Charmonium Radiative Transitions

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(for the BESIII collaboration)
• What to measure

• What have done with old datasets
  $1.06 \times 10^8 \psi(3686) \ 2009$

• What will do with new datasets
  $\sim 3.5 \times 10^8 \psi(3686) \ 2012$
  $\sim 1 \times 10^9 J/\psi \ data$
  $\sim 5 \text{ fb}^{-1} \ data \ above \ 4.0 \ \text{GeV}$
What to measure

$$\Gamma(J/\psi \to \gamma \eta_c)$$

PDG2014: $1.58 \pm 0.37$ keV  
Lattice QCD $2.49 \pm 0.19$ keV  
Error is large  
PRD 86,094501

$\eta_c$ lineshape

large difference among the measurements  
Interference common phase in $\psi(3686) \to \gamma \eta_c$?

$\mathcal{B}(\psi(3686) \to \gamma \eta_c(2S))$

$(7 \pm 2 \pm 4) \times 10^{-4}$ (PDG2014),  
The systematic error dominated by $\mathcal{B}(\eta_c(2S) \to KK\pi)$

$\mathcal{B}(\psi(3686) \to \gamma \eta_c)$

$(0.34 \pm 0.05) \times 10^{-2}$ (PDG2014)
What have done with old data

- $\eta_c$ line-shape
- $\psi(3686)$ M1 transition
- $h_c$ E1 transition

- M1 transition $\psi(3686) \rightarrow \gamma \eta_c(2S)$
  - first observation

- $\psi(3686) \rightarrow \gamma \gamma J/\psi$

106 M $\psi(3686)$ events
Simultaneous fit with modified Breit-Wigner (hindered M1)
Significance of interference is $15\sigma$
(may partly explain the discrepancy among measurements)
Suggest a common phase in all the modes.

\[
\eta_c \text{ mass (MeV)} = 2984.3 \pm 0.6 \pm 0.6 \text{ MeV/c}^2
\]

\[
\eta_c \text{ width (MeV)} = 32.0 \pm 1.2 \pm 1.0 \text{ MeV}
\]

Relative phases are consist with each other within 3\sigma.

Suggest a common phase in all the modes.

\[
\Delta M_{hf}(1S) \equiv M(J/\psi) - M(\eta_c) = 112.6 \pm 0.8 \text{ MeV/c}^2
\]

agree well with quark-model and lattice computation.
$h_c$ E1 transition to $\eta_c$

Huge interference in $\psi(3686) \rightarrow \gamma \eta_c$

The $\eta_c$ amplitude in $h_c$ decays is larger than in $\psi(3686)$ decays

Weaker interference in $h_c \rightarrow \gamma \eta_c$

Easier and better than $\psi(3686) \rightarrow \gamma \eta_c$

**Signal:** \[ [E^3_\gamma \times BW(m) \times f_d(E_\gamma)] \otimes R_i(m) \]

Energy of photon in rest frame of $h_c$

For convergence

Resolution for $i$th mode

**$M(\eta_c) = 2984.40 \pm 1.16 \pm 0.52 \text{ MeV}/c^2**

**$\Gamma(\eta_c) = 36.4 \pm 3.2 \pm 1.7 \text{ MeV}$**
The first observation of the M1 transition $\psi(3686) \to \gamma \eta_c(2S)$

$M_{\eta_c(2S)} = 3637.6 \pm 2.9 \pm 1.6 \text{ MeV}/c^2$

$\Gamma_{\eta_c(2S)} = 16.9 \pm 6.4 \pm 4.8 \text{ MeV}$

$\mathcal{B}(\psi(3686) \to \gamma \eta_c(2S)) = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}$

Systematic error is dominated by $\mathcal{B}(\eta_c(2S) \to KK\pi)$
Direct two-photon transition $\psi(3686) \rightarrow \gamma\gamma J/\psi$

- Sensitive to the coupling between $c\bar{c}$ and $D\bar{D}$ meson pairs
- E1 transition $\psi(3686) \rightarrow \gamma\chi_{cJ} \rightarrow \gamma\gamma J/\psi$

\[ \mathcal{B}(\times 10^{-4}) \]

- $\gamma\gamma J/\psi$ = $3.1 \pm 0.6^{+0.8}_{-1.0}$, 6.6σ
- $\gamma(\gamma J/\psi)_{\chi_{c0}}$ = $15.1 \pm 0.3 \pm 1.0$
- $\gamma(\gamma J/\psi)_{\chi_{c1}}$ = $337.7 \pm 0.9 \pm 18.3$
- $\gamma(\gamma J/\psi)_{\chi_{c2}}$ = $187.4 \pm 0.7 \pm 10.2$
What we do with the new data

$1.06 \times 10^8 \psi(3686) \ 2009$

$\sim 3.5 \times 10^8 \psi(3686) \ 2012$

$\sim 1 \times 10^9 \ J/\psi \ \text{data}$

$\sim 5 \ \text{fb}^{-1} \ \text{data \ above \ 4.0 \ GeV}$
\[
\Gamma(J/\psi/\psi(3686) \rightarrow \gamma \eta_c) \quad \eta_c \text{ lineshape}
\]

**Inclusive**

Difficult to deal with the interference

**Exclusive**

Seems simpler than inclusive method

Need to know a branching ratio in high precision

How?

Use \( h_c \rightarrow \gamma \eta_c \) \hspace{1cm} \text{Seems small interference}

inclusive and exclusive
\( \psi(3686) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c \)

PRL 104,132002 \( 1.06 \times 10^8 \psi(3686) \) events

Select inclusive \( \pi^0 \) in \( \psi(3686) \) decays

Select E1 photon in \( h_c \rightarrow \gamma \eta_c \) (E1 tagged)

Absolute branching fraction
\[ \mathcal{B}(h_c \rightarrow \gamma \eta_c) = (54.3 \pm 6.7 \pm 5.2)\% \]

dominated by BKG shape

Will be improved
Now $\psi(3686) \sim 4.5$ times of old datasets. And $\sim 5$ fb$^{-1}$ data above 4.0 GeV $\pi\pi h_c$ \sim 2 times with part of data $\pi^+\pi^- h_c$.

Together we have $\sim 9$ times $h_c$ signals.

- Measure $\mathcal{B}(h_c \to \gamma \eta_c)$ using inclusive method.
- $\mathcal{B}(\eta_c \to X)$ for 16 exclusive modes. More precise $\eta_c$ lineshape.

\[
\mathcal{B}(\eta_c \to K_S^0 K^{\pm} \pi^{\mp}) = (2.60 \pm 0.29(stat) \pm 0.34 \pm 0.25(syst))\% \text{ PRD 86,092009}
\]

reduce to one-third

Due to $\mathcal{B}(\psi(3686) \to \pi^0 h_c) \cdot \mathcal{B}(h_c \to \gamma \eta_c)$, Will be improved

\[\text{dominant systematic errors}\]

- N($\psi(3686)$): 4% 
- Tracking: 8%
- Photon: 3%
- Bkg shape: 4.7%
- Kinematic fit: 6.8%

\[\text{More reliable MC}\]

- B($J/\psi/\psi(3686) \to \gamma \eta_c$) using exclusive method. PWA?
  Understand the difference.
Inclusive

Seems difficult at BESIII, \(\sim 50\) MeV photon

Exclusive

\[ \mathcal{B}(\eta_c(2S) \to X), \text{ error } > 60\% \text{ PDG 2014} \]

Difficult to measure \(\mathcal{B}(\eta_c(2S) \to X)\) at BESIII

Hope this work will be done at Belle or Babar.

Try to search other transitions of the \(\eta_c(2S)\)

\[ \eta_c(2S) \to \pi^+\pi^-\eta_c \]
\[ \eta_c(2S) \to \gamma J/\psi \]
\[ \eta_c(2S) \to \gamma h_c \]
Summary

• The $\eta_c$ parameters are measured through M1 transition of $\psi(3686)$ and E1 transition of $h_c$. The most accurate measurement.

• First observation of M1 transition $\psi(3686) \rightarrow \gamma\eta_c(2S)$.

• First observation of two-photon transition $\psi(3686) \rightarrow \gamma\gamma J/\psi$.

• We can measure $\Gamma(J/\psi/\psi(3686) \rightarrow \gamma\eta_c)$ more precisely with new data.

More results will come out.
Back-up
\( \eta_c \), lightest charmonium state

- Large uncertainties compared to other charmonium states.
- Big difference between different measurements (\( \gamma \gamma \) fusion, B decays \( \cdots \))
- Distortion of \( \eta_c \) line-shape in \( \psi(3686) \rightarrow \gamma \eta_c \) compared with \( J/\psi \rightarrow \gamma \eta_c \)
- 1S Hyperfine splitting.

\[ \text{asymmetric} \]

\[ \text{symmetric} \]
• Use $1.06 \times 10^8 \psi(3686)$ events.

• Full interference between $\gamma \eta_c$ and non-resonant $\psi(3686)$ radiative decay.

• Six modes to reconstruct the $\eta_c$:
  $K_S K^+ \pi^-, K^+ K^- \pi^0, \eta \pi^+ \pi^-$,
  $K_S K^+ \pi^+ \pi^- \pi^-, K^+ K^- \pi^+ \pi^- \pi^0, 3(\pi^+ \pi^-)$.

$$F(m) = \sigma \otimes \left[ \epsilon(m) \left| e^{i\phi} E_{\gamma}^{7/2} S(m) + \alpha N(m) \right|^2 \right] + B(m)$$

resolution, Interference phase, Non-resonant component

Mass-dependent efficiency, Hindered M1 transition
$h_c$ E1 transition to $\eta_c$

Huge interference in $\psi(3686) \rightarrow \gamma\eta_c$

The $\eta_c$ amplitude in $h_c$ decays is much larger than in $\psi(3686)$ decay.
Interference term in $h_c \rightarrow \gamma\eta_c$ is much Smaller than that in $\psi(3686) \rightarrow \gamma\eta_c$

Means $\eta_c$ line-shape from $h_c$ E1 transition can be measured easier and better than $\psi(3686)$?

Branching ratio of $h_c \rightarrow \gamma\eta_c$
$\psi(3686) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c$, 16 $\eta_c$ exclusive decays

Simultaneous fit to combine 16 $\eta_c$ decay modes.
$\eta_c(2S)$ signal:

$$\left[ E_\gamma^3 \times BW(m) \times f_d(E_\gamma) \times \epsilon(m) \right] \otimes G(\delta m, \sigma)$$

M1 transition

For convergence

Mass shift and detector resolution, fixed to linear extrapolation from $\gamma \chi_{cJ}$

$\chi_{cJ}$: MC shape $\otimes$ Gaussian, fixed

Background:

$e^+e^- \rightarrow KK\pi(\gamma_{ISR/FSR})$, MC shape, normalized to the measurements with data

$e^+e^- \rightarrow \pi^0 KK\pi$, Novosibirsk function, measured with data and fixed

$\omega K^+ K^-$ for $K^+ K^- \pi^0$ mode, double Gaussian, measured with data and fixed.
The first observation of the M1 transition $\psi(3686) \rightarrow \gamma \eta_c(2S)$

- First observed by Belle in the process $B^+ \rightarrow K^\pm \eta_c(2S)$, $\eta_c(2S) \rightarrow K_S^0 K^\pm \pi^\mp$, confirmed in two-photon production and double-charmonium production.
- Experimental challenge: search for real photon $\sim 50$ MeV.
- The branching ratio $\mathcal{B}(\psi(3686) \rightarrow \gamma \eta_c(2S))$ is predicted to be in $(0.1 - 6.2) \times 10^{-4}$.
- Chance with $1.06 \times 10^8 \psi(3686)$ data at BESIII.
- Two modes: $\eta_c(2S) \rightarrow K_S^0 K^\pm \pi^\mp$, $K^+ K^- \pi^0$
• Lightest charmonium state above open charm threshold, assigned to be a dominant $1^3D_1$ with a small $2^3S_1$ admixture.

• Non-$D\bar{D}$ branching fraction, 
  $(14.7 \pm 3.2)\%$ by BESIII, $(-3.3 \pm 1.4^{+6.6}_{-4.8})\%$ by CLEO

• Exclusive modes:
  Hadronic transition: $\pi\pi J/\psi$, $\eta J/\psi$, E1 radiative transition $\gamma \chi c_{J}(J = 0,1)$

What about $\gamma \eta_{c}/\eta_{c}(2S)$?

$\mathcal{B}(\psi(3770) \to \gamma \eta_{c}) = (6.3^{+8.4}_{-4.4}) \times 10^{-4}$, $\mathcal{B}(\psi(3770) \to \gamma \eta_{c}(2S)) = (6.7^{+7.2}_{-4.4}) \times 10^{-5}$

Consider the intermediate meson loop (IML). (PRD 84,074005)
Background:

- $e^+e^- \rightarrow \pi^0 K^0_\pm \pi^\mp$, measured with data and fixed

- $e^+e^- \rightarrow (\gamma_{\text{ISR}}/\gamma_{\text{FSR}}) K^0_\pm \pi^\mp$, fixed, using Born cross section of $e^+e^- \rightarrow K^0_\pm \pi^\mp$ by BABAR.

- Tail of the $\psi(3686)$, including $\gamma_{\text{ISR}} \psi(3686), \psi(3686) \rightarrow \gamma X$

\[
N^b_{\psi(3686)} = \sigma(s) \times \mathcal{L} \times \epsilon \times B
\]

\[
\sigma(s) = \int_0^{x_{\text{cut}}} W(s, x) \cdot BW(s'(x)) \cdot F_x(s'(x)) \, dx
\]

- ISR $\gamma$-emission probability
- Relativistic
- Phase space factor