Multiquarks and spectroscopy results from the B factories

Chengping Shen    shencp@fudan.edu.cn
Outline

• Introduction
  – Evidence of $X(3872)$ in $B^\pm \rightarrow X(3872)K^\pm$ from BaBar
  – $X(3872)$ absolute BRs
  – Observation of $Y(4626)$ in $e^+e^- \rightarrow D_s^+ D_{s1}(2536)^- / D_s^+ D_{s2}^*(2573)^-$ from Belle
  – Observation of $Y_b(10750)$ in $e^+e^- \rightarrow \pi^+\pi^- Y(nS)$ from Belle

• Summary
Hadrons: normal & multiquarks (exotic)

- Quark model: hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks

- QCD does not forbid hadrons with $N_{\text{quarks}} \neq 2, 3$
  - Glueball: $N_{\text{quarks}} = 0$ (gg, ggg, ...)
  - Hybrid: $N_{\text{quarks}} = 2$ (or more) + excited gluon
  - Multiquark state: $N_{\text{quarks}} > 3$
  - Molecule: bound state of more than 2 hadrons
  - ...
Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

M. Gell-Mann, Phys. Lett. 8, 214 (1964)

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from anti-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber \( n_t - n_f \) would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin \( \frac{1}{2} \) and \( z = -\frac{1}{3} \), so that the four particles \( d^- \), \( s^- \), \( u^0 \) and \( b^0 \) exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon \( b \) if we assign to the triplet \( t \) the following properties: spin \( \frac{1}{2} \), \( z = -\frac{1}{3} \), and baryon number \( \frac{1}{3} \). We then refer to the members \( u^\frac{2}{3}, d^\frac{1}{3}, \) and \( s^\frac{1}{3} \) of the triplet as "quarks" 6) \( q \) and the members of the anti-triplet as anti-quarks \( \bar{q} \). Baryons can now be constructed from quarks by using the combinations \( (qqq) \), \( (qqq\bar{q}) \), etc., while mesons are made out of \( (q\bar{q}) \), \( (qqq\bar{q}) \), etc. It is assuming that the lowest baryon configuration \( (qqq) \) gives just the representations 1, 8, and 10 that have been observed, while the lowest meson configuration \( (q\bar{q}) \) similarly gives just 1 and 8.
Main Contributors of Exotics
Variety of recorded reactions

\[ J^{\text{PC}} = 0^{-}, 1^{-}, 1^{++}, \text{in factorization limit}. \]
~20 multi-quark states are observed since 2003 with high significance
BES, Belle, BaBar, CDF, D0, LHCb, ATLAS, CMS
Some examples of multi-quark candidates:

\[ X(3872) \rightarrow J/\psi \pi^+ \pi^- \], \[ Z^+(4430) \rightarrow \Psi' \pi^+ \], \[ X(4140) \rightarrow J/\psi \phi \], \[ Z_b^+(10610) \rightarrow Y \pi^+ \], \[ Z_b^+(10650) \rightarrow Y \pi^+ \], \[ P_c^+(4450) \rightarrow J/\psi p \], \[ P_c^+(4380) \rightarrow J/\psi p \]
XYZ particles

Charmonium-like (XYZ) particles
New type of hadron (multi-quark ...)?

\[ n (2S+1) \]
\[ L J \]
n radial quantum number
S total spin of c & cbar
L orbital angular momentum
L = 0, 1, 2 ... correspond to S, P, D, ...
J = S + L
P = \((-1)^{L+1}\) parity
C = \((-1)^{L+S}\) charge conj.

Prog. Part. Nucl. Phys 93 (2017) 143

If I could remember the names of all these particles, I'd be a botanist. - E. Fermi
Too many models!

– Theory 1: screened potential
– Theory 2: hybrids with excited gluons
– Theory 3: tetraquark states
– Theory 4: meson molecules
– Theory 5: cusps effect
– Theory 6: final state interaction
– Theory 7: coupled-channel effect
– Theory 8: mixing of normal quarkonium and exotics
– Theory 9: mixture of all these effects
– Theories …

We need clear features to identify exotic hadronic states!
XYZ states

Success = X + Y + Z
What is the X(3872)?

- **Mass:** Very close to $D^0D^{*0}$ threshold
- **Width:** Very narrow, $0.96^{+0.19}_{-0.18} \pm 0.21$ MeV [LHCb, arXiv:2005.13422]
- **$J^{PC} = 1^{++}$**
- **Production**
  - In $pp/\bar{pp}$ collision – rate similar to charmonia
  - In $B$ decays – $KX$ similar to $\bar{c}c$, $K^*X$ smaller than $\bar{c}c$
  - $Y(4260) \rightarrow \gamma + X(3872)$
- **Decay BR:** open charm $\sim 50\%$, charmonium $\sim 0\%$
- **Nature** (very likely exotic)
  - Loosely $\bar{D}^0D^{*0}$ bound state (like deuteron)?
  - Mixture of excited $\chi_{c1}$ and $\bar{D}^0D^{*0}$ bound state?
The determination of the $B(B^\pm\to X(3872)K^\pm)$ leads to $B(X(3872)\to J/\psi\pi^+\pi^-)$, bringing useful information regarding the complex nature of the $X(3872)$.

The original tetraquark model [PRD 71, 014028 (2005)] predicts it to be about 50%. Various molecular models [PRD 72, 054022 (2005); PRD 69, 054008 (2004)] predict it to be $\lesssim 10\%$.

Increase signal efficiency by a factor of 3 by retaining all B tag candidate instead of the best one.

There is 3σ evidence of the decay $B^\pm\to X(3872)K^\pm$, detected for the first time using this recoil technique.

$B(B^\pm\to X(3872)K^\pm) = (2.1 \pm 0.6 \pm 0.3) \times 10^{-4}$
Absolute branching fractions of $X(3872)$ decays

- Globally analyzing the measurements by BESIII, Belle, Babar, LHCb
- The absolute branching fractions of $X(3872)$ is free parameters in the fitting

\[
\chi^2(x) = \sum_{i=1}^{25} \frac{(x_i - \overline{x})^2}{\sigma_i^2},
\]

- Statistical uncertainties are dominant for most measurements.
- Possible correlation between the systematics of different measurements in an experiments is neglected.

Absolute branching fractions of $X(3872)$ decays

Fitting results


<table>
<thead>
<tr>
<th>Parameter index</th>
<th>Decay mode</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$X(3872) \rightarrow \pi^+\pi^- J/\psi$</td>
<td>$(4.1^{+1.9}_{-1.1})%$</td>
</tr>
<tr>
<td>2</td>
<td>$X(3872) \rightarrow D^0 \bar{D}^0 + c.c.$</td>
<td>$(52.4^{+25.3}_{-14.3})%$</td>
</tr>
<tr>
<td>3</td>
<td>$X(3872) \rightarrow \gamma J/\psi$</td>
<td>$(1.1^{+0.6}_{-0.3})%$</td>
</tr>
<tr>
<td>4</td>
<td>$X(3872) \rightarrow \gamma\psi(3686)$</td>
<td>$(2.4^{+1.3}_{-0.8})%$</td>
</tr>
<tr>
<td>5</td>
<td>$X(3872) \rightarrow \pi^0 \chi_{c1}$</td>
<td>$(3.6^{+2.2}_{-1.6})%$</td>
</tr>
<tr>
<td>6</td>
<td>$X(3872) \rightarrow \omega J/\psi$</td>
<td>$(4.4^{+2.3}_{-1.3})%$</td>
</tr>
<tr>
<td>7</td>
<td>$B^+ \rightarrow X(3872) K^+$</td>
<td>$(1.9 \pm 0.6) \times 10^{-4}$</td>
</tr>
<tr>
<td>8</td>
<td>$B^0 \rightarrow X(3872) K^0$</td>
<td>$(1.1^{+0.5}_{-0.4}) \times 10^{-4}$</td>
</tr>
<tr>
<td>$X(3872) \rightarrow \text{unknown}$</td>
<td></td>
<td>$(31.9^{+18.1}_{-31.5})%$</td>
</tr>
</tbody>
</table>

- $X(3872) \rightarrow \pi^+\pi^- J/\psi \sim (4.1^{+1.9}_{-1.1})\%$
- $X(3872) \rightarrow D^0 D^{*0} \sim (52.4^{+25.3}_{-14.3})\%$
- Unknown decay $\sim (31.9^{+18.1}_{-31.5})\%$

- Statistical uncertainties are dominant.
- At Belle II, we need improve the measurements related with $X(3872)$ decays
Motivation: \( Y(4260) \) and \( Y(4660) \) with \( c\bar{c}s\bar{s} \) component

- \( Y(4626): \, e^+e^- \to D_s^+ D_{s1}(2536)^- / D_s^+ D_{s2}^*(2573)^- + c.c. \)

- \( Y(4260) \to f_0(980)(\to \pi^+\pi^-)J/\psi, \, Y(4660) \to f_0(980)(\to \pi^+\pi^-)\psi(2S) \)

  \[ f_0(980) \text{ has a } s\bar{s} \text{ component, and } \psi \text{ has a } c\bar{c} \text{ component.} \]

- It is natural to search for such \( Y \) states with a quark component of \( (c\bar{s})(c\bar{s}) \), e.g., \( D_s D_{s1}(2536) \) and \( D_s D_{s2}^*(2573) \).
Analysis method

Taking $e^+e^- \rightarrow D_S^+D_{s1}(2536)^-$ as an example

$$e^+e^- \rightarrow \gamma_{ISR}D_S^+D_{s1}(2536)^-(\rightarrow \bar{D}^*0K^-/D^{*-}K^0_S)$$

We require full reconstruction of the $\gamma_{ISR}$, $D_S^+$, and $K^-/K^0_S$.

- $D_S^+ \rightarrow \phi\pi^+, \bar{K}^0K^+, K^0K^0, K^+K^0\pi^+\pi^0, K^0\pi^0K^+, K^{*+}K^0, \eta\pi^+, \text{and } \eta'\pi^+$

- For the signals, the spectrum of the mass recoiling against the $D_S^+K^-\gamma_{ISR}$ system should be accumulated at the $\bar{D}^*0/D^{*-}$ nominal mass.

$$M_{\text{rec}}(\gamma_{ISR}D_S^+K^-/K^0_S) = \sqrt{(E_{\text{c.m.}} - E_{\gamma_{ISR}D_S^+K^-/K^0_S})^2 \left(p_{\gamma_{ISR}D_S^+K^-/K^0_S}^*\right)^2}$$

- To improve the $M(D_S^+D_{s1}(2536)^-)$ resolution, $M_{\text{rec}}(\gamma_{ISR}D_S^+K^-/K^0_S)$ is constrained to be the nominal mass of the $\bar{D}^*0/D^{*-}$. 
After applying the $\bar{D}^* / D^*$ mass constraint

One possible background is from $e^+e^- \to D_s^{*+}(\to D_s^+\gamma)D_{s1}(2536)^-$. No obvious structure is observed in the $e^+e^- \to D_s^{*+}(\to D_s^+\gamma)D_{s1}(2536)^-$. 

An unbinned simultaneous likelihood fit:

- Signal: a BW convolved with a Gaussian function, then multiplied by an efficiency function
- $D_{s1}(2536)^-$ mass sidebands: a threshold function
- $e^+e^- \to D_s^{*+}D_{s1}(2536)^-$ background contribution: a threshold function
- A non-resonant contribution: a two-body phase space form

$M = (4625.9^{+6.2}_{-6.0} \text{ (stat.)} \pm 0.4 \text{ (syst.)}) \text{ MeV/c}^2$

$\Gamma = (49.8^{+13.9}_{-11.5} \text{ (stat.)} \pm 4.0 \text{ (syst.)}) \text{ MeV}$

$\Gamma_{ee} \times B(Y \to D_s^{*+}D_{s1}(2536)^-) \times B(D_{s1}(2536)^- \to \bar{D}^* K^-) = (14.3^{+2.8}_{-2.6} \text{ (stat.)} \pm 1.5 \text{ (syst.)}) \text{ eV}$
$e^+ e^- \rightarrow D_s^+ D_{s2}^{*+} (2573)^- ( \rightarrow \bar{D}s K^- ) + c. c. \text{ via ISR at Belle}$

To improve the $M_{\text{rec}}(\gamma_{\text{ISR}})$ resolution, $M_{\text{rec}}(\gamma_{\text{ISR}} D_s^+ K^-)$ is constrained to the nominal mass of the $\bar{D}^0$.

Belle, PRD101, 091101(R) (2020)

An unbinned simultaneous likelihood fit:
- Signal: a BW convolved with a Gaussian function, then multiplied by an efficiency function
- $D_{s2}^{*+} (2573)^-$ mass sidebands: a threshold function
- A non-resonant contribution: a two-body phase space form

\[
M = (4619.8^{+8.9}_{-8.0} \text{ (stat.)} \pm 2.3 \text{ (syst.)}) \text{ MeV/c}^2
\]
\[
\Gamma = (47.0^{+31.3}_{-14.8} \text{ (stat.)} \pm 4.6 \text{ (syst.)}) \text{ MeV}
\]
\[
\Gamma_{ee} \times B(Y \rightarrow D_s^+ D_{s2}^{*+} (2573)^-) \times B(D_{s2}^{*+} (2573)^- \rightarrow \bar{D}s K^-) = (14.7^{+5.9}_{-4.5} \text{ (stat.)} \pm 3.6 \text{ (syst.)}) \text{ eV}
\]
Interpretations of Y(4626)

- A tetraquark state in a chiral constituent quark model with a scaling method [Y.Tan and J. L. Ping, PRD101, 054010 (2020)].

- A P-wave tetraquark state $[cs][\bar{c}\bar{s}]$ with 1$^{--}$ in the multiquark color flux-tube model [C. R. Deng, H. Cheng and J.L. Ping, PRD 101, 054039 (2020)].


- A molecular state from interaction $D_s^*\bar{D}_{s1}(2536) - D_s\bar{D}_{s1}(2536)$ [J. He, J. T. Zhu, and D. Y. Chen, EPJC 80, 246 (2020)].


$Y(4630) = Y(4660)\,?$

- These states may be the same
- Need improved precision

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle, $\Lambda_c^+\Lambda_c^-$</td>
<td>$4634^{+8}<em>{-7}^{+5}</em>{-8}$</td>
<td>$92^{+40}<em>{-24}^{+10}</em>{-21}$</td>
</tr>
<tr>
<td>Belle, $\pi^+\pi^-\psi(2S)$</td>
<td>$4652\pm10\pm8$</td>
<td>$68\pm11\pm1$</td>
</tr>
<tr>
<td>BaBar, $\pi^+\pi^-\psi(2S)$</td>
<td>$4669\pm21\pm3$</td>
<td>$104\pm48\pm10$</td>
</tr>
<tr>
<td>Belle, $D^+<em>sD^-</em>{s1}(2536)$</td>
<td>$4626^{+7}<em>{-7}^{+1}</em>{-1}$</td>
<td>$49.8^{+14}<em>{-12}^{+4}</em>{-4}$</td>
</tr>
<tr>
<td>Belle, $D^+<em>sD^{*+}</em>{s2}(2573)$</td>
<td>$4620^{+9}<em>{-8}^{+2}</em>{-2}$</td>
<td>$47.0^{+32}<em>{-15}^{+5}</em>{-5}$</td>
</tr>
</tbody>
</table>
\( \Upsilon(5S) \) and \( \Upsilon(6S) \) in \( e^+e^- \rightarrow \pi^+\pi^- \gamma(nS) \)

- tag \( \gamma(nS) \rightarrow \mu^+\mu^- \) and select \( \pi^+\pi^- \)

\( \Upsilon(5S): \)
- Mass = \((10891.9 \pm 3.2 \pm 0.6_{1.5}) \) MeV
- Width = \((53.7 \pm 7.1_{5.6} \pm 0.9_{5.4}) \) MeV

\( \Upsilon(6S): \)
- Mass = \((10987.5 \pm 6.4_{2.5} \pm 2.2_{2.1}) \) MeV
- Width = \((61 \pm 9_{19} \pm 2_{20}) \) MeV
- \( \phi = -1.0 \pm 0.4 \pm 1.0_{0.1} \) rad

- Results agree with previous measurements
- State at 10.75 GeV?

Belle, PRD 93, 011101(R) (2016)
Update cross sections of $e^+e^{-} \rightarrow \pi^+\pi^- \gamma(nS)$

- Same data samples, but with improved analysis

Previous analysis
- tag $\gamma(nS) \rightarrow \mu^+\mu^-$ and select $\pi^+\pi^-$
- Count numbers of events in signal and sideband regions
- Reported visible cross section

New analysis
- tag $\gamma(nS) \rightarrow \mu^+\mu^- / e^+e^-$ and select $\pi^+\pi^-$
- Fit with well constrained signal and background shapes
- Initial state radiation correction is considered, and ISR of $\gamma(5S)$ peak data supply useful information on the cross section line shapes

Precision improves by 30% + observation of $Y(10750)$!

Belle, JHEP 1910, 220 (2019)
Black error bars: statistical
Red error bars: uncorrelated systematic errors
Structure at 10.75 GeV is more significant

Fits to energy dependent cross sections

\[ \left| \text{BW}^{(n)}_{Y(5S)} \right| + \left| e^{i\gamma_n} \text{BW}^{(n)}_{Y(6S)} \right| + \left| e^{i\beta_n} \text{BW}^{(n)}_{\text{new}} \right| + \left| e^{i\gamma_n} \text{BW}^{(n)}_{Y((n+1)S)} \right|^2 \otimes \text{Gaussian} \]

\[ F_{BW}(s, M, \Gamma, \Gamma_{ee} \times B_f) = \frac{12\pi \Gamma \Gamma_{ee} \times B_f}{s - M^2 + iM\Gamma} \sqrt{\frac{\Gamma_f(s)}{\Gamma_f(M^2)}}. \]
Fit results to $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ cross sections

Scan data: 22 points, each point 1 fb$^{-1}$

$\Upsilon(10860)$ on-resonance data: 121 fb$^{-1}$, between 10.864 and 10.868 GeV

Continuum data at 10.52 GeV, 60 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>$\Upsilon(10860)$</th>
<th>$\Upsilon(11020)$</th>
<th>New structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ (MeV/c$^2$)</td>
<td>$10885.3 \pm 1.5^{+2.2}_{-0.9}$</td>
<td>$11000.0^{+4.0}<em>{-4.5}^{+1.0}</em>{-1.3}$</td>
<td>$10752.7 \pm 5.9^{+0.7}_{-1.1}$</td>
</tr>
<tr>
<td>$\Gamma$ (MeV)</td>
<td>$36.6^{+4.5}_{-3.9}^{+0.5}$</td>
<td>$23.8^{+8.0}_{-6.8}^{+0.7}$</td>
<td>$35.5^{+17.6}_{-11.3}^{+3.9}$</td>
</tr>
</tbody>
</table>

Global significance: 6.7$\sigma$

$\Gamma_{ee} \times \mathcal{B}$ (in eV)

A range due to multi-solutions
Interpretation of the Y(10750)

- **D-wave bottomonium**

- **B(∗)B(∗) dynamically generated pole**

- **Hybrid**

- **Tetraquark state**
Summary

• Lots of progress in the study of exotic states at B-factories
• More experimental and theoretical efforts are needed to understand heavy flavor spectroscopy
• BESIII, Belle II, LHCb, … will take more data and continue the study

Thanks a lot!
Thanks for your attention

沈成平      shencp@buaa.edu.cn
Light hadron spectroscopy is complicated
Many broad and overlapping states discovered, some not yet – need complicated PWA technology
Below open-charm/bottom threshold: good agreement between experiments and theoretical predictions
Above open-charm/open-bottom threshold: some expected states not discovered yet
**Resonances in $e^+e^-$ annihilation near 2.2 GeV**

- Recently, BESIII reported the existence of a resonance near 2.2 GeV in $e^+e^- \to K^+K^-$ with a large width of $(140\pm12\pm21)$ MeV [PRD 99, 032001 (2019)].
- The $e^+e^- \to K_sK_L$ cross section from 1.98 to 2.54 GeV is measured via ISR by BABAR with a data sample of 469 fb$^{-1}$.
- The $e^+e^- \to K_sK_L$ results are used together with previous BABAR results for the $e^+e^- \to K^+K^-$ [PRD 88, 032013 (2020)], $e^+e^- \to \pi^+\pi^-$, $e^+e^- \to \pi^+\pi^-\eta$, and $e^+e^- \to \pi^+\pi^-\omega$ cross sections to investigate the nature of the above resonance structure reported by BESIII.

**Fit to the BESIII and BABAR $e^+e^- \to K^+K^-$ cross sections:**

The $e^+e^- \to K^+K^-$ cross section is fitted by a sum of resonant and non-resonant contribution.

<table>
<thead>
<tr>
<th>$M_R$</th>
<th>2227 $\pm$ 9 $\pm$ 9 MeV/c$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_R$</td>
<td>127 $\pm$ 14 $\pm$ 4 MeV</td>
</tr>
<tr>
<td>$\sigma_R$</td>
<td>39 $\pm$ 6 $\pm$ 4 pb</td>
</tr>
<tr>
<td>$\phi$</td>
<td>143 $\pm$ 8 $\pm$ 9 deg</td>
</tr>
</tbody>
</table>

**BABAR, PRD 101, 012011 (2020)**
Simultaneous fit to the \( e^+e^- \rightarrow K^+K^-, e^+e^- \rightarrow \pi^+\pi^-, e^+e^- \rightarrow \pi^+\pi^-\eta \) cross sections

The solid curves: the simultaneous fit to the \( e^+e^- \rightarrow \pi^+\pi^- \) and \( e^+e^- \rightarrow \pi^+\pi^-\eta \) cross sections.

The dashed curves: the simultaneous fit to the \( e^+e^- \rightarrow K^+K^-, e^+e^- \rightarrow \pi^+\pi^-, e^+e^- \rightarrow \pi^+\pi^-\eta \) cross sections.

Fitted by a sum of resonant and non-resonant function

The existence of the isovector resonance \( \rho(2230) \) with a 4.6\( \sigma \) significance seen in \( e^+e^- \rightarrow \pi^+\pi^- \) and \( e^+e^- \rightarrow \pi^+\pi^-\eta \) cross sections.

All three cross sections are well described by a model with \( \rho(2230) \) mass and width.