Report on the Paris meeting on heavy baryons and exotics

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Arles, November 2018


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- June 2018
- Spectroscopy of heavy baryons and exotics
- Production
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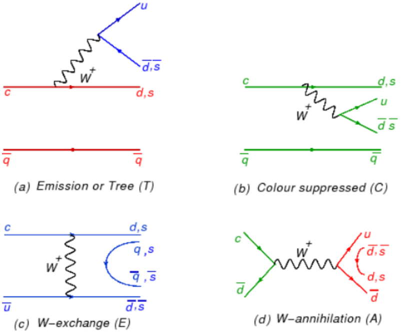
- Organizers: Emi Kou (Orsay), Matthew Charles (Paris), Jean-Marc Richard (Lyon), Patrick Robbe (Orsay), Yanxi Zhang (Tsinghua)
- Also recent workshop at CERN about perspectives with LHCb upgrade

Decay of charmed particles

- History: the shock of 1980 (Bacino et al.)

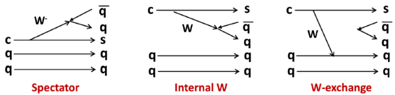
$$\tau(D^+)/tau(D^0) \gtrsim 4.5$$

- Confirmed at CERN (Baldini 1982) and Fermilab (Bacino, 1982)
- Explained by W-emission, W-exchange $c\bar{s}$-fusion, and interferences



Decay of charmed particles

- Extended to baryons



- Results at first rather puzzling

Weak decays

TABLE I. Lifetime of flavored mesons and baryons (in s) (Amsler *et al.*, 2008). Lifetimes of Ξ_b^- and Ω_b^-; see also Aaltonen *et al.* (2009).

$K^\pm$	$(123.85\pm0.24)\times10^{-10}$	K_S^0	$(0.8953\pm0.0005)\times10^{-10}$
K_L^0	$(511.4\pm2.1)\times10^{-10}$	$D^\pm$	$(1040\pm7)\times10^{-15}$
D^0	$(410.1\pm1.5)\times10^{-15}$	D_s	$(500\pm7)\times10^{-15}$
$B^\pm$	$(1638\pm11)\times10^{-15}$	B^0	$(1530\pm9)\times10^{-15}$
B_s	$(1466\pm59)\times10^{-15}$		
Λ	$(2.631\pm0.020)\times10^{-10}$	$\Sigma^\pm$	$(0.8018\pm0.0026)\times10^{-10}$
Ξ^0	$(2.90\pm0.09)\times10^{-10}$	Ξ^-	$(1.639\pm0.015)\times10^{-10}$
Ω^-	$(0.821\pm0.011)\times10^{-10}$	Λ_c	$(200\pm6)\times10^{-15}$
Ξ_c^+	$(442\pm26)\times10^{-15}$	Ξ_c^0	$(112^{+13}_{-10})\times10^{-15}$
Ω_c^0	$(69\pm12)\times10^{-15}$	Λ_b	$(1230\pm74)\times10^{-15}$
Ξ_b^-	$(1490^{+200}_{-180})\times10^{-15}$	Ω_b^-	$(1130^{+530}_{-400})\times10^{-15}$

Singly-heavy baryons

- Rather well documented now
- In particular CLEOc and other B factories
- And colliders.
- Usually well understood. One exception is DØ's $\Omega_b(bss)$, with $\Omega_b - \Lambda_b$ about 100 MeV higher than expected
- CDF and LHCb mass more plausible ($\Omega_b - \Lambda_b \simeq \Omega_c - \Lambda_c$)

Singly-heavy baryons

- Latest results discussed by Shen, Lyuboviskij, He
- In particular, set of 5 new Ω_c^* , with various J^P assignments

Observation of Five New Narrow Ω_c^0 States Decaying to $\Xi_c^+ K^-$

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **118**, 182001 – Published 2 May 2017

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\text{MeV}, 95\%\,\text{CL}$		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\,\text{MeV}, 95\%\,\text{CL}$		

- And various interpretations
- Valery Lyubovitskij discussed the structure (and decay) of heavy baryons in the CCQM (Covariant Constituent Quark Model) a kind of variant of QCD sum rules

Doubly-heavy baryons

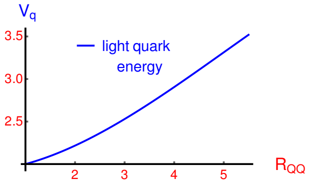
- Experimental situation reviewed by Murdo Thomas Traill
- SELEX (Fermilab) found Ξ_{cc}^{+} near 3519 MeV in two modes ($\Lambda_c + \cdots$, $D + \cdots$)
- Non confirmed by FOCUS,BaBar, Belle, LHCb
- Various claims by SELEX for isospin partners, never published
- LHCb Ξ_{cc}^{++} near 3621 MeV $\to \Lambda_c K^- \pi\pi$ (2017)
- Expl. if $\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+})$
- Second paper (2018) $\Xi_{cc}^{++} \to \Xi_c^{+}\pi$
- Lifetime $\tau(\Xi_{cc}^{++} = 256^{+22}_{-20}((stat)) \pm 14(\text{stat})$ fs
- to be compared to ~ 200 for Λ_c, ~ 500 for D_s, ~ 1000 for D^+, ~ 400 for D^0
- old ~ 70 for Ω_c, new ~ 270 by LHCb this year

Doubly-heavy baryons

- Interesting talk by Brodsky, who hardly gives up SELEX results
- And suggests the possibility of two types of DCB
  - $[cq]c$ type SELEX
  - $[cc]q$ type LHCb
  - Pandora box?
- Talk by JMR about constituent models
- Discuss diquark-quark vs. Born-Oppenheimer
- Diquark either as a fundamental constituent
- Or an approximation to the 3-quark problem? Not very good. First excitations within QQ.
- Born-Oppenheimer (1927) best suited
- Provide with an effective QQ pot. to be compared to the $Q\bar{Q}$ one

Doubly-heavy baryons

- Obviously $r(QQ) \ll r(Qq)$ in (QQq) for large M/m
- The two heavy quarks are clustered in the ground state
- But the naive diquark model is misleading
- The diquark internal energy is modified by the third quark,
- The first excitations are within QQ



Born-Oppenheimer potential for (QQq), $M/m = 5$, $V \propto \sum_{i<j} r_{ij}$
Fleck, R., PTP 82 (1989) 760

Exotics: general considerations

- Many candidates, e.g.,
- *Z* baryon of the 60, coming back as light pentaquark
- Baryonium

Volume 72B, number 1 PHYSICS LETTERS 5 December 1977

EVIDENCE FOR A NARROW WIDTH BOSON OF MASS 2.95 GeV

Bari–Bonn–CERN–Daresbury–Glasgow–Liverpool–Milano–Purdue–Vienna Collaboration

- Many speculations *Arx Tarpei Capoli Proxima* ("the Tarpeian Rock is close to the Capitol")
- Dibaryon H, ...
- Heavy pentaquark $\bar{c}uuds$ $\bar{c}ddus$, $\bar{c}ssud$ (Gignoux et al., Lipkin)

Exotics: sociology

- As $QQ\bar{q}\bar{q}$ becomes fashionable
- Matthew effects
  - 11th hour effect *So the last will be first, and the first last* (Matthew 20.16)
  - *For to him who has will more be given; and from him who has not, even what he has will be taken away* (Mathew 25.29)
    See R. Merton, *The Matthew effect in Science* Science, 159:56-63 (1968)
- Early papers 1981 $\rightarrow$ conscientiously or inadvertently omitted

Favorable symmetry breaking in $QQ\bar{q}\bar{q}$

- Symmetry breaking $\searrow$ ground state energy.
  For instance $p^2 + x^2 + \lambda\, x$, gives $E = 1 - \lambda^2/4$
- In 4-body, often benefits to threshold
  For instance, $(\mu^+, \mu^+, \mu^-, \mu^-)$ stable becomes
  (M^+, m^+, M^-, m^-) unstable if $M/m \gtrsim 2.2$ (Varga, Bressanini)
- Charge-conjugation breaking benefits to the 4-body system

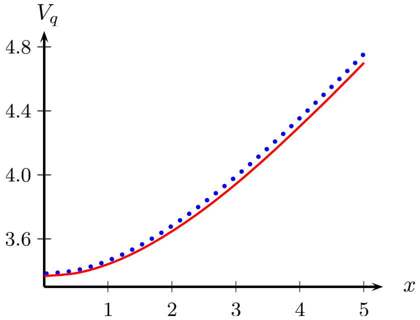
$$H = \frac{\boldsymbol{p}_1^2}{2\,M} + \frac{\boldsymbol{p}_2^2}{2\,M} + \frac{\boldsymbol{p}_3^2}{2\,m} + \frac{\boldsymbol{p}_4^2}{2\,m} + V = H_{\text{even}} + H_{odd}$$

$$= \left[\sum_i \frac{\boldsymbol{p}_i^2}{2\,\mu} + V\right] + \left(\frac{1}{4\,M} - \frac{1}{4\,m}\right)\left(\boldsymbol{p}_1^2 + \boldsymbol{p}_2^2 - \boldsymbol{p}_3^2 - \boldsymbol{p}_4^2\right),$$

- μ kept constant: $|M - m| \nearrow \quad \Rightarrow \quad E \searrow$ at fixed threshold
- H_2 much more stable than Ps_2, and in a chromoelectric quark model (flavor independent) $QQ\bar{q}\bar{q}$ becomes stable above some critical M/m

$QQ\bar{q}\bar{q}$

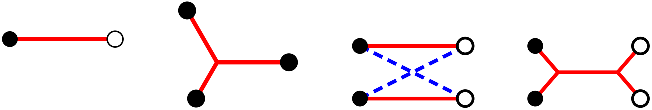
- Doubly-heavy tetraquark in the BO limit
- If restricted to color $\bar{3}3$



- Implies $QQ\bar{q}\bar{q} \simeq QQq + Qqq - Q_barq$ (see Eichten+Quigg)
- But this is more favorable with admixture of color $\bar{6}6$ configurations

Stability of $QQ\bar{q}\bar{q}$: bb or cc?

- $bb\bar{q}\bar{q}$ for sure. See, e.g., the talk on Lattice QCD by Bicudo (Lisbon),
- $cc\bar{u}\bar{d}$ in some models, for $J^P = 1^+$, thanks to favorable chromomagnetism
- $bc\bar{q}\bar{q}$ suggested by string model of confinement
- under discussion with some lattice groups



- The flip-flop interaction gives more attraction, if not restricted by the Pauli principle

Signature of $QQ\bar{q}\bar{q}$?

- $bb\bar{q}\bar{q}$ decays weakly. Already discussed in some papers
- $bc\bar{u}\bar{d}$, if below $D + \bar{B}^*$, weakly
- $cc\bar{u}\bar{d}$
  - If very loosely bound: peak in $DD\pi$
  - if loosely bound: $DD\gamma$
  - if deeply bound (unlikely) : weak decay

All-heavy $bb\bar{b}\bar{b}$

- A few speculations
- Some predictions of bing in the quark model
- Based on erroneous 4-body calculations!
  - Some authors consistent: also wrong on tetraneutron
  - Some authors very good on quarkonium, but $\searrow$ as $n \nearrow$ *Corruptio optimorum pessima*[1]
- Reasoning like: the heavier the quark, the mode deeply bound $QQ\bar{Q}\bar{Q}$
- But the threshold also decreases!

[1] The corruption of the best is the worst

Other exotics

- Anticharmed pentaquark $\bar{Q}qqqq$
  - favorable chromomagnetic interaction (Gignoux et al., Lipkin, 1987)
  - Searched for at Fermilab (Ashery et al.) and HERA not conclusive
  - Not found stable in recent revisits
- Double charm dibaryon $QQqqqq$: same conclusion
- Hidden-charm pentaquark in the continuum
  - Technical progress: real scaling (Hiyama, Oka, Hosaka, R.)
  - Clear separation of genuine resonances
  - Candidates with $(3/2)^-$ and $(5/2)^-$, but too high in simple models
- Hidden-charm pentaquark below threshold
  - Some states predicted below lowest mes. + bar.
  - Quantum numbers # from LHCb pentaquarks
  - New final states to be analyzed (Valcarce, Vijande, R.)

Outlook

- Drastic revision of $\tau(\Omega_c)$
- Other lifetimes to be re-mesured? and SL BR?
- New excitations identified in *Qqq* sectors, some strikingly narrow
- *QQq* gives access to the effective
- And resurrected speculations on $QQ\bar{q}\bar{q}$ which could be the first stable multiquark apart from the deuteron
- A consequence of flavor independence and favorable *C*-symmetry breaking