Exotic Hadrons with Heavy Quarks


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IHEP, Pekin U., Nankai U., 2013
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3 Outlook
Molecules: History

- Hadron–hadron pairs bound by Yukawa-type of forces
- Note: sometimes critical for 2-body, so very exotic hadron–hadron–hadron systems anticipated (Borromean binding),
- Any hadron containing light quark(s) experiences nuclear forces,
- Usually weaker than for nucleon,
- But effect enhanced by larger masses
- Remember: for

\[ H = \frac{p^2}{m} - g V(r) = \frac{1}{m} \left[ p^2 - m g V(r) \right], \]

the existence of a discrete spectrum depends on \( m g \),
- Molecular binding by pion exchange rather selective, due to the spin and isospin factors

\[ V \propto \sigma_i \cdot \sigma_j \tilde{\tau}_i \cdot \tilde{\tau}_j \]
Molecules: lessons from baryonium

- The idea of building mesons from $\bar{N}N$ is rather old. This was part of the “bootstrap” program in the 50s. In short, every hadron is made of hadrons. This corresponds to an infinite set of infinitely intricated coupled equations, of which approximate solutions were searched.
- For instance $\Delta \simeq (N + \pi)$
- Why not meson = baryon + antibaryon?
- Early work by Fermi and Yang: $\bar{N}N$ more attractive on the average than $NN$
- Later work by Sakata et al. within SU(3), before the quarks
- Selection rules for the pion exchange $\propto \sigma_i \cdot \sigma_j \tilde{\tau}_i \cdot \tau_j$ either positive or negative,
- Also coherences from the various exchanges ($\pi$, $\rho$, etc.)
Molecules: light baryonium

Strong coherences in proton–proton spin-orbit
Strong coherences in $\bar{N}N$ tensor forces.

Spin 1/2 – Spin 1/2 dynamics with tensor forces:

- very weak, e.g. muonium ($\mu^+ e^-$): small deformation
- weak, e.g. ($\bar{c}c$): gives leptonic coupling to $^3D_1$ states,
- strong, e.g., proton-neutron: significant contribution to deuterium binding
- very strong, e.g., ($\bar{N}N$) with isospin $I = 0$: gives an exotic ordering $^3P_0$, a combination of $^3S_1$ and $^3D_1$, etc., favouring natural parity

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**TABLE I. Signs of meson-exchange contributions to Wigner ($V_C$), spin-spin ($V_{SS}$), spin-orbit ($V_{LS}$), and tensor ($V_T$) potentials for the NN system.**

<table>
<thead>
<tr>
<th>Meson</th>
<th>$V_C$</th>
<th>$V_{SS}$</th>
<th>$V_{LS}$</th>
<th>$V_T$</th>
<th>$V_C$</th>
<th>$V_{SS}$</th>
<th>$V_{LS}$</th>
<th>$V_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>$\rho$</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>$\omega$</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>$\delta$</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>+</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

**TABLE II. Signs of contributions to $V_C$, $V_{SS}$, $V_{LS}$, $V_T$ for the $\bar{N}N$ system.**

<table>
<thead>
<tr>
<th>Meson</th>
<th>$V_C$</th>
<th>$V_{SS}$</th>
<th>$V_{LS}$</th>
<th>$V_T$</th>
<th>$V_C$</th>
<th>$V_{SS}$</th>
<th>$V_{LS}$</th>
<th>$V_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0</td>
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<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>$\rho$</td>
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<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>$\omega$</td>
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<td>+</td>
<td>-</td>
<td>+</td>
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<td>+</td>
<td>-</td>
</tr>
<tr>
<td>$\delta$</td>
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<td>0</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>$\epsilon$</td>
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<td>-</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>
Hidden-strangeness molecules

Several attempts:

- Dover and Goldhaber
  
  Possibility of $N\,N$, $\Lambda\,\Lambda$, $\Sigma\,\Sigma$, and $\Xi\,\Xi$ quasinuclear states

- Weinstein and Isgur
  *Phys. Rev. D 41, 2236–2257 (1990)*

**KK molecules**

a one of the many contributions to the debate on scalar mesons
Molecules: hidden charm

Early speculations

Dover, Kahana, Trueman


**Possibility of Charmed Hypernuclei**

*Bound States of Charmed Baryons and anti-Baryons.*
Published in *Phys. Rev. D16 (1977) 799-815*

In the line of the speculations on baryonium, stimulated by the observations of peaks in antiproton cross-sections and in $\bar{p}p \rightarrow \gamma + X$. These peaks were not confirmed at LEAR (Low Energy Antiproton Ring) at CERN in the 80s-90s. Enhancements, however, seen in baryon–antibaryon pairs from quarkonium decay or heavy-meson decay.
Molecules: hidden charm

Very early speculations

- Already for $\psi'$

Progress of Theoretical Physics, Vol. 54, No. 2, August 1975

A Possible Model for New Resonances

--- Exotics and Hidden Charm ---

Yoichi Iwasaki

Research Institute for Fundamental Physics
Kyoto University, Kyoto

(Received January 23, 1975)

We assign $\psi(3685)$ to an exotic meson $c\bar{c}(p\bar{p}+n\bar{n})$ and $\psi(3105)$ to a vector meson $c\bar{c}$, respectively. Then we can explain naturally two facts: 1) $\psi(3685)$ decays strongly to $\psi(3105)+2\pi$ and 2) there is very little $\psi(3685)$ production compared with $\psi(3105)$ production in $p\bar{p}$ scattering at Brookhaven. In this model we expect two broad resonances at 3.7–4.1 GeV and at $\sim$4.1 GeV. We also predict another resonance at $\sim$6.2 GeV, which will be a sharp resonance if the mass is smaller than twice the mass of the lowest mass state of $c\bar{c}$.

We can explain the small branching ratio of the decay $\psi(3000)\rightarrow2\pi$, assigning $\psi(3000)$ to an exotic meson $\psi(3000)(p\bar{p}+n\bar{n})$. We make some speculations on the decays of $\psi(3685)$ and other exotic mesons.

In fact, these states were identified as radial excitations.

- The same story was repeated for some higher resonances,

Hydronic molecules and the charmonium atom

M. B. Voloshin and L. B. Okun

Institute of Theoretical and Experimental Physics
(February 16, 1976)


We consider the possible existence of levels in a system consisting of a charmed particle and a charmed antiparticle; these levels result from exchange of ordinary mesons ($\omega, \phi, \chi, \psi$, etc.). An interpretation of the resonances in $\psi'\bar{\psi}'$ annihilation in the region 3.9–4.8 GeV is presented.

Molecular Charmonium: A New Spectroscopy?

A. De Rujula, Howard Georgi, and S. L. Glashow

Harvard Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 22 November 1976)

Recent data compel us to interpret several peaks in the cross section of $\omega\psi'$ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in $\psi'\bar{\psi}'$ annihilation.
More recent flavoured-meson molecules

- In the 80s, the Yukawa interaction of charmed mesons $D = (c\bar{q})$, $D^* (c\bar{q})$ was stressed by Manohar & Wise, Ericson & Karl, Törnqvist, who predicted the existence of molecules $D^{(*)} D^{(*)}$ or $D^{(*)} \bar{D}^{(*)}$.

- Hence the $X(3872)$, discovered near the $D - \bar{D}^*$ threshold was greeted as a success of this approach,

- Other states seen in various experiments $X$, $Y$, $Z$, both with hidden charm or hidden beauty, and even some charged candidates (genuine exotics if confirmed).

- On the other hand, some properties suggest a structure of radially excited $Q\bar{Q}$,

- Most states are probably a mixture of $(c\bar{c})$ and $D^{(*)} \bar{D}^{(*)}$.
Flavour baryons as molecules?

A long story

Model Calculation for the $Y_0^{*}(1405)$ Resonance State

R. H. Dalitz and T. C. Wong
Theoretical Physics Department, Oxford University, Oxford, England,

and

G. Rajasekaran
Tata Institute for Fundamental Research, Bombay, India

Charmed baryons as soliton–D meson bound states

Mannque Rho
Service de Physique Théorique, CEN Saclay, F-91191 Gif sur Yvette, France

D.O. Riska
Research Institute for Theoretical Physics, University of Helsinki, 20B Silwanorenpen, SF-00170 Helsinki 17, Finland

and

N.N. Scoccola
Institute of Theoretical Physics, University of Regensburg, W-8400 Regensburg, FRG

Received 6 August 1990, revised manuscript received 30 August 1990

Hadronic molecules for charmed and bottom baryons near thresholds

Yasuhiro Yamaguchi, Shunsuke Ohkoda, Shigeo Yasui, and Atsushi Hosaka

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Flavour-exotic baryons as molecules?

- Also a long story
- starting with the so-called “Z” resonance, to become “Θ”
- regularly revisited in particular for heavy flavour

PHYSICAL REVIEW D 84, 014032 (2011)
Exotic baryons from a heavy meson and a nucleon: Negative parity states

Yasuhiro Yamaguchi,1 Shunsuke Ohkoda,1 Shigehiro Yasui,2 and Atsushi Hosaka1
Further molecules: meson–meson with double charm?

From the deuteron to deusons, an analysis of deuteronlike meson-meson bound states

Nils A. Törnqvist

Exotic $Q\overline{Q}qq$ states in QCD

Aneesh V. Manohar

*CERN, TH-Division, CH-1211 Geneva 23, Switzerland*

Mark B. Wise

*California Institute of Technology, Pasadena, CA 91125, USA*

Strength of pion exchange in hadronic molecules

T.E.O. Ericson, G. Karl

Exotic mesons with double charm and bottom flavor

S. Ohkoda, Y. Yamaguchi, S. Yasui, K. Sudo, and A. Hosaka

*Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka, 567-0047, Japan*

*KEK Theory Center, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization, I-1, Oho, Ibaraki, 305-0801, Japan*

*Nishogakusha University, 8-16, Sambancho, Chiyoda, Tokyo, 102-8336, Japan*

Coupled-channel analysis of the possible $D^{(*)}D^{(*)}$, $\overline{B}^{(*)}\overline{B}^{(*)}$ and $D^{(*)}\overline{B}^{(*)}$ molecular states

Ning Li, Zhi-Feng Sun, Xiang Liu, and Shi-Lin Zhu

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Further molecules: baryon-baryon with charm $C \geq 2$?

- $C = 2$
- Several attempts to study the stability of $(cqq) + (cqq)$.

**Possible $\Lambda c\Lambda c$ molecular bound state**

Wakafumi Meguro, Yan-Rui Liu, Makoto Oka

- Question: should one also consider the $(ccq) + (qqq)$ threshold,
- Similar to $\Lambda \Lambda \leftrightarrow \Xi N$ mixing in hypernuclear physics.
- $C = 4$
- Charm $+4$ Frömel, Julia-Diaz & Riska: a whole periodic table of nuclei made of double-charm baryons?

**Bound states of heavy flavor hyperons**

F. Frömel, B. Juliá-Diaz, D.O. Riska

- Again, $(ccq) + (ccq) \leftrightarrow (ccc) + (cqq)$ should be included.
Equivalence of (sum of) s-channel and t-channel exchanges

led Rosner to predict new states, \((q^2\bar{q}^2)\) in the quark language, preferentially coupled to baryon–antibaryon. **Baryonium** was born!

*Physical Review Letters* 21, 13 (1968)

**Possibility of Baryon–Antibaryon Enhancements with Unusual Quantum Numbers**

Jonathan L. Rosner

Arguments are presented in favor of \(B=0\) enhancements in the 10, 10*, and 27 representations of SU (3) which decay mainly into a baryon and...
Already the Pandora-box syndrome


- Baryonium + baryon suggests pentaquark
- Pentaquark + baryon suggests dibaryon
- etc.

Exotics
Quark model of baryonium. 1. “True baryonium”

Alternative to the quasi-nuclear model mentioned above. Jaffe, Rossi and Veneziano, etc., describe these (tentative) new mesons as

$$(qq) - (\bar{q}\bar{q})$$,

the orbital barrier preventing from rearrangement into two $(q\bar{q})$ mesons.

Note: this clustering is postulated, not really demonstrated from a 4-body calculation.

Thus: preferentially coupled to baryon–antibaryon by string breaking and $(q\bar{q})$ creation.
Chan-Hong Mo et al. went further and imagined color sextet diquarks. Thus the decay into baryon–antibaryon is also suppressed, and the state is predicted as very narrow! They invented colour chemistry!

Even more controversial, as $qq$ forces as perhaps not attractive in this colour channel.

Many further papers, Sorba et al. DeSwart et al., etc.
Tetraquark model of light scalars

Within the bag model, but the argument is more general, it was realised that the cost of an orbital excitation of $q\bar{q}$ is equivalent to the cost of a pair creation. Thus competition for the description of scalar mesons, and an endless series of discussions, with mixing and other refinements.
Chromomagnetism-1

- In the late 70s, Jaffe studied the properties of
  \[ V_{ss} = \sum_{i<j} -\frac{K}{m_i m_j} \sigma_i \cdot \sigma_j \tilde{\lambda}_i \cdot \tilde{\lambda}_j v_{ss}(r_{ij}), \]

- Or bag model analogue, assuming
  - Perturbative treatment
  - Equal masses for \( u, d, s \)
  - \( \langle v_{ss}(r_{ij}) \rangle \) universal

- This focusing on the properties of the chromo-magnetic operator
  \[ \mathcal{O} = \sum_{i<j} \sigma_i \cdot \sigma_j \tilde{\lambda}_i \cdot \tilde{\lambda}_j \]

- And found striking coherences, in particular for \( H = (uuddss) \)
- Namely attractive and
  \[ \langle \mathcal{O} \rangle_H = 3 \langle \mathcal{O} \rangle_\Lambda, \]

- \( H \) is bound by about 150 MeV below the degenerate threshold
  \( \Lambda\Lambda = N\Xi = \Sigma\Sigma, \)
Further studies (e.g., DeSwart et al., Sorba et al., . . . ) indicated that this model favours the most asymmetric flavour configurations.

The role of flavour illustrated in the $P = (\bar{c}uuds)$ (Lipkin, Gignoux et al, 1987)

with charm and strangeness

If $M \to \infty$ and SU(3), same 150 MeV binding below $D + N$ as $H$ below $\Lambda \Lambda$

SU(3) triplet $\bar{Q}uuds$, $\bar{Q}ddus$, $\bar{Q}ssud$. 
However, the $H$ was never found, in spite of intensive search,
The $P$ not found in one experiment,
And, careful studies (Oka, Yazaki, . . . , Karl et al., Rosner, . . .) indicated that a proper account for
- SU(3) breaking
- Self consistent short-range correlation $\langle \nu_{ss}(r_{ij}) \rangle$
spoils the binding. See, however, recent lattice QCD results.
Nevertheless, chromomagnetism remains an important tool for multiquark dynamics,
For instance, \textit{ab-initio} calculation of hadron–hadron forces.
Chromo-electricity-1

- Flavour independence is an important property of QCD,
- Gluons couple to colour, not to flavour,
- ∃ limit where $V(r)$ becomes universal,
- as in QED, where the same potential holds for $e^−$, $μ^−$, $\bar{p}$, with very different masses,
- Several level-order or hierarchy pattern of QED do not depend on the specific Coulomb shape of $V$, but are consequences of the universality,
- For instance, $(μ^+ μ^-)$ deeper than $(e^+ e^-)$
- and, also, $(b\bar{b})$ deeper with respect to $B\bar{B}$ than $(c\bar{c})$ with respect to $D\bar{D}$ threshold.
The pattern of \((m_1^+, m_2^+, m_3^-, m_4^-)\) molecules in QED studied in detail,

Equal mass case \((m^+, m^+, m^-, m^-)\) barely bound, e.g., positronium molecule, postulated in 1945, demonstrated in 1947, and experimentally found in 2007.

Two masses \((M^+, m^+, M^-, m^-)\) (breaking of particle identity) hardly survives spontaneous dissociation into \((M^+, M^-) + (m^-, m^-)\), and becomes unstable for \(M/m \gtrsim 2\)

Two masses \((M^+, M^+, m^-, m^-)\) (breaking of charge conjugation) becomes more and more stable, as \(M/m \nearrow\), in particular, \(H_2 = (p, p, e^-, e^-)\) more stable than \(Ps_2\) (larger percentage of extra binding with respect to the threshold, richer spectrum of stable excitations, etc.).
Similarly, explicit quark-model calculations of \((Q, Q, \bar{q}, \bar{q})\)

Using a simple extrapolation of the quark-antiquark potential of mesons,

and the quark-quark-quark potential of baryons

\[
V = -\frac{16}{3} \sum_{i<j} \tilde{\lambda}_i \cdot \tilde{\lambda}_j \, V(r_{ij}) ,
\]

gives:

- in the equal-mass case: no binding
- as \(M/m\) ↑: binding occurs and becomes more and more pronounced.

With current models for the early calculations: \((c, c, \bar{q}, \bar{q})\) at the edge, \((b, b, \bar{q}, \bar{q})\) bound.

Hence a new type of exotic hadrons predicted (1982), due to the combination of several quark flavours.

Many refinements in the literature

Alternative approaches (Molecules, QCD SR, . . .)
Chromo-electricity-4

- Several issues:
  - potential model for states including light quarks,
  - **Two-body character** of the quark interaction?
  - etc.

- The two-body character already addressed for baryons vs. mesons

- The above colour additive gives
  \[ V_B = \frac{1}{2} [V_M(r_{12}) + V_M(r_{23}) + V_M(r_{31})] \]

- But the phenomenology of baryons hardly distinguish this confinement from the naive pairwise ansatz
Chromo-electricity-5

- The generalization to tetraquarks involves *flip-flop* and *connected Steiner diagrams*.

\[
V_4 = \min(V_f, V_s), \quad V_s = \min[v(r_{13}) + v(r_{24}), v(r_{14}) + v(r_{23})].
\]

- If treated in the adiabatic approximation, it gives more often binding than the simple additive model.
- In particular for the *tetraquark* states \((QQ\bar{q}\bar{q})\),
- Non-adiabatic corrections under investigation (Vijande, Valcarce, R.)
Pentaquarks

- 1987, chromomagnetic pentaquark (Lipkin, Gignoux et al.),
- In the 00s, chiral pentaquark (Diakonov et al., exp. in Japan, many papers)
- In the chromelectric limit

including all permutations

- Gives stability in the adiabatic approximation, for a variety of mass ratios.
- The dynamics is dominated by the flip-flop term
String potential: hexaquark

Collaboration with J. Vijande and A. Valcarce

- Found stable if antisymmetrisation is disregarded
String potential: hexaquark
Collaboration with J. Vijande and A. Valcarce

Found stable if antisymmetrisation is disregarded
Recent developments for the string potential

Adiabaticity and color mixing in tetraquark spectroscopy
J. Vijande, A. Valcarce, and J.-M. Richard

- flip–flop gives more binding than the simple additive model
- it is treated in the adiabatic approximation
- for each set of positions \( \{r_i\} \), the colour state is adjusted
- this means that the Fermi statistics is violated for identical quarks
- we compared four models
  - flip-flop model, treated adiabatically
  - flip-flop model reformulated as a colour operator
  - additive model
  - additive model in the adiabatic approximation
- Result: when treated similarly, both models give very close results for the masses
Differences in some detailed properties
For instance in the large $M/m$ limit of $(QQ\bar{q}\bar{q})$,

Effective MM interaction $V_{\text{eff}}(R)$. Left: flip-flop, right: additive
For instance, the probability of $W$-exchange in $(bc\bar{u}\bar{d})$ is not the same in the two models
Technical details

\[ \hat{V}_{TT} = g_3 g'_3 V_{TT} + (1 - g_3 g'_3) \]

\[ \times \left[ \frac{3}{4} \frac{V_{1'1'}}{g_1} + \frac{3}{4} \frac{V_{11} + V_{1'1'}}{g'_1} \right], \]

where

\[ V_{11} = r_{13} + r_{24}, \quad V_{1'1'} = r_{14} + r_{23}, \quad V_{TT} = r_{12} + r_{34} + r_{12,34}. \]

\[ g_3 = g \left( \frac{V_{33}}{V_{11}} \right), \quad g'_3 = g \left( \frac{V_{33}}{V_{1'1'}} \right), \quad g_1 = 1 - g'_1 = g \left( \frac{V_{11}}{V_{1'1'}} \right). \]

\[ V_{TM} = \frac{3}{4\sqrt{2}} \left\{ V_{11} - V_{1'1'} \right\}, \quad V_{MM} = \frac{1}{4} \left\{ 3 V_{11} + 3 V_{1'1'} - 2 \hat{V}_{TT} \right\}, \]
Production of tetraquarks with two heavy flavours

- Already several estimates
- Comparison \((ccq)\) vs. \((cc\bar{q}\bar{q})\) analogous to meson/baryon ratio once the \(qq\) diquark is produced (Oka et al.)
- Weak decay of heavy mesons or baryons containing both beauty and charm such as \((bcq)\) or \((b\bar{c})\)
Many predictions over the years,
But experimental candidates not always found where they were most predicted,
The amount of post-dictions reveals the flexibility of phenomenological models,
Too many reasonable models, with interesting success in some sectors: molecules, multiquarks in potential models, hybrid states with constituent gluons, etc.
Probably redundancies and mixing among these configurations should be further clarified,
**Proliferation?** A recurrent problem in multiquark spectroscopy: a model that works for a given experimental candidate predicts many other states,
Outlook-2

- Renewed interest on **Yukawa dynamics** beyond nuclear physics and hypernuclear physics
- to include **charm** and **beauty**,
- Stimulated by results of B-factories and colliders (BELLE, BaBar, CLEO, Tevatron, LHC, ...)
- **Convergent predictions** of exotics in the sector with **two heavy flavours**
- Which is now accessible.