Nonleptonic decays of baryons in covariant confined quark model

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Contents

Charmed baryons

- SU(3) (u,d,s): M. Gell-Mann, G.Zweig, 1964
- SU(4) (u,d,s,c):. B.J. Bjorken, S.L. Glashow (1964)
  S. L. Glashow, J. Iliopoulos, L. Maiani (GIM mechanism) (1970)
- Charmed baryons: A. De Rújula, H. Georgi, S.L. Glashow, 1975.
- **Numerous states with charm C=0 and C=1 was discovered.**
- **Three weakly decaying baryons with C=2 expected:**

$$\Xi_{cc}^{++} = ccu \quad \text{and} \quad \Xi_{cc}^{+} = ccd \qquad \text{isospin doublet}$$

$$\Omega_{cc}^{+} = ccs \qquad \text{isospin singlet}$$

- **Tremendous theoretical activities in describing doubly heavy baryon:**
  - Likhoded, Kiselev et al. (nonrelativistic potential model, nonrelativistic QCD SR)
  - Faustov, Galkin et al. (relativistic quark model)
  - Dhir, Sharma at al. (effective quark mass scheme)
  - Chang, Li et al. (non-relativistic harmonic oscillator model)
  - Karliner, Rosner et al. (masses in naive quark model)
  - Hernández, Nieves et al. (nonrelativistic quark model)
  - Aliev, Azizi et al. (QCD SR)
  - Ivanov, Körner, Lyubovitskij et al. (quark confinement model)
  - ...

Charmed baryons in SU(4): $4 \otimes 4 \otimes 4 = 20_S \oplus 20_M \oplus 20'_M \oplus 4_A$

15. Quark model **13**

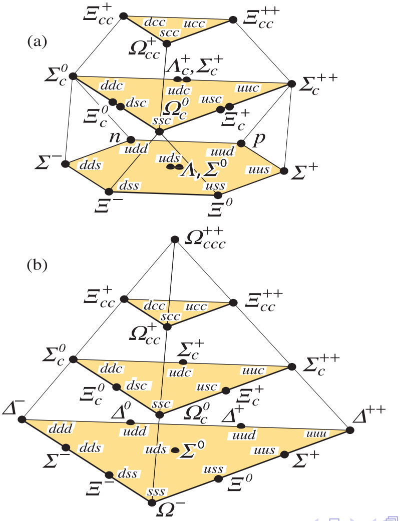


Figure 15.4: SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The

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

LHCb collaboration reported:

- Observation of the Ξ_{cc}^{++} in the $\Lambda_c^+ K^- \pi^- \pi^+$ mass spectrum. The mass was found to be

$$M_{\Xi_{cc}^{++}} = 3621.40 \pm 0.78 \text{ MeV}$$

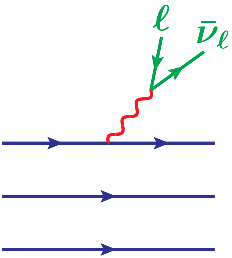
- Measurement of the lifetime:

$$\tau_{\Xi_{cc}^{++}} = 0.256 \pm 0.027 \text{ ps}$$

- Observation of the decay:

$$\Xi_{cc}^{++} \to \Xi_c^+ + \pi^+$$

Semileptonic decays of baryons

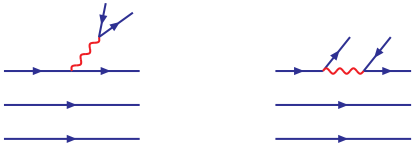


- Likhoded, Kiselev et al. (nonrelativistic potential model)
- Wang, Xing et al. (flavor SU(3) symmetry)
- Zhao (quark-diquark model)
- Albertus, Hernandez et al. (nonrelativistic quark model)
- Faustov, Galkin et al. (relativisti quark model)
- Shi, Wang et al. (QCD Sum Rule)
- Ivanov, Körner, Lyubovitskij et al. (quark confinement model)
- .

Nonleptonic two-body weak decays of baryons

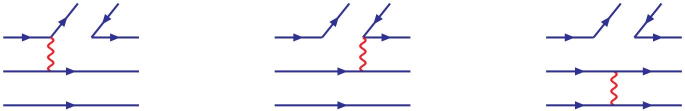
- Ground states of baryons with $J^P = \frac{1}{2}^+$ can decay only weakly via the internal W-exchange.
- The nonleptonic two-body decays of baryons have five different color-flavor quark topologies.
- They can be divided into two groups:
  - reducible tree-diagrams
  - irreducible W–exchange diagrams
- The tree-diagrams are factorized into the lepton decay of the emitted meson and the baryon-baryon transition matrix elements of the weak currents.
- W–exchange diagrams are more difficult to evaluate from first principles.
- First attempts to estimate the W–exchange contributions have been made by using a pole model approach.
- It was shown that W–exchange contributions are sizeable and cannot be neglected.

Topology of nonleptonic weak decays



Ia Ib

Tree diagrams



IIa IIb III

W-exchange diagrams

Classification of two-body nonleptonic decays

	I_a	I_b	II_a	II_b	III
$\Xi_{cc}^{++} \to \Sigma_c^{(*)\,++} + \bar{K}^{(*)\,0}$	-	$\surd$	—	—	—
$\Xi_{cc}^{++} \to \Xi_c^{(\prime,*)\,+} + \pi^+(\rho^+)$	$\surd$	—	—	$\surd$	—
$\Xi_{cc}^{++} \to \Sigma^{(*)\,+} + D^{(*)+}$	—	—	—	$\surd$	—
$\Xi_{cc}^{+} \to \Xi_c^{(\prime,*)\,0} + \pi^+(\rho^+)$	$\surd$	—	$\surd$	—	—
$\Xi_{cc}^{+} \to \Lambda_c^+(\Sigma_c^{(*)+}) + \bar{K}^{(*)0}$	—	$\surd$	$\surd$	—	—
$\Xi_{cc}^{+} \to \Sigma_c^{(*)++} + K^{(*)-}$	—	—	$\surd$	—	—
$\Xi_{cc}^{+} \to \Xi_c^{(\prime,*)\,+} + \pi^0(\rho^0)$	—	—	$\surd$	$\surd$	—
$\Xi_{cc}^{+} \to \Xi_c^{(\prime,*)\,+} + \eta(\eta')$	—	—	$\surd$	$\surd$	—
$\Xi_{cc}^{+} \to \Omega_c^{(*)\,0} + K^{(*)\,+}$	—	—	$\surd$	—	—
$\Xi_{cc}^{+} \to \Lambda^0(\Sigma^{(*)0}) + D^{(*)+}$	—	—	—	$\surd$	$\surd$
$\Xi_{cc}^{+} \to \Sigma^{(*)+} + D^{(*)0}$	—	—	—	—	$\surd$
$\Xi_{cc}^{+} \to \Xi^{(*)0} + D_s^{(*)+}$	—	—	—	—	$\surd$
$\Omega_{cc}^{+} \to \Xi_c^{(\prime,*)\,+} + \bar{K}^{(*)0}$	—	$\surd$	—	$\surd$	—
$\Omega_{cc}^{+} \to \Xi^{(*)\,0} + D^{(*)+}$	—	—	—	$\surd$	—
$\Omega_{cc}^{+} \to \Omega_c^{(*)\,0} + \pi^+(\rho^+)$	$\surd$	—	—	—	—

Tree-diagrams

There are two classes of tree-diagram decays

- The first class of decays is solely contributed to by the two topologies Ia and Ib.

$$B_1(q_1\, q_2\, q_3) \to B_2(q_1'\, q_2'\, q_3') + M(q_m \bar{q}_{\bar{n}})\,.$$

  A necessary condition for the contribution of the factorizing class of decays is that a quark pair $q_i q_j = q_i' q_j'$ is shared by the parent and daughter baryon B_1 and B_2, respectively. A sufficient condition for the factorizing class of decays is that (i) q_m is not among q_1, q_2, q_3 and (ii) $q_{\bar{n}}$ is not among q_1', q_2', q_3'.

$$\Xi_{cc}^{++} \to \Sigma_c^{(*)++} + \bar{K}^{(*)0} \qquad\qquad \Omega_{cc}^{+} \to \Omega_c^{(*)0} + \pi^+(\rho^+)$$

  which proceed via the tree graphs alone.

- The second class of decays involves in addition to the tree topologies also the W–exchange topologies IIb which do not contribute because of the Körner, Pati, and Woo (KPW) theorem. There are two groups of decays that belong to this class given by

$$\Xi_{cc}^{++} \to \Xi_c'^{(*)+} + \pi^+(\rho^+) \qquad\qquad \Omega_{cc}^{+} \to \Xi_c'^{(*)+} + \bar{K}^{(*)0}$$

Nonleptonic double charmed baryon decays

We will consider the decays that belong to the same topology class:

$$\Xi_{cc}^{++} \to \Xi_c^{+}\,(\Xi_c^{\prime +}) + \pi^{+}(\rho^{+}) \qquad \text{T-Ia and W-IIb}$$

$$\Omega_{cc}^{+} \to \Xi_c^{+}\,(\Xi_c^{\prime +}) + \bar{K}^{0}(K^{*\,0}) \qquad \text{T-Ib and W-IIb}$$

Quantum numbers and interpolating currents:

Baryon	J^P	Interpolating current	Mass (MeV)
Ξ_{cc}^{++}	$\frac{1}{2}^{+}$	$\varepsilon_{abc}\,\gamma^{\mu}\gamma_5\,u^a(c^b C\gamma_\mu c^c)$	3620.6
Ω_{cc}^{+}	$\frac{1}{2}^{+}$	$\varepsilon_{abc}\,\gamma^{\mu}\gamma_5\,s^a(c^b C\gamma_\mu c^c)$	3710.0
$\Xi_c^{\prime +}$	$\frac{1}{2}^{+}$	$\varepsilon_{abc}\,\gamma^{\mu}\gamma_5\,c^a(u^b C\gamma_\mu s^c)$	2577.4
Ξ_c^{+}	$\frac{1}{2}^{+}$	$\varepsilon_{abc}\,c^a(u^b C\gamma_5 s^c)$	2467.9

Körner-Pati-Woo (KPW) theorem

J.G. Körner, Nucl. Phys. B25, 282 (1971); J.C. Pati and C.H. Woo, Phys. Rev. D3, 2920 (1971)

The W–exchange contributions to the above decays fall into two classes:

- The decays with a $\Xi_c^{\prime +}$-baryon containing a symmetric $\{us\}$ diquark described by the interpolating current $\varepsilon_{abc}\,(u^b C \gamma_\mu s^c)$.
- The W–exchange contribution is strongly suppressed due to the KPW theorem which states that the contraction of the flavor antisymmetric current-current operator with a flavor symmetric final state configuration is zero in the $SU(3)$ limit.
- The decays with a Ξ_c^{+}-baryon containing an antisymmetric $[us]$ diquark described by the interpolating current $\varepsilon_{abc}\,(u^b C \gamma_5 s^c)$.
- In this case the W–exchange contribution is not a priori suppressed.

Effective Hamiltonian and nonlocal quark currents

The effective Hamiltonian describing the $\bar{s}c \to \bar{u}d$ transition is given by

$$\mathcal{H}_{\rm eff} = -\frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^\dagger \, (C_1 \, \mathcal{Q}_1 + C_2 \, \mathcal{Q}_2)$$

$$\mathcal{Q}_1 = (\bar{s}_a O_L c_b)(\bar{u}_b O_L d_a) \qquad \mathcal{Q}_2 = (\bar{s}_a O_L c_a)(\bar{u}_b O_L d_b)$$

The notation is $O^\mu_{L/R} = \gamma^\mu(1 \mp \gamma_5)$.

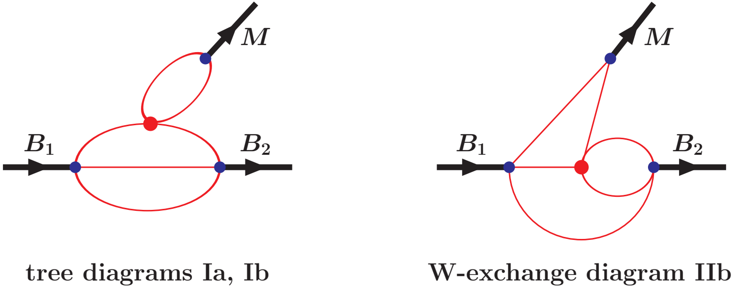
The nonlocal version of the interpolating currents:

$$J_B(x) = \int dx_1 \int dx_2 \int dx_3 \, F_B(x; x_1, x_2, x_3) \, \varepsilon^{a_1 a_2 a_3} \Gamma_1 q_1^{a_1}(x_1) \left(q_2^{a_2}(x_2) C \Gamma_2 q_3^{a_3}(x_3)\right)$$

$$F_B = \delta^{(4)}\Big(x - \sum_{i=1}^{3} w_i x_i\Big) \Phi_B\Big(\sum_{i<j} (x_i - x_j)^2\Big)$$

where $w_i = m_i/(\sum_{j=1}^{3} m_j)$ and m_i is the quark mass. Γ_1, Γ_2 are the Dirac strings of the initial and final baryons.

Matrix elements



$$< B_2\, M | \mathcal{H}_{\rm eff} | B_1 >= \frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^\dagger\, \bar{u}(p_2) \Big(12\, C_T\, M_T + 12\, (C_1 - C_2)\, M_W \Big) u(p_1).$$

$$C_T = \begin{cases} C_T = +(C_2 + \xi C_1) & \text{charged meson} \\ C_T = -(C_1 + \xi C_2) & \text{neutral meson} \end{cases}$$

The factor of $\xi = 1/N_c$ is set to zero in the numerical calculations.

Tree-diagram contribution: factorization

The contribution from the tree diagram factorizes into two pieces:

$$M_T = M_T^{(1)} \cdot M_T^{(2)}$$

$$M_T^{(1)} = N_c\, g_M \int \frac{d^4 k}{(2\pi)^4 i} \widetilde{\Phi}_M(-k^2)\, \mathrm{tr}\left[O_L S_d(k - w_d q)\Gamma_M S_{s(u)}(k + w_{s(u)} q)\right]$$

$$M_T^{(2)} = g_{B_1} g_{B_2} \int \frac{d^4 k_1}{(2\pi)^4 i} \int \frac{d^4 k_2}{(2\pi)^4 i} \widetilde{\Phi}_{B_1}\left(-\vec{\Omega}_1^{\,2}\right)\widetilde{\Phi}_{B_2}\left(-\vec{\Omega}_2^{\,2}\right)$$
$$\times \quad \Gamma_1 S_c(k_2)\gamma^\mu S_c(k_1 - p_1) O_R S_{u(s)}(k_1 - p_2)\widetilde{\Gamma}_2 S_{s(u)}(k_1 - k_2)\gamma_\mu \gamma_5$$

The $M_T^{(1)}$ is related to the leptonic decay constants:

$$M_T^{(1)} = \begin{cases} -f_P \cdot q & \text{pseudoscalar meson} \\ +f_V m_V \cdot \epsilon_V & \text{vector meson} \end{cases}$$

W-exchange diagram contribution: no factorization

$$
\begin{aligned}
M_W &= g_{B_1} g_{B_2} g_M \int \frac{d^4 k_1}{(2\pi)^4 i} \int \frac{d^4 k_2}{(2\pi)^4 i} \int \frac{d^4 k_3}{(2\pi)^4 i} \widetilde{\Phi}_{B_1}\Big(-\vec{\Omega}_1^{\,2}\Big) \widetilde{\Phi}_{B_2}\Big(-\vec{\Omega}_2^{\,2}\Big) \widetilde{\Phi}_M(-P^2) \\
&\times \; 2\Gamma_1 S_c(k_1)\gamma^\mu S_c(k_2)(1-\gamma_5) S_d(k_2-k_1+p_2)\Gamma_M S_{s(u)}(k_2-k_1+p_1)\gamma_\mu\gamma_5 \\
&\times \; \mathrm{tr}\Big[S_{u(s)}(k_3)\widetilde{\Gamma}_2 S_{s(u)}(k_3-k_1+p_2)(1+\gamma_5)\Big]
\end{aligned}
$$

Here $\Gamma_1 \otimes \widetilde{\Gamma}_2 = I \otimes \gamma_5$ for $B_2 = \Xi_c^+$ and $-\gamma_\nu\gamma_5 \otimes \gamma^\nu$ for $B_2 = \Xi_c^{\prime\,+}$.

To verify the KPW theorem in the case of $B_2 = \Xi_c^{\prime\,+}$ we use the identity

$$
\mathrm{tr}\Big[S_u(k_3)\gamma_\nu S_s(k_3-k_1+p_2)\Big] = -\,\mathrm{tr}\Big[S_s(-k_3+k_1-p_2)\gamma_\nu S_u(-k_3)\Big]
$$

Then by shifting $k_3 \to -k_3 + k_1 - p_2$ one gets the same expression with opposite sign and $u \leftrightarrow s$ interchange. Thus, if $m_u = m_s$ then $M_W \equiv 0$.

It directly confirms the KPW–theorem.

Invariant and helicity amplitudes

The transition amplitudes in terms of invariant amplitudes:

$$< B_2\, P|\mathcal{H}_{\rm eff}|B_1 > \;=\; \frac{G_F}{\sqrt{2}} V_{cs} V^\dagger_{ud}\; \bar{u}(p_2)\,(A + \gamma_5\, B)\, u(p_1)$$

$$< B_2\, V|\mathcal{H}_{\rm eff}|B_1 > \;=\; \frac{G_F}{\sqrt{2}} V_{cs} V^\dagger_{ud}$$

$$\times\;\; \bar{u}(p_2)\, \epsilon^{*}_{V\delta} \left(\gamma^\delta V_\gamma + p_1^\delta V_p + \gamma_5\gamma^\delta V_{5\gamma} + \gamma_5 p_1^\delta\, V_{5p}\right) u(p_1)$$

The helicity amplitudes in terms of invariant amplitudes:

$$H^V_{\frac{1}{2}\,t} = \sqrt{Q_+}\, A \qquad H^A_{\frac{1}{2}\,t} = \sqrt{Q_-}\, B$$

$$H^V_{\frac{1}{2}\,0} = +\sqrt{Q_-/q^2}\left(m_+\, V_\gamma + \tfrac{1}{2} Q_+\, V_p\right) \qquad H^V_{\frac{1}{2}\,1} = -\sqrt{2Q_-}\, V_\gamma$$

$$H^A_{\frac{1}{2}\,0} = +\sqrt{Q_+/q^2}\left(m_-\, V_{5\gamma} + \tfrac{1}{2} Q_-\, V_{5p}\right) \qquad H^A_{\frac{1}{2}\,1} = -\sqrt{2Q_+}\, V_{5\gamma}$$

Here $m_\pm = m_1 \pm m_2$, $Q_\pm = m_\pm^2 - q^2$ **and** $|\mathbf{p}_2| = \lambda^{1/2}(m_1^2, m_2^2, q^2)/(2m_1)$.

The parity relations: $H^V_{-\lambda_2,-\lambda_M} = +H^V_{\lambda_2,\lambda_M}\,,\; H^A_{-\lambda_2,-\lambda_M} = -H^A_{\lambda_2,\lambda_M}$

Decay widths

The semileptonic decay widths read

$$\Gamma(B_1 \to B_2 + \ell^+ \nu_\ell) = \int_0^{(M_1-M_2)^2} dq^2 \, \frac{d\,\Gamma(B_1 \to B_2 + \ell^+ \nu_\ell)}{dq^2},$$

$$\frac{d\,\Gamma(B_1 \to B_2 + \ell^+ \nu_\ell)}{dq^2} = \frac{1}{192\pi} G_F^2 \frac{|\mathrm{p}_2| q^2}{M_1^2} |V_{ij}|^2 \mathcal{H}_V \, .$$

The two-body decay widths read

$$\Gamma\Big(B_1 \to B_2 + P(V)\Big) = \frac{G_F^2}{32\pi} |V_{cs} V_{ud}^\dagger|^2 \frac{|\mathrm{p}_2|}{m_1^2} \mathcal{H}_{P(V)}$$

$$\mathcal{H}_P = \Big|H_{\frac{1}{2}\,t}\Big|^2 + \Big|H_{-\frac{1}{2}\,t}\Big|^2,$$

$$\mathcal{H}_V = \Big|H_{\frac{1}{2}\,0}\Big|^2 + \Big|H_{-\frac{1}{2}\,0}\Big|^2 + \Big|H_{\frac{1}{2}\,1}\Big|^2 + \Big|H_{-\frac{1}{2}\,-1}\Big|^2,$$

where $H = H^V - H^A$.

Semileptonic decays

Cabibbo-favored semileptonic decays of double heavy charm baryons induced by the charm level $c \to s$ transition ($\ell = e^+,\ \mu^+$).

	Γ $[10^{-13}$ ГэВ]	Γ $[10^{-13}$ ГэВ]	B [%]
$1/2^+ \to 1/2^+$			
$\Xi_{cc}^{++} \to \Xi_c^+ + \ell^+\nu_\ell$	0.70	0.77 ± 0.37 [1]	2.72
$\Xi_{cc}^{++} \to \Xi_c^{\prime +} + \ell^+\nu_\ell$	0.97	0.53 ± 0.35 [1]	3.76
$\Xi_{cc}^{+} \to \Xi_c^0 + \ell^+\nu_\ell$	0.69	0.77 ± 0.37 [1]	2.00
$\Xi_{cc}^{+} \to \Xi_c^{\prime 0} + \ell^+\nu_\ell$	0.97	0.53 ± 0.35 [1]	2.79
$\Omega_{cc}^{+} \to \Omega_c^0 + \ell^+\nu_\ell$	1.82	1.25 ± 0.80 [1]	7.07
$1/2^+ \to 3/2^+$			
$\Xi_{cc}^{++} \to \Xi_c^{*+} + \ell^+\nu_\ell$	0.22	—	0.86
$\Xi_{cc}^{+} \to \Xi_c^{*0} + \ell^+\nu_\ell$	0.22	—	0.64
$\Omega_{cc}^{+} \to \Omega_c^{*0} + \ell^+\nu_\ell$	0.40	0.32 [2]	1.27

[1] Y. J. Shi, W. Wang and Z. X. Zhao, Eur. Phys. J. C 80, no.6, 568 (2020).

[2] Z. X. Zhao, Eur. Phys. J. C 78, no.9, 756 (2018).

Tree-diagrams $1/2^+ \to 1/2^+ + 0^-$

	Γ [10^{-13} GeV]	$\mathcal{B}$ [%]	P_{B_2}
$\Xi_{cc}^{++} \to \Sigma_c^{++} + \bar{K}^0$	0.32	1.25	-0.96
$\Xi_{cc}^{++} \to \Xi_c^{\prime +} + \pi^+$	0.78	3.03	-0.94
$\Omega_{cc}^{+} \to \Xi_c^{\prime +} + \bar{K}^0$	0.17	0.54	-0.97
$\Omega_{cc}^{+} \to \Omega_c^0 + +\pi^+$	1.58	5.05	-0.94

Tree-diagrams $1/2^+ \to 1/2^+ + 1^-$

	Γ [10^{-13} GeV]	$\mathcal{B}$ [%]	$\mathcal{F}_L$	$\mathcal{F}_T$	P_{B_2}
$\Xi_{cc}^{++} \to \Sigma_c^{++} + \bar{K}^{*0}$	1.44	5.61	0.47	0.53	-0.82
$\Xi_{cc}^{++} \to \Xi_c'^{+} + \rho^+$	4.14	16.10	0.49	0.51	-0.74
$\Omega_{cc}^{+} \to \Xi_c'^{+} + \bar{K}^{*0}$	0.75	2.39	0.45	0.55	-0.79
$\Omega_{cc}^{+} \to \Omega_c^{0} + \rho^+$	8.29	26.44	0.48	0.52	-0.71

Tree-diagrams $1/2^+ \to 3/2^+ + 0^-$

$1/2^+ \to 3/2^+ + 0^-$	Γ [10^{-13} GeV]	Γ [10^{-13} GeV]	B [%]
$\Xi_{cc}^{++} \to \Sigma_c^{*++} + \bar{K}^0$	0.06		0.25
$\Xi_{cc}^{++} \to \Xi_c^{*+} + \pi^+$	0.16		0.63
$\Omega_{cc}^{+} \to \Xi_c^{*\,+} + \bar{K}^0$	0.03		0.10
$\Omega_{cc}^{+} \to \Omega_c^{*0} + \pi^+$	0.31	0.43 [2]	1.00

Tree-diagrams $1/2^+ \to 3/2^+ + 1^-$

$1/2^+ \to 3/2^+ + 1^-$	Γ [10^{-13} GeV]	Γ [10^{-13} GeV]	B [%]
$\Xi_{cc}^{++} \to \Sigma_c^{*++} + \bar{K}^{*0}$	0.42		1.62
$\Xi_{cc}^{++} \to \Xi_c^{*\,\prime +} + \rho^+$	1.15	0.485 [2]	4.48
$\Omega_{cc}^{+} \to \Xi_c^{*\,\prime +} + \bar{K}^{*0}$	0.21		0.67
$\Omega_{cc}^{+} \to \Omega_c^{*0} + \rho^+$	2.23	0.99 [2]	7.11

Tree-diagrams $1/2^+ \to 3/2^+ + 1^-$

$1/2^+ \to 3/2^+ + 1^-$	F_L^P	F_T^P	$F_T^{\prime P}$
$\Xi_{cc}^{++} \to \Sigma_c^{*++} + \bar{K}^{*0}$	-0.01	-0.10	-0.31
$\Xi_{cc}^{++} \to \Xi_c^{*\prime +} + \rho^+$	-0.01	-0.08	-0.24
$\Omega_{cc}^{+} \to \Xi_c^{*\prime +} + \bar{K}^{*0}$	-0.01	-0.10	-0.30
$\Omega_{cc}^{+} \to \Omega_c^{*0} + \rho^+$	-0.01	-0.08	-0.24

$\Omega_{cc}^{+} \to \Xi_c'^{+} + \bar{K}^0(\bar{K}^{*0})$

Helicity	Tree diagram	W diagram	total
$H^V_{\frac{1}{2}\,t}$	0.20	−0.01	0.19
$H^A_{\frac{1}{2}\,t}$	0.25	−0.01	0.24
$\Gamma(\Omega_{cc}^{+} \to \Xi_c'^{+} + \bar{K}^0) = 0.15 \cdot 10^{-13}$ GeV			
$H^V_{\frac{1}{2}\,0}$	−0.25	0.04×10^{-1}	−0.25
$H^A_{\frac{1}{2}\,0}$	−0.50	0.01	−0.49
$H^V_{\frac{1}{2}\,1}$	0.27	−0.01	0.26
$H^A_{\frac{1}{2}\,1}$	0.56	0.04×10^{-2}	0.56
$\Gamma(\Omega_{cc}^{+} \to \Xi_c'^{+} + \bar{K}^{*0}) = 0.74 \cdot 10^{-13}$ GeV			

$\Omega_{cc}^{+} \to \Xi_{c}^{+} + \bar{K}^{0}(\bar{K}^{*\,0})$

Helicity	Tree diagram	W diagram	total
$H^{V}_{\frac{1}{2}\,t}$	-0.35	1.06	0.71
$H^{A}_{\frac{1}{2}\,t}$	-0.10	0.31	0.21
$\Gamma(\Omega_{cc}^{+} \to \Xi_{c}^{+} + \bar{K}^{0}) = 0.95 \cdot 10^{-13}$ GeV			
$H^{V}_{\frac{1}{2}\,0}$	0.50	-0.69	-0.19
$H^{A}_{\frac{1}{2}\,0}$	0.18	-0.45	-0.27
$H^{V}_{\frac{1}{2}\,1}$	-0.11	-0.24	-0.35
$H^{A}_{\frac{1}{2}\,1}$	-0.18	0.66	0.48
$\Gamma(\Omega_{cc}^{+} \to \Xi_{c}^{+} + \bar{K}^{*\,0}) = 0.62 \cdot 10^{-13}$ GeV			

$$\Xi_{cc}^{++} \to \Xi_c'^{+} + \pi^+(\rho^+)$$

Helicity	Tree diagram	W diagram	total
$H^V_{\frac{1}{2}t}$	-0.38	-0.01	-0.39
$H^A_{\frac{1}{2}t}$	-0.55	-0.02	-0.57
$\Gamma(\Xi_{cc}^{++} \to \Xi_c'^{+} + \pi^+) = 0.82 \cdot 10^{-13}$ GeV			
$H^V_{\frac{1}{2}0}$	0.60	0.04×10^{-1}	0.61
$H^A_{\frac{1}{2}0}$	1.20	0.01	1.21
$H^V_{\frac{1}{2}1}$	-0.49	-0.01	-0.50
$H^A_{\frac{1}{2}1}$	-1.27	0.01×10^{-1}	-1.27
$\Gamma(\Xi_{cc}^{++} \to \Xi_c'^{+} + \rho^+) = 4.27 \cdot 10^{-13}$ GeV			

$$\Xi_{cc}^{++} \to \Xi_c^{+} + \pi^{+}(\rho^{+})$$

Helicity	Tree diagram	W diagram	total
$H^V_{\frac{1}{2}\,t}$	-0.70	0.99	0.29
$H^A_{\frac{1}{2}\,t}$	-0.21	0.30	0.09
$\Gamma(\Xi_{cc}^{++} \to \Xi_c^{+} + \pi^{+}) = 0.18 \cdot 10^{-13}$ GeV			
$H^V_{\frac{1}{2}\,0}$	1.17	-0.70	0.47
$H^A_{\frac{1}{2}\,0}$	0.45	-0.44	0.003
$H^V_{\frac{1}{2}\,1}$	-0.20	-0.23	-0.43
$H^A_{\frac{1}{2}\,1}$	-0.41	0.62	0.21
$\Gamma(\Xi_{cc}^{++} \to \Xi_c^{+} + \rho^{+}) = 0.63 \cdot 10^{-13}$ GeV			

Comparison with other approaches. Abbr.: M=NRQM, T=HQET

Mode	Width (in 10^{-13} GeV)					
	our	Dhir	Jiang	Wang	Yu	Likhoded
$\Omega_{cc}^{+} \to \Xi_c^{\prime +} + \bar{K}^0$	0.15	0.31 (M) 0.59 (T)				
$\Omega_{cc}^{+} \to \Xi_c^{+} + \bar{K}^0$	0.95	0.68 (M) 1.08 (T)				
$\Omega_{cc}^{+} \to \Xi_c^{\prime +} + \bar{K}^{*\,0}$	0.74		$2.64^{+2.72}_{-1.79}$			
$\Omega_{cc}^{+} \to \Xi_c^{+} + \bar{K}^{*\,0}$	0.62		$1.38^{+1.49}_{-0.95}$			
$\Xi_{cc}^{++} \to \Xi_c^{\prime +} + \pi^+$	0.82	1.40 (M) 1.93 (T)		1.10		
$\Xi_{cc}^{++} \to \Xi_c^{+} + \pi^+$	0.18	1.71 (M) 2.39 (T)		1.57	1.58	2.25
$\Xi_{cc}^{++} \to \Xi_c^{\prime +} + \rho^+$	4.27		$4.25^{+0.32}_{-0.19}$	4.12	3.82	
$\Xi_{cc}^{++} \to \Xi_c^{+} + \rho^+$	0.63		$4.11^{+1.37}_{-0.86}$	3.03	2.76	6.70

References

- N. Sharma and R. Dhir, Phys. Rev. D 96, 113006 (2017).
- R. Dhir and N. Sharma, Eur. Phys. J. C 78, 743 (2018).
- L. J. Jiang, B. He and R. H. Li, Eur. Phys. J. C 78, 961 (2018).
- W. Wang, F. S. Yu and Z. X. Zhao, Eur. Phys. J. C 77, 781 (2017).
- F. S. Yu, H. Y. Jiang, R. H. Li, C. D. Lü, W. Wang and Z. X. Zhao, Chin. Phys. C 42, 051001 (2018).
- V. V. Kiselev and A. K. Likhoded, Phys. Usp. 45, 455 (2002) [Usp. Fiz. Nauk 172, 497 (2002)].
- A. V. Berezhnoy, A. K. Likhoded and A. V. Luchinsky, Phys. Rev. D 98, 113004 (2018).

Estimating uncertainties in the decay widths

- The only free parameter in our approach is the size parameter Λ_{cc}.
- We have chosen $\Lambda_{cc} = \Lambda_c = 0.8675$ GeV.
- To estimate the uncertaintity caused by the choice of the size parameter we allow the size parameter to vary from 0.6 to 1.135 GeV.
- We evaluate the mean $\bar{\Gamma} = \sum \Gamma_i / N$ and the mean square deviation $\sigma^2 = \sum (\Gamma_i - \bar{\Gamma})^2 / N$.
- The rate errors amount to $6 - 15\%$.

Mode	Width (in 10^{-13} GeV)
$\Omega_{cc}^+ \to \Xi_c'^+ + \bar{K}^0$	0.14 ± 0.01
$\Omega_{cc}^+ \to \Xi_c'^+ + \bar{K}^{*\,0}$	0.72 ± 0.06
$\Omega_{cc}^+ \to \Xi_c^+ + \bar{K}^0$	0.87 ± 0.13
$\Omega_{cc}^+ \to \Xi_c^+ + \bar{K}^{*\,0}$	0.58 ± 0.07
$\Xi_{cc}^{++} \to \Xi_c'^+ + \pi^+$	0.77 ± 0.05
$\Xi_{cc}^{++} \to \Xi_c'^+ + \rho^+$	4.08 ± 0.29
$\Xi_{cc}^{++} \to \Xi_c^+ + \pi^+$	0.16 ± 0.02
$\Xi_{cc}^{++} \to \Xi_c^+ + \rho^+$	0.59 ± 0.04

Λ-hyperon

- Mass of Λ-hyperon $m_\Lambda = 1.115683 \pm 0.000006$ **GeV**.
- Mean life of Λ-hyperon $\tau_\Lambda = 2.632 \pm 0.020 \cdot 10^{-10}$ s.
- Modes

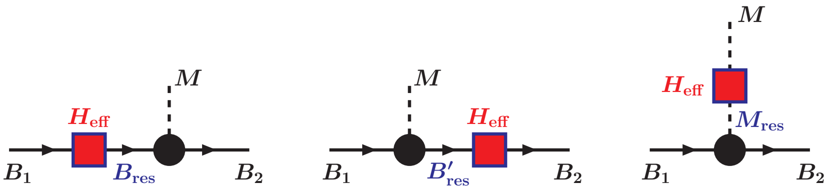
$$Br(\Lambda \to p\pi^-) = (63.9 \pm 0.5)\%,$$
$$Br(\Lambda \to n\pi^0) = (35.8 \pm 0.5)\%$$

.

- Approaches and authors:
  - Sakurai, Balachandran, Nussinov et al.(vector-meson dominance and current algebra)
  - Nakagawa, Trofimenkoff et al. (nonrelativistic model)
  - Shifman, Vainshtein et al. (effective field theory)
  - Nardulli et al.(pole model)
  - Wu, Rosner et al. (constituent quarks model)
  - Donoghue, Praszalowicz et al. (Skyrme model)
  - Galic, Tadic (MIT bag model)
  - ...

There are two classes of the Feynman diagrams generating matrix elements of these processes:

- short-distance (SD) diagrams,
- long-distance (LD) or pole diagrams.



Matrix element

Matrix element of $\frac{1}{2}^+ \to \frac{1}{2}^+ + 0^-$ decay reads

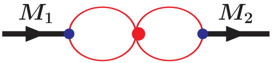
$$
\begin{aligned}
M(B_1 \to B_2 + M) &= M_{\rm SD}(B_1 \to B_2 + M) \\
&+ M_{\rm LD_1}(B_1 \to B_{\rm res} \to B_2 + M) + M_{\rm LD_2}(B_1 \to B'_{\rm res} + M \to B_2 + M)\,,
\end{aligned}
$$

$$
\begin{aligned}
M_{\rm SD} &= i^4\, \bar u(p_2)\, \Gamma_{B_1 B_2 M}(p_1, p_2, q)\, u(p_1)\,,\\
M_{\rm LD_1} &= i^6 \int \frac{d^4k}{(2\pi)^4 i}\, \bar u(p_2)\, \Gamma_{B_{\rm res} M B_2}(k, p_2, q)\, S_{B_{\rm res}}(k)\, \Gamma_{B_1 B_{\rm res}}(p_1, k)\, u(p_1)\,,\\
M_{\rm LD_2} &= i^6 \int \frac{d^4k}{(2\pi)^4 i}\, \bar u(p_2)\, \Gamma_{B_{\rm res} B_2}(k, p_2)\, S_{B_{\rm res}}(k)\, \Gamma_{B_1 M B_{\rm res}}(p_1, k, q)\, u(p_1)\,,
\end{aligned}
$$

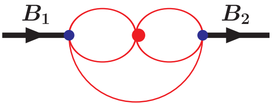
The propagator of the $\frac{1}{2}^+$ resonances is the ordinary Dirac propagator,

$$
S(p) = \frac{1}{m_{\rm res} - \not{p}} = \frac{m_{\rm res} + \not{p}}{m^2_{\rm res} - p^2}\,.
$$

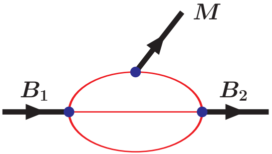
Feynman diagrams



Слабый M_1-M_2 переход



Слабый B_1-B_2 переход

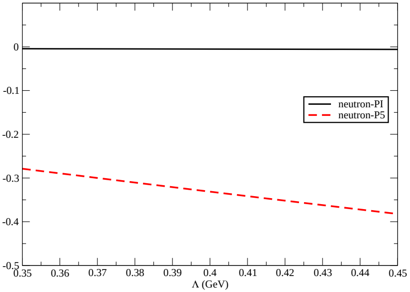


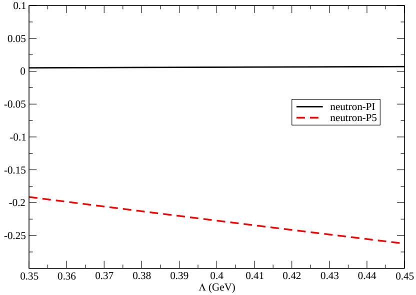
Сильный $B_1 B_2 M$ переход

The invariant matrix elements for the pole diagrams with intermediate $\frac{1}{2}^+$ resonances

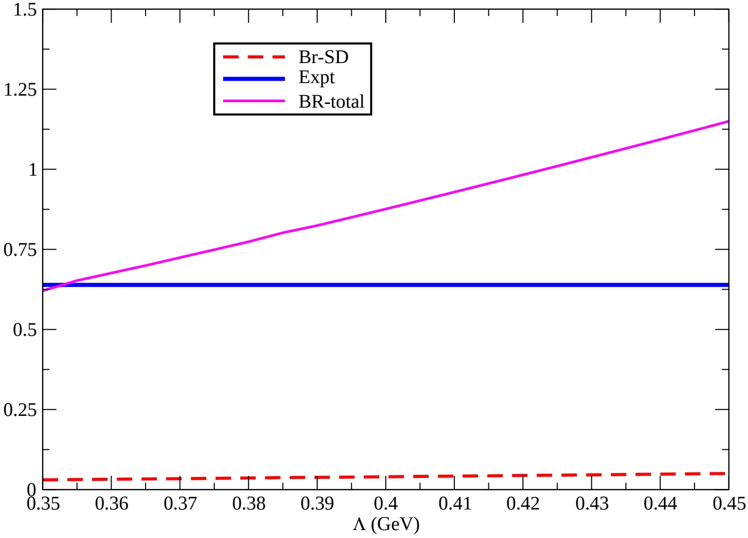
$$
\begin{aligned}
\widetilde{M}_{\mathrm{LD}_1} &\equiv \widetilde{M}_n = \bar{u}(p_2)\left(A_n + \gamma_5 B_n\right)u(p_1)\,, \\
A_n &= -\frac{B_{\Lambda n}(C_{n\pi p} - m_\Lambda D_{n\pi p})}{m_n + m_\Lambda}\,, \qquad B_n = -\frac{A_{\Lambda n}(C_{n\pi p} + m_\Lambda D_{n\pi p})}{m_n - m_\Lambda}\,, \\
\widetilde{M}_{\mathrm{LD}_2} &\equiv \widetilde{M}_\Sigma = \bar{u}(p_2)\left(A_\Sigma + \gamma_5 B_\Sigma\right)u(p_1)\,, \\
A_\Sigma &= -\frac{B_{\Sigma^+ p}(C_{\Lambda\pi\Sigma^+} - m_p D_{\Lambda\pi\Sigma^+})}{m_\Sigma + m_p}\,, \qquad B_\Sigma = -\frac{A_{\Sigma^+ p}(C_{\Lambda\pi\Sigma^+} + m_p D_{\Lambda\pi\Sigma^+})}{m_\Sigma - m_p}
\end{aligned} \tag{1}
$$

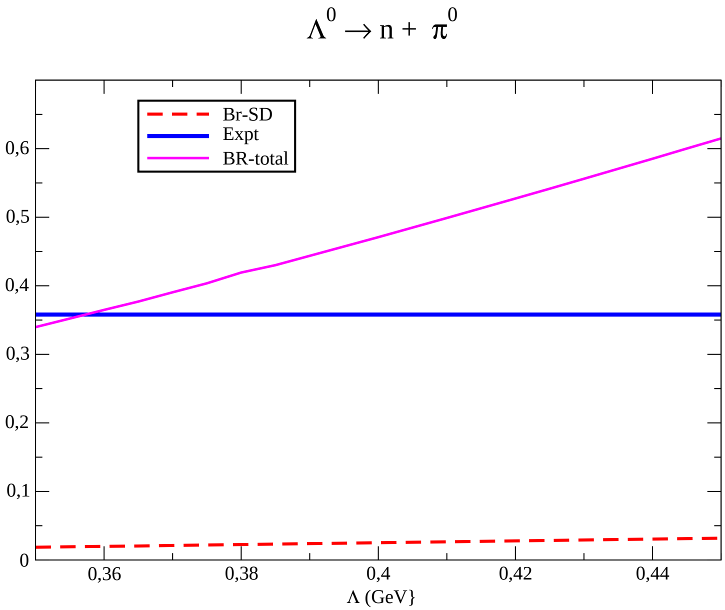
Dependence of the helicities $PI \equiv H^V_{1/2\,t}$ and $P5 \equiv H^A_{1/2\,t}$ on the size parameter in the case of the neutron resonance. Left panel: the decay $\Lambda \to p + \pi$; right panel: the decay $\Lambda \to n + \pi$.





$$\Lambda^0 \to p + \pi^-$$




$\Lambda^0 \to n + \pi^0$
Br-SD
Expt
BR-total
0
0,1
0,2
0,3
0,4
0,5
0,6
0,36
0,38
0,4
0,42
0,44
Λ (GeV}

$\Lambda \to p\pi^-$

SD contibutions to the amplitudes A and B of the decay $\Lambda \to p\pi^-$ in units of GeV^2.

	Ia	IIa	IIb	III	Sum(SD)
$A_{\rm SD}$	$-0.372 \cdot 10^{-1}$	$0.269 \cdot 10^{-3}$	$0.300 \cdot 10^{-1}$	$0.213 \cdot 10^{-1}$	$0.144 \cdot 10^{-1}$
$B_{\rm SD}$	-0.345	-0.116	0.167	-0.452	-0.746

LD contibutions to the amplitudes A and B of the decay $\Lambda \to p\pi^-$ in units of GeV^2.

	n	Σ^+	K	K^*	$\frac{1}{2}^-$	Sum(LD)
$A_{\rm LD}$	$-2.1 \cdot 10^{-3}$	$-9.5 \cdot 10^{-3}$	0	$2.6 \cdot 10^{-2}$	$0.9 \cdot 10^{-1}$	$1.1 \cdot 10^{-1}$
$B_{\rm LD}$	-2.55	$2.3 \cdot 10^{-1}$	$2.8 \cdot 10^{-2}$	0	0	-2.3

$\Lambda \to n\pi^0$

SD contibutions to the amplitudes A and B of the decay $\Lambda \to n\pi^0$ in units of GeV^2.

	Ib	IIa	IIb	III	Sum(SD)
$A_{\rm SD}$	$-0.120 \cdot 10^{-1}$	$0.190 \cdot 10^{-3}$	$0.211 \cdot 10^{-1}$	$0.150 \cdot 10^{-1}$	$0.243 \cdot 10^{-1}$
$B_{\rm SD}$	-0.112	$-0.82 \cdot 10^{-1}$	0.119	-0.319	-0.394

LD contibutions to the amplitudes A and B of the decay $\Lambda \to n\pi^0$ in units of GeV^2.

	n	Σ^0	K	K^*	$\frac{1}{2}^-$	Sum
$A_{\rm LD}$	$-1.5 \cdot 10^{-3}$	$-6.6 \cdot 10^{-3}$	0	$8.4 \cdot 10^{-3}$	$6.2 \cdot 10^{-2}$	$0.6 \cdot 10^{-1}$
$B_{\rm LD}$	-1.83	$1.6 \cdot 10^{-1}$	$0.9 \cdot 10^{-2}$	0	0	-1.67

THANK YOU FOR YOUR ATTENTION