Productions and decays of charmed baryons for the study of structures

Atsushi Hosaka [1]

Research Center for Nuclear Physics, Osaka University
and
Advanced Science Research Center, Japan Atomic Energy Association

1. Background

Much interest of hadron spectroscopy is motivated by recent observations of *exotic* hadron data which have not been expected and are not easily explained by conventional theories [1]. Many data are observed near the threshold region of charm quark $c\bar{c}$ production. Because quarks are confined, at the threshold the produced $c\bar{c}$ pair dissociates into charmed (open charm) mesons D and $\bar{D}$. The threshold energy is about 1 GeV higher than the charmonium ground state η_c, which is enough to create a light quark $q\bar{q}$ pair. When such amount of energy is deposited to the system, the string breaks between the excited $c\bar{c}$ pair and the extra $q\bar{q}$ are created at the ends of the broken string. The resulting four quarks may rearrange spontaneously into various configurations such as hadronic molecules or compact tetraquark of diquark-diquark pair.

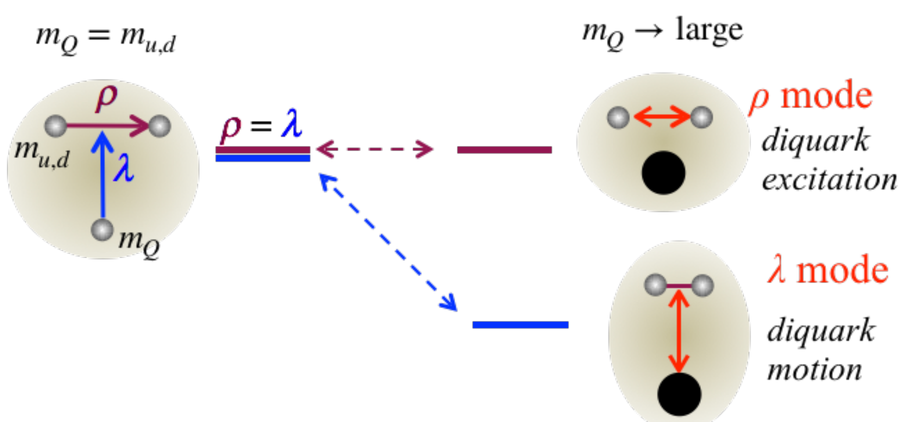

Figure 1: The λ and ρ modes of charmed (singly heavy quark) baryons.

To understand what happens quantitatively there we need to know the dynamics of the mixed states of light and heavy quarks, such as their interactions, correlations and even the

[1] e-mail:hosaka@rcnp.osaka-u.ac.jp

formation of themselves as effective degrees of freedom. One of good and simplest laboratories for the study of such dynamics is the charmed baryon of cqq. A unique feature there is that if the charmed baryons are regarded as three-body systems of constituent quarks, two excitation modes that are called λ and ρ modes are possible. They are the motions of the light diquark (qq) and the charm quark, and those of two light quarks with the charm quark as a spectator as shown in Fig. 1. As a *universal kinematic effect of isotope shift*, the energy of the λ mode is lowered and differs from that of the ρ mode by some hundred MeV. Not only the energy difference these modes show very much different production and decay properties. The identification of such dynamics will confirm the nature of constituent quarks and relevant dynamics such as diquark correlations. This will eventually provides the basis for the understanding of the exotic observations.

2. Strategy

Experimentally, the study of charmed baryons is planned at the J-PARC experiments where the high momentum beam line of the secondary pion and the spectrometer systems are designed [2]. These will enable the so called missing mass spectroscopy by knowing the momenta of target, beam and meson as shown in Fig. 2. In this way, series of baryons will be excited and studied at once. The decay properties will be studied separately by observing the decaying mesons and baryons.

This article reports our recent activities for the productions and decays of charmed baryons in the theory group at RCNP based on the published and unpublished papers. Part of the works have been and will be conducted by international collaborations with Korean group at Inha University, and also by discussions with the experimental group.

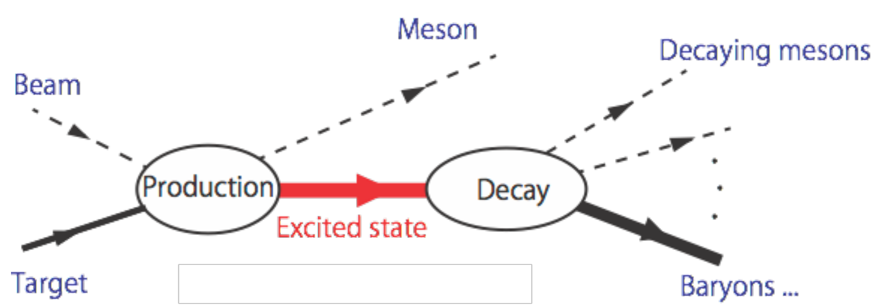

Figure 2: Schematic picture for charmed baryon productions.

3. Productions

Theoretical status of production rates in the energy region that we are interested in is not well established. Perhaps this is one of the most difficult problems in non-perturbative QCD. In

Refs. [3, 4], we have applied a phenomenological method based on the Regge theory. While its absolute values are unknown, energy dependence of production rates is predicted by assuming the dominant Regge trajectory. By comparing the existing data of strangeness productions such as

$$\pi p \to K^*(K) Y \tag{1}$$

where Y denotes a hyperon such as Λ or Σ) at one energy point, then the resulting energy dependence is well reproduced by the vector Reggeon exchange. In this way, we can fix the unknown strength in he Regge amplitude for the strangeness production. In Ref. [], we have extended this amplitude to charm productions and predicted the charm production rates about 10^{-4} of those of the strangeness, of order 10 [nb] or less. This is consistent with the current status of the null charm production experiments at Brookhaven which set the upper limit of about 10 [nb] [5]. In the J-PARC experiment, their sensitivity is of order ~ 1 [nb], and therefore, there will be a good chance to observe charm productions.

For the study of structure in terms of production rates, we need to establish the relations between them. This is done by having good models of structure and reaction mechanism. For this we resort to simple models/pictures for them. For the structure of charmed baryons we rely on the quark model as we discussed in Section 1. For productions, we propose one-quark and two-quark processes where one and two quarks in the baryon are participating the charm (or strange) quark productions as shown in Fig. 3. The picture of the one-quark process works well for hyperon productions once the quarks are replaced by nucleons and hyperons, and has become an ideal example to prove experimentally single-particle orbits for the hyperon motion in hyper nuclei.

We have explored one-quark process and predicted production rates of various charmed baryons and of strange hyperons. We have then observed clear correspondences of production rates and structures. Moreover, a unique feature is that excited states are equally or even more produced for charmed baryons while for strangeness excited states are suppressed. This is qualitatively understood by angular momentum matching; a large angular momentum transfer is needed when heavy charm quarks are produced. A caveat in this process is that only λ modes are excited, which is expected from the left panel of Fig. 3, where two light quarks stay as spectators during the reaction process. Furthermore, for high energy processes such as charm productions, a large (linear) momentum transfer is needed which causes suppression of the production rates due to momentum mismatch.

On the right panel of Fig. 3 shown is the two-quark process where two quarks of baryons participate the reactions. In this process, both λ and ρ modes may be excited and a large momentum is shared by two quarks, thus the momentum mismatch is improved. Currently we are finalizing the formulation of the two-quark process and will report results elsewhere.

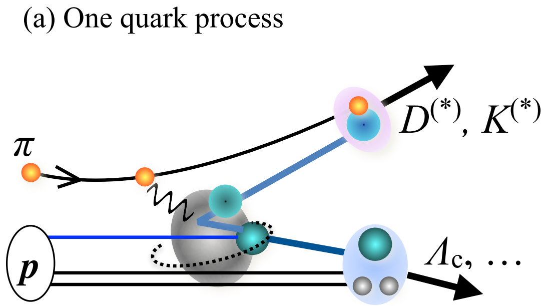

Figure 3: One (left) and two (right) quark processes. Blue lines indicate quarks participating the reaction.

4. Decays

Lastly in this report we briefly discuss decays of charmed baryons which is another useful method for the discussion of the structure of charmed baryons. As a sample study, in Refs. [6, 7], we have examined decays of $\Lambda_c(2595)$, $J^P = 1/2^-$ and $\Lambda_c(2625)$, $J^P = 3/2^-$. The decays occur in two steps as

$$\Lambda_c(2595), \Lambda_c(2625) \to \pi\Sigma_c(2455) \text{ and } \pi\Sigma_c(2520) \to \Lambda_c(2286)\pi\pi \tag{2}$$

where the two intermediate states $\Sigma_c(2455)$ and $\Sigma_c(2520)$ contribute to the decay rates in a coherent manner.

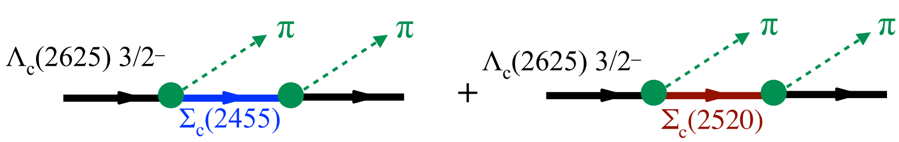

Figure 4: Two step decay processes of $\Lambda_c(2625)$. The same processes apply to $\Lambda_c(2595)$.

For actual computations, we again employ the quark model wav functions. In the quark model, the spin-parity $J = 1/2^-, 3/2^-$ states for $\Lambda_c(2595)$ and $\Lambda_c(2625)$ are formed by three different configurations; one λ mode and two ρ modes, which are equally candidates of them, or their superpositons are. The three configurations however show very different decay pattern. Shown in Fig. 5 are the Dalitz plots of the decay of $\Lambda_c(2625)$ and mass distributions of $\pi\Lambda_c(2286)$, the projections of the Dalitz plots onto the horizontal axis . Those different patterns will be useful to differentiate the structure of the baryons.

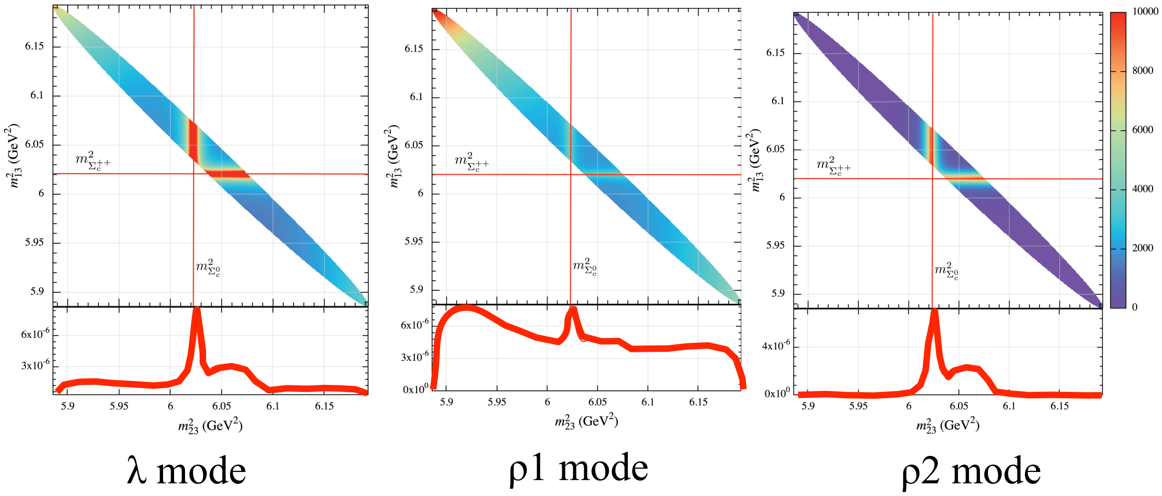

Figure 5: Two step decay processes of $\Lambda_c(2595)$ and $\Lambda_c(2620)$.

5. Prospects

In this report, we have proposed production mechanisms of strange and charm quarks according to the number of reaction steps; an analogue in nuclear reactions. This is perhaps suited to the study of constituent nature of baryons. The unknown factor in our study is the basic interactions for each steps. In one-quark process we assume a vector type coupling with unknown strength, which was however fixed by existing strangeness production data. For the two-quark process in Ref. [8] we have employed an instanton induced interaction for simplicity. This however does not contain the leading order interaction of vector type as expected in the Regge theory at high energies. We need more study on the basic question of the interaction.

The last remark is on the relevance of the theoretical studies of hadron reactions in relation with observed exotic data. Many hadron reactions are coupled channel problems where not only resonance structure but also various threshold phenomena may cause unexpected behaviors in observed spectrum. This is perhaps the most needed task from the theory side, for which we have started collaborations in our theory group at RCNP. We hope to report results elsewhere.

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