Systematic studies of isospin-violating transitions in charmonium with BESIII

Olga Bondarenko (KVI-CART, University of Groningen) on behalf of the BESIII collaboration
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Outline:
- Charmonium
- ICML effects
- Isospin-violating transitions
- Measurements @ BESIII
Charmonium – bound state of $c\bar{c}$ quarks

- Simplest two-quark system
  $\rightarrow$ ideal test of confinement

- The $J/\psi$ is discovered in 1974: the 40th anniversary!

- Narrow states below open-charm threshold
  $\rightarrow$ low-background beacons of QCD!

- Promising energy regime to search for exotic states of QCD!

- Heavy charm quark
  $\rightarrow$ relative velocity between quarks small
  $\rightarrow$ allows for non-relativistic framework + relativistic corrections

$\Gamma(J/\psi) = 93$ keV

$PRL\ 33,\ 1453\ (1974)$
Charmonium: Potential theory vs experiment

Charmonium is an excellent laboratory for Standard Model tests

Charmonium: Potential theory vs experiment

Charmonium is an excellent laboratory for Standard Model tests


Open charm threshold

Precision spectroscopy!

Established

New States

Potential Theory

Discovery opportunities!
Charmonium: Potential theory vs experiment

Discovery opportunities!

XYZ Studies: Yuping GUO, Fri 30 May, 09:30

Charm physics: Peilian LIU, Fri 30 May, 17:10
Session B

Charmonium physics: this talk

Precision spectroscopy!

Not to miss!
M1 Radiative Transition

\[ \Gamma(\psi' \rightarrow \gamma \eta_c) = 0.97 \pm 0.14 \text{ keV} \]

*CLEOc, PRL 102, 011801 (2009)*

Non-relativistic Potential Model
\[ \Gamma(\psi' \rightarrow \gamma \eta_c) = 9.7 \text{ keV} \]

One order of magnitude difference!

Mass [MeV]

- 3900
- 3700
- 3500
- 3300
- 3100

\[ J^P_C = \]

- 0^+ \quad \eta_c
- 1^- \quad J/\psi

\[ ^1S_0 \quad ^3S_1 \]

\[ \eta' \quad \psi' \quad \gamma \]
M1 Radiative Transition

Mass [MeV]

3900
3700
3500
3300
3100
2900

$J^{PC} = \begin{array}{cc}
1S_0 & 3S_1 \\
0^+ & 1^- \end{array}$

Experiment:
\[ \Gamma(\psi' \rightarrow \gamma \eta_c) = 0.97 \pm 0.14 \text{ keV} \]

*CLEO$_c$, PRL 102, 011801 (2009)*

Non-relativistic Potential Model
\[ \Gamma(\psi' \rightarrow \gamma \eta_c) = 9.7 \text{ keV} \]

One order of magnitude difference!

+ Intermediate Charmed Meson Loops (ICML)
\[ \Gamma(\psi' \rightarrow \gamma \eta_c) = 2.05^{+2.65}_{-1.75} \text{ keV} \]

*G.Li and Q.Zhao, PRD 84, 074005 (2011)*

Quenched Lattice
\[ \Gamma(\psi' \rightarrow \gamma \eta_c) = 0.4 \pm 0.8 \text{ keV} \]

*Better agreement!*

J.Dudek et al., PRD 73, 094504 (2009)

Influence of virtual decay channels can be significant
Experiment:
\[ M(\psi') - M(\eta_c') = 48.5 \pm 3.3 \text{ MeV} \]

*BESIII, PRL 109, 042003(2012)*

Potential (Coulomb+linear) Model
\[ M(\psi') - M(\eta_c') = 67 \text{ MeV} \]

Potential Model + ICML
\[ M(\psi') - M(\eta_c') = 46 \text{ MeV} \]

*Eichten et al., PRD 69, 094019 (2004)*

It is tempting to conclude that the \( \psi' - \eta_c' \) splitting reflects the influence of virtual decay channels.

*E.Eichten at al., PRD 69, 094019 (2004)*
Isospin violating transitions

Sources of symmetry breaking:
- the up-down quark mass difference
- electromagnetic interaction

EM contribution for $\psi' \rightarrow \pi^0 J/\psi$ is much smaller than the quark-mass difference.

Tree-level contribution
(0$^\text{th}$ order QCD multipole expansion)

$$R = \frac{B(\psi' \rightarrow \pi^0 J/\psi)}{B(\psi' \rightarrow \eta J/\psi)} \iff \frac{m_u}{m_d} = 0.4 \pm 0.01$$

Using CLEOc data
Isospin violating transitions

Sources of symmetry breaking:
• the up-down quark mass difference
• electromagnetic interaction

EM contribution for $\psi' \to \pi^0 J/\psi$ is much smaller than the quark-mass difference.

Tree-level contribution
(0\textsuperscript{th} order QCD multipole expansion)

Result contradicts previous estimates from light-meson mass ratio:

\[
\frac{m_u}{m_d} = \frac{M_{K^\pm}^2 - M_{K^0}^2 + 2M_{\pi^0}^2 - M_{\pi^\pm}^2}{M_{K^0}^2 - M_{K^\pm}^0 + M_{\pi^\pm}^2} = 0.56
\]

Weinberg (1977); Gasser, Leutwyler (1982); Leutwyler (1996)
Isospin violating transitions: Intermediate Charmed-Meson loops (ICML)

Effective Field Theory (non-multipole effect)

\[ R = \frac{B(\psi' \rightarrow \pi^0 J/\psi)}{B(\psi' \rightarrow \eta J/\psi)} = \text{TreeLevel} \left( \leftrightarrow \frac{m_u}{m_d} \right) + \text{Loops}! \]


Are these charmed-meson loops important?
Contributions of ICML in charmonium transitions depend on:
- quantum numbers of the states,
- momentum $q$ of the $\pi^0$,
- velocity $\nu$ of the heavy meson in ICML: $\nu/c \sim \sqrt{(2M_D - M_\Psi)/M_D}$

<table>
<thead>
<tr>
<th>Transition</th>
<th>Suppression Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>$(\nu/c)^{-1}$</td>
</tr>
<tr>
<td>SP</td>
<td>$q^2 \over (\nu/c)^3 M_D^2$</td>
</tr>
</tbody>
</table>

We are interested in $\pi^0$(isospin) transitions between various charmonium states in order to reveal the hadronic-loop contributions (communication with Juelich+IHEP theory groups).
The BESIII Detector & Data Sets

Magnet yoke
SC magnet, 1T
RPC
TOF, 90ps
Be beam pipe

MDC, 120 mm
0.5% at 1 GeV/c

Csl(Tl) calorimeter, 2.5% @ 1 GeV

Total weight 730 ton,
~40,000 readout chnls,
Data rate: 5kHz, 50Mb/s

\[ 0.1 \times 10^9 \text{ decays} \]

\[ 1.9 \times 10^9 \text{ decays} \]

\[ 0.5 \times 10^9 \text{ decays} \]

plus 0.8 fb\(^{-1}\) R scan, 104 energy points between 3.85 and 4.59 GeV
Isospin violating $\psi' \rightarrow \pi^0 J/\psi$ @BESIII

Low background! A clean probe!

Mass [MeV]

3700

$\psi'$

3100

$J/\psi$

$J^{PC} = 1^{-+}$

$\eta$

$\pi^0$

$B(\psi' \rightarrow \pi^0 J/\psi) / B(\psi' \rightarrow \eta J/\psi) \times 100\%$

<table>
<thead>
<tr>
<th>EFT</th>
<th>11 ± 6 (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO-c</td>
<td>3.88 ± 0.23 ± 0.05</td>
</tr>
<tr>
<td>BESIII</td>
<td>3.74 ± 0.06 ± 0.04</td>
</tr>
</tbody>
</table>


PRD 78, 011102 (2008)

PRD 86, 092008 (2012)

Most accurate measurement to date!
**Isospin violating $\psi' \rightarrow \pi^0 h_c$ @BESIII**

Tiny branching fraction! First Measurement!

Theory, NREFT: charmed-meson loops contribution is about 10% → tiny!

Tree-level diagram + dimensional analysis:

$$B(\psi' \rightarrow \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \cdot 10^{-4}$$

PRL 104, 132002 (2010)

$$\Gamma(\psi' \rightarrow \pi^0 h_c) = (0.9 \pm 0.6) C^2 \text{ keV}, \ C \approx 1$$

F.-K. Guo, PRD 82, 034025 (2010)

$$\Gamma(\psi' \rightarrow \pi^0 h_c) = (0.26 \pm 0.05) \text{ keV}$$

BESIII

Results are in agreement, the NREFT approach is promising
Isospin violating $\chi_{c0,2} \rightarrow \pi^0 \eta_c$ @BESIII

90% CL Upper Limits on the branching fractions are set for the first time
Isospin violating transitions @ BESIII

A lot of new results! Are these sensitive results?
## Discussion: Theory vs Experiment

<table>
<thead>
<tr>
<th>Transition</th>
<th>$SF$, number</th>
<th>NREFT prediction</th>
<th>BESIII measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SS$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\psi' \to \pi^0 J/\psi$</td>
<td>0.53$^{-1}$</td>
<td>$\Gamma = (0.048 \pm 0.025) g_2^2 g_2'^2$ keV</td>
<td>$\Gamma = (0.38 \pm 0.02)$ keV</td>
</tr>
<tr>
<td>$\psi' \to \eta J/\psi'$</td>
<td>0.53$^{-1}$</td>
<td>$\Gamma = (0.43 \pm 0.23) g_2^2 g_2'^2$ keV</td>
<td>$\Gamma = (10.26 \pm 0.41)$ keV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$R = (11 \pm 6)$%</td>
<td>$R = (3.74 \pm 0.07)$%</td>
</tr>
<tr>
<td>$SP$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\psi' \to \pi^0 h_c$</td>
<td>0.03</td>
<td>$\Gamma_{\text{loop}} = 2.1 \times 10^{-7} g_1^2 g_2'^2 \sim 10^{-5}$ keV</td>
<td>$\Gamma = (0.26 \pm 0.05)$ keV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Gamma = (0.9 \pm 0.6) C^2$ keV</td>
<td></td>
</tr>
<tr>
<td>$\eta'<em>c \to \pi^0 \chi</em>{c0}$</td>
<td>0.1</td>
<td>$\Gamma_{\text{loop}} = 1.0 \times 10^{-5} g_1^2 g_2'^2$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Gamma = 1.5 \pm 0.4$ keV</td>
<td></td>
</tr>
<tr>
<td>$h_c \to \pi^0 J/\psi$</td>
<td>0.2</td>
<td>$\Gamma_{\text{loop}} = 1.9 \times 10^{-4} g_1^2 g_2^2 \sim 10^{-2}$ keV</td>
<td>-</td>
</tr>
<tr>
<td>$\chi_{c0} \to \pi^0 \eta_c$</td>
<td>0.2</td>
<td>$\Gamma_{\text{loop}} = 3.3 \times 10^{-4} g_1^2 g_2^2 \sim 10^{-2}$ keV</td>
<td>$\Gamma &lt; 18.8$ keV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Gamma \sim 1$ keV*</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c2} \to \pi^0 \eta_c$</td>
<td>0.3</td>
<td>-</td>
<td>$\Gamma &lt; 7.1$ keV</td>
</tr>
</tbody>
</table>

*private communication*

The NREFT predictions are compatible with the BESIII results.
Summary

- Effects of intermediate charmed-meson loops on charmonium transitions below the open charm threshold are subject of extensive experimental and theoretical studies.

- Systematic studies of isospin-violating transitions are performed @ BESIII.

- These studies will help to constrain existing theoretical models.

- The NREFT predictions are compatible with the BESIII measurements.

- A good control of intermediate charmed-meson loops will help to access fundamental parameters (e.g. light-quark masses).
Thanks to the BESIII Collaboration

~350 members
50 institutions from 11 countries
Summary

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The BESIII Physics Program

DD and charm physics
ψ and charmonium physics
Spectroscopy of light hadrons
Charmonium above the Open-Charm Threshold

**Experiment:**
\[ M(\psi'') = 3773.2 \pm 0.3 \text{ MeV} \]

**Potential (Coulomb+linear) Model**
\[ M(\psi'') = 3810 \text{ MeV} \]

**Coupled-Channels Model**
\[ M(\psi'') = 3755 \text{ MeV} \]

Influence of virtual decay channels is significant above the open charm threshold