# Charmonium radiative decays

Chang-Zheng Yuan

*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*

(Dated: November 20, 2006)

## Abstract

The radiative decays of the bound $c\bar{c}$ states provide an excellent laboratory for studying charmonium decay dynamics, and the light hadron spectroscopy. With unprecedented statistics at BESIII, the radiative decays of vectors, as well as pseudoscalars, and states with other quantum numbers can be studied.

PACS numbers: 14.40.Gx, 14.40.Cs, 13.25.Gv

## I. INTRODUCTION

At BESIII, there will be huge data samples of vector charmonium states, such as $J/\psi$, $\psi'$, and $\psi''$, and possibly not small samples for $\psi(4040)$, $\psi(4160)$, $\psi(4415)$. The non-vector charmonium states, including pseudoscalars, $\eta_c$ and $\eta_c'$, and the $P$-wave states $\chi_{cJ}$, can be produced via radiative transition of the vector states, considering the large transition rates (except $\psi' \to \gamma\eta_c'$), the data samples of these states are also large. This makes the study of the radiative decays of charmonium into light hadrons possible.

The radiative decays of the vector charmonia have been used extensively for the study of the light hadron spectroscopy, especially in $J/\psi$ decays, this has been reviewed in the hadron spectroscopy part of this Yellow Report. The study of the other charmonium states is rather limited. In the following sections, we will review the study of the radiative decays of the states other than $J/\psi$, and prospect what one can achieve at BESIII.

## II. RADIATIVE DECAYS OF VECTOR CHARMONIA

The dominant radiative decays of vector charmonia is proceed via the diagram shown in Fig. 1. The rate of the photon radiated from the final states quarks is expected to be very small, and has been proved by the experimental observation, such as $J/\psi \to \gamma\pi^0$ [1, 2]. In the pQCD calculation, assuming emission of hard gluons, the inclusive decay rate of $J/\psi$ is around 6%, while that for $\psi'$ decays is around 1% [3]. There is no estimation of the other vector charmonia, such as $\psi''$, $\psi(4040)$, and so on, but it is expected the rates to be very small since all these states are above the open charm threshold, and thus the dominant decay mode is the OZI allowed decays.

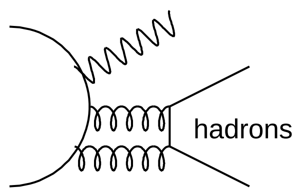


FIG. 1: Radiative decays of vector charmonium state into light hadrons.

This category of $\psi'$ decays is expected to be about 1%, but the measurements are very

TABLE I: Branching fractions of $\psi'$ radiative decays, only modes observed are listed, for a complete list of al the measurements, refer to PDG [2].

| Mode | Branching Fraction ($\times 10^{-5}$) | Experiment | Comment |
|---|---|---|---|
| $\gamma\eta'(958)$ | $15.4 \pm 3.1 \pm 2.0$ | BESI [4] | |
| | $12.4 \pm 2.7 \pm 1.5$ | BESII [6] | |
| $\gamma\eta\pi^+\pi^-$ | $36.0 \pm 14.2 \pm 18.3$ | BESII [6] | |
| $\gamma f_2(1270)$ | $21.2 \pm 1.9 \pm 3.2$ | BESI [5] | |
| $\gamma f_0(1710) \to \gamma\pi\pi$ | $3.01 \pm 0.41 \pm 1.24$ | BESI [5] | |
| $\gamma f_0(1710) \to \gamma K\bar{K}$ | $6.04 \pm 0.90 \pm 1.32$ | BESI [5] | |
| $\gamma p\bar{p}$ | $2.9 \pm 0.4 \pm 0.4$ | BESII [7] | mass $< 2.9$ GeV/$c^2$ |
| $\gamma 2(\pi^+\pi^-)$ | $39.6 \pm 3.2 \pm 5.4$ | BESII [7] | mass $< 2.9$ GeV/$c^2$ |
| $\gamma K_S^0 K^+\pi^- + c.c.$ | $24.7 \pm 3.4 \pm 3.5$ | BESII [7] | mass $< 2.9$ GeV/$c^2$ |
| $\gamma\pi^+\pi^- K^+K^-$ | $19.1 \pm 2.8 \pm 4.8$ | BESII [7] | mass $< 2.9$ GeV/$c^2$ |
| $\gamma\pi^+\pi^- p\bar{p}$ | $2.8 \pm 1.2 \pm 0.4$ | BESII [7] | mass $< 2.9$ GeV/$c^2$ |

limited. The only observation so far is $\psi' \to \gamma\eta'$ [4], $\gamma\pi\pi$ and $\gamma K\bar{K}$ [5], with total branching fraction about 0.05%. The final states with three pseudoscalars have been measured by BESII, without observing any significant structure in $\eta\pi^+\pi^-$ and $K\bar{K}\pi$ mass spectrum, the upper limit of the production of the pseudoscalar states $\eta(1405)$ or $\eta(1475)$ are set at 90% C.L [6].

Most recent study of the $\psi'$ radiative decay is from BES [7], where the total and differential branching fractions of $\psi' \to \gamma p\bar{p}$, $\gamma 2(\pi^+\pi^-)$, $\gamma K_S^0 K^+\pi^- + c.c.$, $\gamma\pi^+\pi^- K^+K^-$, and $\gamma\pi^+\pi^- p\bar{p}$ are measured for the invariant mass of the charged particle system less than 2.9 GeV/$c^2$, the total branching fraction of all these modes is about 0.1%, which is about 10% of the total radiative decays of the $\psi'$. Unfortunately, due to the low statistics, the possible production of the intermediate states can not be studied. The observed modes are listed in Table I, together with the branching fractions.

As the dominant decay dynamics of $\psi'$ or $J/\psi$ radiative decay is the $c\bar{c}$ emit a real photon and then annihilated into two gluons, it is expected that the glueball states, if exist, should be produced copiously. This has been a well spreading argument why $J/\psi$ radiative decays should be studied carefully to search for this kind of mesons. This same argument also hold for $\psi'$ radiative decays, in spite of the obvious disadvantage of low production rate. However, this disadvantage is not true any more at BESIII, due to the large (or huge) data sample, together with the obvious advantage that the allowed mass range for investigation is larger than in $J/\psi$ decays.

As has been calculated in LQCD [8], except the $J^{PC} = 0^{++}$ glueball, which is at about 1.7 GeV/$c^2$, and $J^{PC} = 2^{++}$ glueball, which is at about 2.3 GeV/$c^2$, the states with other $J^{PC}$ have rather large mass, above 2.5 GeV/$c^2$ for $J^{PC} = 0^{-+}$ and around 3 GeV/$c^2$ for $J^{PC} = 2^{-+}$, considering the widths of these states, the study of them in $J/\psi$ decays is a little bit cumbersome. However, it is more suitable to be searched for in $\psi'$ decays.

As has been observed in $\psi'$ hadronic decays, although $\psi'$ radiative decay should have similar property as $J/\psi$ does expected from very naive model, the $\psi'$ and $J/\psi$ radiative decays may turned out to be very different. For example, in the decays into $\gamma\pi\pi$, the relative strength of the resonances in $\pi\pi$ mass could be very different, thus the two decays supply different information, and may be very helpful for understanding of the meson spectroscopy. Another advantage of using the $\psi'$ data is that the background is very different, for example, in $\gamma\pi^+\pi^-$ channels, there is almost no background from $\rho\pi$ in $\psi'$ decays, while this is the dominant background in $J/\psi$ decays since $J/\psi \to \rho\pi$ is the largest two-body hadronic mode in $J/\psi$ decays.

While the $J^{PC} = 0^{++}$ and $2^{++}$ states can be very well studied in their decays into a pair of pseudoscalars, such as $\pi\pi$, $K\bar{K}$, $\eta\eta$, $\eta'\eta'$, or $\eta\eta'$, the $J^{PC} = 0^{-+}$ and $2^{-+}$ states can be studied in their decays into three pseudoscalars, such as $\eta\pi\pi$, $K\bar{K}\pi$, $\eta K\bar{K}$, $\eta'\pi\pi$ and so on. The final states like $\gamma p\bar{p}$ and $\gamma\Lambda\bar{\Lambda}$ can be used to search for the glueball with any quantum numbers, if the mass is above the baryon-antibaryon mass threshold.

The dominant decay modes of the glueballs are expected to be those multi-hadron final states, however, the spin-parity analysis of multi-hadron final states is expected to be very complicated, due to the contributions of many mesons with different spin-parity, and many different kinds of intermediate states. The technique used to study the spin-parity of the states, the partial wave analysis (PWA), in case of many parameters in the fit, may give meaningless results.

TABLE II: calculated branching fractions of $\chi_{cJ} \to \gamma V$ from Ref. [9], in unit of $\times 10^{-6}$.

| Mode | $\chi_{c0}$ | $\chi_{c1}$ | $\chi_{c2}$ |
|---|---|---|---|
| $\gamma\rho$ | 1.2 | 14 | 4.4 |
| $\gamma\omega$ | 0.13 | 1.6 | 0.50 |
| $\gamma\phi$ | 0.46 | 3.6 | 1.1 |

## III. RADIATIVE DECAYS OF PSEUDOSCALAR CHARMONIA

So far there is no measurement on the radiative decays of $\eta_c$, let alone its excited states, $\eta_c(2S)$.

The decay rates of $\eta_c$ to a $\gamma$ and a vector meson (like $\rho$, $\omega$ and $\phi$) is of great interest to probe the wave function of the $\eta_c$, which is suspected that the mixing from $\eta$ and $\eta'$ may exist to explain for example the decay rates of $J/\psi \to \gamma\eta$ and $\gamma\eta'$ [1]. The decays of a pure $c\bar{c}$ states into $\gamma V$ may be very weak, however, if the mixing from the $\eta$ and $\eta'$ exists, the decay rate may be enhanced to a much higher level. So far there is no theoretical estimation of the rates yet, either with or without the mixing from light quarks.

If the photon is emitted from the $c\bar{c}$ quark in $\eta_c$, the decay will be quite similar to $\eta_c \to \gamma\gamma$, with one real photon replaced by a virtual one and further coupled to a vector meson. Since $\mathcal{B}(\eta_c \to \gamma\gamma) = (2.8 \pm 0.9) \times 10^{-4}$ [2], the decay rates of $\eta_c \to \gamma V$ should not be very different from that if estimated from Vector Meson Dominance model.

## IV. RADIATIVE DECAYS OF P-WAVE CHARMONIA

There is no experimental information on the radiative decays of the $P$-wave charmonia, including $\chi_{c0}$, $\chi_{c1}$, and $\chi_{c2}$.

A recent theoretical calculation of $\chi_{cJ} \to \gamma V$, $V = \rho$, $\omega$, or $\phi$, was given in Ref. [9] based on nonrelativistic quantum chromodynamics, the results are shown in Table II. The branching fractions are at a level which can be searched for, or be observed, using the $\psi'$ data sample at BESIII.

## V. DISCUSSIONS AND CONCLUSIONS

From the above analysis, we conclude the radiative decays of the vector charmonium states, especially of $J/\psi$ and $\psi'$, should be studied in great care for the understanding of the light hadron spectroscopy, as well as for a better understanding of the charmonium decay dynamics. While the decays of $J/\psi$ are much rich, the study of the $\psi'$ is rather limited, more effort should be made to find possible new phenomena in $\psi'$ decays.

The search for the decays into $\gamma$+Vector allows a probe for the wave functions of $\eta_c$ and $\chi_{cJ}$ states, to test whether there is mixture from the light quark mesons.

---


[1] N. Brambilla *et al.*, arXiv:hep-ph/0412158, and references therein.

[2] Particle Data Group, W. M. Yao *et al.*, J. Phys. G **33**, 1 (2006).

[3] P. Wang, C. Z. Yuan and X. H. Mo, Phys. Rev. D **70**, 114014 (2004) [arXiv:hep-ph/0410300], and references therein.

[4] J. Z. Bai *et al.* [BES Collaboration], Phys. Rev. D **58**, 097101 (1998) [arXiv:hep-ex/9806002].

[5] J. Z. Bai *et al.* [BES Collaboration], Phys. Rev. D **67**, 032004 (2003).

[6] M. Ablikim *et al.* [BES Collaboration], Phys. Rev. D **74**, 072001 (2006) [arXiv:hep-ex/0607023].

[7] M. Ablikim *et al.* [BES Collaboration], [arXiv:hep-ex/0611xxx].

[8] Y. Chen *et al.*, Phys. Rev. D **73**, 014516 (2006).

[9] Y. J. Gao, Y. J. Zhang, and K. T. Chao, Chin. Phys. Lett. **23**, 2376 (2006), hep-ph/0607278.