SEARCH FOR DOUBLY HEAVY BARYON VIA WEAK DECAYS

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Using the factorization approach and taking into account the final state interaction, we calculate the two body non-leptonic decays of doubly heavy baryons. After comparing the semi-leptonic decays and all possible hadronic decay channels, we found some channels with large branching ratios. Taking the detection efficiency into consideration, we suggest $\Xi^{++}\bar{c}c$ as the first search goal and $\Xi^{++}\bar{c}c \to \Lambda^0 c K^- \pi^+ + \pi^+$ and $\Xi^{++}\bar{c}c \to \Xi^0 c \pi^+$ as the golden discovery channels with $\Lambda^0$ reconstructed by $pK^-\pi^+$ and $\Xi^0 \to pK^-\pi^+$, respectively.

1 Motivation

Doubly or triply heavy flavor baryons with two or three heavy quarks ($b$ or $c$ quark) are predicted by the quark model, whose existence is also allowed by the QCD theory. However, the experimental search of these states is very slow. The first evidence was reported by the SELEX experiment for $\Xi^{+}\bar{c}c$ in 2002.\textsuperscript{1,2} However, it has never been confirmed by later experiments with larger data, such as FOCUS,\textsuperscript{3} BaBar\textsuperscript{4} and Belle.\textsuperscript{5,6} Utilizing as large as 0.65 fb\textsuperscript{-1} data, the LHCb collaboration even performed a thorough search in the discovery channel used by SELEX, $\Xi^{+}\bar{c}c \to \Lambda^0 c K^- \pi^+$, but did not find any significant signal.\textsuperscript{7} On the theoretical side, analysis on the production of doubly heavy baryons\textsuperscript{8,9} indicates a large possibility of observing $\Xi^{+}\bar{c}c$ at LHC. Therefore searching for the doubly heavy baryons was proposed as an important physical goal by the LHCb collaboration. Although there had been a lot of research on the masses and decay constants of doubly heavy baryons, people knew little about doubly heavy baryon decays. To make the experimental searching more efficient, it became urgent and necessary to study the branching ratios of doubly heavy baryon decays.

As ground states of doubly heavy baryons, they can only decay weakly. There are a huge number of decay channels to study, since there are many hadronic states below their mass scale. After a careful study of all possible decay channels of the doubly heavy baryons, we give suggestions of some golden channels with large branching ratios and all charged final states for experimental search.\textsuperscript{10} Following our suggestions, the LHCb experiment\textsuperscript{11} did find the $\Xi^{+}\bar{c}c$ state through one of our suggested decay channels $\Xi^{++}\bar{c}c \to \Lambda^+_c K^- \pi^+ \pi^+$ with $\Lambda^+_c$ reconstructed by $pK^-\pi^+$.

2 Theoretical study of doubly heavy baryons decays

Comparing to the doubly heavy baryons with $b$ quark(s), the doubly charm baryons are easier to be observed because their production needs less energy. Under the flavor $SU(3)$ symmetry doubly charm baryons $\Xi^{++}_{cc}, \Xi^{+}_{cc}$ and $\Omega^{+}_{cc}$ form a spin-$\frac{1}{2}$ and a spin-$\frac{3}{2}$ triplets. The latter triplet will decay to the former one via electromagnetic or strong interactions. As ground states, the spin-$\frac{1}{2}$ triplet can only decay weakly through one of the $c$ quarks.
Lifetime is an important point in the choice of the candidates. On one hand the branching ratios are related directly to the lifetime of the mother particle, on the other hand particles with longer lifetimes will be easier to be identified in experiments. Different theoretical work gives quite different predictions for the lifetimes of doubly charm baryons, which makes it hard to judge by the absolute values of lifetimes. Luckily, because of the effect of destructive Pauli interference it is expected that $\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+}) \sim \tau(\Omega_{cc})$. Their ratio is predicted to be $R_\tau \equiv \tau_{\Xi_{cc}^{++}} / \tau_{\Xi_{cc}^{+}} = 0.25 \sim 0.37$ with less theoretical uncertainty. Therefore we suggested $\Xi_{cc}^{++}$ as a prior candidate in experimental search. This is contrary to the finding of the SELLEX experiment, who declared the discovering of $\Xi_{cc}^{+}$ instead of $\Xi_{cc}^{++}$.

2.1 Semileptonic decays

![Figure 1](image1.png)  
**Figure 1** – Semileptonic decay of a doubly charm baryon.

![Figure 2](image2.png)  
**Figure 2** – Baryon to baryon transition depicted by light front quark model in the diquark picture.

On the theoretical side the simplest case is semi-leptonic decays (shown in Fig. 1), whose amplitudes can be factorized safely into a leptonic and a hadronic part. The hadronic part is a $R$ interference it is expected that $\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+}) \sim \tau(\Omega_{cc})$. Their ratio is predicted to be $R_\tau \equiv \tau_{\Xi_{cc}^{++}} / \tau_{\Xi_{cc}^{+}} = 0.25 \sim 0.37$ with less theoretical uncertainty. Therefore we suggested $\Xi_{cc}^{++}$ as a prior candidate in experimental search. This is contrary to the finding of the SELLEX experiment, who declared the discovering of $\Xi_{cc}^{+}$ instead of $\Xi_{cc}^{++}$.

The key task is the calculation of the form factors $f_{1,2,3}(q^2)$ and $g_{1,2,3}(q^2)$ defined in Eq.(1). The first calculation is made in the light front quark model (LFQM) and the diquark picture. Figure 2 depicts a baryon to baryon transition in the diquark model. The hadronic part is $R$ interference it is expected that $\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+}) \sim \tau(\Omega_{cc})$. Their ratio is predicted to be $R_\tau \equiv \tau_{\Xi_{cc}^{++}} / \tau_{\Xi_{cc}^{+}} = 0.25 \sim 0.37$ with less theoretical uncertainty. Therefore we suggested $\Xi_{cc}^{++}$ as a prior candidate in experimental search. This is contrary to the finding of the SELLEX experiment, who declared the discovering of $\Xi_{cc}^{+}$ instead of $\Xi_{cc}^{++}$.

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$$
\begin{align*}
BR(\Xi_{cc}^{++} \to \Xi_{cc}^{+} l^+ \nu_l) &= 5.25 \times 10^{-2}, \\
BR(\Xi_{cc}^{++} \to \Xi_{cc}^{0} l^+ \nu_l) &= 5.84 \times 10^{-2}, \\
BR(\Xi_{cc}^{++} \to \Lambda_{cc}^{+} l^+ \nu_l) &= 4.81 \times 10^{-3}, \\
BR(\Xi_{cc}^{++} \to \Sigma_{cc}^{+} l^+ \nu_l) &= 4.38 \times 10^{-3},
\end{align*}
$$

where the two decays in the first line of Eq. (2) are induced by $c \to s$ transition and those in the second line by $c \to d$ transition. One can see that branching ratios of the two Cabibbo favored decays are at the order of $10^{-2}$ which is about 10 times larger than the Cabibbo suppressed ones. For the sake of particle reconstruction in experiments one needs to take the secondary decays into consideration, which decreases the branching ratios by a factor of $10^{-2}$. As a result, the branching ratios of semi-leptonic decays used in experimental research are expected to be of the order $10^{-4}$. Comparing to non-leptonic decays, whose branching ratios are of the order $10^{-3} \sim 10^{-4}$, the semi-leptonic decays are not competitive, what’s more, the largest disadvantage of semi-leptonic decays is the phenomena of missing energy in experiments caused by the neutrinos.
2.2 Non-leptonic decays

We first consider the simplest non-leptonic decays: a doubly charm baryon decays into a single charm baryon and a meson. Theoretically non-leptonic charm decays are difficult to deal with. The scale of charm is very special, which is much higher than $\Lambda_{\text{QCD}}$ but not high enough for a good heavy quark mass expansion. The non-perturbative QCD plays a major role, which restricts the application of most factorization theories. The factorization assisted topological diagrammatic approach, which works well in charm meson decays to predict the $\Delta A_{\text{CP}}$ successfully\(^{15}\), also does not work here, since there are not enough experimental data. Therefore the doubly charm baryon decays need to be considered from the beginning. The leading order topological diagrams contributions in decays of doubly charm baryon to a single charm baryon and a meson can be classified into the diagrams in Fig. 3.\(^{10}\)

![Figure 3](image)

**Figure 3** – Topologies of two body nonleptonic decays of doubly charm baryons.

From the experience of D meson decays,\(^{15}\) we notice that the emission diagram (denoted by T) is dominated by the short distance contribution, which can be factorized as production of a meson decay constant and a weak transition of baryon to baryon. With the form factors evaluated in LFQM,\(^{13}\) this contribution is easy to calculate. Considering the detection efficiency and comparing among the theoretical results, we find that among short distance contribution denominated decays $\Xi^{++}_{cc} \rightarrow \Xi^{+}_{c}\pi^{+}$ is the best channel for detection with $\Xi^{+}_{c}$ reconstructed by the final state $pK^{-}\pi^{+}$. The secondary decay $\Xi^{+}_{c} \rightarrow pK^{-}\pi^{+}$ is estimated to have a branching ratio of about two percent.\(^{10}\)

Similar to the D meson decays, long distance contribution is dominating in other diagrams. This part of contribution has never been calculated in the literature and we evaluate it firstly with the rescattering mechanism of the final-state-interaction. The rescattering mechanism is induced by quark exchanges, and it can be calculated as triangle diagrams by using the effective Lagrangian with couplings at hadron level. The depiction of this mechanism is shown in Fig. 4 with the $t$-channel rescattering diagram of $\Xi^{++}_{cc} \rightarrow \Xi^{(0)+}\rho^{+} \rightarrow \Sigma^{++}_{c} K^{*0}$ as an example. The calculated branching ratios are expected to have large errors because of the uncertain hadronic parameters. In order to reduce ambiguity, we use their ratios instead of branching fractions to draw conclusions. Most of the theoretical uncertainties due to the hadronic parameters canceled in the ratios. Our sample results of ratios of the long distance dominated decays are listed in Table 1.

![Figure 4](image)

**Figure 4** – The rescattering diagram of $\Xi^{++}_{cc} \rightarrow \Xi^{(0)+}\rho^{+} \rightarrow \Sigma^{++}_{c} K^{*0}$. Shown at quark and hadron level.

We find that $\Xi^{++}_{cc} \rightarrow \Sigma^{++}_{c} K^{*0}$ decay has the largest branching fraction at the order of several percent. The secondary decays can be $\Sigma^{++}_{c} \rightarrow \Lambda^{+}_{c}\pi^{+}$ and $K^{*0} \rightarrow K^{-}\pi^{+}$. The total 4-body decay is very difficult to calculate precisely, but our estimation shows that $\mathcal{B}(\Xi^{++}_{cc} \rightarrow \Lambda^{+}_{c} K^{-}\pi^{+}\pi^{+})$ can even reach $\mathcal{O}(10\%)$ because of the rich resonant contributions. In detection, $\Lambda^{+}_{c}$ can be reconstructed by $pK^{-}\pi^{+}$.\(^{10}\)
Table 1: Branching fractions of $\Xi_{cc}^{++}$ and $\Xi_{cc}^{+}$ decays with the long-distance contributions, relative to that of $\Xi_{cc}^{++} \to \Sigma_{c}^{++}(2455)K^{0}$.

| Baryons Modes | $\overline{B}_{LD}$ |
|---------------|---------------------|
| $\Xi_{cc}^{++}(ccu)$ $\Sigma_{c}^{++}(2455)K^{0}$ | defined as 1 |
| p$D^{+}$ | 0.04 |
| p$D^{+}$ | 0.0008 |
| $\Xi_{cc}^{+}(ccd)$ $\Lambda_{c}^{+}K^{0}$ | $(R_{\tau}/0.3) \times 0.22$ |
| $\Sigma_{c}^{++}(2455)K^{-}$ | $(R_{\tau}/0.3) \times 0.01$ |
| $\Xi_{c}^{+}\rho^{0}$ | $(R_{\tau}/0.3) \times 0.04$ |
| $\Lambda D^{+}$ | $(R_{\tau}/0.3) \times 0.004$ |
| p$D^{0}$ | $(R_{\tau}/0.3) \times 0.001$ |

3 Conclusion

In the purpose of finding out the golden decay channels for experimental search, we systematically analyzed the properties and decays of doubly heavy baryons. Utilizing the form factors of doubly heavy baryon to single heavy baryon weak transition, the branching fractions of the semi-leptonic decays and the two body non-leptonic decays of doubly charm baryons are calculated. We find that $\Xi_{cc}^{++} \to \Lambda_{c}^{+}K^{-}\pi^{+}\pi^{+}$ with $\Lambda_{c} \to pK^{-}\pi^{+}$ has the first priority. In 2017, the LHCb collaboration declares the discovery of $\Xi_{cc}^{++}$ via this decay following our suggestions. We also suggest the $\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+}$ decay with $\Xi_{c}^{+} \to pK^{-}\pi^{+}$ as a good candidate for experimental search. As for the search of $\Xi_{cc}^{+}$ state, our calculation shows that $\Xi_{cc}^{+} \to \Lambda_{c}^{+}\overline{K}^{0}(\to K^{-}\pi^{+})$ is a prior candidate.

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