Weak Decays of Triply Heavy Baryons

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In collaboration with Wei Wang

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Background

Discovery of Ξ_{cc}^{++}


CERN-EP-2017-156
LHCb-PAPER-2017-018
12 September 2017

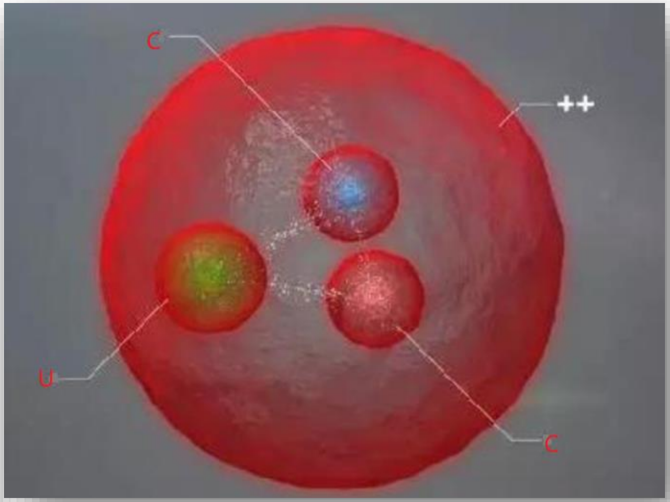
arXiv:1707.01621v2 [hep-ex] 14 Sep 2017

Observation of the doubly charmed baryon Ξ_{cc}^{++}

LHCb collaboration†

Abstract

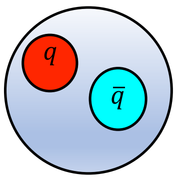
A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the Λ_c^+ baryon is reconstructed in the decay mode $pK^-\pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon Ξ_{cc}^{++}. The difference between the masses of the Ξ_{cc}^{++} and Λ_c^+ states is measured to be $1334.94 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst})\,\text{MeV}/c^2$, and the Ξ_{cc}^{++} mass is then determined to be $3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14\,(\Lambda_c^+)\,\text{MeV}/c^2$, where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $1.7\,\text{fb}^{-1}$, and confirmed in an additional sample of data collected at 8 TeV.



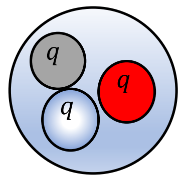
$$m_{\Xi_{cc}^{++}} = (3621.40 \pm 0.72 \pm 0.27 \pm 0.14)\text{MeV}.$$

Quark model

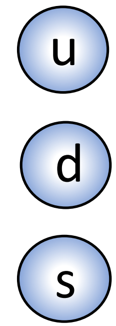
- In 1964, Gell-Mann and Zweig proposed a way to build the numerous hadrons out of three fundamental quarks.



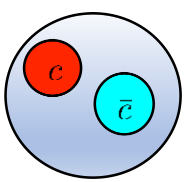
Meson

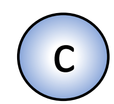


Baryo
n



- The 1974 discovery of the J/ψ (and thus the charm quark) ushered in a series of breakthroughs which are collectively known as the November Revolution.





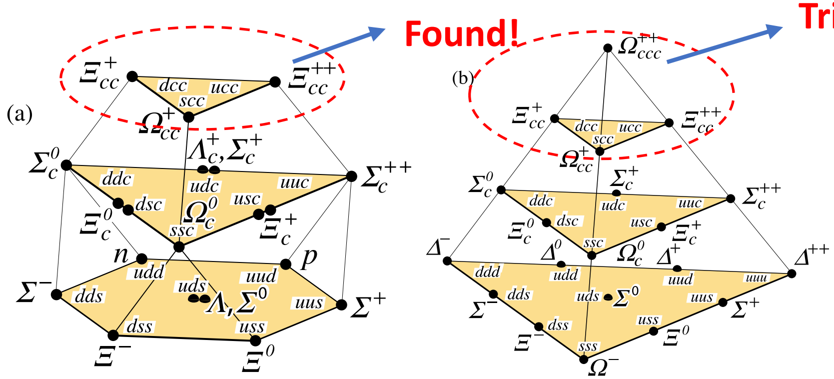
Quark model

- For baryons with four flavors u,d,s,c, a 20-plet for JP =1/2+ and JP =3/2+, respectively

$J^P = 1/2^+$

Found!

Triply heavy baryon



$J^P = 3/2^+$

Baryons with three heavy quarks：

The last missing pieces of the lowest-lying baryon multiplets in quark model !

Lifetime and branching ratios

➢ Previous studies of triply heavy baryons concentrated on three facets:

(1) **Spectroscopy:** Y. Jia, JHEP (2006); A. P. Martynenko, Phys. Lett. B (2008); Z. G. Wang, Commun. Theor. Phys. (2012)……

(2) **Production:** Y. Q. Chen and S. Z. Wu, JHEP 2011; M.A. Gomshi Nobary and R. Sepahvand, Phy.Rev.D(2005);

(3) **Decays:** C.Q.Geng, Y.K.Hsiao, C.W.Liu and T.H.Tsai, JHEP(2017)

	This work
$\Omega_{ccc}(\frac{3}{2}^+)$	4.99 ± 0.14
$\Omega_{ccb}(\frac{1}{2}^+)$	8.23 ± 0.13
$\Omega_{ccb}(\frac{3}{2}^+)$	8.23 ± 0.13
$\Omega_{bbc}(\frac{1}{2}^+)$	11.50 ± 0.11
$\Omega_{bbc}(\frac{3}{2}^+)$	11.49 ± 0.11
$\Omega_{bbb}(\frac{3}{2}^+)$	14.83 ± 0.10
$\Omega_{ccc}(\frac{3}{2}^-)$	5.11 ± 0.15
$\Omega_{ccb}(\frac{1}{2}^-)$	8.36 ± 0.13
$\Omega_{ccb}(\frac{3}{2}^-)$	8.36 ± 0.13
$\Omega_{bbc}(\frac{1}{2}^-)$	11.62 ± 0.11
$\Omega_{bbc}(\frac{3}{2}^-)$	11.62 ± 0.11
$\Omega_{bbb}(\frac{3}{2}^-)$	14.95 ± 0.11

(Z. G. Wang, Commun. Theor. Phys. 2012)

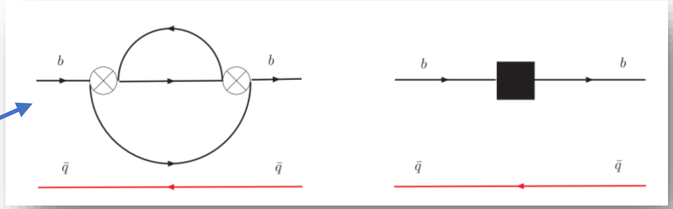
$$\Omega_{ccc}^{++} \to (\Xi_{cc}^{++}\bar{K}^0, \Omega_{cc}^{+}\pi^+, \Xi_c^+ D^+)$$

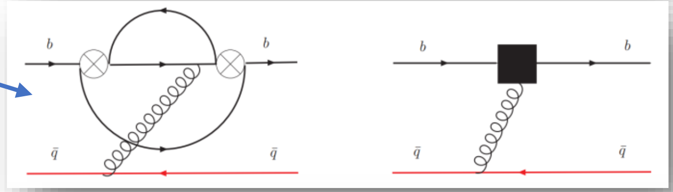
The cross sections at the LHC with √s = 7 TeV are found to reach the 0.1 nb level

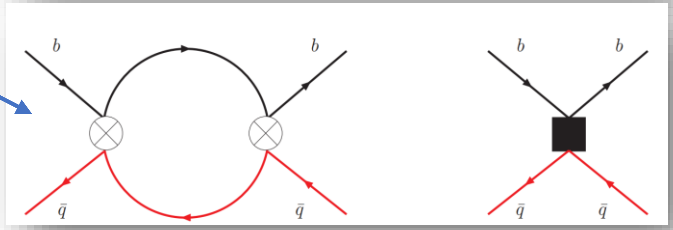
- Lifetimes or the total decay widths are among the most fundamental properties of the involved triply heavy baryons.
- A theoretical tools that describes the decay widths of inclusive decays is heavy quark expansion.
- The total decay rate is given by matrix elements of operators below:

(A. Lenz, Int. J. Mod. Phys. A, 2015)

$$\Gamma(H) = \frac{G_F m_Q^5}{192\pi^3}|V_{CKM}|^2\left(c_{3,Q}\frac{\langle H|\bar{c}c|H\rangle}{2m_H} + \frac{c_{5,Q}}{m_Q^2}\frac{\langle H|\bar{Q}g_s\sigma_{\mu\nu}G^{\mu\nu}Q|H\rangle}{2m_H} + \frac{c_{6,Q}}{m_Q^3}\frac{\langle H|(\bar{Q}q)_\Gamma(\bar{q}Q)_\Gamma|H\rangle}{m_H}\right).$$







- $c_{3,c}$ = 6.29±0.72 at LO and 11.61±1.55 at NLO. **(A. Lenz, Int. J. Mod. Phys. A, 2015)**

$$\Gamma(\Omega_{ccc}^{++}) = \begin{cases} (2.18 \pm 0.25) \times 10^{-12}\mathrm{GeV}, & \mathrm{LO} \\ (4.03 \pm 0.54) \times 10^{-12}\mathrm{GeV}, & \mathrm{NLO} \end{cases},$$

$$\tau(\Omega_{ccc}^{++}) = \begin{cases} (302 \pm 35) \times 10^{-15}s, & \mathrm{LO} \\ (164 \pm 22) \times 10^{-15}s, & \mathrm{NLO} \end{cases}.$$

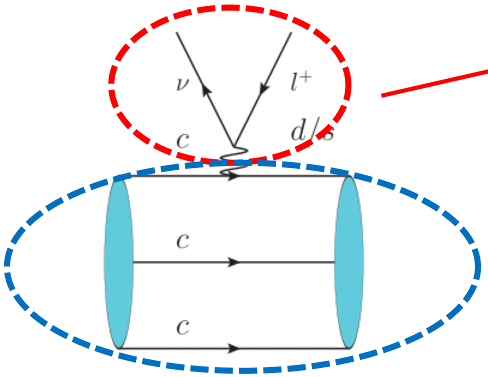
$$\Gamma(\Omega_{bbb}^{-}) = \begin{cases} (1.47 \pm 0.01) \times 10^{-12}\mathrm{GeV}, & \mathrm{LO} \\ (1.92 \pm 0.02) \times 10^{-12}\mathrm{GeV}, & \mathrm{NLO} \end{cases},$$

$$\tau(\Omega_{bbb}^{-}) = \begin{cases} (0.45 \pm 0.03) \times 10^{-12}s, & \mathrm{LO} \\ (0.34 \pm 0.04) \times 10^{-12}s, & \mathrm{NLO} \end{cases}.$$

- For process: $\Omega_{ccc}^{++} \to \Omega_{cc}^{+}\, \ell^{+}\nu$, leptonic amplitudes can be calculated in electroweak perturbation theory. While the hadronic matrix element can be parametrized in terms of form factors:

The $c \to q\bar{\ell}\nu$ transition is induced by the effective electro-weak Hamiltonian:

$$\mathcal{H}_{e.w.} = \frac{G_F}{\sqrt{2}} \left[V_{cq}^{*}\bar{q}\gamma^{\mu}(1-\gamma_5)c\bar{\nu}_{\ell}\gamma_{\mu}(1-\gamma_5)\ell\right] + h.c.,$$



$$\Gamma(\Omega_{ccc}^{++} \to \Omega_{cc}^{+} l^{+}\nu) = 1.41 \times 10^{-13}\text{GeV}$$

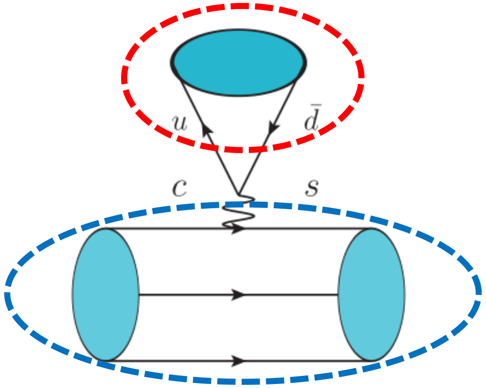
$$\mathcal{B}(\Omega_{ccc}^{++} \to \Omega_{cc}^{+} l^{+}\nu) = 3.6\%$$

$$\langle \Omega_{cc}^{+}(p')|\bar{s}\gamma^{\mu}c|\Omega_{ccc}^{++}(p)\rangle = \bar{u}(p')\left[\frac{f_1\gamma^{\mu}P^{\alpha}}{m_{\Omega_{ccc}^{++}} - m_{\Omega_{cc}^{+}}} + \frac{f_2 P^{\mu}P^{\alpha}}{m^2_{\Omega_{ccc}^{++}} - m^2_{\Omega_{cc}^{+}}} + \frac{if_3\sigma^{\mu\nu}q_{\nu}P^{\alpha}}{m^2_{\Omega_{ccc}^{++}}} + f_4 g^{\alpha\mu}\right]u^{\alpha}(p),$$

$$\langle \Omega_{cc}^{+}(p')|\bar{s}\gamma^{\mu}\gamma_5 c|\Omega_{ccc}^{++}(p)\rangle = \bar{u}(p')\left[\frac{g_1\gamma^{\mu}P^{\alpha}}{m_{\Omega_{ccc}^{++}} + m_{\Omega_{cc}^{+}}} + \frac{g_2 P^{\mu}P^{\alpha}}{m^2_{\Omega_{ccc}^{++}} - m^2_{\Omega_{cc}^{+}}} + \frac{ig_3\sigma^{\mu\nu}q_{\nu}P^{\alpha}}{m^2_{\Omega_{ccc}^{++}}} + g_4 g^{\alpha\mu}\right]\gamma_5 u^{\alpha}(p),$$

- For process: $\Omega_{ccc}^{++} \to \Omega_{cc}^{+}\ \pi^{+}$, one may use the factorization approach to predict its decay widths. Using the form factors, we have the decay width:

$$\Gamma(\Omega_{ccc}^{++} \to \Omega_{cc}^{+}\pi^{+}) = \frac{\sqrt{\lambda}G_F^2}{64\pi m_{\Omega_{ccc}^{++}}^3}|V_{cs}V_{ud}|^2 f_\pi^2 \left[|H_{t,-1/2}^{V,1/2}|^2 + |H_{t,-1/2}^{A,1/2}|^2\right]$$



$$\Gamma(\Omega_{ccc}^{++} \to \Omega_{cc}^{+}\pi^{+}) = 6.20 \times 10^{-14}\text{GeV}.$$

$$\mathcal{B}(\Omega_{ccc}^{++} \to \Omega_{cc}^{+}\pi^{+}) = 1.5\%.$$

- Some literature shows that 10^4 - 10^5 events of triply heavy baryons Ω_{ccc}^{++} can be accumulated for 10 fb^{-1} integrated luminosity at LHC.

(Y. Q. Chen and S. Z. Wu, JHEP 2011; Wei Wang, Yue-Long Shen, and Cai-Dian Lu,Phys.Rev.D)

$$\Gamma(\Omega_{ccc}^{++} \to \Omega_{cc}^{+} l^{+} \nu) = 1.41 \times 10^{-13} \mathrm{GeV}$$
$$\mathcal{B}(\Omega_{ccc}^{++} \to \Omega_{cc}^{+} l^{+} \nu) = 3.6\%$$

$$\Gamma(\Omega_{ccc}^{++} \to \Omega_{cc}^{+} \pi^{+}) = 6.20 \times 10^{-14} \mathrm{GeV}.$$
$$\mathcal{B}(\Omega_{ccc}^{++} \to \Omega_{cc}^{+} \pi^{+}) = 1.5\%.$$

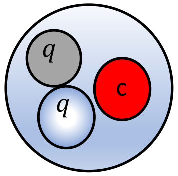
Events $(\Omega_{ccc}^{++} \to \Omega_{cc}^{+} \pi^{+})$ ~ $(10^4 – 10^5)$ × 1.5% = (150-1500)

SU(3) Analysis

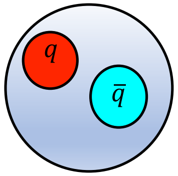
SU(3) light flavor symmetry is a powerful tool to analize decays of heavy hadrons.

m_u~2.2 MeV m_d~4.7 MeV m_s~96 MeV Λ_{QCD}~225 MeV

$$T_{\mathbf{c\bar{3}}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}.$$



$$M_8 = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -2\frac{\eta}{\sqrt{6}} \end{pmatrix}.$$



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Triply heavy baryon belongs to SU(3) singlet.

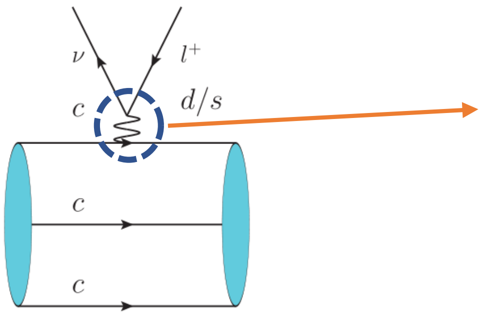
Ω_{ccc}^{++} Ω_{ccb}^{+} Ω_{cbb}^{0} Ω_{bbb}^{-}

SEMI-LEPTONIC Ω_{ccc}^{++} DECAY

The $c \to q\bar{\ell}\nu$ transition is induced by the effective electro-weak Hamiltonian:

$$\mathcal{H}_{e.w.} = \frac{G_F}{\sqrt{2}} \left[V_{cq}^* \bar{q}\gamma^\mu(1-\gamma_5)c\bar{\nu}_\ell\gamma_\mu(1-\gamma_5)\ell\right] + h.c.,$$

The heavy-to-light quark operators will form an SU(3) triplet , denoted as H3, with the components :

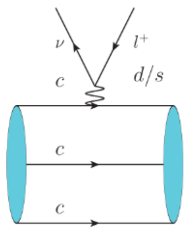


(a)

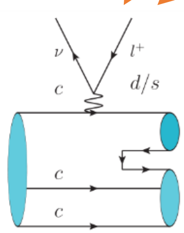
$$H_3 = \begin{pmatrix} 0 \\ V_{cd}^* \\ V_{cs}^* \end{pmatrix}.$$

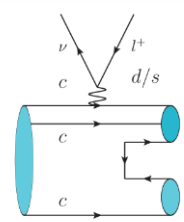
SEMI-LEPTONIC $\mathbf{\Omega_{ccc}^{++}}$ DECAY

➢ At hadron level, the effective Hamiltonian for three-body and four-body semileptonic Ω_{ccc}^{++} decays can be constructed as:



$$\mathcal{H}_{\rm eff} = a_1\Omega_{ccc}(\overline{T}_{cc})_i(H_3)^i\ \bar{\nu}_\ell\ell + a_2\Omega_{ccc}(\overline{T}_{cc})_i(M_8)^i_j(H_3)^j\ \bar{\nu}_\ell\ell$$
$$+a_3\Omega_{ccc}(\overline{T}_{c\bar{3}})_{[ij]}\overline{D}^i(H_3)^j\ \bar{\nu}_\ell\ell + a_4\Omega_{ccc}(\overline{T}_{c6})_{\{ij\}}\overline{D}^i(H_3)^j\ \bar{\nu}_\ell\ell.$$





SEMI-LEPTONIC Ω_{ccc}^{++} DECAY

channel	amplitude	channel	amplitude
$\Omega_{ccc}^{++} \to \Xi_{cc}^{+} \ell^+ \nu_\ell$	$a_1 V_{cd}^*$	$\Omega_{ccc}^{++} \to \Lambda_c^+ D^0 \ell^+ \nu_\ell$	$a_3 V_{cd}^*$
$\Omega_{ccc}^{++} \to \Omega_{cc}^{+} \ell^+ \nu_\ell$	$a_1 V_{cs}^*$	$\Omega_{ccc}^{++} \to \Xi_c^+ D^0 \ell^+ \nu_\ell$	$a_3 V_{cs}^*$
$\Omega_{ccc}^{++} \to \Xi_{cc}^{++} \pi^- \ell^+ \nu_\ell$	$a_2 V_{cd}^*$	$\Omega_{ccc}^{++} \to \Xi_c^0 D^+ \ell^+ \nu_\ell$	$a_3 V_{cs}^*$
$\Omega_{ccc}^{++} \to \Xi_{cc}^{++} K^- \ell^+ \nu_\ell$	$a_2 V_{cs}^*$	$\Omega_{ccc}^{++} \to \Xi_c^0 D_s^+ \ell^+ \nu_\ell$	$-a_3 V_{cd}^*$
$\Omega_{ccc}^{++} \to \Xi_{cc}^{+} \pi^0 \ell^+ \nu_\ell$	$-\frac{a_2 V_{cd}^*}{\sqrt{2}}$	$\Omega_{ccc}^{++} \to \Sigma_c^+ D^0 \ell^+ \nu_\ell$	$\frac{a_4 V_{cd}^*}{\sqrt{2}}$
$\Omega_{ccc}^{++} \to \Xi_{cc}^{+} \overline{K}^0 \ell^+ \nu_\ell$	$a_2 V_{cs}^*$	$\Omega_{ccc}^{++} \to \Sigma_c^0 D^+ \ell^+ \nu_\ell$	$a_4 V_{cd}^*$
$\Omega_{ccc}^{++} \to \Xi_{cc}^{+} \eta \ell^+ \nu_\ell$	$\frac{a_2 V_{cd}^*}{\sqrt{6}}$	$\Omega_{ccc}^{++} \to \Xi_c'^+ D^0 \ell^+ \nu_\ell$	$\frac{a_4 V_{cs}^*}{\sqrt{2}}$
$\Omega_{ccc}^{++} \to \Omega_{cc}^{+} K^0 \ell^+ \nu_\ell$	$a_2 V_{cd}^*$	$\Omega_{ccc}^{++} \to \Xi_c'^0 D^+ \ell^+ \nu_\ell$	$\frac{a_4 V_{cs}^*}{\sqrt{2}}$
$\Omega_{ccc}^{++} \to \Omega_{cc}^{+} \eta \ell^+ \nu_\ell$	$-\sqrt{\frac{2}{3}} a_2 V_{cs}^*$	$\Omega_{ccc}^{++} \to \Xi_c'^0 D_s^+ \ell^+ \nu_\ell$	$\frac{a_4 V_{cd}^*}{\sqrt{2}}$
		$\Omega_{ccc}^{++} \to \Omega_c^0 D_s^+ \ell^+ \nu_\ell$	$a_4 V_{cs}^*$

- The light pseudoscalar mesons can be replaced by their vector counterparts. For instance the K^0 can be replaced by a K^{*0} , which is reconstructed by the $K^-\pi^+$ final state.
- Inspired by the experimental data on D meson decays, we can infer that branching fractions for the c → s channels are about a few percents.
- A number of relations for decay widths can be easily read off from this table:

$$\Gamma(\Omega_{ccc}^{++} \to \Xi_{cc}^{++} K^- \ell^+ \nu_\ell) = \Gamma(\Omega_{ccc}^{++} \to \Xi_{cc}^{+} \overline{K}^0 \ell^+ \nu_\ell) = \frac{3}{2}\Gamma(\Omega_{ccc}^{++} \to \Omega_{cc}^{+} \eta \ell^+ \nu_\ell).$$

NON-LEPTONIC Ω_{ccc}^{++} DECAY

- Nonleptonic charm quark decays into light quarks are classified into three groups:

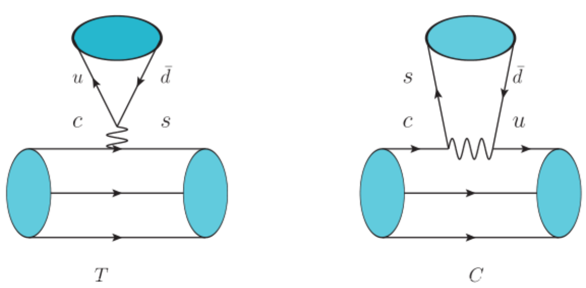
$$c \to s\bar{d}u, \quad c \to u\bar{d}d/\bar{s}s, \quad c \to d\bar{s}u.$$

- These operators transform under the flavor SU(3) symmetry as

$$\mathbf{3}\otimes\bar{\mathbf{3}}\otimes\mathbf{3} = \mathbf{3}\oplus\mathbf{3}\oplus\bar{\mathbf{6}}\oplus\mathbf{15}.$$

- Decays into a doubly-charmed baryon and one light meson

$$\mathcal{H}_{eff} \ = \ a_1\Omega_{ccc}(\overline{T}_{cc})_i(M_8)^k_j(H_{\overline{6}})^{ij}_k + a_2\Omega_{ccc}(\overline{T}_{cc})_i(M_8)^k_j(H_{15})^{ij}_k.$$



NON-LEPTONIC Ω_{ccc}^{++} DECAY

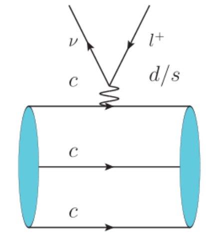
channel	amplitude	channel	amplitude
Cabibbo-allowed	channels	Singly Cabibbo-suppressed	channels
$\Omega_{ccc}^{++} \to \Xi_{cc}^{++}\overline{K}^0$	$(a_2 - a_1)V_{ud}V_{cs}^*$	$\Omega_{ccc}^{++} \to \Xi_{cc}^{++}\pi^0$	$\frac{(a_2-a_1)V_{us}V_{cs}^*}{\sqrt{2}}$
$\Omega_{ccc}^{++} \to \Omega_{cc}^{+}\pi^+$	$(a_1 + a_2)V_{ud}V_{cs}^*$	$\Omega_{ccc}^{++} \to \Xi_{cc}^{++}\eta$	$\sqrt{\frac{3}{2}}\,(a_1 - a_2)\,V_{us}V_{cs}^*$
Doubly Cabibbo-suppressed	channels	$\Omega_{ccc}^{++} \to \Xi_{cc}^{+}\pi^+$	$(a_1 + a_2)\,(-V_{us}V_{cs}^*)$
$\Omega_{ccc}^{++} \to \Xi_{cc}^{++}K^0$	$(a_1 - a_2)\,(-V_{us}V_{cd}^*)$	$\Omega_{ccc}^{++} \to \Omega_{cc}^{+}K^+$	$(a_1 + a_2)\,V_{us}V_{cs}^*$
$\Omega_{ccc}^{++} \to \Xi_{cc}^{+}K^+$	$(a_1 + a_2)\,V_{us}V_{cd}^*$		

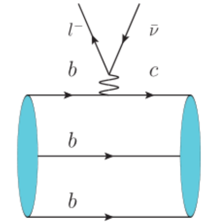
- The light pseudoscalar mesons can be replaced by their vector counterparts.
- Some CKM allowed channels are about a few percents.
- A number of relations for decay widths can be read off from this table:

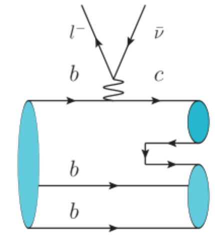
$$\Gamma(\Omega_{ccc}^{++} \to \Xi_{cc}^{++}\eta) = 3\Gamma(\Omega_{ccc}^{++} \to \Xi_{cc}^{++}\pi^0) \quad \Gamma(\Omega_{ccc}^{++} \to \Xi_{cc}^{+}\pi^+) = \Gamma(\Omega_{ccc}^{++} \to \Omega_{cc}^{+}K^+)$$

SEMI-LEPTONIC DECAYS

1. $\Omega_{ccc}^{++} \to T_{cc}\ \nu_\ell \bar{\ell}$
2. $\Omega_{ccc}^{++} \to T_{cc}\ M\ \nu_\ell \bar{\ell}$
3. $\Omega_{ccc}^{++} \to T_{c\bar{3},6}\ D\ \nu_\ell \bar{\ell}$
4. $\Omega_{bbb}^{-} \to \Omega_{cbb}^{0}\ \bar{\nu}_\ell \ell$
5. $\Omega_{bbb}^{-} \to T_{bb}\ D\ \bar{\nu}_\ell \ell$
6. $\Omega_{bbb}^{-} \to T_{bc}\ B\ \bar{\nu}_\ell \ell$
7. $\Omega_{bbb}^{-} \to T_{bb}\ \bar{\nu}_\ell \ell$
8. $\Omega_{bbb}^{-} \to T_{bb}\ M\ \bar{\nu}_\ell \ell$
9. $\Omega_{bbb}^{-} \to T_{b\bar{3},6}\ B\ \bar{\nu}_\ell \ell$







Similar semi-leptonic decays of Ω_{ccb}^{+} and Ω_{cbb}^{0} have also been considered.

NON-LEPTONIC $\mathbf{\Omega_{ccc}^{++}}$ DECAY

1. $\Omega_{ccc}^{++} \to T_{cc}\ M$
2. $\Omega_{ccc}^{++} \to T_{cc}\ M\ M$
3. $\Omega_{ccc}^{++} \to T_{c\bar{3},6}\ D$
4. $\Omega_{ccc}^{++} \to T_{c\bar{3},6}\ D\ M$

NON-LEPTONIC $\mathbf{\Omega_{bbb}^{-}}$ DECAY

1. $\Omega_{bbb}^{-} \to T_{bb}\ J/\psi$
2. $\Omega_{bbb}^{-} \to T_{bb}\ J/\psi\ M$
3. $\Omega_{bbb}^{-} \to T_{b\bar{3},6}\ J/\psi\ B$
4. $\Omega_{bbb}^{-} \to \Omega_{cbb}^{0}\ \overline{D}$
5. $\Omega_{bbb}^{-} \to \Omega_{cbb}^{0}\ \overline{D}\ M$

NON-LEPTONIC $\mathbf{\Omega_{bbb}^-}$ DECAY

6. $\Omega_{bbb}^- \to \Omega_{cbb}\ M$
7. $\Omega_{bbb}^- \to \Omega_{cbb}\ M\ M$
8. $\Omega_{bbb}^- \to T_{bb}\ D$
9. $\Omega_{bbb}^- \to T_{bb}\ D\ M$
10. $\Omega_{bbb}^- \to T_{b\bar{3},6}\ D\ B$
11. $\Omega_{bbb}^- \to T_{bb}\ \overline{D}$
12. $\Omega_{bbb}^- \to T_{bb}\ \overline{D}\ M$
13. $\Omega_{bbb}^- \to T_{b\bar{3},6}\ \overline{D}\ B$
14. $\Omega_{bbb}^- \to T_{bb}\ M$
15. $\Omega_{bbb}^- \to T_{bb}\ M\ M$
16. $\Omega_{bbb}^- \to T_{b\bar{3},6}\ B$
17. $\Omega_{bbb}^- \to T_{b\bar{3},6}\ B\ M$

Similar non-leptonic decays of Ω_{ccb}^+ and Ω_{cbb}^0 have also been considered.

Golden channels

- Based on the above analysis, we first give a collection of the CKM allowed decay channels for the Ω_{ccc}^{++}

channel	channel	channel	channel
$\Omega_{ccc}^{++} \to \Omega_{cc}^{+} \ell^+ \nu_\ell$	$\Omega_{ccc}^{++} \to \Xi_c^{\prime +} D^0 \ell^+ \nu_\ell$	$\Omega_{ccc}^{++} \to \Xi_c^{0} D^+ \ell^+ \nu_\ell$	$\Omega_{ccc}^{++} \to \Xi_{cc}^{+} \overline{K}^0 \ell^+ \nu_\ell$
$\Omega_{ccc}^{++} \to \Xi_c^{+} D^0 \ell^+ \nu_\ell$	$\Omega_{ccc}^{++} \to \Xi_c^{\prime 0} D^+ \ell^+ \nu_\ell$	$\Omega_{ccc}^{++} \to \Xi_{cc}^{++} K^- \ell^+ \nu_\ell$	$\Omega_{ccc}^{++} \to \Omega_c^{0} D_s^+ \ell^+ \nu_\ell$
$\Omega_{ccc}^{++} \to \Xi_{cc}^{++} \overline{K}^0$	$\Omega_{ccc}^{++} \to \Omega_{cc}^{+} \pi^+$		
$\Omega_{ccc}^{++} \to \Xi_{cc}^{++} \overline{K}^0 \pi^0$	$\Omega_{ccc}^{++} \to \Xi_{cc}^{+} \pi^+ \overline{K}^0$	$\Omega_{ccc}^{++} \to \Xi_{cc}^{++} K^- \pi^+$	$\Omega_{ccc}^{++} \to \Omega_{cc}^{+} K^+ \overline{K}^0$
$\Omega_{ccc}^{++} \to \Xi_c^{+} D^+$	$\Omega_{ccc}^{++} \to \Xi_c^{\prime +} D^+$		
$\Omega_{ccc}^{++} \to \Lambda_c^{+} D^+ \overline{K}^0$	$\Omega_{ccc}^{++} \to \Xi_c^{+} D_s^+ \overline{K}^0$	$\Omega_{ccc}^{++} \to \Xi_c^{+} D^+ \pi^0$	$\Omega_{ccc}^{++} \to \Xi_c^{0} D^+ \pi^+$
$\Omega_{ccc}^{++} \to \Xi_c^{+} D^0 \pi^+$			
$\Omega_{ccc}^{++} \to \Sigma_c^{++} D^0 \overline{K}^0$	$\Omega_{ccc}^{++} \to \Xi_c^{\prime 0} D^+ \pi^+$	$\Omega_{ccc}^{++} \to \Xi_c^{\prime +} D^0 \pi^+$	$\Omega_{ccc}^{++} \to \Omega_c^{0} D^+ K^+$
$\Omega_{ccc}^{++} \to \Sigma_c^{++} D^+ K^-$	$\Omega_{ccc}^{++} \to \Xi_c^{\prime +} D_s^+ \overline{K}^0$	$\Omega_{ccc}^{++} \to \Xi_c^{\prime +} D^+ \pi^0$	$\Omega_{ccc}^{++} \to \Omega_c^{0} D_s^+ \pi^+$
$\Omega_{ccc}^{++} \to \Sigma_c^{+} D^+ \overline{K}^0$			

- Nonleptonic Ω_{ccc}^{++} decay such as $\Omega_{ccc}^{++} \to \Xi_{cc}^{++} K^- \pi^+$ might be used to search for Ω_{ccc}^{++} especially at LHC, since their branching fractions are sizable, and the final state can be easily to identify. This will make use of the doubly heavy baryon Ξ_{cc}^{++} which has been just discovered by LHCb.

- Based on the above analysis, we first give a collection of the CKM allowed decay channels for the Ω_{bbb}^-

channel	channel	channel	channel
$\Omega_{bbb}^- \to \Xi_{bb}^0 D^0 \ell^- \bar{\nu}_\ell$	$\Omega_{bbb}^- \to \Xi_{bc}^+ B^- \ell^- \bar{\nu}_\ell$	$\Omega_{bbb}^- \to \Omega_{bb}^- D_s^+ \ell^- \bar{\nu}_\ell$	$\Omega_{bbb}^- \to \Omega_{bc}^0 \overline{B}_s^0 \ell^- \bar{\nu}_\ell$
$\Omega_{bbb}^- \to \Xi_{bb}^- D^+ \ell^- \bar{\nu}_\ell$	$\Omega_{bbb}^- \to \Xi_{bc}^0 \overline{B}^0 \ell^- \bar{\nu}_\ell$		
$\Omega_{bbb}^- \to \Omega_{bb}^- J/\psi$	$\Omega_{bbb}^- \to \Xi_b^{\prime 0} B^- J/\psi$	$\Omega_{bbb}^- \to \Xi_{bb}^0 K^- J/\psi$	$\Omega_{bbb}^- \to \Omega_b^- \overline{B}_s^0 J/\psi$
$\Omega_{bbb}^- \to \Xi_b^0 B^- J/\psi$	$\Omega_{bbb}^- \to \Xi_b^{\prime -} \overline{B}^0 J/\psi$	$\Omega_{bbb}^- \to \Xi_{bb}^- \overline{K}^0 J/\psi$	$\Omega_{bbb}^- \to \Xi_b^- \overline{B}^0 J/\psi$
$\Omega_{bbb}^- \to \Omega_{bbc}^0 D_s^-$	$\Omega_{bbb}^- \to \Omega_{bbc}^0 D^- \overline{K}^0$	$\Omega_{bbb}^- \to \Omega_{bbc}^0 \overline{D}^0 K^-$	
$\Omega_{bbb}^- \to \Omega_{bbc}^0 \pi^-$	$\Omega_{bbb}^- \to \Omega_{bbc}^0 K^0 K^-$		
$\Omega_{bbb}^- \to \Xi_{bb}^- D^0$	$\Omega_{bbb}^- \to \Xi_{bb}^- D^+ \pi^-$	$\Omega_{bbb}^- \to \Xi_{bb}^- D^0 \pi^0$	$\Omega_{bbb}^- \to \Omega_{bb}^- D^0 K^0$
$\Omega_{bbb}^- \to \Lambda_b^0 B^- D^0$	$\Omega_{bbb}^- \to \Sigma_b^- B^- D^+$	$\Omega_{bbb}^- \to \Xi_b^- \overline{B}_s^0 D^0$	$\Omega_{bbb}^- \to \Xi_b^{\prime -} B^- D_s^+$
$\Omega_{bbb}^- \to \Xi_{bb}^0 D^0 \pi^-$	$\Omega_{bbb}^- \to \Sigma_b^- \overline{B}^0 D^0$	$\Omega_{bbb}^- \to \Omega_{bb}^- D_s^+ \pi^-$	$\Omega_{bbb}^- \to \Xi_b^{\prime -} \overline{B}_s^0 D^0$
$\Omega_{bbb}^- \to \Xi_b^- B^- D_s^+$	$\Omega_{bbb}^- \to \Xi_{bb}^- D_s^+ K^-$	$\Omega_{bbb}^- \to \Sigma_b^0 B^- D^0$	

- For nonleptonic decays of Ω_{bbb}^- , the largest branching fraction might reach 10^{-3}. Taking into account its daughter decays, we expect the branching fraction for Ω_{bbb}^- decaying into charmless final state is at most 10^{-9}. Thus the triply bottom baryon can be only observed with a large amount of data in future, such as the high luminosity LHC.

Summary

Summary

- On experimental side, light hadrons with no heavy quark, singly heavy baryons, and doubly heavy baryons have been established, but triply heavy baryons are still missing.

- In this work we study semileptonic and nonleptonic weak decays of triply heavy baryons Ω_{ccc}^{++} Ω_{ccb}^{+} Ω_{cbb}^{0} Ω_{bbb}^{-} by using SU(3) flavor symmetry.

- We point out that branching fractions for Cabibbo allowed processes showed below may reach a few percents,

$$\Omega_{ccc}^{++} \to (\Xi_{cc}^{++}\overline{K}^0, \Xi_{cc}^{++}K^-\pi^+, \Omega_{cc}^{+}\pi^+, \Xi_c^+ D^+, \Xi_c' D^+, \Lambda_c D^+ \overline{K}^0, \Xi_c^+ D^0 \pi^+, \Xi_c^0 D^+ \pi^+)$$

- We suggest our experimental colleagues to perform a search at hadron colliders and the electron and positron collisions in future, which will presumably lead to discoveries of triply heavy baryons and complete the baryon multiplets.

Thank you !

Back up

and thus for the decay rate

$$\boxed{\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 \left[c_{3,b}\frac{\langle B|\bar{b}b|B\rangle}{2M_B} + \frac{c_{5,b}}{m_b^2}\frac{\langle B|\bar{b}g_s\sigma_{\mu\nu}G^{\mu\nu}b|B\rangle}{2M_B} + \frac{c_{6,b}}{m_b^3}\frac{\langle B|(\bar{b}q)_\Gamma(\bar{q}b)_\Gamma|B\rangle}{M_B} + ...\right]}. \tag{2.52}$$

The individual contributions in Eq.(2.52) have the following origin and interpretation:

A. Ω_{ccc}^{++}

The dimension 6 operators arise from the interaction between the decaying heavy quark and the spectator quarks. For the Ω_{ccc}^{++} baryon, such operator do not contribute since two charm quarks can not scatter at leading order. At the lowest order in $1/m_c$, the $\bar{c}c$ operator gives the charm quark number in the Ω_{ccc}^{++} baryon:

$$\frac{\langle\Omega_{ccc}^{++}|\bar{c}c|\Omega_{ccc}^{++}\rangle}{2m_{\Omega_{ccc}^{++}}} = 3 + \mathcal{O}(1/m_c). \tag{7}$$

A. Semileptonic Ω_{ccc} decays

The $c \to q\bar{\ell}\nu$ transition is induced by the effective electro-weak Hamiltonian:

$$\mathcal{H}_{e.w.} = \frac{G_F}{\sqrt{2}} \left[V_{cq}^* \bar{q}\gamma^\mu(1-\gamma_5)c\bar{\nu}_\ell\gamma_\mu(1-\gamma_5)\ell\right] + h.c.,$$

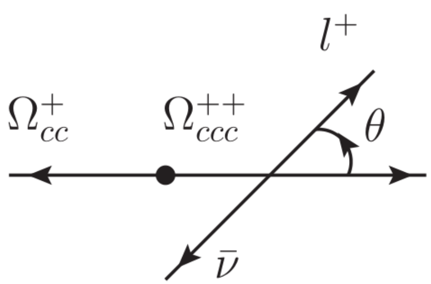


FIG. 2: Kinematics for the $\Omega_{ccc}^{++} \to \Omega_{cc}^{+} l^{+} \bar{\nu}$ decay. In the Ω_{ccc}^{++} rest frame, the Ω_{cc}^{+} moves on the opposite of the z axis. In the lepton pair $l^{+}\bar{\nu}$ rest frame, the l^{+} flying direction and the z axis intersect with the polar angle θ.

$$\Gamma(\Omega_{ccc}^{++} \to \Xi_{cc}^{+} l^{+} \nu) \ = \ 1.29 \times 10^{-14} \mathrm{GeV}. \tag{40}$$

Masses for triply and doubly heavy baryons are taken from the QCD sum rules calculations [13, 58]:

$$m_{\Omega_{ccc}^{++}} = 4.99\mathrm{GeV}, \quad m_{\Xi_{cc}^{+}} = 3.57\mathrm{GeV}, \quad m_{\Omega_{cc}^{+}} = 3.71\mathrm{GeV}. \tag{41}$$

$$
\begin{aligned}
(T_{10})^{111} &= \Delta^{++}, \quad (T_{10})^{112} = (T_{10})^{121} = (T_{10})^{211} = \frac{1}{\sqrt{3}}\Delta^{+}, \\
(T_{10})^{222} &= \Delta^{-}, \quad (T_{10})^{122} = (T_{10})^{212} = (T_{10})^{221} = \frac{1}{\sqrt{3}}\Delta^{0}, \\
(T_{10})^{113} &= (T_{10})^{131} = (T_{10})^{311} = \frac{1}{\sqrt{3}}\Sigma'^{+}, \ (T_{10})^{223} = (T_{10})^{232} = (T_{10})^{322} = \frac{1}{\sqrt{3}}\Sigma'^{-}, \\
(T_{10})^{123} &= (T_{10})^{132} = (T_{10})^{213} = (T_{10})^{231} = (T_{10})^{312} = (T_{10})^{321} = \frac{1}{\sqrt{6}}\Sigma'^{0}, \\
(T_{10})^{133} &= (T_{10})^{313} = (T_{10})^{331} = \frac{1}{\sqrt{3}}\Xi'^{0}, \ (T_{10})^{233} = (T_{10})^{323} = (T_{10})^{332} = \frac{1}{\sqrt{3}}\Xi'^{-}, \\
(T_{10})^{333} &= \Omega^{-}. \qquad (17)
\end{aligned}
$$

The octet has the expression:

$$
T_8 = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda^0 & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda^0 \end{pmatrix}. \qquad (18)
$$

The triply heavy baryons form an SU(3) singlet, while doubly heavy baryons are an SU(3) triplet:

$$
T_{cc} = \begin{pmatrix} \Xi_{cc}^{++}(ccu) \\ \Xi_{cc}^{+}(ccd) \\ \Omega_{cc}^{+}(ccs) \end{pmatrix}, \quad T_{bc} = \begin{pmatrix} \Xi_{bc}^{+}(bcu) \\ \Xi_{bc}^{0}(bcd) \\ \Omega_{bc}^{0}(bcs) \end{pmatrix}, \quad T_{bb} = \begin{pmatrix} \Xi_{bb}^{0}(bbu) \\ \Xi_{bb}^{-}(bbd) \\ \Omega_{bb}^{-}(bbs) \end{pmatrix}. \qquad (19)
$$

Singly charmed and bottom baryons with two light quarks can form an anti-triplet or sextet. For the anti-triplet and sextet, we have the matrix expression:

$$T_{\mathbf{c\bar{3}}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}, \quad T_{\mathbf{c6}} = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ & \frac{1}{\sqrt{2}}\Xi_c'^+ \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}}\Xi_c'^0 \\ \frac{1}{\sqrt{2}}\Xi_c'^+ & \frac{1}{\sqrt{2}}\Xi_c'^0 & \Omega_c^0 \end{pmatrix}. \tag{20}$$

In the meson sector, a light pseudo-scalar meson is formed by a light quark and one light antiquark. It forms an octet:

$$M_8 = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \overline{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}, \tag{21}$$

while the singlet η_1 is not considered. Our analysis is also applicable to light vector mesons and other light mesons. The charmed meson forms an SU(3) anti-triplet:

$$D_i = \left(D^0, \ D^+, \ D_s^+ \right), \tag{22}$$

and the anti-charmed meson forms an SU(3) triplet:

$$\overline{D}^i = \left(\overline{D}^0, \ D^-, \ D_s^- \right). \tag{23}$$

The above two SU(3) triplets are also applicable to the bottom mesons.

In the following we will construct the hadron-level effective Hamiltonian for various decay modes. It is necessary to point out that a hadron in the final state must be created by its anti-particle field. For instance, in order to produce a Ξ_{ccu}^{++}, one must use the $\overline{\Xi_{ccu}^{++}}$ in the Hamiltonian, and the doubly heavy baryon anti-triplet is abbreviated as $\overline{T}_{cc}$.

Penguin contributions in charm quark decays are highly suppressed, and thus are neglected in our analysis. Tree operators transform under the flavor SU(3) symmetry as $\mathbf{3}\otimes\bar{\mathbf{3}}\otimes\mathbf{3} = \mathbf{3}\oplus\mathbf{3}\oplus\bar{\mathbf{6}}\oplus\mathbf{15}$. For charm quark decays, the vector representation H_3 will vanishes as an approximation. For the $c \to su\bar{d}$ transition, we have

$$(H_{\bar{6}})^{31}_{2} = -(H_{\bar{6}})^{13}_{2} = V_{ud}V^*_{cs}, \quad (H_{15})^{31}_{2} = (H_{15})^{13}_{2} = V_{ud}V^*_{cs}, \tag{49}$$

while for the doubly Cabibbo suppressed $c \to du\bar{s}$ transition, we have

$$(H_{\bar{6}})^{21}_{3} = -(H_{\bar{6}})^{12}_{3} = V_{us}V^*_{cd}, \ (H_{15})^{21}_{3} = (H_{15})^{12}_{3} = V_{us}V^*_{cd}. \tag{50}$$

CKM matrix elements for $c \to u\bar{d}d$ and $c \to u\bar{s}s$ transitions are approximately equal in magnitude but different in sign. Here we take $V_{ud}V^*_{cd} = -V_{us}V^*_{cs}$, with both contributions, one has the nonzero components:

$$\begin{aligned}(H_{\bar{6}})^{31}_{3} = -(H_{\bar{6}})^{13}_{3} = (H_{\bar{6}})^{12}_{2} = -(H_{\bar{6}})^{21}_{2} = V_{us}V^*_{cs},\\ (H_{15})^{31}_{3} = (H_{15})^{13}_{3} = -(H_{15})^{12}_{2} = -(H_{15})^{21}_{2} = V_{us}V^*_{cs}.\end{aligned} \tag{51}$$

If the final state contains a bottom meson and a light baryon (octet), we have

$$
\begin{aligned}
\mathcal{H}_{\rm eff} \;=\;& c_1\Omega_{cbb}\overline{B}^k\epsilon_{ijl}(\overline{T}_8)^l_k(H_3'')^{[ij]}+c_2\Omega_{cbb}\overline{B}^i\epsilon_{ijl}(\overline{T}_8)^l_k(H_3'')^{[jk]}\\
&+c_3\Omega_{cbb}\overline{B}^m\epsilon_{ijl}(\overline{T}_8)^l_kM^k_m(H_3'')^{[ij]}+c_4\Omega_{cbb}\overline{B}^j\epsilon_{ijl}(\overline{T}_8)^l_kM^k_m(H_3'')^{[im]}\\
&+c_5\Omega_{cbb}\overline{B}^k\epsilon_{ijl}(\overline{T}_8)^l_kM^j_m(H_3'')^{[im]}+c_6\Omega_{cbb}\overline{B}^m\epsilon_{ijl}(\overline{T}_8)^l_kM^j_m(H_3'')^{[ik]}\\
&+c_7\Omega_{cbb}\overline{B}^i\epsilon_{ijl}(\overline{T}_8)^l_kM^j_m(H_3'')^{[km]}+c_8\Omega_{cbb}\overline{B}^i\epsilon_{ijl}(\overline{T}_8)^l_k(H_6'')^{\{jk\}}\\
&+c_9\Omega_{cbb}\overline{B}^j\epsilon_{ijl}(\overline{T}_8)^l_kM^k_m(H_6'')^{\{im\}}+c_{10}\Omega_{cbb}\overline{B}^k\epsilon_{ijl}(\overline{T}_8)^l_kM^j_m(H_6'')^{\{im\}}\\
&+c_{11}\Omega_{cbb}\overline{B}^m\epsilon_{ijl}(\overline{T}_8)^l_kM^j_m(H_6'')^{\{ik\}}+c_{12}\Omega_{cbb}\overline{B}^i\epsilon_{ijl}(\overline{T}_8)^l_kM^j_m(H_6'')^{\{km\}}. \qquad (89)
\end{aligned}
$$

Decay amplitudes for different channels are obtained by expanding the above Hamiltonian and are collected in Tab. XXI. One can find the amplitudes c_1 and c_2 are not independent, they always

TABLE XXI: Amplitudes for Ω_{cbb} decays into a bottom meson and a light baryon (octet)

channel	amplitude	channel	amplitude
$\Omega_{cbb}^0 \to B^- \Sigma^+$	$(-2c_1 - c_8)\, V_{ub} V_{cs}^*$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Lambda^0$	$\sqrt{\frac{2}{3}}\,(-2c_1)\, V_{ub} V_{cd}^*$
$\Omega_{cbb}^0 \to \overline{B}^0 \Lambda^0$	$\frac{(-2c_1+3c_8) V_{ub} V_{cs}^*}{\sqrt{6}}$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Sigma^0$	$-\sqrt{2} c_8 V_{ub} V_{cd}^*$
$\Omega_{cbb}^0 \to \overline{B}^0 \Sigma^0$	$\frac{(2c_1+c_8) V_{ub} V_{cs}^*}{\sqrt{2}}$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Xi^0$	$(-2c_1 + c_8)\, V_{ub} V_{cs}^*$
$\Omega_{cbb}^0 \to \overline{B}^0 n$	$(2c_1 - c_8)\, V_{ub} V_{cd}^*$	$\Omega_{cbb}^0 \to B^- p$	$(2c_1 + c_8)\, V_{ub} V_{\rm cd}^*$
$\Omega_{cbb}^0 \to B^- \Lambda^0 \pi^+$	$-\frac{(2c_3+c_4-c_5+c_6-2c_7-c_9+c_{10}+3c_{11}+2c_{12}) V_{ub} V_{cs}^*}{\sqrt{6}}$	$\Omega_{cbb}^0 \to \overline{B}^0 n \overline{K}^0$	$(c_4 + c_5 + c_9 + c_{10})\, V_{ub} V_{cs}^*$
$\Omega_{cbb}^0 \to B^- \Lambda^0 K^+$	$-\frac{(4c_3+2c_4+c_5+2c_6-c_7-2c_9-c_{10}+c_{12}) V_{ub} V_{cd}^*}{\sqrt{6}}$	$\Omega_{cbb}^0 \to \overline{B}^0 n \eta$	$\frac{(2c_3+c_4+2c_5+c_6+c_7+c_9+c_{11}-c_{12}) V_{ub} V_{cd}^*}{\sqrt{6}}$
$\Omega_{cbb}^0 \to B^- \Sigma^+ \pi^0$	$\frac{(-2c_3-c_4-c_5-c_6+c_9+c_{10}+c_{11}) V_{ub} V_{cs}^*}{\sqrt{2}}$	$\Omega_{cbb}^0 \to \overline{B}^0 \Xi^- K^+$	$(c_4 - c_7 - c_9 + c_{12})\, V_{ub} V_{cs}^*$
$\Omega_{cbb}^0 \to B^- \Sigma^+ K^0$	$-(c_5 + c_7 + c_{10} + c_{12})\, V_{ub} V_{cd}^*$	$\Omega_{cbb}^0 \to \overline{B}^0 \Xi^0 K^0$	$-(2c_3 + c_6 + c_{11})\, V_{ub} V_{cs}^*$
$\Omega_{cbb}^0 \to B^- \Sigma^+ \eta$	$\frac{(-2c_3-c_4+c_5-c_6+2c_7+c_9+3c_{10}+c_{11}+2c_{12}) V_{ub} V_{cs}^*}{\sqrt{6}}$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Lambda^0 \pi^0$	$\frac{(c_9+2c_{10}+c_{12}) V_{ub} V_{cd}^*}{\sqrt{3}}$
$\Omega_{cbb}^0 \to B^- \Sigma^0 \pi^+$	$\frac{(2c_3+c_4+c_5+c_6-c_9-c_{10}-c_{11}) V_{ub} V_{cs}^*}{\sqrt{2}}$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Lambda^0 \overline{K}^0$	$-\frac{(2c_3+c_4+2c_5+c_6+c_7+c_9+2c_{10}+3c_{11}+c_{12}) V_{ub} V_{cs}^*}{\sqrt{6}}$
$\Omega_{cbb}^0 \to B^- \Sigma^0 K^+$	$\frac{(-c_5-c_7+c_{10}+2c_{11}+c_{12}) V_{ub} V_{cd}^*}{\sqrt{2}}$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Lambda^0 \eta$	$\frac{1}{3}\,(4c_3 - c_4 - 2c_5 + 2c_6 - c_7)\, V_{ub} V_{cd}^*$
$\Omega_{cbb}^0 \to B^- n \pi^+$	$(2c_3 + c_4 + c_6 - c_7 - c_9 + c_{11} + c_{12})\, V_{ub} V_{cd}^*$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Sigma^+ \pi^-$	$(-c_4 + c_7 - c_9 + c_{12})\, V_{ub} V_{cd}^*$
$\Omega_{cbb}^0 \to B^- \Xi^0 K^+$	$-(2c_3 + c_4 + c_6 - c_7 - c_9 + c_{11} + c_{12})\, V_{ub} V_{cs}^*$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Sigma^+ K^-$	$(-2c_3 - c_4 - c_6 + c_7 - c_9 + c_{11} + c_{12})\, V_{ub} V_{cs}^*$
$\Omega_{cbb}^0 \to \overline{B}^0 \Lambda^0 \pi^0$	$\frac{(2c_3+c_4-c_5+c_6-2c_7-c_9+c_{10}+3c_{11}+2c_{12}) V_{ub} V_{cs}^*}{2\sqrt{3}}$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Sigma^0 \pi^0$	$(c_7 - c_4)\, V_{ub} V_{cd}^*$
$\Omega_{cbb}^0 \to \overline{B}^0 \Lambda^0 K^0$	$-\frac{(4c_3+2c_4+c_5+2c_6-c_7+2c_9+c_{10}-c_{12}) V_{ub} V_{cd}^*}{\sqrt{6}}$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Sigma^0 \overline{K}^0$	$\frac{(2c_3+c_4+c_6-c_7+c_9-c_{11}-c_{12}) V_{ub} V_{cs}^*}{\sqrt{2}}$
$\Omega_{cbb}^0 \to \overline{B}^0 \Lambda^0 \eta$	$\frac{1}{6}\,(-2c_3 + 5c_4 + c_5 - c_6 - 4c_7 + 3c_9 + 3c_{10} - 3c_{11})\, V_{ub} V_{cs}^*$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Sigma^0 \eta$	$\frac{(c_9-2c_{11}-c_{12}) V_{ub} V_{cd}^*}{\sqrt{3}}$
$\Omega_{cbb}^0 \to \overline{B}^0 \Sigma^+ \pi^-$	$(-2c_3 - c_6 + c_{11})\, V_{ub} V_{cs}^*$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Sigma^- \pi^+$	$(-c_4 + c_7 + c_9 - c_{12})\, V_{ub} V_{cd}^*$
$\Omega_{cbb}^0 \to \overline{B}^0 \Sigma^0 \pi^0$	$-\frac{1}{2}\,(2c_3 - c_4 - c_5 + c_6 + c_9 + c_{10} - c_{11})\, V_{ub} V_{cs}^*$	$\Omega_{cbb}^0 \to \overline{B}_s^0 n \overline{K}^0$	$(2c_3 + c_6 + c_{11})\, V_{ub} V_{cd}^*$
$\Omega_{cbb}^0 \to \overline{B}^0 \Sigma^0 K^0$	$\frac{(c_5+c_7+c_{10}+2c_{11}+c_{12}) V_{ub} V_{cd}^*}{\sqrt{2}}$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Xi^- \pi^+$	$(c_5 + c_7 - c_{10} - c_{12})\, V_{ub} V_{cs}^*$
$\Omega_{cbb}^0 \to \overline{B}^0 \Sigma^0 \eta$	$\frac{(2c_3+c_4-c_5+c_6-2c_7-c_9-3c_{10}-c_{11}-2c_{12}) V_{ub} V_{cs}^*}{2\sqrt{3}}$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Xi^- K^+$	$(-c_4 - c_5 + c_9 + c_{10})\, V_{ub} V_{cd}^*$
$\Omega_{cbb}^0 \to \overline{B}^0 \Sigma^- \pi^+$	$(c_4 + c_5 - c_9 - c_{10})\, V_{ub} V_{cs}^*$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Xi^0 \pi^0$	$\frac{(-c_5-c_7+c_{10}+c_{12}) V_{ub} V_{cs}^*}{\sqrt{2}}$
$\Omega_{cbb}^0 \to \overline{B}^0 \Sigma^- K^+$	$(-c_5 - c_7 + c_{10} + c_{12})\, V_{ub} V_{cd}^*$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Xi^0 K^0$	$-(c_4 + c_5 + c_9 + c_{10})\, V_{ub} V_{cd}^*$
$\Omega_{cbb}^0 \to \overline{B}^0 n \pi^0$	$-\frac{(2c_3+c_4+c_6-c_7+c_9+2c_{10}+c_{11}+c_{12}) V_{ub} V_{cd}^*}{\sqrt{2}}$	$\Omega_{cbb}^0 \to \overline{B}_s^0 \Xi^0 \eta$	$\frac{(4c_3+2c_4+c_5+2c_6-c_7+2c_9+3c_{10}+2c_{11}+c_{12}) V_{ub} V_{cs}^*}{\sqrt{6}}$
$\Omega_{cbb}^0 \to B^- p \pi^0$	$\frac{(2c_3+c_4+c_6-c_7-c_9-2c_{10}-c_{11}-c_{12}) V_{ub} V_{\rm cd}^*}{\sqrt{2}}$	$\Omega_{cbb}^0 \to B^- p \overline{K}^0$	$(c_5 + c_7 + c_{10} + c_{12})\, V_{ub} V_{\rm cs}^*$
$\Omega_{cbb}^0 \to B^- p \eta$	$\frac{(2c_3+c_4+2c_5+c_6+c_7-c_9-c_{11}+c_{12}) V_{ub} V_{\rm cd}^*}{\sqrt{6}}$	$\Omega_{cbb}^0 \to \overline{B}^0 p \pi^-$	$(2c_3 + c_4 + c_6 - c_7 + c_9 - c_{11} - c_{12})\, V_{ub} V_{\rm cd}^*$
$\Omega_{cbb}^0 \to \overline{B}^0 p K^-$	$(c_4 - c_7 + c_9 - c_{12})\, V_{ub} V_{\rm cs}^*$	$\Omega_{cbb}^0 \to \overline{B}_s^0 p K^-$	$(2c_3 + c_6 - c_{11})\, V_{ub} V_{\rm cd}^*$

Currently, the best determination of the magnitudes of the CKM matrix elements is:[6]

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}.$$

This can also be written in matrix notation as:

$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix},$$

or using the Cabibbo angle

$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix},$$

where the various $|V_{ij}|^2$ represent the probability that the quark of j flavor decays into a quark of i flavor. This 2 × 2 rotation matrix is called the Cabibbo matrix.

Commonly used prefixed versions [edit]

Conversion to SI units[5][6]

Unit	Symbol	m^2	cm^2
megabarn	Mb	10^{-22}	10^{-18}
kilobarn	kb	10^{-25}	10^{-21}
barn	b	10^{-28}	10^{-24}
millibarn	mb	10^{-31}	10^{-27}
microbarn	μb	10^{-34}	10^{-30}
nanobarn	nb	10^{-37}	10^{-33}
picobarn	pb	10^{-40}	10^{-36}
femtobarn	fb	10^{-43}	10^{-39}
attobarn	ab	10^{-46}	10^{-42}
zeptobarn	zb	10^{-49}	10^{-45}
yoctobarn	yb	10^{-52}	10^{-48}

The tree operators transform under the flavor SU(3) symmetry as $\mathbf{3} \otimes \bar{\mathbf{3}} \otimes \mathbf{3} = \mathbf{3} \oplus \mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$.

群论相关

SU(3)群的李代数是 A_2,它的嘉当矩阵和素根展开式:

$$A = \begin{pmatrix} 2 & -1 \\ -1 & 2 \end{pmatrix}, \qquad \begin{array}{c} \mathbf{r}_1 = 2\omega_1 - \omega_2 \\ \mathbf{r}_2 = -\omega_1 + 2\omega_2 \end{array} .$$

在单纯李代数不可约表示 $\mathbf{M}$ 中，状态基记做 $|\,\mathbf{M},\mathbf{m}\rangle$，它是 H_μ 的共同本征态

$$H_\mu \mid \mathbf{M},\mathbf{m}\rangle = m_\mu \mid \mathbf{M},\mathbf{m}\rangle.$$

降算符 $\mathbf{F}_\mu$ 对这些状态基作用，使权 $\mathbf{m}$ 减少一个素根 $\mathbf{r}_\mu$。$\mathbf{F}_\mu$ 和 $\mathbf{E}_\mu$ 在这些状态基中的矩阵元为

$$F_\mu \mid \mathbf{M},\mathbf{m} - n\mathbf{r}_\mu\rangle = \sqrt{(m_\mu - n)(n+1)} \mid \mathbf{M},\mathbf{m} - (n+1)\mathbf{r}_\mu\rangle\,,$$

$$E_\mu \mid \mathbf{M},\mathbf{m} - (n+1)\mathbf{r}_\mu\rangle = \sqrt{(m_\mu - n)(n+1)} \mid \mathbf{M},\mathbf{m} - n\mathbf{r}_\mu\rangle\,.$$

要把各个不可约表示的正交归一的状态基找出来并且用夸克态来表达。

主权图分解：

$$
\begin{aligned}
(1,0)\times(1,0)\times(0,1) &\simeq [(1,0)\times(0,1)]\times(1,0)\\
&\simeq [(1,1)+(0,0)]\times(1,0)\,.
\end{aligned}
$$

$$
\begin{aligned}
(1,1)\times(1,0) &\simeq (2,1)+(0,2)+(1,0)\\
(0,0)\times(1,0) &\simeq (1,0).
\end{aligned}
$$

Charmed Baryon Weak Decays with SU(3) Flavor Symmetry

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Abstract

We study the semileptonic and non-leptonic charmed baryon decays with $SU(3)$ flavor symmetry, where the charmed baryons can be $\mathbf{B}_c = (\Xi_c^0, \Xi_c^+, \Lambda_c^+)$, $\mathbf{B}'_c = (\Sigma_c^{(++,+,0)}, \Xi_c^{\prime(+,0)}, \Omega_c^0)$, $\mathbf{B}_{cc} = (\Xi_{cc}^{++}, \Xi_{cc}^+, \Omega_{cc}^+)$, or $\mathbf{B}_{ccc} = \Omega_{ccc}^{++}$. With $\mathbf{B}_n^{(\prime)}$ denoted as the baryon octet (decuplet), we find that the $\mathbf{B}_c \to \mathbf{B}'_n \ell^+ \nu_\ell$ decays are forbidden, while the $\Omega_c^0 \to \Omega^- \ell^+ \nu_\ell$, $\Omega_{cc}^+ \to \Omega_c^0 \ell^+ \nu_\ell$, and $\Omega_{ccc}^{++} \to \Omega_{cc}^+ \ell^+ \nu_\ell$ decays are the only existing Cabibbo-allowed modes for $\mathbf{B}'_c \to \mathbf{B}'_n \ell^+ \nu_\ell$, $\mathbf{B}_{cc} \to \mathbf{B}'_c \ell^+ \nu_\ell$, and $\mathbf{B}_{ccc} \to \mathbf{B}_{cc}^{(\prime)} \ell^+ \nu_\ell$, respectively. We predict the rarely studied $\mathbf{B}_c \to \mathbf{B}_n^{(\prime)} M$ decays, such as $\mathcal{B}(\Xi_c^0 \to \Lambda^0 \bar{K}^0,\ \Xi_c^+ \to \Xi^0 \pi^+) = (8.3 \pm 0.9, 8.0 \pm 4.1) \times 10^{-3}$ and $\mathcal{B}(\Lambda_c^+ \to \Delta^{++} \pi^-,\ \Xi_c^0 \to \Omega^- K^+) = (5.5 \pm 1.3, 4.8 \pm 0.5) \times 10^{-3}$. For the observation, the doubly and triply charmed baryon decays of $\Omega_{cc}^+ \to \Xi_c^+ \bar{K}^0$, $\Xi_{cc}^{++} \to (\Xi_c^+ \pi^+,\ \Sigma_c^{++} \bar{K}^0)$, and $\Omega_{ccc}^{++} \to (\Xi_{cc}^{++} \bar{K}^0, \Omega_{cc}^+ \pi^+, \Xi_c^+ D^+)$ are the favored Cabibbo-allowed decays, which are accessible to the BESIII and LHCb experiments.

$$
\begin{aligned}
\frac{d\Gamma}{dq^2 d\cos\theta} \;=\;& \frac{\sqrt{\lambda} G_F^2 q^2}{1024\pi^3 m_I^3}\left(1-\frac{m_l^2}{q^2}\right)^2 \left((m_I+m_f)^2-q^2\right)|V_{\rm CKM}|^2 \\
&\times\Bigg\{(|H^{V,3/2}_{1,-1/2}|^2+|H^{A,3/2}_{1,-1/2}|^2+|H^{V,1/2}_{1,1/2}|^2+|H^{A,1/2}_{1,1/2}|^2)\left(1+\cos^2\theta+\frac{m_l^2}{q^2}\sin^2\theta\right) \\
&-4\cos\theta {\rm Re}[H^{V,3/2}_{1,-1/2}(H^{A,3/2}_{1,-1/2})^*+H^{V,1/2}_{1,1/2}(H^{A,1/2}_{1,1/2})^*] \\
&+(|H^{V,1/2}_{0,-1/2}|^2+|H^{A,1/2}_{0,-1/2}|^2)\left(2\sin^2\theta+\frac{2m_l^2}{q^2}\cos^2\theta\right)+(|H^{V,1/2}_{t,-1/2}|^2+|H^{A,1/2}_{t,-1/2}|^2)\frac{2m_l^2}{q^2} \\
&-4\cos\theta\frac{m_l^2}{q^2}\left({\rm Re}[H^{V,1/2}_{0,-1/2}(H^{V,1/2}_{t,-1/2})^*+H^{A,1/2}_{0,-1/2}(H^{A,1/2}_{t,-1/2})^*]\right)\Bigg\}.
\end{aligned}
$$

$$
\begin{aligned}
H^{V,3/2}_{1,-1/2} &= H^{V,-3/2}_{-1,1/2}=f_4, \quad H^{A,3/2}_{1,-1/2}=-H^{A,-3/2}_{-1,-1/2}=\frac{g_4\sqrt{\hat\lambda}}{\hat f_+}, \\
H^{V,1/2}_{0,-1/2} &= H^{V,-1/2}_{0,1/2}=-\frac{f_1(1+\hat m_f)\hat f_-}{\sqrt6(1-\hat m_f)\sqrt{\hat q^2}}-\frac{\hat\lambda f_2}{\sqrt6(1-\hat m_f^2)\sqrt{\hat q^2}}+\frac{f_3\hat f_-\sqrt{\hat q^2}}{\sqrt6}+\frac{f_4(1+\hat q^2-\hat m_f^2)}{\sqrt6\sqrt{\hat q^2}}, \\
H^{A,1/2}_{0,-1/2} &= -H^{A,-1/2}_{0,1/2}=\frac{g_1\hat\lambda(1-\hat m_f)}{\sqrt6(1+\hat m_f)\sqrt{\hat q^2}}-\frac{g_2\sqrt{\hat\lambda}\hat f_-}{\sqrt6(1-\hat m_f^2)\sqrt{\hat q^2}}+\frac{g_3\sqrt{\hat\lambda}\sqrt{\hat q^2}}{\sqrt6}+\frac{g_4\sqrt{\hat\lambda}(1+\hat q^2-\hat m_f^2)}{\sqrt6\hat f_+\sqrt{\hat q^2}}, \\
H^{V,1/2}_{t,-1/2} &= H^{V,-1/2}_{t,1/2}=-\frac{(f_1+f_2-f_4)\sqrt{\hat\lambda}}{\sqrt{6\hat q^2}}, \\
H^{A,1/2}_{t,-1/2} &= -H^{A,-1/2}_{t,1/2}=\frac{(g_1-g_2+g_4)\hat f_-}{\sqrt{6\hat q^2}}, \\
H^{V,1/2}_{1,1/2} &= H^{V,-1/2}_{-1,-1/2}=-\frac{f_1\hat f_-}{\sqrt3(1-\hat m_f)}+\frac{f_3(1+\hat m_f)\hat f_-}{\sqrt3}+\frac{f_4}{\sqrt3}, \\
H^{A,1/2}_{1,1/2} &= -H^{A,-1/2}_{-1,-1/2}=-\frac{g_1\sqrt{\hat\lambda}}{\sqrt3(1+\hat m_f)}-\frac{g_3\sqrt{\hat\lambda}(1-\hat m_f)}{\sqrt3}-\frac{f_4\sqrt{\hat\lambda}}{\sqrt3\hat f_+}.
\end{aligned}
$$

For the color-allowed decay channel, one may use the factorization approach to predict its decay widths. Using the form factors, we have the decay width:

$$\Gamma(\Omega_{ccc}^{++} \to \Omega_{cc}^{+}\pi^{+}) \;=\; \frac{\sqrt{\lambda}G_F^2}{64\pi m^3_{\Omega_{ccc}^{++}}}|V_{\rm cs}V_{ud}|^2 f_\pi^2 \left[|H_{t,-1/2}^{V,1/2}|^2 + |H_{t,-1/2}^{A,1/2}|^2\right], \tag{53}$$

where the H_is are helicity amplitudes:

$$H_{t,-1/2}^{V,1/2} \;=\; -\frac{(f_1+f_2-f_4)\sqrt{\hat{\lambda}}}{\sqrt{6\hat{m}_\pi^2}}, \quad H_{t,-1/2}^{A,1/2} = \frac{(g_1-g_2+g_4)\hat{f}_-}{\sqrt{6\hat{m}_\pi^2}}. \tag{54}$$

In the above equation, we used $\hat{m}_{\Omega_{cc}^+} = m_{\Omega_{cc}^+}/m_{\Omega_{ccc}^{++}}$, $\hat{m}_\pi = m_\pi/m_{\Omega_{ccc}^{++}}$, and the abbreviations

$$\begin{aligned}
\lambda \equiv \lambda(m^2_{\Omega_{ccc}^{++}}, m^2_{\Omega_{cc}^{+}}, m^2_\pi) = (m^2_{\Omega_{ccc}^{++}} - m^2_{\Omega_{cc}^{+}} - m^2_\pi)^2 - 4m^2_{\Omega_{cc}^{+}} m^2_\pi, \\
\hat{\lambda} \equiv \lambda(1, \hat{m}^2_{\Omega_{cc}^{+}}, \hat{m}^2_\pi) = (1 - \hat{m}^2_{\Omega_{cc}^{+}} - \hat{m}^2_\pi)^2 - 4\hat{m}^2_{\Omega_{cc}^{+}} \hat{m}^2_\pi, \\
\hat{f}_- = (1 - \hat{m}_{\Omega_{cc}^{+}})^2 - \hat{m}^2_\pi.
\end{aligned} \tag{55}$$

D. Charmless $b \to q_1 \bar{q}_2 q_3$ Decays

1. *Decays into a doubly bottom baryon bbq and a light meson*

The charmless $b \to q$ ($q = d, s$) transition is controlled by the weak Hamiltonian $\mathcal{H}_{eff}$:

$$\mathcal{H}_{e.w.} = \frac{G_F}{\sqrt{2}} \Big\{ V_{ub} V_{uq}^* \big[C_1 O_1^{\bar{u}u} + C_2 O_2^{\bar{u}u} \big] - V_{tb} V_{tq}^* \big[\sum_{i=3}^{10} C_i O_i \big] \Big\} + \text{h.c.}, \tag{74}$$

where O_i is a four-quark operator or a moment type operator. The four-quark operators O_i are given as follows:

$$\begin{aligned}
O_1^{\bar{u}u} &= (\bar{q}^i u^j)_{V-A} (\bar{u}^j b^i)_{V-A}, \quad O_2^{\bar{u}u} = (\bar{q}u)_{V-A} (\bar{u}b)_{V-A}, \\
O_3 &= (\bar{q}b)_{V-A} \sum_{q'} (\bar{q}' q')_{V-A}, \quad O_4 = (\bar{q}^i b^j)_{V-A} \sum_{q'} (\bar{q}'^j q'^i)_{V-A}, \\
O_5 &= (\bar{q}b)_{V-A} \sum_{q'} (\bar{q}' q')_{V+A}, \quad O_6 = (\bar{q}^i b^j)_{V-A} \sum_{q'} (\bar{q}'^j q'^i)_{V+A}, \\
O_7 &= \frac{3}{2} (\bar{q}b)_{V-A} \sum_{q'} e_{q'} (\bar{q}' q')_{V+A}, \quad O_8 = \frac{3}{2} (\bar{q}^i b^j)_{V-A} \sum_{q'} e_{q'} (\bar{q}'^j q'^i)_{V+A}, \\
O_9 &= \frac{3}{2} (\bar{q}b)_{V-A} \sum_{q'} e_{q'} (\bar{q}' q')_{V-A}, \quad O_{10} = \frac{3}{2} (\bar{q}^i b^j)_{V-A} \sum_{q'} e_{q'} (\bar{q}'^j q'^i)_{V-A}.
\end{aligned} \tag{75}$$

In the above the q denotes a d quark for the $b \to d$ transition or an s quark for the $b \to s$ transition, while $q' = u, d, s$. The V and A denotes the vector and axial-vector currents. In the SU(3) group, penguin operators behave as the **3** representation while tree operators can be decomposed in terms of a vector $H_{\mathbf{3}}$, a traceless tensor antisymmetric in upper indices, $H_{\overline{\mathbf{6}}}$, and a traceless tensor symmetric in upper indices, $H_{\mathbf{15}}$.

For the $\Delta S = 0(b \to d)$ decays, the non-zero components of the effective Hamiltonian are:

$$(H_3)^2 = 1, \quad (H_{\overline{6}})^{12}_1 = -(H_{\overline{6}})^{21}_1 = (H_{\overline{6}})^{23}_3 = -(H_{\overline{6}})^{32}_3 = 1,$$
$$2(H_{15})^{12}_1 = 2(H_{15})^{21}_1 = -3(H_{15})^{22}_2 = -6(H_{15})^{23}_3 = -6(H_{15})^{32}_3 = 6, \tag{76}$$

and all other remaining entries are zero. For the $\Delta S = 1(b \to s)$ decays the nonzero entries in the $H_{\mathbf{3}}$, $H_{\overline{\mathbf{6}}}$, $H_{\mathbf{15}}$ are obtained from Eq. (76) with the exchange $2 \leftrightarrow 3$.

Variational Study of Weakly Coupled Triply Heavy Baryons

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Abstract

Baryons made of three heavy quarks become weakly coupled, when all the quarks are sufficiently heavy such that the typical momentum transfer is much larger than $\Lambda_{\rm QCD}$. We use variational method to estimate masses of the lowest-lying *bcc*, *ccc*, *bbb* and *bbc* states by assuming they are Coulomb bound states. Our predictions for these states are systematically lower than those made long ago by Bjorken.

Covariant Light-Front Approach for B_c transition form factors

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In the covariant light-front quark model, we investigate the form factors of B_c decays into $D, D^*, D_s, D_s^*, \eta_c, J/\psi, B, B^*, B_s, B_s^*$ mesons. The form factors in the spacelike region are directly evaluated. To extrapolate the form factors to the physical region, we fit the form factors by adopting a suitable three-parameter form. At the maximally recoiling point, $b \to u, d, s$ transition form factors are smaller than $b \to c$ and $c \to d, s$ form factors, while the $b \to u, d, s, c$ form factors at the zero recoiling point are close to each other. In the fitting procedure, we find that parameters in $A_2^{B_c B^*}$ and $A_2^{B_c B_s^*}$ strongly depend on decay constants of B^* and B_s^* mesons. Fortunately, semileptonic and nonleptonic B_c decays are not sensitive to these two form factors. We also investigate branching fractions, polarizations of the semileptonic B_c decays. $B_c \to (\eta_c, J/\psi)l\nu$ and $B_c \to (B_s, B_s^*)l\nu$ decays have much larger branching fractions than $B_c \to (D, D^*, B, B^*)l\nu$. For the three kinds of $B_c \to Vl\nu$ decays, longitudinal contributions are comparable with the transverse contributions. These predictions will be tested on the ongoing and forthcoming hadron colliders.

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