions. Since this work is the first attempt of the two-quark process, we consider a simple case, i.e. the forward angle scattering. Those at finite angles is left for future works. To demonstrate the production rates, we set the momentum of the pion at $k_{\text{Lab}}^\pi = 5 \text{ GeV}$ for the hyperons and $k_{\text{Lab}}^{\pi} = 20 \text{ GeV}$ for charmed baryons. These momenta provide sufficient energies to create $s\bar{s}$ or $c\bar{c}$ pair. In the two-quark process, the momentum $\vec{q}$ is shared by the heavy quark and a light quark in the heavy baryon, which may excite both $\lambda$- and $\rho$-modes. This contrasts with the one-quark process where only one quark receives the transferred momentum and possible excitations are only $\lambda$-modes.

A more detailed discussion about momentum-transfer and structure dependences of the production rates will be given elsewhere.

TABLE I. Production rates of various heavy baryons, $R(Y)$, which are normalized by that of the ground-state $\Lambda(\frac{1}{2}^+)$ where $Y_s$ and $Y_c$ are for the strange and charmed baryons, respectively. $j$ is a coupled spin, so-called a brown muck spin, by spin and orbital angular momentum of a diquark in the baryons.

| $l=0$ | $\Lambda \left( \frac{1}{2}^+ \right) \Sigma \left( \frac{1}{2}^+ \right) \Sigma \left( \frac{1}{2}^+ \right)$ |
|-------|--------------------------------------------------|
| $R(Y_s)$ | 1 | 3.2 | 0 |
| $R(Y_c)$ | 1 | 2.9 | 0 |
| $l_\lambda = 1$ | $\Lambda \left( \frac{1}{2}^- \right) \Sigma \left( \frac{3}{2}^- \right) \Sigma \left( \frac{1}{2}^- \right) \Sigma \left( \frac{3}{2}^- \right) \Sigma \left( \frac{3}{2}^- \right) \Sigma \left( \frac{3}{2}^- \right)$ |
| $j=1$ | $j=1$ | $j=0$ | $j=1$ | $j=1$ | $j=2$ | $j=2$ |
| $R(Y_s)$ | 0.004 | 0.010 | 0.007 | 0.015 | 0.007 | 0.038 | 0 |
| $R(Y_c)$ | 0.10 | 0.20 | 0.12 | 0.23 | 0.12 | 0.58 | 0 |
| $l_\rho = 1$ | $\Lambda \left( \frac{1}{2}^- \right) \Lambda \left( \frac{3}{2}^- \right) \Lambda \left( \frac{5}{2}^- \right) \Lambda \left( \frac{1}{2}^- \right) \Lambda \left( \frac{3}{2}^- \right) \Lambda \left( \frac{3}{2}^- \right)$ |
| $j=0$ | $j=1$ | $j=1$ | $j=2$ | $j=2$ | $j=1$ | $j=1$ |
| $R(Y_s)$ | 0.017 | 0.039 | 0.018 | 0.10 | 0 | 0.016 | 0.032 |
| $R(Y_c)$ | 0.22 | 0.43 | 0.22 | 1.1 | 0 | 0.20 | 0.41 |

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