Analysis of heavy baryon lifetimes

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	ps
Λ_b^0	1.471 ± 0.009
Ξ_b^0	1.480 ± 0.030
Ξ_b^-	1.572 ± 0.040
Ω_b^-	$1.64^{+0.18}_{-0.17}$

PDG current values of bottom baryon lifetimes become stable since 2018

$$\tau(\Xi_b^-) > \tau(\Xi_b^0) \simeq \tau(\Lambda_b^0)$$

Uncertainty in $\tau(\Omega_b^-)$ is too large to draw a conclusion

(in units of fs)

PDG ('04 ~ '18)	442 ± 26	200 ± 6		69 ± 12
LHCb ('18)				268 ± 26
LHCb ('19)	457 ± 6	203.5 ± 2.2	154.5 ± 2.6	
PDG ('20)	456 ± 5	202.4 ± 3.1	153 ± 6	268 ± 26
LHCb ('21)			148.0 ± 3.2	276.5 ± 14.1
PDG ('22,'23)	453 ± 5	201.5 ± 2.7	151.9 ± 2.4	268 ± 26
Belle II ('22)		203.20 ± 1.18		243 ± 49
World Ave ('23)	453 ± 5	202.9 ± 1.1	150.5 ± 1.9	272.6 ± 12.0

LHCb ('21) & Belle ('22) data were not taken into account by PDG ('23)

- **$\tau(\Omega_c^0)$ obtained by LHCb ('18) from semileptonic Ω_b^- decays is nearly four times larger. It has been confirmed by LHCb ('21) using promptly produced Ω_c^0 baryons**

$$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$$

$$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$$

- **$\tau(\Xi_c^0)$ becomes 3.3σ larger due to new measurements from LHCb ('19, '21)**

Lifetimes of heavy baryons

Heavy quark expansion:

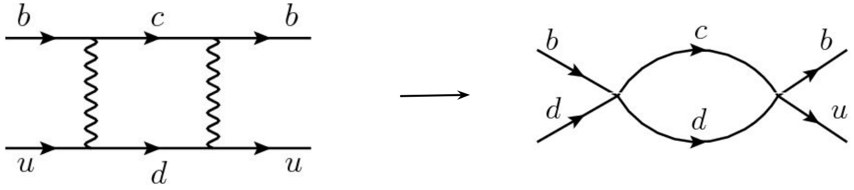
$$\Gamma(\mathcal{B}_Q) = \frac{1}{2M_{\mathcal{B}_Q}} \mathrm{Im}\langle \mathcal{B}_Q|\mathcal{T}|\mathcal{B}_Q\rangle = \frac{G_F^2 m_Q^5}{192\pi^3}\left(A_0 + \frac{A_2}{m_Q^2} + \frac{A_3}{m_Q^3} + \frac{A_4}{m_Q^4} + \cdots\right)$$

$$\mathcal{T} = \frac{G_F^2 m_Q^5}{192\pi^3}\left[\left(\mathcal{O}_3 + \frac{1}{m_Q^2}\mathcal{O}_5 + \frac{1}{m_Q^3}\mathcal{O}_6 \cdots\right)_2 + \left(\frac{1}{m_Q^3}\tilde{\mathcal{O}}_6 + \frac{1}{m_Q^4}\tilde{\mathcal{O}}_7 \cdots\right)_4 \cdots\right]$$

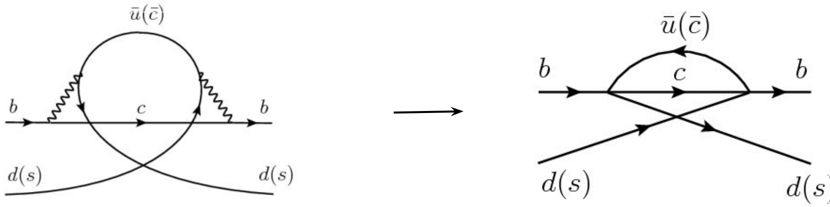
$$\Rightarrow \quad \Gamma(\mathcal{B}_Q) = \frac{G_F^2 m_Q^5}{192\pi^3}\left[\mathcal{C}_3\left(1 - \frac{\mu_\pi^2 - \mu_G^2}{2m_Q^2}\right) + 2\mathcal{C}_5\frac{\mu_G^2}{m_Q^2} + \mathcal{C}_\rho\frac{\rho_D^3}{m_Q^3}\right] + \Gamma_6 + \Gamma_7$$

- A_0 term from the decay of heavy quark Q
  ⇒ Lifetimes of all heavy hadrons H_Q are the same in $m_Q \to \infty$ limit
- No linear $1/m_Q$ correction from A_1 term , known as Luke's theorem
- A_2 term arises from kinetic & chromomagnetic operators
- A_3 term consists of dim-6 2-quark Darwin operator & 4-quark operators which will induce the spectator effects responsible for lifetime differences
- A_4 term includes dim-7 4-quark operators which will induce $1/m_c$ corrections to spectator effects

Spectator effects described by dim-6 four-quark operators: <u>dim-7 4-quark</u>

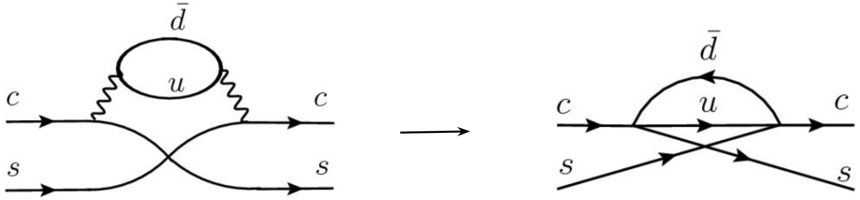


W-exchange



destructive P.I. — **constructive**

(Pauli interference)



constructive P.I. — **destructive**

(only for charmed baryons)

- **Although spectator effects are** $1/m_Q^3$ **suppressed, they are numerically important due to a p.s. enhancement factor of** $16\pi^2$ **relative to heavy quark decay**

Subleading $1/m_Q$ corrections to spectator effects are obtained by expanding forward scattering amplitude in light quark momentum and matching the result onto operators containing derivative insertions

Gabbiani, Onishchenko, Petrov ('03,'04)

⇒ dim-7 four-quark operators:

$$P_1^q = m_q \bar{Q}(1-\gamma_5) q \bar{q}(1-\gamma_5) Q, \qquad P_2^q = m_q \bar{Q}(1+\gamma_5) q \bar{q}(1+\gamma_5) Q,$$

$$P_3^q = \frac{1}{m_Q} \bar{Q} \overleftarrow{D}_\rho \gamma_\mu (1-\gamma_5) D^\rho q \bar{q} \gamma^\mu (1-\gamma_5) Q, \qquad P_4^q = \frac{1}{m_Q} \bar{Q} \overleftarrow{D}_\rho (1-\gamma_5) D^\rho q \bar{q}(1+\gamma_5) Q,$$

and $\widetilde{P}_i^q$ obtained from P_i^q by interchanging colors of Q and $\bar{q}$

⇒ dim-7 4-quark operator is either dim-6 4-quark operator times m_q or 4-quark operator with two derivatives suppressed by $1/m_Q$

Beneke, Buchalla, Dunietz ('96): width difference in B_s-$\underline{B}_s$ system

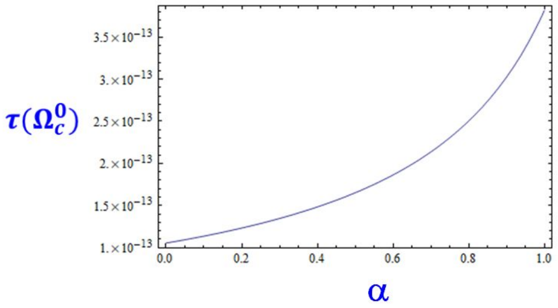
Gabbiani, Onishchenko, Petrov ('03,'04): lifetime difference of heavy hadrons

Lenz, Rauh ('13): D meson lifetimes

Effects of dim-7 4-quark operators on charmed baryon lifetimes were explored in 2017-2018. Preliminary results with the conjecture that Ω_c^0 is no longer shortest-lived and that $\tau(\Omega_c^0) > \tau(\Lambda_c^+)$ were first reported at 2018 HIEPA Workshop (March 19-21, 2018, Beijing).

	$\Gamma^{\rm dec}$	$\Gamma^{\rm ann}$	$\Gamma_-^{\rm int}$	$\Gamma_+^{\rm int}$	$\Gamma_{\rm SL}$	$\Gamma^{\rm tot}$	$\tau(10^{-13}s)$	$\tau_{\rm expt}(10^{-13}s)$
Λ_c^+	1.012	1.883	−0.209	0.021	0.308	3.015	2.18	2.00 ± 0.06
Ξ_c^+	1.012	0.115	−0.189	0.353	0.524	1.854	3.55	4.42 ± 0.26
Ξ_c^0	1.012	2.160		0.351	0.524	4.083	1.61	$1.12^{+0.13}_{-0.10}$
Ω_c^0	1.155	0.126		0.346	0.520	2.855	2.31	0.69 ± 0.12

$\Gamma(\Xi_c^+)$ is suppressed, while $\Gamma(\Lambda_c^+)$ is enhanced, so that $\tau(\Xi_c^+)/\tau(\Lambda_c^+)$ becomes 1.63 . However, $\Gamma_+^{int}(\Omega_c^0)$ becomes negative and $\Gamma^{SL}(\Omega_c^0)$ too small. Introduce a parameter α to $\Gamma_{dim-7}^{int}(\Omega_c^0)$ & $\Gamma_{dim-7}^{SL}(\Omega_c^0)$.
In general, Ω_c^0 is no longer shortest-lived. For example, α = 0.75 leads to $\tau(\Omega_c^0) = 2.3 \times 10^{-13}$s and hence $\tau(\Omega_c^0) > \tau(\Lambda_c^+)$.



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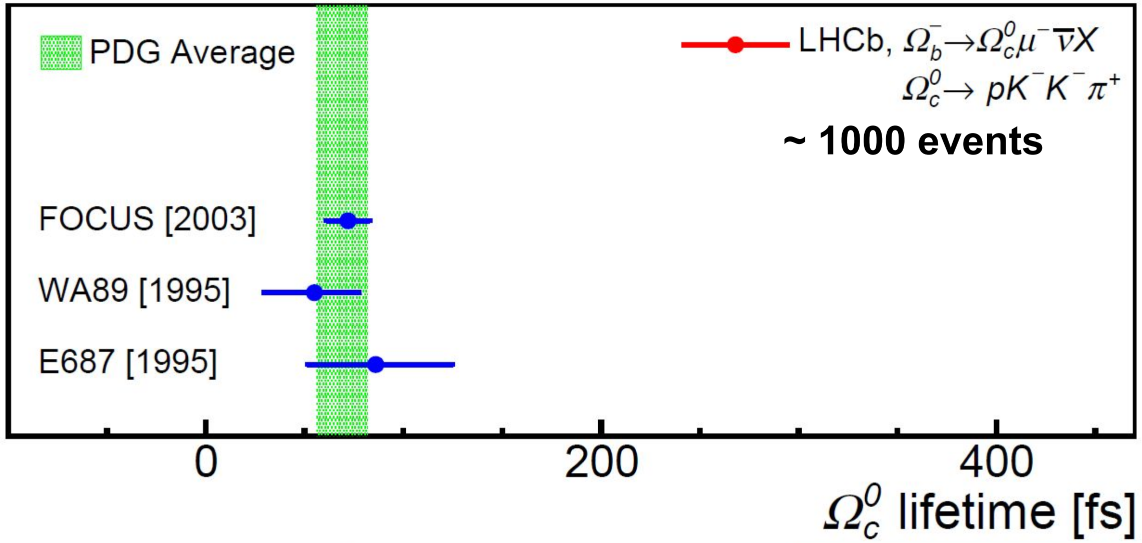
An ad hoc parameter α was introduced to ensure the validity of HQE for Ω_c^0

$\tau(\Omega_c^0)$ = 231 fs for α = 0.25

Less than three months later, LHCb's new measurement of $\tau(\Omega_c^0)$ = (268±24±10±2) fs was first reported by Mariana Fontana on June 8th of 2018, which is nearly four-times larger than the world average of (69±12) fs obtained from fixed target experiments!

Ω_c^0 lifetime measurements

			events
FOCUS	$72 \pm 11 \pm 11$ fs	$\Xi^- K^- \pi^+ \pi^+$, $\Omega^- \pi^+$	64
E687	$86\ ^{+27}_{-20} \pm 28$ fs	$\Sigma^+ K^- K^- \pi^+$	86
WA89	$55\ ^{+13}_{-11}\ ^{+18}_{-23}$ fs	$\Xi^- K^- \pi^+ \pi^+$, $\Omega^- \pi^+ \pi^+ \pi^-$	25



M. Fontana (INFN Cagliari and CERN) LHCP - Bologna 08-06-2018 15 / 13

In this talk, I'll focus on the baryon matrix elements which constitute the major uncertainties in the predictions of heavy baryon lifetimes

$$\Gamma(\mathcal{B}_Q) = \frac{G_F^2 m_Q^5}{192\pi^3}\left[\mathcal{C}_3\left(1-\frac{\mu_\pi^2-\mu_G^2}{2m_Q^2}\right)+2\mathcal{C}_5\frac{\mu_G^2}{m_Q^2}+\mathcal{C}_\rho\frac{\rho_D^3}{m_Q^3}\right]+\Gamma_6+\Gamma_7$$

Nonperturbative baryonic matrix elements:

2-quark operator m.e. $\mu_\pi^2, \mu_G^2, \rho_D^3$; **4-quark operator m.e.** $\langle O_{4q}\rangle$

$$\mu_\pi^2 = \langle \overline{Q}_v (i\vec{D})^2 Q_v\rangle_{\mathcal{B}_Q}$$

$$\mu_G^2 = \frac{g_s}{2}\langle \overline{Q}_v \sigma_{\mu\nu} G^{\mu\nu} Q_v\rangle_{\mathcal{B}_Q}$$

$$\rho_D^3 = ig_s\left\langle \overline{Q}_v (iD_\mu) G^{0\mu} Q_v\right\rangle_{\mathcal{B}_Q}$$

$$\langle \mathcal{O}\rangle_{\mathcal{B}_Q} \equiv \frac{1}{2M_{\mathcal{B}_Q}}\langle \mathcal{B}_Q|\mathcal{O}|\mathcal{B}_Q\rangle$$

Matrix elements $\mu_\pi^2, \mu_G^2, \rho_D^3$ should be independent of heavy quark mass m_Q , so are $\langle O_{4q}\rangle$ in heavy quark limit

$\langle O_{4q}\rangle$ are conventionally evaluated using NRQM

(in units of $10^{-3} GeV^3$)

Model	$(\mathcal{B}_Q, q)$	(Λ_b, q_I)	(Ξ_b, q_I)	(Ξ_b, s)	(Ω_b, s)	(Λ_c, q_I)	(Ξ_c, q_I)	(Ξ_c, s)	(Ω_c, s)
	$L^q_{\mathcal{B}_Q}$	$-13(5)$	$-14(5)$	$-18(6)$	$-126(60)$	$-5.1(15)$	$-5.4(16)$	$-7.4(22)$	$-46(14)$
NRQM	$S^q_{\mathcal{B}_Q}$	$7(2)$	$7(2)$	$9(3)$	$-21(10)$	$2.5(8)$	$2.7(8)$	$3.7(11)$	$-7.7(23)$
	$P^q_{\mathcal{B}_Q}$	0	0	0	0	0	0	0	0

$$S^q_{T_Q} = -\frac{1}{2} L^q_{T_Q}$$

$$S^q_{\Omega_Q} = \frac{1}{6} L^q_{\Omega_Q}$$

Gratrex, Melic, Nisandzic ('22) for c-baryons;
Gratrex, Lenz, Melic, Nisandzic, Piscopo, Rusov ('23) for b-baryons

$$L^q_{\mathcal{B}_Q} \equiv \langle (\overline{Q}_\alpha L^\mu q_\alpha)\,(\bar{q}_\beta L_\mu Q_\beta)\rangle_{\mathcal{B}_Q}$$

$$S^q_{\mathcal{B}_Q} \equiv \langle (\overline{Q}_\alpha q_\alpha)\,(\bar{q}_\beta Q_\beta)\rangle_{\mathcal{B}_Q}\,,$$

$$P^q_{\mathcal{B}_Q} \equiv \langle (\overline{Q}_\alpha \gamma_5 q_\alpha)\,(\bar{q}_\beta \gamma_5 Q_\beta)\rangle_{\mathcal{B}_Q}$$

- **In $m_Q \to \infty$ limit, L_{Λ_Q}, S_{Λ_Q}, P_{Λ_Q} are independent of m_Q**
- **Within NRQM, the magnitudes of 4-quark operator matrix elements in the bottom sector are much larger than that in the charm sector**

$$L^q_{\Lambda_b} = -\left|\psi^{\Lambda_b}_{bq}(0)\right|^2 \propto -\left|\psi^{B}_{b\bar{q}}(0)\right|^2 = -\frac{1}{12} f_B^2 m_B \qquad \left|\psi^{B}_{b\bar{q}}(0)\right| \gg \left|\psi^{D}_{c\bar{q}}(0)\right|$$

$$L^q_{\Lambda_c} = -\left|\psi^{\Lambda_c}_{cq}(0)\right|^2 \propto -\left|\psi^{D}_{c\bar{q}}(0)\right|^2 = -\frac{1}{12} f_D^2 m_D \qquad \Rightarrow \quad \left|L^q_{\Lambda_b}\right| \gg \left|L^q_{\Lambda_c}\right|$$

$$\left|L_{\Lambda_b}\right| \approx 2.5\left|L_{\Lambda_c}\right| \sim \left|L_{\Lambda}\right| \quad \Rightarrow \quad \text{far from expectation of heavy quark limit}$$

- **In MIT bag model**

$$\psi = \begin{pmatrix} iu(r)\chi \\ v(r)\boldsymbol{\sigma}\cdot\hat{\mathbf{r}}\chi \end{pmatrix}$$

$$L_{\Lambda_Q} = -\int d^3r\,\{[u_Q^2(r)u_q^2(r) + v_Q^2(r)v_q^2(r)] + [u_Q^2(r)v_q^2(r) + v_Q^2(r)u_q^2(r)]\}$$

with $u(r)$, $v(r)$ being the large and small components of the quark wave function

$|L_{\Lambda_b}| = 3.23\times10^{-3}$, $|L_{\Lambda_c}| = 2.39\times10^{-3} \Rightarrow$ **weak dependence on heavy flavor**

- **In NR limit, $v_Q \to 0, v_q \to 0$, $L_{\Lambda_Q} = -\int d^3r\, u_Q^2(r)u_q^2(r) = -\left|\psi_{Qq}^{\Lambda_Q}(0)\right|^2$. It is customary to consider hyperfine splittings in heavy baryons and mesons and then apply the relation $\left|\psi_{Q\bar{q}}^{M}(0)\right|^2 = \frac{1}{12}f_M^2 m_M$ which is derived and valid under heavy quark limit**

- **In NRQM, it is important to evaluate 4-quark matrix elements directly in terms of baryon wave functions in momentum space. The momentum integrals are expressed in terms of harmonic oscillator parameters α_ρ, α_λ for ρ- and λ-mode excitation, respectively. $\Rightarrow$ check dependence of 4-quark m.e. on m_Q**

- **Alternatively, we consider the improved bag model**

HYC, Liu, JHEP 07 (2023) 114

Improved bag model

- **MIT bag model yields too small baryonic matrix elements compared to NRQM**
- **Static bag model has an issue with center-of-mass motion (CMM) of the bag**

Chao-Qiang Geng, Chia-Wei Liu, Ten-Hsueh Tsai ('20);
Liu, Geng ('22)

Bag quarks are unentangled; they obey free Dirac equation

$\langle \mathbf{p}_{\mathcal{B}} \rangle = \langle \mathbf{p}_{q_1} + \mathbf{p}_{q_2} + \mathbf{p}_{q_3} \rangle = 0\,,$ (recall that $\langle \mathbf{p}_q \rangle = 0$)

$\langle \mathbf{p}^2_{\mathcal{B}} \rangle = \langle (\mathbf{p}_{q_1} + \mathbf{p}_{q_2} + \mathbf{p}_{q_3})^2 \rangle = \langle \mathbf{p}^2_{q_1} \rangle + \langle \mathbf{p}^2_{q_2} \rangle + \langle \mathbf{p}^2_{q_3} \rangle > 0$ because $\langle \mathbf{p}^2_q \rangle = E_q^2 - M_q^2 > 0$

The variance of $\sigma^2_{\mathbf{p}_{\mathcal{B}}} \equiv \langle \mathbf{p}^2_{\mathcal{B}} \rangle - \langle \mathbf{p}_{\mathcal{B}} \rangle^2$ is referred to CMM of the bag. A physical bag with a definite momentum should not have CMM as $\sigma^2_{\mathbf{p}_{\mathcal{B}}} = 0$

MIT bag model: Poincare invariance is not kept

$$|\Lambda_c^+, \uparrow\rangle = \int \frac{1}{\sqrt{6}} \epsilon^{\alpha\beta\gamma} d^\dagger_{a\alpha}(\vec{x}_1) u^\dagger_{b\beta}(\vec{x}_2) c^\dagger_{c\gamma}(\vec{x}_3) \Psi^{abc}_{A_\uparrow(duc)}(\vec{x}_1, \vec{x}_2, \vec{x}_3)[d^3\vec{x}]|0\rangle$$

In the homogeneous bag model (HBM) of Geng, Liu, Tsai ('20)

$$\Psi^{(\mathrm{HB})}(\vec{x}_1,\vec{x}_2,\vec{x}_3)=\int d^3\vec{x}_\Delta \Psi^{(\mathrm{SB})}(\vec{x}_1-\vec{x}_\Delta,\vec{x}_2-\vec{x}_\Delta,\vec{x}_3-\vec{x}_\Delta)$$

$$\Psi^{(\mathrm{HB})}(\vec{x}_1+\vec{d},\vec{x}_2+\vec{d},\vec{x}_3+\vec{d})=\Psi^{(\mathrm{HB})}(\vec{x}_1,\vec{x}_2,\vec{x}_3)$$

⇒ Wave function is invariant under space translation
⇒ Quarks are no longer constrained in specific regions

Quarks are bounded and entangled in the following way:

$$\Psi^{(\mathrm{HB})}(\vec{x}_1,\vec{x}_2,\vec{x}_3)=0\,,\quad \text{for}\quad |\vec{x}_i-\vec{x}_j|>2R$$

$\hat{\mathbf{P}}|\Lambda_c^+\rangle=\hat{\mathbf{P}}^2|\Lambda_c^+\rangle=0$ CMM is thus taken away from the static bag

Model	$(\mathcal{B}_Q, q)$	(Λ_b, q_I)	(Ξ_b, q_I)	(Ξ_b, s)	(Ω_b, s)	(Λ_c, q_I)	(Ξ_c, q_I)	(Ξ_c, s)	(Ω_c, s)
	$L^q_{\mathcal{B}_Q}$	-5.44	-5.15	-5.88	-34.12	-4.83	-4.87	-5.34	-31.63
BM	$S^q_{\mathcal{B}_Q}$	2.44	2.32	2.74	-5.41	1.96	1.98	2.32	-4.65
	$P^q_{\mathcal{B}_Q}$	-0.27	-0.25	-0.20	-0.62	-0.44	-0.44	-0.34	-1.12
	$L^q_{\mathcal{B}_Q}$	$-13(5)$	$-14(5)$	$-18(6)$	$-126(60)$	$-5.1(15)$	$-5.4(16)$	$-7.4(22)$	$-46(14)$
NRQM	$S^q_{\mathcal{B}_Q}$	7(2)	7(2)	9(3)	$-21(10)$	2.5(8)	2.7(8)	3.7(11)	$-7.7(23)$
	$P^q_{\mathcal{B}_Q}$	0	0	0	0	0	0	0	0

in units of $10^{-3} GeV^3$

evaluated at μ_H scale

- The matrix element P_{B_Q} is nonzero in the BM. Unlike the case in NRQM, L_{B_Q} and $S_{B_Q} - P_{B_Q}$ in the BM vary less than 10% w.r.t. heavy flavor,
- Both BM & NRQM are consistent for L_{B_c} but differ largely in L_{B_b}

QCDSR evaluated at $\mu = m_b$: $L_{\Lambda_b} = -(13.1 \pm 2.6)$ Z. X. Zhao et al. ('23)

Evolution to μ_H: $L_{\Lambda_b} = \begin{cases} -(7.6 \pm 1.5) & \mu_H = 0.8\text{ GeV} \\ -(9.6 \pm 1.9) & \mu_H = 1.2\text{ GeV} \end{cases}$

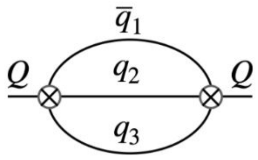
Lifetimes of bottom baryons

$\mathcal{B}_Q$		$\Gamma_3^{\rm NL}$	$\Gamma_3^{\rm SL}$	Γ_ρ	$\Gamma_6^{\rm NL}$	$\Gamma_6^{\rm SL}$	$\Gamma_7^{\rm NL}$	$\Gamma_7^{\rm SL}$	τ	$\tau_{\rm exp}$
Λ_b^0	LO	2.28	1.67	0	0.07	0	0.02	0	1.63 ± 0.15	1.471 ± 0.009
	NLO	2.78	1.56	-0.02	0.11	0	0.02	0	1.48 ± 0.22	
Ξ_b^0	LO	2.28	1.67	0	0.07	0	0.01	0	1.63 ± 0.15	1.480 ± 0.030
	NLO	2.78	1.56	-0.02	0.11	0	0.01	0	1.49 ± 0.22	
Ξ_b^-	LO	2.28	1.67	0	-0.09	0	0	0	1.70 ± 0.27	1.572 ± 0.040
	NLO	2.78	1.57	-0.02	-0.07	0	0	0	1.55 ± 0.23	
Ω_b^-	LO	2.28	1.67	0	-0.17	0	-0.04	0	1.76 ± 0.28	$1.64^{+0.18}_{-0.17}$
	NLO	2.77	1.55	-0.03	-0.15	0	-0.04	0	1.60 ± 0.25	

τ in units of 10^{-12} s

Uncertainties arise from $m_b, \mu_H, I^q_{B_b}$, and the deviation of full QCD from HQET

- **All predicted lifetimes are improved to NLO. Contributions from dim-7 operators are very small, although NLO corrections to them are still absent**
- **Γ_7^{NL} contributes constructively (destructively) to Γ^{NL} for Λ_b^0 & Ξ_b^0 (Ω_b^-)**
- **$\Gamma_3 \gg \Gamma_6 > \Gamma_7$ for b-baryons**
- **$\tau(\Omega_b^-) > \tau(\Xi_b^-) > \tau(\Xi_b^0) \simeq \tau(\Lambda_b^0)$**

Γ_3:


Lifetimes of bottom baryons

	BM	NRQM	Expt
	1.48 ± 0.22		1.471 ± 0.009
	1.49 ± 0.22		1.480 ± 0.030
	1.55 ± 0.23		1.572 ± 0.040
	1.60 ± 0.25		

NRQM: Gratrex, Lenz, Melic, Nisandzic, Piscopo, Rusov ('23) in kinetic mass scheme to dim-6 level

We use the pole mass $m_b = 4.70 \pm 0.10$ GeV, 2-loop (1-loop) result for upper (lower) bounds

Excellent agreement between theory and experiment for bottom baryon lifetimes even at dim-6 level

$\mathcal{B}_Q$		$\Gamma_3^{\rm NL}$	$\Gamma_3^{\rm SL}$	Γ_ρ	$\Gamma_6^{\rm NL}$	$\Gamma_6^{\rm SL}$	$\Gamma_7^{\rm NL}$	$\Gamma_7^{\rm SL}$	τ	$\tau_{\rm exp}$
Λ_c^+	LO	0.85	0.40	0	0.75	0.01	0.49	0	2.63 ± 51	2.029 ± 0.011
	NLO	1.27	0.35	0.07	1.26	0.01	0.49	0	1.92 ± 0.37	
Ξ_c^0	LO	0.86	0.40	0	1.74	0.36	0.22	-0.15	1.92 ± 0.37	1.505 ± 0.019
	NLO	1.27	0.35	0.07	2.01	0.18	0.22	-0.15	1.66 ± 0.32	
Ξ_c^+	LO	0.86	0.40	0	0.26	0.35	-0.09	-0.15	4.04 ± 0.94	4.53 ± 0.05
	NLO	1.27	0.35	0.07	0.38	0.18	-0.09	-0.15	3.27 ± 0.76	
Ω_c^0	LO	0.91	0.42	0	2.34	1.22	-1.09	-0.83	2.22 ± 0.46	2.73 ± 0.12
	NLO	1.34	0.37	0.11	2.37	0.61	-1.09	-0.83	2.30 ± 0.58	

τ in units of 10^{-13} s

Uncertainties arise from $m_c, \mu_H, I^q_{B_c}$, and the deviation of full QCD from HQET

- **All predicted lifetimes are improved to NLO except for Ξ_c^+**
- **$\Gamma_6 > \Gamma_3$ for c-baryons, recalling that $\Gamma_3 > \Gamma_6$ for b-baryons**
- **Because of large destructive contributions from Γ_7^{NL} and Γ_7^{SL}, Ω_c^0 could live longer than Λ_c^+**

to dim-6 $\Rightarrow$ $\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$

to dim-7 $\Rightarrow$ $\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$

(τ in units of 10^{-13} s)

	BM	NRQM	Expt
	1.92 ± 0.37		2.029 ± 0.011
	1.66 ± 0.32		1.505 ± 0.019
	3.27 ± 0.76		4.53 ± 0.05
	2.30 ± 0.58		2.73 ± 0.12

NRQM: **Gratrex, Melic, Nisandzic ('22) in the pole mass scheme**

We use the pole mass $m_c = 1.59 \pm 0.09$ GeV, 2-loop (1-loop) result for upper (lower) bounds

While the predicted lifetimes for Λ_c^+ and Ξ_c^0 are improved in the bag model, $\tau(\Xi_c^+)$ becomes even worse.

Semileptonic inclusive BFs: $\mathcal{BF}_e^{\rm SL} \equiv \tau(\mathcal{B}_Q)\Gamma(\mathcal{B}_Q \to Xe^+\nu_\ell)$

(in %)

	BM	NRQM	Expt
	4.57 ± 0.54		3.95 ± 0.35
	4.40 ± 0.61		—
	8.57 ± 0.49		—
	1.88 ± 1.69		—
	9.90 ± 0.03		—
	9.94 ± 0.06		—
	10.38 ± 0.09		—
	10.76 ± 0.14		—

Predicted BFs of $\Xi_c^+ \to Xe^+\nu_e$, $\Omega_c^0 \to Xe^+\nu_e$ in bag model and NRQM both in the pole mass scheme are in sharp contrast $\Rightarrow$ allowed to discriminate between different models

Conclusions

- Baryonic matrix elements are evaluated in the improved bag model. Heavy quark limit holds reasonably well in BM but is badly respected in NRQM.

- HQE in $1/m_b$ works well for the lifetimes of bottom baryons.

- HQE in $1/m_c$ fails to provide a satisfactory description of the lifetimes charmed baryons to $O(1/m_c^3)$. Need to consider subleading $1/m_c$ corrections to spectator effects.

- The Ω_c^0 lifetime could live longer than Λ_c^0 due to the suppression from $1/m_c$ corrections arising from dim-7 4-quark operators

Backup Slides

Model		Λ_b^0	$\Xi_b^{0,-}$	Ω_b^-	Λ_c^+	$\Xi_c^{0,+}$	Ω_c^0
	μ_π^2	4.66(28)	4.45(27)	4.34(80)	4.42(81)	4.30(80)	4.20(80)
BM	μ_G^2	0	0	2.09(12)	0	0	1.95(38)
	ρ_D^3	2.29(23)	2.38(24)	2.66(27)	2.06(21)	2.22(22)	2.68(27)
	μ_π^2	5.0(6)	5.4(6)	5.6(6)	5.0(15)	5.5(17)	5.5(17)
NRQM	μ_G^2	0	0	1.93(68)	0	0	2.6(8)
	ρ_D^3	3.1(9)	3.7(9)	5.0(21)	4(1)	5.5(20)	6(2)

$\mu^2_{\pi,G}$ in units of $10^{-1} GeV^2$

ρ^3_D in units of $10^{-2} GeV^3$

NRQM: Gratrex, Melic, Nisandzic ('22) for c-baryons; Gratrex, Lenz, Melic, Nisandzic, Piscopo, Rusov ('23) for b-baryons

- In the bag model μ_π^2, μ_G^2, ρ_D^3 all depend weakly on the heavy quark flavor
- In both BM & NRQM, ρ_D^3 respects the same hierarchy $\Omega_Q > \Xi_Q > \Lambda_Q$ induced by the strange quark mass. It shares similar values for T_Q & Ω_Q in the bag model.

$$\rho_D^3 = -4\pi\alpha_s \sum_q \frac{1}{24}\left(4L^q_{\mathcal{B}_Q} - \tilde{L}^q_{\mathcal{B}_Q} - 6S^q_{\mathcal{B}_Q} + 2\tilde{S}^q_{\mathcal{B}_Q} + 6P^q_{\mathcal{B}_Q} - 2\tilde{P}^q_{\mathcal{B}_Q}\right)$$

$\mathcal{B}_Q$		$\Gamma_3^{\rm NL}$	$\Gamma_3^{\rm SL}$	τ	$\tau_{\rm exp}$
Λ_c^+	LO	$0.85(29)_m$	$0.40(13)_m$	$2.63(46)_m(15)_\mu(12)_4(11)_s$	$2.029(11)$
	NLO	$1.27(42)_m$	$0.35(11)_m$	$1.92(34)_m(11)_\mu(10)_4(5)_s$	
Ξ_c^0	LO	$0.86(28)_m$	$0.40(14)_m$	$1.92(31)_m(14)_\mu(12)_4(7)_s$	$1.505(19)$
	NLO	$1.27(42)_m$	$0.35(12)_m$	$1.66(28)_m(11)_\mu(9)_4(6)_s$	
Ξ_c^+	LO	$0.86(28)_m$	$0.40(14)_m$	$4.04(92)_m(10)_\mu(9)_4(12)_s$	$4.53(5)$
	NLO	$1.27(42)_m$	$0.35(12)_m$	$3.27(75)_m(7)_\mu(6)_4(6)_s$	
Ω_c^0	LO	$0.91(30)_m$	$0.42(14)_m$	$2.22(44)_m(14)_\mu(12)_4(1)_s$	$2.43(12)$
	NLO	$1.34(44)_m$	$0.37(12)_m$	$2.30(51)_m(10)_\mu(9)_4(24)_s$	
Λ_b	LO	$2.28(33)_m$	$1.67(18)_m$	$1.63(15)_m(1)_\mu(0)_4(1)_s$	$1.471(9)$
	NLO	$2.78(42)_m$	$1.56(17)_m$	$1.48(22)_m(1)_\mu(0)_4(1)_s$	
Ξ_b^0	LO	$2.28(33)_m$	$1.67(18)_m$	$1.63(15)_m(1)_\mu(1)_4(1)_s$	$1.480(30)$
	NLO	$2.78(41)_m$	$1.56(17)_m$	$1.49(22)_m(0)_\mu(0)_4(0)_s$	
Ξ_b^-	LO	$2.28(33)_m$	$1.67(18)_m$	$1.70(27)_m(1)_\mu(1)_4(1)_s$	$1.572(40)$
	NLO	$2.78(41)_m$	$1.56(17)_m$	$1.55(23)_m(1)_\mu(0)_4(1)_s$	
Ω_b^-	LO	$2.28(33)_m$	$1.67(18)_m$	$1.76(28)_m(2)_\mu(2)_4(1)_s$	$1.64^{+0.18}_{-0.17}$
	NLO	$2.77(41)_m$	$1.55(16)_m$	$1.60(25)_m(1)_\mu(0)_4(1)_s$	

Uncertainties from $m_Q, \mu_H, \langle O_{4q}\rangle$, deviation of full QCD from HQET are denoted by the subscripts $m, \mu, 4, s$, respectively.

Matrix elements of dim-7 4-quark operators:

$$\langle P_i^q \rangle_{\mathcal{B}_Q} = m_q \left(S_{\mathcal{B}_Q}^q + P_{\mathcal{B}_Q}^q \right) \quad \text{for } i = 1, 2 \,,$$

$$\langle P_3^q \rangle_{\mathcal{B}_Q} = E_q L_{\mathcal{B}_Q}^q \,, \quad \langle P_4^q \rangle_{\mathcal{B}_Q} = E_q (S_{\mathcal{B}_Q}^q - P_{\mathcal{B}_Q}^q)$$