Meson Spectroscopy
Methods, Measurements & Machines

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Klaus Götzen
GSI Darmstadt
Mesons – are they really interesting?

Look at the American Physical Society Highlights 2013!

[http://physics.aps.org/articles/v6/139]

Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics 6, 139 (2013) | DOI: 10.1103/Physics.6.139

*Physics looks back at the standout stories of 2013.*

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_4$ (3900), are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

... Three quarks for Muster Mark !?
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... Three quarks for Muster Mark !?

Four
What is a meson?

Definition: **Meson** → **Hadron with B = 0**

→ in contrast to simple quark anti-quark (q̅q) allows a huge variety of states!
What is a meson?

Definition: **Meson** $\rightarrow$ **Hadron with** $B = 0$

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You can basically add whatever you want ...
What is a meson?

Definition: **Meson → Hadron with B = 0**

→ in contrast to simple quark anti-quark \((q\bar{q})\) allows a huge variety of states!

Meson

You can basically add whatever you want ...

... as long as you add something with the **opposite baryon number**
Meson Variations

Commonly discussed:

- Conventional \((q\bar{q})_1\)
- Hybrid \((q\bar{q})_8g\)
- Tetraquark \((q\bar{q}q\bar{q})_1\)
- Diquarkonium \((qq)_{\frac{3}{2}}(\bar{q}\bar{q})_{\frac{3}{2}}\)
- Molecule \((q\bar{q})_1(q\bar{q})_1\)
- Hadro-quarkonium \((Q\bar{Q})_1(q\bar{q})_1\)
- Glueball \((gg)_1\) or \((ggg)_1\)

[e.g. Braaten, PRD90(2014)014044]
Identify Exotic Mesons

• 1\textsuperscript{st} order exotic
  – Simple to spot: QN invalid for q\bar{q} states (e.g. \(|Q|, |S|, |C|>1\ldots\))

• 2\textsuperscript{nd} order exotic (spin exotic)
  – Special for q\bar{q} states: some spin-parity values (J\textsuperscript{PC}) are forbidden

\[ J\textsuperscript{PC} = 0^{--}, 0^{+-}, 1^{--}, 2^{+-}, 3^{--}, \ldots \Rightarrow \text{exotic meson} \]

• 3\textsuperscript{rd} order exotic (crypto exotic)
  – No (obvious) difference to q\bar{q} states \(\Rightarrow\) hard to identify!
  – Can mix with conventional states
  – Carefully study the decays & properties!

\[
\begin{pmatrix}
M_1 \\
M_2
\end{pmatrix}
= \begin{pmatrix}
\cos & -\sin \\
\sin & \cos
\end{pmatrix}
\cdot
\begin{pmatrix}
q\bar{q} \\
\text{exotic}
\end{pmatrix}
\]
Main properties: Mass \( m \), width \( \Gamma \), Spin-Parity \( J^{PC} \), decays \( B(M \rightarrow f_i) \)

Complex dynamics, e.g.
\[
T(m) = \frac{\Gamma}{m_0 - m - i\frac{\Gamma}{2}} = A \cdot e^{i\phi}, \quad I = |T|^2
\]

Interference of multiple resonances \( T_i \Rightarrow I = |\Sigma c_i T_i|^2 \) (strength \( c_i \))

Typically: Amplitude Analysis (or Partial Wave Analysis) needed to disentangle signals and determine resonance properties
Properties and Dynamics of Mesons

- Main properties: Mass $m$, width $\Gamma$, Spin $\mathbf{S}$, Parity $\mathcal{P}$, decays $B(M\rightarrow f_i)$
- Complex dynamics, e.g. $I = |T|^2$
- Interference of multiple resonances $\Rightarrow I = |\sum c_i T_i|^2$ (strength $c_i$)
  $\Rightarrow$ Typically: Amplitude Analysis (or Partial Wave Analysis) needed to disentangle signals and determine resonance properties
Light Quark Sector
• Many states found
Light Meson Spectrum

- Many states found
- Predictions not perfect

Light mesons (u,d,s quarks)
• Many states found
• Predictions not perfect
• Broad states
  ⇒ Strong overlap + mixing
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• Apply ordering to identify supernumerary states

→ $J^P C$ Multiplets (Nonets)

**Light Meson Spectrum - Multiplets**
Light Meson Spectrum - Multiplets

- Many states found
- Predictions not perfect
- Broad states
  ⇒ Strong overlap + mixing

- Apply ordering to identify supernumerary states

→ $J^P C$ Multiplets (Nonets)

- Avoid mixing with $q\bar{q}$ by looking for spin-exotic states

\[ \begin{align*}
\pi(1300) & \quad K(1460) \\
K(1385) & \quad \eta(1405) \\
\eta(1750) & \quad \omega(1420) \\
\phi(1710) & \quad \eta(1405) \\
\phi(1860) & \quad \eta(1405) \\
\end{align*} \]

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Dalitz Plot Analysis $\pi_1(1400)$ (Crystal Barrel)

- Analyse 3-body reaction: $\bar{p}n \rightarrow \pi^- \pi^0 \eta$ @ rest

⇒ Dalitz Plot Analysis
  - 2D intensity study in 3 body reactions
  - 2 variables describe complete dynamics
  - reveals 2-body resonances in the system

- Find set of resonances $T_i$ and coefficients $c_i$, so that $I = |\sum c_i T_i|^2$ describes data

- Fit demands $X \rightarrow \eta \pi$ (both $0^{-+}$) with $L=1$
  ($m_X = 1400 \pm 30$ MeV, $\Gamma_X = 310 \pm 70$ MeV)

⇒ $J^{PC}(X) = 1^{-+}$, $X$ called $\pi_1(1400)$
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Partial Wave Analysis $\pi_1(1600)$ (COMPASS)

- Observation of hybrid candidate @ COMPASS: $\pi_1(1600)$

- Diffractive dissociation $\pi^- \rightarrow \pi^- \pi^- \pi^+$ with $\pi^-$ beam ($p=190$ GeV/c) on Pb

$\Rightarrow$ Partial Wave Analysis (PWA) - 2 stages

1. Mass independent fit in $m_{3\pi}$ slices
   $\Rightarrow$ Contributions & interferences of different $X^- \rightarrow (\pi^+\pi^-)_{ib} \pi^-$

2. Fit with model assumptions for the observed partial waves (resonances)
1. Mass independent fit
   - 5 observables $\tau$ ($m_{\text{isobar}} + 4$ angles)
   - Offer 42 partial waves to the fit
   - Fit production amplitudes to describe distributions of $\tau$

$\rightarrow$ Intensities of partial waves (PW)
$\rightarrow$ Relative phases between PW
COMPASS PWA Fit

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COMPASS PWA Fit

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   - Offer 42 partial waves to the fit
   - Fit production amplitudes to describe distributions of $\tau$
     → Intensities of partial waves (PW)
     → Relative phases between PW

2. Mass dependent fit
   - Select significant partial waves
   - Fit model amplitudes to these PW to extract parameters of resonances

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Fit Result

- Significant intensity in $1^{-+}$ wave
- Physical motion of relative phase to other resonances

→ Exotic resonance $\pi_1(1600)$  ($m_\chi = 1660 \pm 10$ MeV, $\Gamma_\chi = 269 \pm 47$ MeV)
Heavy Quarks - Charmonium
Charmonium

- Advantages:
  Lower level density
  Longer lifetime (small width)
- Charmonium predictions fitted well until 2003
Charmonium

• Advantages:
  Lower level density
  Longer lifetime (small width)

• Charmonium predictions fitted well until 2003

• Since 2003: $\approx 20$ new charmonium-like states not fitting well the predictions

• Five (almost) 1st order exotics
  $Z(3900)^+ ... Z(4430)^+$

• Some very close to DD-like thresholds
  $X(3872), Z(3900), Z(4020), ...$
The charged Z+'s

- Z+'s all decay to $c\bar{c} \pi^+$
- Charged and too heavy for excited light meson
  \[ \Rightarrow \text{Minimum quark content } c\bar{c}u\bar{d} \text{ (first time proof of exotic matter!!)} \]

<table>
<thead>
<tr>
<th>Name</th>
<th>$\Gamma$ [MeV]</th>
<th>$c\bar{c}$ decay</th>
<th>open charm</th>
<th>closeby DD</th>
<th>$\Delta m$ to DD [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z(3900)$^+$</td>
<td>35 ± 7</td>
<td>$J/\psi$</td>
<td>$\pi^+$</td>
<td>(D$^0\bar{D}^*$)$^+$</td>
<td>9.3 ± 3.4</td>
</tr>
<tr>
<td>Z(4020)$^+$</td>
<td>10 ± 6</td>
<td>$h_c$</td>
<td>$\pi^+$</td>
<td>(D$^<em>\bar{D}^</em>$)$^+$</td>
<td>6.7 ± 2.4</td>
</tr>
<tr>
<td>Z(4050)$^+$</td>
<td>82 ± 40</td>
<td>$\chi_c(1P)$</td>
<td>$\pi^+$</td>
<td>?</td>
<td>34 ± 2.4</td>
</tr>
<tr>
<td>Z(4250)$^+$</td>
<td>177 ± 100</td>
<td>$\chi_c(1P)$</td>
<td>$\pi^+$</td>
<td>?</td>
<td>-38 ± 50</td>
</tr>
<tr>
<td>Z(4430)$^+$</td>
<td>200 ± 50</td>
<td>$\psi(2S)$</td>
<td>$\pi^+$</td>
<td>?</td>
<td>12 ± 40</td>
</tr>
</tbody>
</table>

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Nature of the Z's

Some of the possibilities ruled out, but many still possible

- Conventional (qq)_1
- Hybrid (qq)_{8g}
- Tetraquark (q\bar{q}qq\bar{q})_1
- Diquarkonium (qq)_{3}(\bar{q}\bar{q})_3
- Molecule (q\bar{q})_1(q\bar{q})_1
- Hadro-quarkonium (Q\bar{Q})_1(q\bar{q})_1
- Glueball (gg)_1 or (ggg)_1
The mysterious $X(3872)$

- Seen by 7 experiments in 6 channels
  (J/ψρ, J/ψω, J/ψγ, ψ′γ, D0D*π0, D*D)
- $J^{PC} = 1^{++}$ → natural candidate for $χ_{c1}(2P)$

Oddities

- 50 - 100 MeV to light for $χ_{c1}(2P)$
- Extremly narrow: $Γ < 1.2$ MeV
- Extremly close to $D^0D^{*0}$ threshold:
  $m_X - m_{D^0D^{*0}} = 0.11 \pm 0.21$ MeV
  → Molecule?!

- If molecule → $d \approx 10$ fm
  - How to re-arrange quarks to form $c\bar{c} \rho$?
  - Why is this loosely bound state produced so abundantly @ CDF in TeV reactions?
Theory about X(3872)

- To clarify nature: **line shape + width measurements essential**

\[
\begin{align*}
D^0 &\rightarrow \text{virtual state} \\
\bar{D}^0 &\rightarrow \text{binding state}
\end{align*}
\]

\[
\begin{align*}
\text{peak} &\rightarrow \text{cusp} \\
\text{D}^0\bar{D}^* &\rightarrow \text{D}^0\bar{D}^* \\
\text{D}^0\bar{D}^0 &\rightarrow \text{D}^0\bar{D}^0
\end{align*}
\]


\[\text{Need } \bar{p}p \text{ scan experiment to get access to the line shape}\]
Measure Multiplets to solve XYZ Puzzle

Different structure assumptions (models) ⇒ Different multiplet patterns

**Diquarkonium**

\[
\begin{align*}
\text{diquarks} & : \ \text{cu} \quad \bar{\text{c}}\bar{\text{u}} \\
\text{di-antiquarks} & : \ \text{cd} \quad \bar{\text{c}}\bar{\text{d}} \\
\text{cs} & : \ \bar{\text{c}}\text{s} \\
\end{align*}
\]

**Molecule**

\[
\begin{align*}
\text{Diquarkonium} & : \ D^+ \quad D^{*+} \\
& : \ D^0 \quad D_2 \\
& : \ D_1 \quad D_{s^+} \\
\text{Molecule} & : \ \bar{D}^0 \quad \bar{D}_2 \\
& : \ \bar{D}_1 \quad D_{s^-} \\
\end{align*}
\]

**Hadro-charmonium**

\[
\begin{align*}
\text{Hadro-charmonium} & : \ \eta_c \\
& : \ J/\psi \quad \chi_c \\
& : \ h_c \quad \psi' \\
\end{align*}
\]

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'Machines'
Present & Future Experiments
Meson Production (1)

- Hadron/gamma beam on fixed target
  
  \[ \text{GlueX: } \gamma \rightarrow p \text{ (9 GeV/c), COMPASS: } \pi/K/p \rightarrow p/\text{nucl.} \text{ (160 - 270 GeV/c)} \]

- Light sector only
- Direct access to exotic QN
- Always a recoil present (complicates analysis)
B-meson decays

- Light & charmonium sector
- Exclusive systems for Dalitz plot analysis
- Suppression of higher spins $J$
Formation/production in $e^+e^-$
[BESIII: $E \leq 4.6$ GeV, Belle2: $E \leq 11$ GeV]

- Light, charmonium & bottomonium sector
- High mass resolution by beam energy precision (Formation)
- $J^{PC}$ limited to $1^{--}$ (Formation)
- Suppression of higher spins $J$

BESIII running
Belle II future
Formation/production in $\bar{p}p$

[\text{PANDA: } E \leq 5.5 \text{ GeV}]

- Light & charmonium sector
- High mass resolution with all $(\bar{q}q)\ J^P_C$ possible
- Currently no running experiment

FermiLab E835 (past)
PANDA (future)
Summary and Prospects

- **Meson spectroscopy**
  → Tool to understand and quantify QCD binding

- **Many new exotic states** discovered in last decade
  – Proof validity of fundamental QCD principle
  – Great opportunity to refine and adapt models

- **Many running and new experiments** in planning
  – Understand conventional states binding
  – Complete the exotic multiplets

- Still some way to go ...

  ... stay tuned for more interesting discoveries!