Double-charmed Baryons

The only experimental information about DCB gives SELEX collaboration:

$$\Xi_{cc}^{+} = (ccd)^{+} \qquad M_{\Xi^{+}} = 3443\,\mathrm{MeV},$$

$$\Xi_{cc}^{+*} = (ccd)^{+} \qquad M_{\Xi^{+*}} = 3520\,\mathrm{MeV},$$

$$\Xi_{cc}^{++} = (ccu)^{++} \qquad M_{\Xi^{++}} = 3541\,\mathrm{MeV},$$

There are several questions to SELEX results:

1) Lifetime

2) Cross sections

Theoretical information about DCB:

1) Mass spectrum

2) Life time and leading decay modes

3) Cross section

Double-charmed Baryons

Mass spectrum theoretical predictions:

- Potential Models (two step calculation)
- QCD Sum Rules
- QCD Effective field theory
- Lattice QCD

PM predictions for ground state *cc*-diquark $\bar{3}_c$ are [V. Kiselev, A.Onishchenko, A.L.]

$$M\left(\Xi_{cc}^{+}\right) = 3478\,\mathrm{MeV}, \qquad 1S1S \qquad 1/2^{+}$$

$$M\left(\Xi_{cc}^{+*}\right) = 3610\,\mathrm{MeV}, \qquad 1S1S \qquad 3/2^{+}$$

$$\Delta M \sim 40\,\mathrm{MeV}$$

Metastable state (2P1S) $\frac{1}{2}^{-}$ (3702) have L=1, S=0 for diquark.

Transitions to the ground state (L=0, S=1) requires simultaneous change of orbital momentum and spin.

Double-charmed Baryons

Sum Rules [V. Kiselev, A.Onishchenko, A.L.]

$$M\left(\Xi_{cc}^{+}\right)=3.47\,\mathrm{GeV}, \qquad \text{(without HF splitting)}$$

Lattice QCD [R.Lewis *et al*]

$$M\left(\Xi_{cc}^{+}\right)=3.600\,\mathrm{GeV} \qquad \pm 20\,\mathrm{MeV}$$

Spin-dependent potential

Hyperfine splitting $\Delta = M\left(\Xi_{cc}^{+*}\right)-M\left(\Xi_{cc}^{+}\right)$ [V. Kiselev, A.Onishchenko, A.L.]

PM: $\Delta = 130\,\mathrm{MeV} \pm 30\ \mathrm{MeV}$

QCDEFT $\Delta = 120\,\mathrm{MeV} \pm 40\ \mathrm{MeV}$ [N.Brambilla *et al*]

Lat.QCD $\Delta = 76.6\,\mathrm{MeV}$ [R.Lewis *et al*]

Excited states spectrum

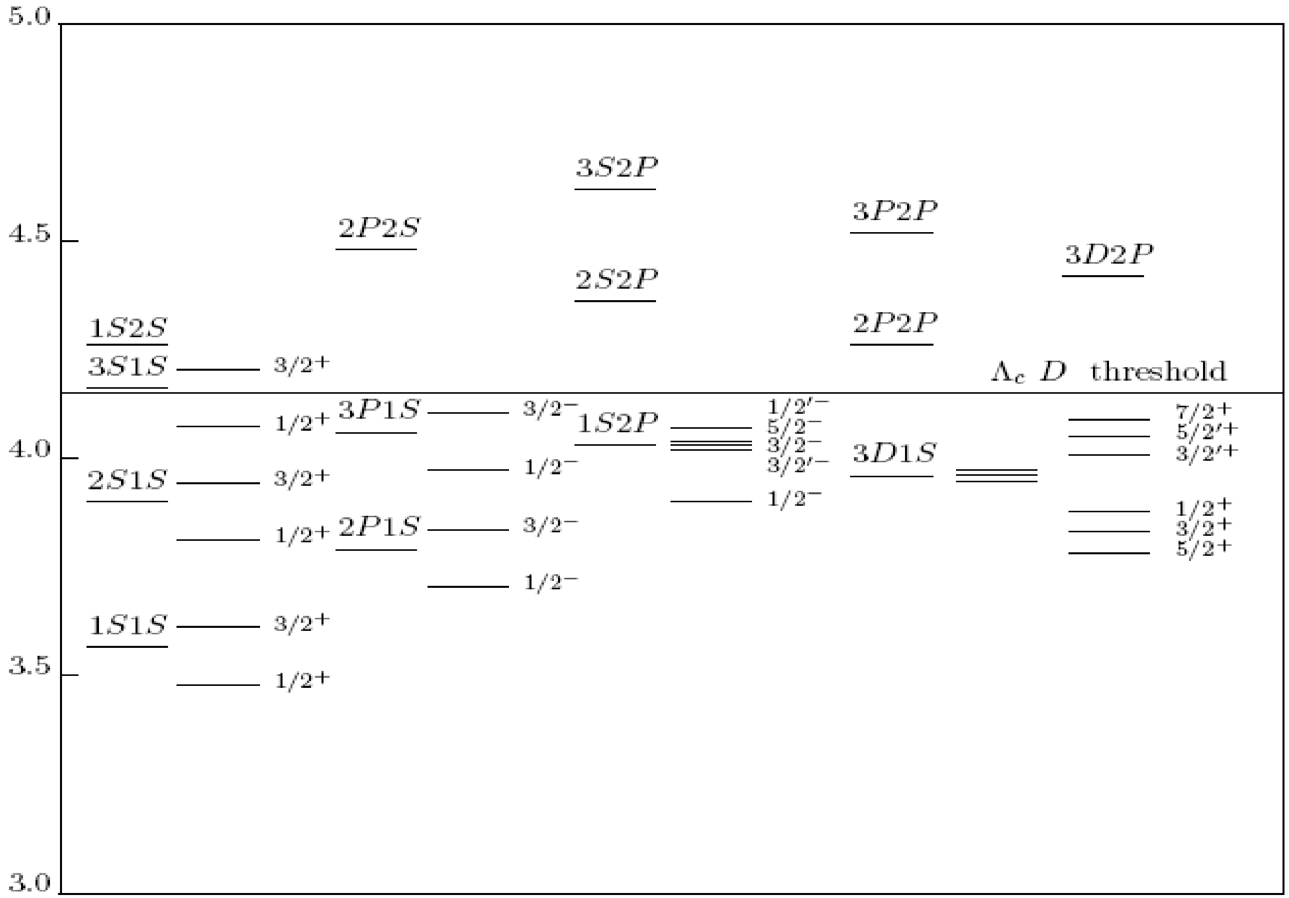


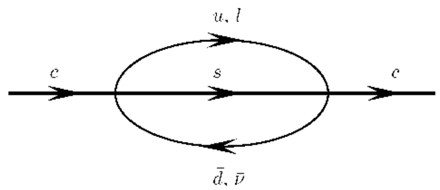
Figure 1: The spectrum of doubly charmed baryons: Ξ_{cc}^{++} and Ξ_{cc}^{+}.

Lifetimes of DCB

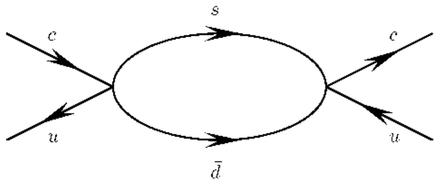
$$\Gamma_{\Xi_{cc}^{(*)}} = \frac{1}{2M_{\Xi_{cc}^{(*)}}} \left\langle \Xi_{cc}^{(*)} \left| T \right| \Xi_{cc}^{(*)} \right\rangle \qquad T = \mathrm{Im} \int d^4x \left\{ T\, H_{eff}(x) H_{eff}(0) \right\}$$

Where $H_{eff} = \frac{G_F}{2\sqrt{2}} V_{uq_1} V_{cq_1}^* \left[C_+(\mu) O_+ + C_-(\mu) O_- \right] + h.c.$ is standard hamiltonian of weak c-quark transitions

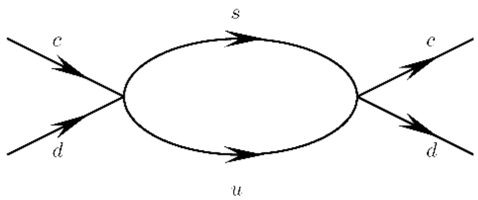
In decays of heavy quarks released energy is significant, so it is possible to expand H_{eff} in the series of local operators suppressed by inverse powers of heavy quark mass



spectator



Pauli interference



EW scattering

Lifetimes of DCB

For example, for semileptonic decay mode

$$\begin{aligned}\Gamma_{sl} \quad = \quad & 4\Gamma_c(\{1-8\rho+8\rho^3-\rho^4-12\rho^2\ln\rho\}+ \\ & E_c\{5-24\rho+24\rho^2-8\rho^3+3\rho^4-12\rho^2\ln\rho\}+ \\ & K_c\{-6+32\rho-24\rho^2-2\rho^4+24\rho^2\ln\rho\}+ \\ & G_c\{-2+16\rho-16\rho^3+2\rho^4+24\rho^2\ln\rho\}),\end{aligned}$$

where

$$\Gamma_c = |V_{cs}|^2 \frac{G_F^2 m_c^5}{192\pi^3},$$

$$K_c = -\left\langle \Xi_{cc}^{(*)}(v) \middle| \overline{c}_v \frac{(iD)^2}{2m_c^2} c_v \middle| \Xi_{cc}^{(*)}(v) \right\rangle,\ G_c = -\left\langle \Xi_{cc}^{(*)}(v) \middle| \overline{c}_v G_{\alpha\beta}\sigma^{\alpha\beta} c_v \middle| \Xi_{cc}^{(*)}(v) \right\rangle,\ E_c = G_c + K_c$$

In numerical estimates we have used following parameter values:

m_c=1.6 GeV m_s=0.45 GeV m_q=0.3 GeQ

M(Ξ^{++}_{cc})=M(Ξ^{+}_{cc})=3.56 GeV ΔM_{HF}=0.1 GeV

$|\psi_{diq}(0)|$ = 0.17 GeV$^{3/2}$

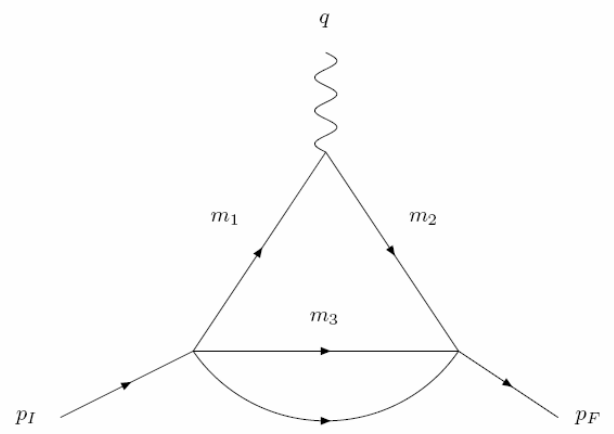
Lifetimes of DCB

Mode or decay mechanism	Width, ps^{-1}	Contribution in % (Ξ_{cc}^{++})	Contribution in % (Ξ_{cc}^{+})
$c_{spec} \to s\bar{d}u$	2.894	124	32
$c \to se^{+}\nu$	0.380	16	4
PI	-1.317	-56	–
WS	5.254	–	59
$\Gamma_{\Xi_{cc}^{++}}$	2.337	100	–
$\Gamma_{\Xi_{cc}^{+}}$	8.909	–	100

$$\tau_{\Xi_{cc}^{++}} = 0.43\,\text{ps}, \qquad \tau_{\Xi_{cc}^{+}} = 0.12\,\text{ps}$$

$$Br\left(\Xi_{cc}^{++} \to l\nu + X\right) = 16\%, \qquad Br\left(\Xi_{cc}^{+} \to l\nu + X\right) = 4\%,$$

Exclusive decays in NRQCD sum rules



Quark loop for 3-point correlator in the baryon decay

For 1/2→1/2 transition there are 6 form-factors:

$$\left\langle \Xi_F\left(p_F\right)\middle| J_\mu \middle| \Xi_I\left(p_I\right)\right\rangle = \bar{u}\left(p_F\right)\left\{\gamma_\mu G_1^V + v_\mu^I G_2^V + v_\mu^F G_3^V + \gamma_5\left(\gamma_\mu G_1^A + v_\mu^I G_2^A + v_\mu^F G_3^A\right)\right\} u\left(p_I\right)$$

These 6 f.f. are independent. However, in NRQCD in LO for small recoil it is possible to obtain following relations:

$$G_1^V + G_2^V + G_3^V = \xi^{IW}(w), \qquad G_1^A = \xi^{IW}(w)$$

Only 2 f.f. are not suppressed by heavy quark mass:

$$G_1^V = G_1^A = \xi^{IW}(w)$$

In the case of zero recoil $\xi^{IW}(1)$ is determined from Borell transfromation

$$\xi^{IW}(w) = \frac{1}{(2\pi)^2}\frac{1}{8M_I M_F Z_I Z_F}\int_{(m_1+m_3)^2}^{s_I^{th}}\int_{(m_1+m_2)^2}^{s_F^{th}}\rho(s_I, s_F, q^2)ds_I ds_F \times \exp(-\frac{s_I - M_I^2}{B_I^2})\exp(-\frac{s_F - M_F^2}{B_F^2}),$$

For $\Xi_{cc} \to \Xi_{cs}$ transition

Mode	$\xi(1)$, sum rules	$\xi(1)$, pot.model
$\Xi_{cc} \to \Xi_{cs}$	0.99	1.

For calculation of exclusive widths one can adopt pole model

$$\xi^{IW}(w) = \xi_0 \frac{1}{1 - \frac{q^2}{m_{pole}^2}} \qquad m_{pole} = 1.85 \ \text{GeV for } c \to s \ \text{transitions.}$$

Mode	Br (%)
$\Xi_{cc}^{+} \to \Xi_c^0 \bar{l}\nu_l$	7.5
$\Xi_{cc}^{+} \to \Xi_c^0 \pi^+$	11.2
$\Xi_{cc}^{+} \to \Xi_c^0 \rho^+$	33.6
$\Xi_{cc}^{++} \to \Xi_c^+ \bar{l}\nu_l$	16.8
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$	15.7
$\Xi_{cc}^{++} \to \Xi_c^+ \rho^+$	46.8

Production of Ξ_{cc}-baryons

In all papers it was assumed, that

$$\sigma[\Xi_{cc}] \equiv \sigma\left[(cc)_3\right]$$

This is quite reasonable assumption in the framework of NRQCD, where, for example, octet states transforms to heavy quarkonium. Analogously, we have to assume, that dissociation of $(cc)_3$ into *DD* is small.

Similar to $c\bar{c}$-quarkonium production cross sections factorizes into hard (pertubative) and soft (non-pertubative) parts.

In both cases second part is described by wave function of bound state at origin.

That's why it is reasonable to compare $J/\psi c\bar{c}$ and $\Xi \bar{c}\bar{c}$ final states. In this case only one uncertainty remains – the of squared wave functions at origin.

4c-sector

LO calculations for σ(4c) at $\sqrt{s} = 10.6\,\mathrm{GeV}$ gives

$$\sigma\left(e^+e^- \to c\bar{c}c\bar{c}\right) \approx 372\,\mathrm{fb}$$

at m_c=1.25 GeV

α_s=0.24

It should be compared with $\sigma_{\mathrm{tot}}(c\bar{c})$

$$\sigma\left(e^+e^- \to c\bar{c}\right) \approx 1.03\,\mathrm{nb}$$

This gives

$$R = \frac{\sigma(4c)}{\sigma(2c)} \sim 3.7\times10^{-4}$$

At Z-pole

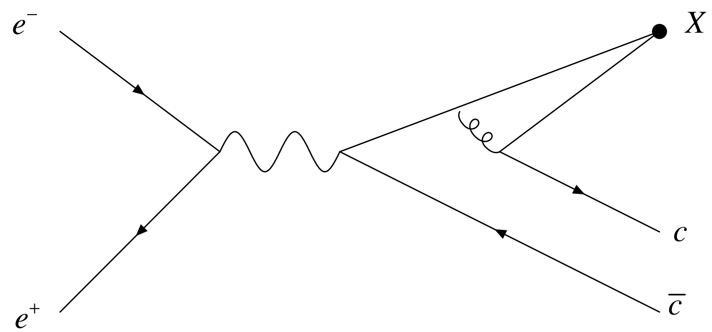
$$R_Z \sim 2.3\times10^{-2}$$

Main uncertainties come from errors in m_c and α_s

X $c\bar{c}$ final state

$$X = (c\bar{c}) = \eta_c,\ J/\psi, \chi_c(1P),\ \psi',\ldots$$

1) Fragmetation mechanism



$$D_{c\to X}(z) = \frac{2(2J+1)}{27\pi}\frac{|R(0)|^2}{m^3}\alpha_s^2\,\phi(z) \qquad z = \frac{2E_X}{\sqrt{s}}$$

M^2/s corrections are neglected ($M^2/s \ll 1$)

X $c\bar{c}$ final state

2) Complete calculations (with M^2/s corrections)

$\sigma(\eta_c) = 40 \quad (49)$ fb,

$\sigma(J/\psi) = 104 \ (148)$ fb,

$\sigma(\chi_{c0}) = \quad (48.8)$ fb

$\sigma(\chi_{c1}) = \quad (13.5)$ fb

$\sigma(\chi_{c2}) = \quad (6.3)$ fb

[A.Berezhnoi, A.L.]

[K.Y. Liu, Z.G. He, K.T. Chao]

Complete calculations deviate from fragmetation calculations at $\sqrt{s} = 10.6\,\mathrm{GeV}$

M^2/s terms are important

X $c\bar{c}$ final state

3) Quark-Hadron duality

$$\int_{2m_c}^{2m_D+\Delta} dm_{c\bar{c}} \frac{d\sigma\left(e^+e^- \to (c\bar{c})_{\text{sing}} + c + \bar{c}\right)}{dm_{c\bar{c}}} = 280\,\text{fb}$$

$m_c = 1.25\,\text{GeV}$ $\qquad \alpha_s = 0.24$ $\qquad \Delta = 0.5\,\text{GeV}$

$$\int d\sigma\left[e^+e^- \to (c\bar{c})_{\text{sing}}^{\text{S=1}} + c + \bar{c}\right] = 204\,\text{fb}$$

$$\int d\sigma\left[e^+e^- \to (c\bar{c})_{\text{sing}}^{\text{S=0}} + c + \bar{c}\right] = 76\,\text{fb}$$

It should be compared with total sum of complete calculations.

$$\sigma_{\text{tot}}\left(Q\bar{Q}\right) = 216\,\text{fb}$$

Q-H duality does not contradict Color Singlet model within uncertainties in m_c α_s and Δ

X cc final state

a) fragmentation approach

S=1 $D_{c\to cc}(z)$ similar to $D_{c\to J/\psi}(z)$

Difference in wave functions $|\Psi_{J/\psi}(0)|^2$ and $|\Psi_{cc}(0)|^2$

Again, similar to J/ψ case, at $\sqrt{s} = 10.6\,\mathrm{GeV}$ complete calculations for vector $(cc)_3$ -diquark are needed

X cc final state

b) Quark-Hadron duality

One inclusive cross section for vector $\overline{3}_c$ in S=1

$$\sigma\left(\Xi_{cc}+c+\overline{c}\right)\sim 115\div 170\,\mathrm{fb}$$

Uncertainties are caused by errors in α_s and Δ

This value is close to results of complete calculations with $\Psi_{cc}(0)$ taken from PM.

Conclusion

1) $\sigma\left(e^+e^- \to \Xi_{cc} + X\right) \sim 100\,\mathrm{fb}$ at $\sqrt{s} = 10.6\,\mathrm{GeV}$
(at LHC $\sigma\left(e^+e^- \to \Xi_{cc} + X\right) \sim 122\,\mathrm{nb}$)

2) For lumonocity L=10^{34} cm^{-2} s^{-1} it gives ~10^4 Ξ_{cc}-baryons per year

3) Taking into account Br ~10^{-1} in exclusive modes we expect 10^3 Ξ_{cc} events per year

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