Exotic Baryons: Past and Future

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**Exotics**: delicate subject

**Arx tarpeia capitoli proxima**

The Tarpeian Rock is close to the Capitol

*Brilliant, imaginative, and anticipating theory*

Senseless model, with unjustified approximations, that contradicts QCD
Exoticism: a time-dependent concept

- $\phi$ was exotic: narrow, branching ratio $K\bar{K}$, ...
- $J/\psi$ was still exotic in 1974
- $\Upsilon$ never exotic
- (ccg) first considered as straightforward ordinary hadrons slowly enter the realm of exotics
- etc.
**Z-baryons-1**

**Differential Cross Sections for $K^+n$ Charge-Exchange Scattering in Deuterium Between 0.64 and 1.51 GeV/c**

G. GIACOMELLI, P. LUGARESI-SERRA, A. MINGUZZI-RANZI and A. M. ROSSI
University of Bologna, INFN, Sezione di Bologna

F. GRIFFITHS, A.A. HIRATA, I.S. HUGHES, R. JENNINGS and B.C. WILSON
University of Glasgow

Measurement and analysis by the Bologna-Glasgow-Rome-Trieste coll.

**Evidence for an $S=+1, I=0$ Resonance in the $K^+n$-Nucleon System**

A. A. Carter
Cavendish Laboratory, Cambridge, England
(Received 20 February 1967; revised manuscript received 6 April 1967)

We evaluate the phase of the $K^+n$-nucleon forward-scattering amplitude from dispersion relations and find a qualitative difference between the $I=0$ and $I=1$ state. With assumptions for the background contributions to the amplitude, we present evidence for an $S=+1, I=0$ resonance.

Another analysis: A.A. Carter, later at work on $\bar{p}p \rightarrow$ two pseudoscalars

**Evidence for New Meson Resonances from the Reaction $\bar{p}p \rightarrow K^+K^-$**

A.A. CARTER
Department of Physics, Queen Mary College, London

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List of candidates
$Z_0(1780)$ with $(1/2)^+$, $Z_0(1865)$ with $(3/2)^-$,
$Z_1(1900)$ (with $(3/2)^+$, $Z_1(2150)$ and $Z_1(2500)$ (several bumps)
based on “delicate” amplitude analyses of data with poor statistics
and no spin measurement.
Still $\exists$ analyses without enough exp. data
Contrasts with the modern serious analyses, e.g., for photoproduction
Light pentaquark

with hundreds of subsequent papers.
Data on tape for years revealed surprises!
For instance $K^- p \rightarrow \pi^- + R^+$ (Amirzadeh et al., 1979)
Singly heavy pentaquark

- Again, mainly a theory prediction
- Following $H = (uuddss)$ predicted in 1977, based on coherences in the chromomagnetic interaction
- Gignoux et al., and Lipkin predicted in 1987 the $P = (\bar{Q}qqqq)$ where $qqqq = uuds, ddsu, ssud$

We thank H.J. Lipkin for very fruitful discussions

- See, also, Lipkin @ baryon80
Singly heavy pentaquark-2

Experimental search: a few experiments

- E791
- HERA
Pentaquark with hidden heavy flavour-1

- Not too much anticipated (chromomagnetism, molecules, . . .)
- Announced by LHCb from $\Lambda_b \rightarrow pKJ/\psi$ fully reconstructed

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \rightarrow J/\psi K^-p$ Decays

R. Aaij et al.
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \rightarrow J/\psi K^-p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb$^{-1}$ acquired with the LHCb detector from 7 and 8 TeV $pp$ collisions. An amplitude analysis of the three-body final state reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred $J^P$ assignments are of opposite parity, with one state having spin $3/2$ and the other $5/2$.

- Background assumed as $\sum J/\psi + \Lambda^{(*)}$
- Quantum # $(3/2)^\pm$ and $(5/2)^\mp$
Pentaquark with hidden heavy flavour-2

- Several authors (Burns et al., Oset et al., …) pointed out the need for other production modes
- Direct hadronic production, or other similar weak decays ± Cabibbo suppressed, ± favoured by FSI

- Isospin and strange partners are also rather welcome to complete the picture in most models
Duality

- Equivalence of av. \textit{s-ch. exch.} vs. \textit{t-ch. exch.}
- 1st at hadron level, now quark diagrams
- For, e.g., \( \pi \pi \) or \( KN \):

\[ \text{Diagram} \]

- See Rosner, D.P. Roy's review, etc, baryonium partner of mesons in \( \bar{N}N \),

\[ \text{Diagram} \]

- Exotic baryon in \( BB \), dibaryon in \( \mathcal{P} - B \), etc.

\[ \text{Diagram} \]
Strings and junctions

- Duality inspired the (hadronic) string model, Artru, Rossi, Veneziano, . . .
- Mesons: $\bullet - \circ$
- Baryons: $\bullet$ junction $J$: almost like a 4th constituent,
- $\sim$ Zweig rule: internal ($J$, $\bar{J}$) annihilation suppressed
- and leading to Lego-type construction of multiquarks
- Baryonium:
- Decays to baryonium + meson or baryon + antibaryon
Strings and junctions

**Pentaquark**

Decays to another pentaquark or into $B\bar{B}$ by double string breaking

**Dibaryon**

Decay to $BB\bar{B}B$ or $BB\bar{B}$?

**Higher baryonium**

Decay to junction-rich hadrons
Strings and junctions
Strings and junctions

At the time of baryonium candidates, the junction-antijunction model challenged by

- **Quasi-nuclear** model (Shapiro et al., Dover et al., ...)
- **Orbital barrier** $qq - \bar{q}\bar{q}$ (Jaffe)
- **Colour excitations** diquarks with colour 6 (Chan H.M. et al.)

**Annihilation** was a problem in all models.

$$\sigma_{\text{ann}} \sim 2 \sigma_{\text{el}}$$
and $\sigma_{c.e.}$ very suppressed
requires a strong annihilation with a non-negligible range
redStrings in potential models

- Mode naive reading of the string diagrams
- Mesons: $V_{\text{conf}} = \lambda r$
- Baryons: $V_{\text{conf}} = \lambda \min J(r_1 J + r_2 J + r_3 J)$ (Artru, Dosch, Merkuriev, Kuti et al., Kogut, . . . )

For 2 quarks and 2 antiquarks, a famous prototype: flip-flop by Lenz et al., in the linear version, $V_{\text{conf}} = \lambda \min (r_{13} + r_{24}, r_{14} + r_{23})$, revisited recently (Valcarce et al., Bicudo et al., Ay et al.), including in the minimisation
Strings in potential models

- Nice geometrical properties of the Steiner trees, back to Fermat & Torricelli,
- Extended to $q^2\bar{q}^2$ (Ay et al., Bicudo et al.)

Fermat-Torricelli solution for baryons using the construction of Napoleon's theorem.

The quarks $\{v_1, v_2\}$ form an equi. triangle with $w_{12}$, the antiquarks $\{v_3, v_4\}$ with $w_{34}$, the line $w_{12}w_{34}$ joining the auxiliary points gives the solution.
Strings in potential models

In space
Properties of the string potential

One can show that

\[
\min \left\{ \alpha |x| + \beta |y| + \gamma |z| \right\} \leq \alpha |x| + \beta |y| + \gamma |z|
\]

where \( x \), \( y \) and \( z \) are the Jacobi coordinates, deduce some upper bound for the energies, and demonstrate stability for some mass configurations.
Strings in potential models

As compared to the usual colour-additive rule

$$V_{\text{col.add.}} = -\frac{3}{16} \lambda \sum_{i<j} \tilde{\lambda}_i \tilde{\lambda}_j r_{ij},$$

the string-inspired tetraquark potential

$$V_{\text{string}} = \lambda \min \left\{ \right\}$$

is more attractive, and thus favours tetraquark binding. It corresponds to a Born-Oppenheimer effective potential, but it spoils the symmetrisation or antisymmetrisation properties. States with different quarks and antiquarks benefit from the optimal $\bar{3}3 - 6\bar{6}$ mixing of colour-singlet states.
Strings in potential models

Same improved attraction for 6-quark potentials. For pentaquark,

\[ V_{\text{string}} = \lambda \min \left\{ \begin{array}{c}
\begin{array}{c}
\bullet \\
\bullet \\
\bullet
\end{array}
, \\
\begin{array}{c}
\bullet \\
\bullet \\
\bullet
\end{array}
\end{array} \right\} \]

PHYSICAL REVIEW C 81, 015205 (2010)

Stability of the pentaquark in a naive string model

but, again, antisymmetrisation is lost. So look at \((\bar{b}, c, s, u, d)\) or similar.
In practice, constituent models try to combine chromoelectric effects (e.g., $QQ$), chromomagnetic effects (à la $H$) and long-range Yukawa attraction to stabilise the effects. See, e.g., the recent discussion by Hozaka et al. for $(QQ\bar{q}\bar{q})$ and ongoing work by Valcarce et al. on dibaryons $(QQqqqq)$. 
A warning: **Pandora box syndrome**

- Many models, custom-designed for 1 or 2 exotics
- Tend to produce many others
- For instance, first molecular models focused on $\pi$-exchange,
- With drastic selection rules
- With vector-exchanges, scalar-exchanges, etc., many more possibilities
- Same problem in early “colour-chemistry”
- Same problem with diquarks: do we predict dibaryons?
2012 excess $H\gamma\gamma$ (now seemingly removed)
More recent 750 GeV bump at LHC,
Suggest the possibility of scalar objects
Among the many scenarios: scalar quarks, with or without supersymmetry, colour 3
Then ($\varsigma\bar{\varsigma}$) “squarkonia” if $\varsigma$ lifetime is long enough.
Remember many speculations about topomonium before it was realised that the $t$ lifetime will be too short!
Baryons $\varsigma q, q$ with spin 0 or 1 (if charged, visible!)
Double scharm baryons $\varsigma\varsigma q$ g.s. with $\ell_{\varsigma\varsigma} = 1$, $J^P = (1/2)^-, (3/2)^-$
Triple scharm baryons $\varsigma\varsigma\varsigma$ will use the same wave function as $N(1900)$ (rescaled), in the HO approximation
\[ \Psi \propto x \times y \exp \left[ -\alpha (x^2 + y^2)/2 \right], \]
first written by Dalitz in the 60s.
THE END
Extra slides
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