Exotic spectroscopy

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Why Hadron Spectroscopy: \textit{laboratory for studying non} pQCD & confinement.

- Asymptotic freedom
- Perturbative
- High energy
- Small distance
- Effective degrees of freedom (models)
- << 0.1 fm

- Non-Perturbative
- Low energy
- Large distance
- Confinement
- Mesons & Baryons
- > 1 fm
- Transition
- 0.1 – 1 fm
- Quantitative understanding of quark and gluon confinement
- Revealing the nature of the mass of the hadrons
- See the QCD degrees of freedom at work
- Validate lattice-QCD predictions
Hadron spectroscopy: lab. for QCD@ work

Bulk of mass of hadrons
Confinement
X,Y, Z, pentaquarks, etc. new hadron states
• Finally to claim new physics also in other sectors, a precise knowledge of non perturbative QCD observables is necessary if they are involved!
Meson spectrum

**Constituent Quark Model**

- Quark-antiquark pairs with total spin $S=0,1$ and orbital angular momentum $L$

$$S = S_1 + S_2 \quad J = L + S$$

$$P = (-1)^{L+1} \quad C = (-1)^{L+S}$$

Not all the $J^P_C$ combinations are allowed:

$$0^{++} \quad 0^{+} \quad 0^{-} \quad 1^{++} \quad 1^{+} \quad 1^{-} \quad 2^{++} \quad 2^{+} \quad 2^{-} \quad 3^{++} \quad 3^{+} \quad 3^{-} \quad 3^{--} \quad ...$$

- SU(3) flavor symmetry

\[
\rightarrow \text{nonet } (8 \oplus 1) \text{ of degenerate states}
\]

- Great success in describing the lower mass states

A number of predicted states is not experimentally observed and assignments are uncertain

Consider light quarks: $u,d,s$

$$\pi, K, \eta, \eta'$$

$$a, K, f, f'$$

$$b, K, h, h'$$

$$\rho, K^*, \omega, \phi$$

$$\pi, K, \eta, \eta'$$

**Meson spectrum diagram**

- Qq Mesons

- Nonets

- Threshold positions shown for the molecular states

- Mass (GeV/c²)

- Angular momentum
The gluons and the meson spectrum

Neutralize color

... the simple way

\[
\begin{align*}
S &= S_1 + S_2 \\
J &= L + S \\
P &= - (-1)^L \\
C &= (-1)^{L+S}
\end{align*}
\]

mesons  baryons

... or the “exotic” way

(flavor) exotic  exotic of the II kind

\[
J^{PC}=0^{--},0^{+-},1^{-+},2^{+-}...
\]
Gluonic excitation models

### Flux tube model
- Gluonic field confined in a tube between q and anti-q
- Linear Regge trajectories
- Hybrid mesons as transverse oscillation of the tube
- Flux-tube breaking give rise to meson decay

### Bag model
- Quarks confined inside a cavity
- Full relativistic
- Gluonic excitation: gluonic field modes by boundary conditions

### CQM + constituent gluon
- \( qq + \) massive transverse quasi-gluon \( J_g^{PgCg} \)
- Gluon adds in relative S-wave to a qq pair is S-wave or P-wave

\[
\begin{align*}
\text{qq in S-wave} + \\
\text{\( J_g^{PgCg} = l^- \) in S-wave}
\end{align*}
\]

Lightest multiplet
\( (0,1,2)^{++}, l^+ \)

\[
\begin{align*}
\text{qq in P-wave} + \\
\text{\( J_g^{PgCg} = l^- \) in S-wave}
\end{align*}
\]

Lightest multiplet
\( 0^-, (l^-)^3, (2^+)^2, 3^-, 0^+, 0^+, l^+, 2^+ \)

or QCD in physical gauge: Guo, Szczepaniak, Santopinto PRD78 056003 (2008)

- Repulsive 3-body force selects \( J_g^{PgCg} = l^+ \) in relative P-wave added to a qq pair is S-wave or P-wave

\[
\begin{align*}
\text{qq in S-wave} + \\
\text{\( J_g^{PgCg} = l^- \) in P-wave}
\end{align*}
\]

Lightest multiplet
\( (0,1,2)^+, l^- \)

\[
\begin{align*}
\text{qq in P-wave} + \\
\text{\( J_g^{PgCg} = l^+ \) in P-wave}
\end{align*}
\]

Lightest multiplet
\( 0^+, (l^+)^3, (2^+)^2, 3^+, (0,1,2)^{++} \)
Start from the study of the glue-lamp (lamp of gluons or “quasi gluon”) as obtained from QCD in physical gauge.

Gluelamp in QCD in physical gauge, Guo, Szczepaniak, Santopinto, PRD78 056003 (2008)

It is easy to study the ccbar–gluon system, i.e. the hybrids (next two slides)
Flux tube and strings

\[ P \times C = +1 \]

\[ J^{PC} = 1^{--} \]

\[ J^{PC} = 1^{+-} \]

\[ P \times C = -1 \]

R \rightarrow 0

"constituent gluons"

R \rightarrow \infty

"gluon chain"

flux tube

"glue-lump"

Gluelamp

Guo, Szczepaniak Santopinto PRD2008

Greensite e Thorn’s chain model

Ostrander Szczepaniak Santopinto PRD2014
Charmonia (qq bar) & hybrids (qqg)

<table>
<thead>
<tr>
<th>$J_g^P$</th>
<th>This work [GeV]</th>
<th>$J^{PC}$</th>
<th>Lattice [14] [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+</td>
<td>4.476</td>
<td>$0^{--}, 1^{---}, 2^{++}, [1^{--}]$</td>
<td>4.291(48), 4.327(36), 4.376(24), [?]</td>
</tr>
<tr>
<td>1-</td>
<td>4.762</td>
<td>$1^{+-}, 2^{++}, [0^{++}, 1^{++}]$</td>
<td>4.521(48), 4.508(48), [?,?]</td>
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<tr>
<td>2+</td>
<td>5.144</td>
<td>$1^{-+}, [2^{--}, 2^{--}, 3^{--}]$</td>
<td>4.696(103), [?,?,?]</td>
</tr>
<tr>
<td>2-</td>
<td>5.065</td>
<td>$2^{+-}, [1^{++}, 2^{++}, 3^{++}]$</td>
<td>4.733(42), [?,?,?]</td>
</tr>
</tbody>
</table>

First exotic $1^{++}$ (in agreement with lattice predictions)

The lightest hybrid supermultiplets

Y(4260)

The lightest hybrid supermultiplet predicted (and explained) for charmonia and bottomonia by QCD in physical gauge, $1^- (0,1,2)^{++}$, is predicted also by LQCD.

**Physical gauge QCD (Hamiltonian)**

**J$^{PC}$ glue**

$J^{PC} Q\bar{Q}$

$1^{+-} \times 0_{S_{QQ}}^{++} = 1^{--}$

$1^{+-} \times 1_{S_{QQ}}^{-+} = \{0^{--}, 1^{+-}, 2^{--}\}$

**Guo, Szczepaniak, Santopinto, PRD2008**

20XX experimental confirmation - discovery?
Y(4260) discovered by BaBar in $J/\psi \pi^+\pi^-$ (2005) confirmed by CLEO, Belle other modes from BaBar $J^{PC}=1^{--}$ (from $e^+e^-$) width $O(100\text{MeV})$

$M = 4252 \pm 6^{+2}_{-3}\text{MeV}$
$\Gamma = 105 \pm 18^{+6}_{-4}\text{MeV}$

Theory: Hybrid candidate
\[ \Lambda_b^0 \rightarrow J/\psi + \Lambda^*, \Lambda^* \rightarrow K^- + p \]

\[ \Lambda_b^0 \rightarrow P^{0+} + K^-, P^{0+} \rightarrow J/\Psi + p \]

\[ P_C^{+}(4450) = (4449.8 \pm 39) \text{ MeV} \]

\[ P_C^{+}(4380) = (4380 \pm 205) \text{ MeV} \]

Statistical significance greater than 9 sigma!
The lightest resonance, the $P_C^+(4380)$, according to LHC$_b$
has a mass $M = 4380 \pm 8 \pm 29$ MeV
and a width $W = 205 \pm 18 \pm 86$ MeV

The predicted theoretical value of the mass is 4404 MeV in
agreement with the experimental $M = 4380 \pm 8 \pm 29$ MeV

Notation:
$P_j^u(M)$ where
$I$ is the number of $s$ quarks;
$J$ the electric charge;
$M$ predicted mass

---

<table>
<thead>
<tr>
<th>$SU_{fl}(3)$ multiplet</th>
<th>$SU_I(2)$ submultiplet</th>
<th>$I$</th>
<th>$Y$</th>
<th>mass (MeV)</th>
<th>isospin states</th>
</tr>
</thead>
<tbody>
<tr>
<td>[21]$_8$ ≡ [8]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[3]</td>
<td>[3]</td>
<td>1/2</td>
<td>1</td>
<td>4404</td>
<td>$P^{00}(4404), P^{0+}(4404)$</td>
</tr>
<tr>
<td>S</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4545</td>
<td>$P^{10}(4545)$</td>
</tr>
<tr>
<td>[2]</td>
<td>[2]</td>
<td>1</td>
<td>0</td>
<td>4609</td>
<td>$P^{1+}(4609), P^{10}(4609)$</td>
</tr>
</tbody>
</table>

Santopinto, Giachino PRD 2017
we have predicted the masses, but also suggested possible decay channels where the experimentalists can try to look for them
In order to observe the isospin partner $P_{00}(4404)$ of the charged $P_{0+}$ we consider a pair creation of the type $d$ anti $d$ (instead of $u$ anti $u$)
Compact Pentaquark

Molecular state $D^* \Sigma_C$
Regarding other pentaquark states, we can consider other hyperons decays

\[
\Xi_b^- \rightarrow J/\psi + \Xi^- \\
\Omega_b^- \rightarrow J/\psi + \Omega^- 
\]

The charged $P^{1+}(4414)$ state is the most interesting from the experimental point of view, since all the final state particles are charged particles, so easier to be detected:

\[
\Xi_b^0 \rightarrow P^{1+} + K^- \\
P^{1+} \rightarrow J/\Psi + \Sigma^+ 
\]
Hidden-charm meson-baryon molecules with full-channel coupling


- **Meson-baryon thresholds** closed to the observed pentaquarks are considered for the first time. **Full-coupled channel analysis** is performed for the first time.

- The meson exchange potential respecting the heavy quark spin symmetry is employed.

- The \( J^P \) assignment of \( P(4380) \) and \( P(4450) \) is \( 3/2^+ \) and \( 5/2^- \), respectively.

- New states are predicted in \( J^P = 3/2^\pm \).
Thanks for the attention!