Spectroscopy of charmed baryons at the J-PARC high-momentum beam line

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Abstract.

The heavy quark baryon spectroscopy is a key way to understand what the building block of hadrons is. The diquark correlation which is expectedly an essential degree of freedom to describe the hadron structure can be investigated from the spectroscopy of charmed baryons. An experiment to observe and investigate the charmed baryons was proposed at the J-PARC high-momentum beam line. The missing mass spectroscopy experiment via the \( \pi^- p \rightarrow Y_c^+ D^{*-} \) reaction at 20 GeV/c will be performed for the systematic measurement of the excitation energy, the production rates and the decay products of charmed baryons. In addition, the properties of the strange baryons can also be measured systematically by using the same experimental setup. From the systematic study of both charmed baryons and hyperons, the diquark correlation can be revealed which is expectedly an essential degree of freedom to describe the hadron structure.

1. Introduction

One of fundamental questions in the hadron physics is how hadrons are formed. The constituent quark model well describes the properties of hadrons with constituent quarks as an effective degree of freedom. The hadron properties, such as hadron mass and magnetic moments of ground state baryons, are well reproduced by the model. However, the constituent quark model doesn’t have enough description for the excited states. There are many undiscovered states which are called as missing resonances. Recently, exotic hadrons, such as \( \Theta^+ \) [1] pentaquark and \( X, Y, Z \) mesons [2], have been reported. The existence of those exotic states suggests that hadrons have much rich internal structure which is beyond the naive quark model. Therefore, investigations of proper effective degrees of freedom to describe hadrons are essential to understand hadron structure.

In order to answer this question, it is necessary to understand the interaction between quarks in hadrons. The quark-quark correlation, namely diquark correlation, is expected to be an
essential degree of freedom to describe hadrons. In the case of light baryons, 3 diquark pairs are correlated each other in an equal weight so that the extraction of diquark correlation is unclear. The magnitude of the color-spin interaction between quarks is proportional to the inverse of the quark mass. When one quark in a baryon is replaced to a heavy quark, one expects that the correlation of two light quarks is stronger than that of the other pairs. As a result, a diquark correlation is expected to be isolated and developed in the baryon structure. Charmed baryons which have one heavy charm quark can provide unique opportunities to study diquark correlation.

2. Diquark correlation in charmed baryons
The nature of the diquark correlation can appear in level structure, decay branching ratios and production rates of charmed baryons. Two excitation modes, called isotope shift, emerge to the level structure. The $\rho$ and $\lambda$ modes are a rotation of the diquark and an orbital excitation between the diquark and the other heavy quark, respectively. Those excited states caused by the diquark correlation appear in the excitation spectrum. It could not be observed in light quark baryons due to the same dynamics of three diquark pairs. From the study of the excitation spectrum of charmed baryons, we can access to the $\rho$ and $\lambda$ excitation modes which are strongly related to the internal structure of the charmed baryons.

One of the approaches to reveal those excitation modes is to measure decay properties. In the case of $\rho$ mode, the rotating diquark decays by emitting a pion. Then, the charmed baryon goes to a light-meson and a charmed baryon pair. On the other hand, in the $\lambda$ mode case, the charmed baryon decays to a charmed meson and a light nucleon pair. Difference of the decay branching ratios is expected for the decay property which provides us information of the excitation modes. In addition, it is found that the production cross section is strongly related to the excitation modes. Charmed baryons are produced via the hadronic reaction, the $p \rightarrow Y_c^{*+} D^{*-}$ reaction. For the production process, the $D^*$ exchange can be taken into account. The generated charm quark from $u$ quark is attached to a spectator diquark pair from the initial state in the proton wave function. Then, a charmed baryon forms from a diquark and a charm quark with an orbital excitation. In this reaction process, the production cross section can be described by the overlapping of wave functions between initial and final states. The production rate has the relation to the spin/isospin configuration of charmed baryons and momentum transfer. As a result, the production cross section has strong dependence on the excitation modes of charmed baryons [3]. From the $D^*$ exchange reaction process, the forward production can produce the $\lambda$-mode excitation because only the orbital motion between the diquark and the charm quark can be excited from the single-step reaction. In the calculation, the interaction between the diquark and the charm quark is neglected so that the $\rho$-mode excitation cannot be produced. The $\rho$-mode excitation is expected to be produced by the double-step process which includes the interaction between the diquark and the charm quark. From the measurement of the $\pi^- p \rightarrow Y_c^{*+} D^{*-}$ reaction, we can observe the charmed baryon states with the different yield according to its internal structure. The production mechanism can gives us unique information of the diquark correlation of charmed baryons.

The purposes of experiment are to observe and investigate the excited states of the charmed baryons [4]. The goal is to reveal the diquark correlation which is expected to be an essential degree of freedom to describe hadrons. The excitation energy and width are measured by the missing mass spectroscopy method by which all the excited states can be observed independent of any dependence of the final state. The measurement of the production rate which strongly related to the spin/isospin configuration of charmed baryons can provide the unique information of the diquark correlation. In addition, the analysis of the decay particles and its decay chain which decays to the known states, the absolute decay branching ratio and the spin/parity of the excited states could also be determined. From the systematic measurement of the excitation
energy, the production cross section and the decay properties, the charmed baryon states could completely be measured.

3. Experiment at the J-PARC High-Momentum Beam Line

The experiment will be performed at the high-momentum beam line which is being constructed until the beginning of 2016 in the J-PARC hadron experimental facility [5]. The high-momentum beam line will be upgraded to unseparated secondary beams with the high-intensity of more than $10^7$/spill and the momentum of up to 20 GeV/$c$. The momentum resolution of the secondary beams is expected to be less than 0.1% by using the momentum dispersive optical method. The high-momentum secondary beams with both high-intensity and high-resolution can be delivered to the experimental area.

For the charmed baryon production, the $\pi^- p \rightarrow Y_c^{++} D^{*-}$ reaction is used with the beam momentum of 20 GeV/$c$. The decay chain of the $D^{*-}$ meson, $D^{*-} \rightarrow D^0 \pi^-$ (branching ratio of 67.7%) and $D^0 \rightarrow K^+ \pi^-$ (branching ratio of 3.88%), is detected for measuring missing masses of produced charmed baryons. The decay products of $K^+$ and $\pi^-$ of 2–16 GeV/$c$ from $D^0$ and $\pi^-$ of 0.5–1.7 GeV/$c$ from $D^{*-}$ are detected by a spectrometer. The decay measurement can also be performed by detecting decay products from the produced charmed baryon, $Y_c^{++}$, such as the $Y_c^{++} \rightarrow \Sigma_c^{+++,0} \pi^- +$ and $Y_c^{++} \rightarrow p D^0$ channels. The recoil momentum of $Y_c^{++}$ is measured by the missing mass method so that the mass of the decay products ($\Sigma_c^{+++,0}$ or $D^0$) can be obtained as a missing mass by only detecting the emitted pion and proton with the momentum of 0.2–1.5 GeV/$c$.

Figure 1 shows a conceptual design of the charmed baryon spectrometer [6]. In the case of the fixed target experiment with the high-momentum beam, all the generated particles, not only the scattered high-momentum particles from the $D^{*-}$ decay but also the decay products from the produced $Y_c^{++}$, are scattered to the forward direction. Therefore, the dipole magnet system which commonly measures both the particles from the $D^{*-}$ decay for the missing mass method and the decay products from the produced $Y_c^{++}$ for the decay measurement is used for the charmed baryon spectrometer. Since the production cross section of charmed baryons is estimated to be $10^{-4}$ smaller than that of the strangeness production ($10^4$–$100$ μb of the $\pi^- p \rightarrow Y^* K$ reaction) [3], the charmed baryon production cross section of 1 nb was assumed for the experimental design. To obtain the production yield, the beam intensity of $6\times10^7$/pulse is used. The high-rate detectors such as scintillating fiber trackers will be installed for the

![Figure 1. The schematic view of the charmed baryon spectrometer.](image-url)
Figure 2. The expected missing mass spectra simulated with the known charmed baryon states. The production rate from the theoretical calculation [3] in the case of \( \sigma(\Lambda_c^+) = 1 \) nb are used for the simulation. The spin/parity of \( \Lambda_c(2940) \) has not been determined yet. In this simulation, it is assumed to be \( J_P = 3/2^+ \).

measurements of the beam momentum and profiles at focal plane and at the upstream of the experimental target, respectively. For beam particle identification, the high-rate Ring-Image Čerenkov counter will be used. The \( D^{*-} \) meson is measured by the forward detector system, the scintillating fiber trackers at the downstream of the target, and the drift chambers and the Ring-Image Čerenkov counter for detecting the high-momentum \( K^+ \) and \( \pi^- \) from \( D^0 \) at the exit of the magnet. For measuring the slow \( \pi^- \) from \( D^{*-} \) at the forward region and the decay particles from \( Y_c^+ \) with the wide angular coverage, it is necessary to detect the particles inside of the magnet. The tracking detectors which have the large angular acceptance are installed at the downstream of the target. The horizontal and vertical directions can be covered by using the detectors installed around the magnet pole and the pad-type detector on the magnet pole face are installed, respectively.

The acceptance for detecting the \( D^{*-} \) decay was estimated to be 50–60% for the excitation states up to 1 GeV by assuming the angular distribution from the dominance of the t-channel production process. The momentum resolution of 0.2% was obtained at 5 GeV/c so that the invariant mass resolution for reconstructing the \( D^0 \) and \( D^{*-} \) are estimated to be 5.5 MeV and 0.6 MeV, respectively. The missing mass resolution of excited states above 2.8 GeV/c are estimated to be \( \sim 10 \) MeV. For the decay measurement, both the polar and azimuthal angles are completely covered more than \( \cos \theta_{\text{CM}} = -0.9 \sim -0.5 \) for the \( \Lambda_c(2940)^+ \rightarrow \Sigma_c(2455)^{++} 0^- \pi^{+-} \) decay modes.

Figure 2 shows an expected missing mass spectrum simulated by the realistic experimental conditions. The main strangeness production background processes were simulated by the JAM code [7], while the PYTHIA code [8] was also used for the comparison. The most effective method of the background reduction is the \( D^* \) tagging. Both the mass region of the \( D^0 \) mass and the Q-value corresponded to the \( D^{*-} \) decay are selected. By using the \( D^* \) tagging, the background reduction of \( 2 \times 10^6 \) can be achieved from the JAM simulation result. The sensitivity of the production cross section was found to be 0.1–0.2 nb in the missing mass region of 2.2 – 3.4 GeV/c².

For simulating the missing mass spectrum, the relative production rates calculated by Ref. [3] are input. In the expected spectrum, the strong dependence of the production rate can be observed. One of the subjects is to measure the production rate of the \( \lambda \)-mode doublet states, such as \( \Lambda_c(2595)(1^-) \) and \( \Lambda_c(2625)(3^-) \) and excited states with \( \Lambda_c(2880)(3^+) \) and \( \Lambda_c(2940)(3^+) \) which are enhanced in the missing mass spectrum. By taken into account the \( \lambda \)-mode picture,
those $\lambda$-mode doublet states have production ratios with $R(\frac{3}{2}^-) = 2$ and $R(\frac{5}{2}^+ \rightarrow \frac{3}{2}^+)$, respectively [3]. The measurement of the production rates of charmed baryons is expected to give a strong evidence of the existence of the excitation modes from the diquark correlation.

4. Systematic study with strange sector
For further understand the excitation mode, the systematic studies of both charm and strange sector are another key way. From the studies of both sectors, the heavy quark mass dependence of the $\lambda$ and $\rho$ excitation mode can be investigated. By changing the mass of heavy quark, the level splitting of the excitation states by the spin-spin interaction are changed according to the heavy quark mass. In addition, in the strange sector, the $\lambda/\rho$-mixing due to the smaller mass of the strange quark has to be taken into account. Excited states of hyperons can be produced via the $\pi^- p \rightarrow Y^* K^*$ reaction. The $t$-channel $\pi^- p \rightarrow Y^* K^*$ reaction favors to produce the $\lambda$-mode. However, the $\rho$-mode states can be produced with a larger fraction compared with the charm sector from a larger fraction of the $\lambda/\rho$-mode mixing. The measurements of hyperons are inseparable for determining the $\lambda/\rho$-mode mixing ratio from the experimental data.

From the measurement of the strange sector, the production rate and the decay branching ratios of known excited states can precisely be determined due to the huge statistics from the much larger production cross section of strangeness. The $\lambda/\rho$-mixing can be determined from the strange sector. In the charm sector, the widths of excitation states are narrower than those of hyperons so that the separation of the excitation states can be much clearer than that of strange sector. In addition, the production rate is found to have strong dependence of the excitation state. The clear distinction of the $\lambda$ and $\rho$ excitation is expected in the charm sector. However, the excited states of not only the charmed baryons but also the hyperons are not completely understood because of the lack of the experimental data. For the J-PARC experiment, the systematic measurements of both charm and strange sectors are also essential to understand the internal structure of hadrons.

5. Summary
The charmed baryon spectroscopy give us a chance to understand the hadron structure. For the properties of the charmed baryon, two light quarks are isolated and form the diquark correlation due to the small color-magnetic interaction between the charm and lighter quarks. The excitation modes from the diquark correlation are reflected to the structure of the excited spectrum and the decay modes of excited states. In addition, the production cross section via the hadronic reaction gives us unique information of the charmed baryon structure. For investigating charmed baryons, we proposed a spectroscopy experiment to observe and investigate excited states of charmed baryons at the J-PARC high-momentum beam line. The systematic measurement of the excitation energy, the production rate and the decay products of charmed baryons will be performed by the spectroscopy experiment. From the systematic study of both charmed baryons and hyperons, the diquark correlation can be revealed which is expectedly an essential degree of freedom to describe the hadron structure.

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