From hyperons to beauty baryons

challenges in heavy-baryon physics

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Outline

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Brief history

From the 50s to the 10s: some milestones

- Strangeness
- Lepton-hadron symmetry, charm?
- GIM
- Hidden charm
- Open charm
- τ suggests beauty
- Hidden beauty
- Open beauty
- B_c
- $X(3872)$, etc.

Weak decays-1

Shock when it was discovered that $\tau(D^+) \neq \tau(D^0)$

$K^\pm$	$(123.85 \pm 0.24) \times 10^{-10}$	K^0_S	$(0.8953 \pm 0.0005) \times 10^{-10}$
K^0_L	$(511.4 \pm 2.1) \times 10^{-10}$	$D^\pm$	$(1040 \pm 7) \times 10^{-15}$
D^0	$(410.1 \pm 1.5) \times 10^{-15}$	D_s	$(500 \pm 7) \times 10^{-15}$
$B^\pm$	$(1638 \pm 11) \times 10^{-15}$	B^0	$(1530 \pm 9) \times 10^{-15}$
B_s	$(1466 \pm 59) \times 10^{-15}$		

Λ	$(2.631 \pm 0.020) \times 10^{-10}$	$\Sigma^\pm$	$(0.8018 \pm 0.0026) \times 10^{-10}$
Ξ^0	$(2.90 \pm 0.09) \times 10^{-10}$	Ξ^-	$(1.639 \pm 0.015) \times 10^{-10}$
Ω^-	$(0.821 \pm 0.011) \times 10^{-10}$	Λ_c	$(200 \pm 6) \times 10^{-15}$
Ξ_c^+	$(442 \pm 26) \times 10^{-15}$	Ξ_c^0	$(112\,^{+13}_{-10}) \times 10^{-15}$
Ω_c^0	$(69 \pm 12) \times 10^{-15}$	Λ_b	$(1230 \pm 74) \times 10^{-15}$
Ξ_b^-	$(1490^{+200}_{-180}) \times 10^{-15}$	Ω_b^-	$(1130^{+530}_{-400}) \times 10^{-15}$

Weak-decays-2

For charm mesons, explanation in terms of $1/m_Q$ expansion, say

- antisymmetrization effects
- W exchange
- annihilation into W

Applied to make predictions for

- charm baryons
- beauty hadrons

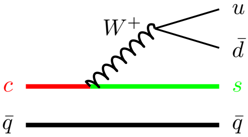
lifetimes, SL ratio, Cabbibo-suppressed ratio, . . . rather successful, but as compared to exp., the spread is

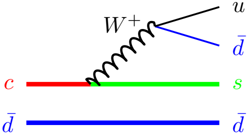
- too narrow for charm
- slightly too wide for beauty

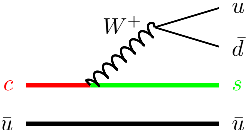
Exp.	Ξ_b^-	Ω_b^-
CDF	$1.32 \pm 0.14 \pm 0.02$	$1.66^{+0.53}_{-0.40} \pm 0.02$
LHCb	$1.55^{+0.10}_{-0.09} \pm 0.03$	$1.54^{0.26}_{-0.21} \pm 0.05$

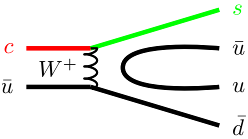
S. Stone, Marseille, 2014.

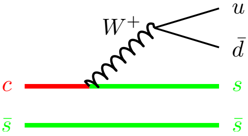
Weak decays-3
Meson decays

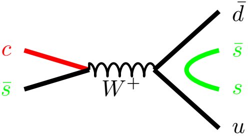




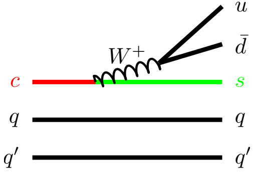


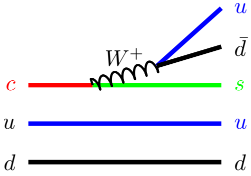


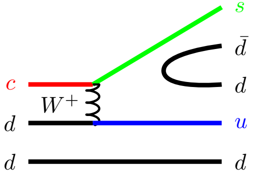


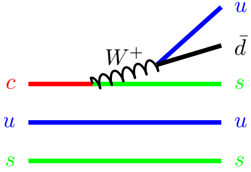


Weak decays-4
Some contributions to baryon decays

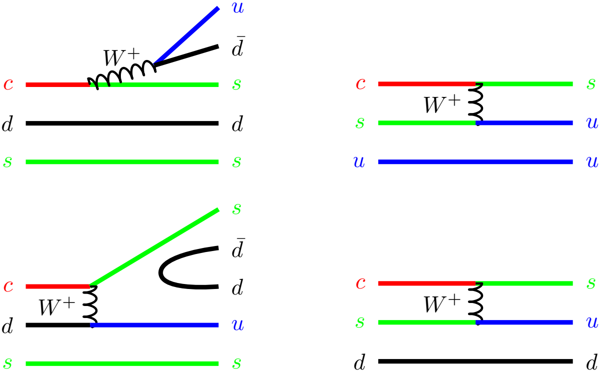








Weak decays-5
Some further contributions to baryon decays



Hyperons-1
Hyperfine splittings

- Early 60s: $\mathrm{SU(3)_F}$ breaking $M = M_0 + |S|\,\alpha + \cdots$
- For instance, $\Omega^- - \Xi^* \simeq \Xi^* - \Sigma^* \simeq \Sigma^* - \Delta$ (equal spacing)
- But $\Sigma - \Lambda$ not very natural
- Chromomagnetism $\to \Sigma - \Lambda$ (DGG, Le Yaouanc. . . , Isgur. . . , . . .)

If $\mathrm{SU(3)_F}$ and spin effects at 1st order and $a \propto \langle \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_j) \rangle$

$$\Lambda = M_0 - \alpha S - \frac{3a}{m^2}\,, \quad \Sigma = M_0 - \alpha S + \frac{3a}{m^2} - \frac{4a}{mM}\,, \quad \Sigma^* = M_0 - \alpha S + \frac{3a}{m^2} + \frac{2a}{mM}\,,$$

from which

$$\frac{2(\Sigma^* - \Sigma)}{\Sigma + 2\Sigma^* - 3\Lambda} = \frac{m}{M} \sim 0.64$$

and several similar relations, but for heavy Q, $a \to a_{ij} = \langle \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_j) \rangle$

Hyperons-2
Coupling to decay channels

- Large splitting between $\Lambda(1520) = (3/2)^-$ and $\Lambda(1405) = (1/2)^-$
- The analogue for strangeness $S = 0$ is very small
- Dalitz: coupling to $\bar{K}N$
- Inspired dozens of further investigations

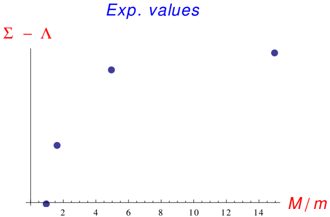
Hyperons-2

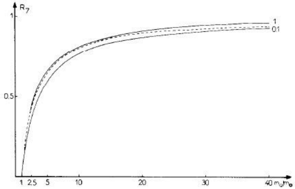
Hyperon-hyperon and hyperon-nucleon interaction

- A whole branch of nuclear physics
- Ongoing activity at J-Parc and Jlab
- $N\Lambda$ unbound
- $\Lambda\Lambda$ seemingly unbound (e.g., ${}^{6}_{\Lambda\Lambda} \not\Rightarrow H + \alpha$)
- (n, p, Λ) bound below $d + \Lambda$
- Speculations on (Λ, Λ, N)
- Or (Λ, Λ, n, n) being Borromean bound states

Ground state of heavy baryons with single flavour

- Good understanding of the spin average masses
- Good description of hyperfine splittings
- Simple quark models, more refined calc. (lattice, Sum rules)
- E.g., $\Sigma_Q - \Lambda_Q$, exp. vs. 1983 calculation





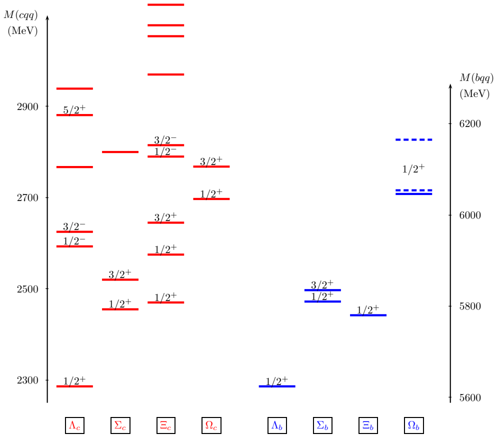
?. The ratio $R_7 = (\Sigma_Q - \Lambda_Q)/(\Sigma, - \Lambda,)$ as a function of m_Q/m_0, for the exponents
1 and for the Y-shaped linear potential (dashed curve). The results for $\beta = 2$ are very c

Ground state of heavy baryons with single flavour
Hyperfine splittings of Ξ_Q

- Similar pattern for $\Xi_Q = (Qsq)$, Ξ'_Q and Ξ^*_Q
- Further complication, 3 masses
- In the Ξ_Q and Xi'_Q, (sq) not pure $s = 0$ or $s = 1$.
- See preamble of the CMS paper: $\Xi'_b - \Xi_b$ is predicted to be about m_π,
- $\Xi^*_b - \Xi'_b \sim 20 - 30\,\text{MeV}$,
- Hence $\Xi^*_b \to \Xi_b + \pi$ allowed
- Ξ'_b contains a sizeable fraction of real or virtual $\Xi_b + \pi$ component.
- Will Ξ'_b be our $\Lambda(1405)$?

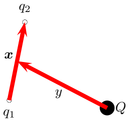
Ground state of heavy baryons with single flavour
Test of flavour independence

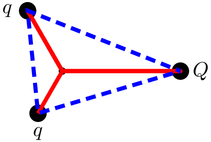
- Smooth behaviour as a function of m_Q expected
- For instance, the Ω_b of DØ was surprising



Excitations of (Qqq)

- One enters her the delicate domain of light quark physics
- With many problems for pseudoscalar mesons, scalar mesons, missing baryon states, . . .
- Many issues, for instance
- Is the linear confinement in mesons generalized as a Y-shape (minimal string) or pairwise?

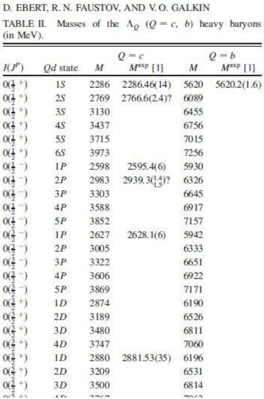




- What is the nature of the Λ(2940) that some models hardly accommodate: double excitation, hybrid, molecule? Another puzzle like Λ(1405)?

Excitations of (*Qqq*)
Diquark issue

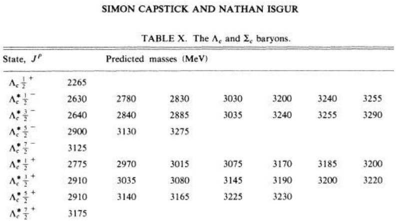
- Already a rich experimental spectroscopy of (*cqq*) and (*bqq*)
- Much more states in the quark-diquark model
- Even more in the symmetric quark model



D. EBERT, R. N. FAUSTOV, AND V. O. GALKIN

TABLE II. Masses of the Λ_Q ($Q = c$, b) heavy baryons (in MeV).

		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	$M^{\rm exp}$ [1]	M	$M^{\rm exp}$ [1]
$0(\frac{1}{2}^+)$	1S	2286	2286.46(14)	5620	5620.2(1.6)
$0(\frac{1}{2}^+)$	2S	2769	2766.6(2.4)?	6089	
$0(\frac{1}{2}^+)$	3S	3130		6455	
$0(\frac{1}{2}^+)$	4S	3437		6756	
$0(\frac{1}{2}^+)$	5S	3715		7015	
$0(\frac{1}{2}^+)$	6S	3973		7256	
$0(\frac{1}{2}^-)$	1P	2598	2595.4(6)	5930	
$0(\frac{1}{2}^-)$	2P	2983	$2939.3(^{1.4}_{1.5})$?	6326	
$0(\frac{1}{2}^-)$	3P	3303		6645	
$0(\frac{1}{2}^-)$	4P	3588		6917	
$0(\frac{1}{2}^-)$	5P	3852		7157	
$0(\frac{3}{2}^-)$	1P	2627	2628.1(6)	5942	
$0(\frac{3}{2}^-)$	2P	3005		6333	
$0(\frac{3}{2}^-)$	3P	3322		6651	
$0(\frac{3}{2}^-)$	4P	3606		6922	
$0(\frac{3}{2}^-)$	5P	3869		7171	
$0(\frac{3}{2}^+)$	1D	2874		6190	
$0(\frac{3}{2}^+)$	2D	3189		6526	
$0(\frac{3}{2}^+)$	3D	3480		6811	
$0(\frac{3}{2}^+)$	4D	3747		7060	
$0(\frac{5}{2}^+)$	1D	2880	2881.53(35)	6196	
$0(\frac{5}{2}^+)$	2D	3209		6531	
$0(\frac{5}{2}^+)$	3D	3500		6814	



SIMON CAPSTICK AND NATHAN ISGUR

TABLE X. The Λ_c and Σ_c baryons.

State, J^P	Predicted masses (MeV)						
$\Lambda_c\,\frac{1}{2}^+$	2265						
$\Lambda_c^*\,\frac{1}{2}^-$	2630	2780	2830	3030	3200	3240	3255
$\Lambda_c^*\,\frac{3}{2}^-$	2640	2840	2885	3035	3240	3255	3290
$\Lambda_c^*\,\frac{5}{2}^-$	2900	3130	3275				
$\Lambda_c^*\,\frac{7}{2}^-$	3125						
$\Lambda_c^*\,\frac{1}{2}^+$	2775	2970	3015	3075	3170	3185	3200
$\Lambda_c^*\,\frac{3}{2}^+$	2910	3035	3080	3145	3190	3200	3220
$\Lambda_c^*\,\frac{5}{2}^+$	2910	3140	3165	3225	3230		
$\Lambda_c^*\,\frac{7}{2}^+$	3175						

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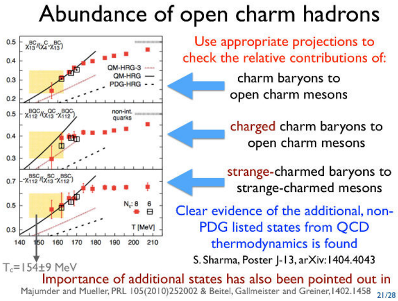
Diquark issue

- One should not aim at filling all the holes in the table
- But focus on the existence of states with both **x** and **y** excited
- Keep in mind that our colleagues of QCD thermodynamics would like to have more states
- See, e.g., talks at Quark Matter, Darmstadt, 2014



Abundance of open charm hadrons

T_c=154±9 MeV

Use appropriate projections to check the relative contributions of:

charm baryons to open charm mesons

charged charm baryons to open charm mesons

strange-charmed baryons to strange-charmed mesons

Clear evidence of the additional, non-PDG listed states from QCD thermodynamics is found

S. Sharma, Poster J-13, arXiv:1404.4043

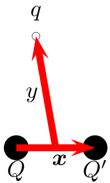
Importance of additional states has also been pointed out in

Majumder and Mueller, PRL 105(2010)252002 & Beitel, Gallmeister and Greiner, 1402.1458

Doubly-heavy baryons-1
Experimental situation

- (ccd) seen by SELEX with $\Lambda_c + K^- + \pi^+$ (PRL)
- (ccd) also seen by SELEX with $D + K^- + p$ (PLB)
- Not seen in other exp. at Fermilab
- Not seen at Babar, Belle and LHCb!!!!!!!!
- On the other hand, double charm production
- e.g., $e^+e^- \to J/\psi + \eta_c(2S)$
- is a little too large, as compared to expectations.
- Paradox: $c\bar{c} + c\bar{c}$ produced, not $cc + \bar{c}\bar{c}$

Heavy baryons with double flavour
Internal dynamics



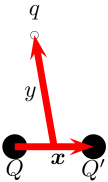
- Probably the most interesting of “ordinary” hadrons

- As it cumulates
  - the relativistic motion of a light quark (as in D, B, etc.)
  - the slow adiabatic motion of two heavy quarks (as in J/ψ, Υ)
- Some approximation are tempting, due to $M(Q) \gg m(g)$,
- And thus $\langle r(QQ)\rangle \ll \langle r(Qq)\rangle$
- Diquark vs. Born–Oppenheimer

Heavy baryons with double flavour
Diquark model

- one postulates the diquark mass,
- calculates it from an *effective* QQ interaction (there is a contribution of the light quark which is often forgotten).
- then one solves the $(QQ) - q$ problem
- first excitation? one calculates a new (QQ) states? This is a shortcoming.
- however, for the $(QQ)_{\mathrm{g.s.}} - q$ excitations, there is the interesting heavy diquark–antiquark symmetry. See, e.g., T. Cohen.

Heavy baryons with double flavour
Born-Oppenheimer

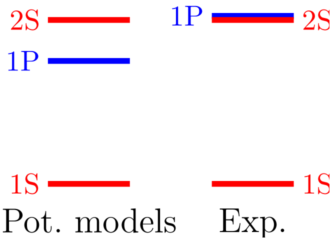


- For given **x**, solve the light quark q motion
- Add direct QQ interaction → adiabatic potential V_{QQ}

- Solve QQ motion in V_{QQ} → first levels
- Second set of levels if one adopts the excited q level
- Very similar to H_2^+ or H_2 in atomic physics
- Tested with NR potentials
- Improved with relativistic treatment or lattice treatment of q motion

Heavy baryons with triple flavour

- The ultimate dream of baryon spectroscopy (Bjorken)
- Analog of $(Q\bar{Q})$ in the baryon sector
- No light quark complication, except for pairs in the field
- Level ordering: long-standing problem of the Roper resonance



- Also problem with spin orbit, etc.
- (ccc), (ccb), (cbb) and (bbb) could be studied in the far future

Exotics-1
Hybrids

- Schematically, hybrid mesons $(Q\bar{Q}g)$,
- Born-Oppenheimer point view:
  - $(Q\bar{Q})$, ground state of the gluon field
  - $(Q\bar{Q}g)$, first excited level
- Similar, in principle for $(Qqqg)$
- But no exotic quantum #, unlike the meson case
- Identification harder

Exotics-2
Multiquark baryons

- Long history
    - Z baryons with strangeness $S=+1$ on the 60s
    - Speculations on $(qqqq\bar{q})$ within “colour chemistry” (Sorba, DeSwart et al.)
    - Light pentaquark more recently, not confirmed
    - 1987: Gignoux et al., Lipkin, $P=(\bar{Q}qqqq)$ based on chromomagnetism
    - Search for P at Fermilab: not conclusive
- LHC can certainly check the above states
- X, Y, Z spectroscopy in the meson sector
- Suggests $Q\bar{Q}$ exotics in the baryon sector, $(Q\bar{Q}qqq)$
- Generalised Born–Oppenheimer approach:
    - $Q\bar{Q}$ lowest adiabatic potential
    - $Q\bar{Q}g$ gluonic excitation
    - $Z(3940)^{+}$ $u\bar{d}$ excitation
    - *to be discovered*: (qqq) excitation

Double-flavour exotics

- $(QQ\bar{q}\bar{q})$ often proposed (first paper in 1982!)
- Converging predictions (potentials, sum rules, lattice)
- As compared to its threshold $(Q\bar{q}) + (Q\bar{q})$
- the lowest $(QQ\bar{q}\bar{q})$ benefits of
  - Better chromoelectric energy (QQ)
  - Better chromomagnetic energy (qq)
- Search might be done in parallel with (QQq)

Heavy exotics
Molecular dynamics

- $X(3872)$ described and even anticipated as $D\bar{D}^* + \mathrm{c.c.}$ (Törnqvist, Voloshin, Ericson , Karl, . . .)
- Many developments
  - Excited mesons, $D_1\bar{D}^{(*)}$, see, e.g., M. Nielsen, Oset, etc.,
  - $\mathrm{Charm} = 2$ sector (Monohar et al., Hozaka, Oka, . . .)
  - Extension to baryons (Riska et al., Oka et al.), e.g., $(ccq) + (ccq)$ bound
  - See, also, Karliner et al., $\Sigma_b^+\Sigma_b^-$, but Σ_b is unstable!
- The above $(Q\bar{Q}qqq)$ can be described as $D^{(*)}\Lambda_c$ or $D^{(*)}\Sigma_c$
- Nuclear potential weaker than $n - p$ binding the deuteron
- But experienced by heavier particles
- Thus possibility of binding

Double-charm dibaryons?

- $(QQqqqq)$ has two thredholds
    - $(Qqq) + (Qqq)$ better chromomagnetic energy
    - $(QQq) + (qqq)$ better chromoelectric energy
- The lowest $(QQqqqq)$ might combine the two advantages
- So, a quark approach could challenge the molecular model of Riska and Hozaka
- Presently under study

Outlook

Many hot issues linked to heavy baryons:

- Interplay between weak decays and quark dynamics
- Rich excitation spectrum of (Qqq):
    - Light quark confinement
    - Diquark clustering
- Double heavy flavour is a priority.
- Triple heavy flavour for the future
- Many exotics to be studied, besides checking the one discovered in Japan, in particular
    - ($QQ\bar{q}\bar{q}$), or, say, DD^*
    - ($Q\bar{Q}qqq$), or say, $\bar{D}^{(*)}\Lambda_c$
    - ($QQqqqq$), or say $\Lambda_c\Lambda_c$, $\Sigma_c\Lambda_c$,...
    - Heavy baryonium, or say, $\Lambda_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_c + \text{c.c.}$,...

THE END

BACKUP SLIDES

QQ interaction in the diquark model

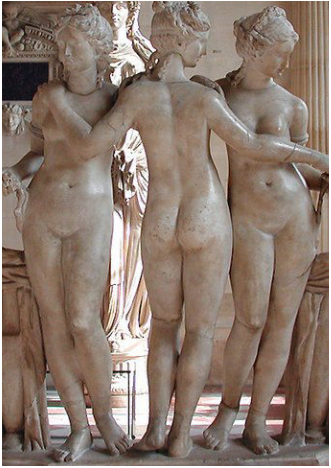
For instance, in the harmonic-oscillator model, with $(QQq) = (1, 2, 3)$,

$$r_{12}^2 + r_{23}^2 + r_{31}^2 = \frac{3}{2}\,\mathbf{x}^2 + \frac{3}{2}\,\mathbf{y}^2 \ ,$$

where $\mathbf{x} = \mathbf{r}_2 - \mathbf{r}_1$
and $\mathbf{y} = (2\mathbf{r}_3 - \mathbf{r}_1 - \mathbf{r}_2)/\sqrt{3}$.

Light quark dynamics

Heavy baryons with triple flavour



Triple beauty