Observation of J/ψ → 3 γ

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Ortho-positronium (o-Ps), the $3\gamma, e^+e^-$ bound state, decays to $3\gamma$ almost exclusively and has long been a fertile ground for precision QED tests [1]. The analog to o-Ps $\rightarrow 3\gamma$ for quantum chromodynamics (QCD), three-photon vector quarkonium decay, has not yet been observed. The rate of three-photon $J/\psi$ decays acts as a probe of the strong interaction [2], most effectively when expressed in relation to $J/\psi \rightarrow \gamma g g, J/\psi \rightarrow 3g, or J/\psi \rightarrow \ell^+\ell^-$ due to similarities at the parton level. Hence, measurements of $B_{3\gamma}, B_{\gamma gg}, B_{3g}$, and $B_{\ell\ell}$ relative to one another (where $B_X = B(J/\psi \rightarrow X)$) provide crucial experimental grounding for QCD predictions [2–4].

In this Letter we report the first observation of $J/\psi \rightarrow 3\gamma$. Rate measurements for other rare or forbidden all-photon decays, $J/\psi \rightarrow \gamma\gamma, 4\gamma, 5\gamma$, and $\gamma\eta_c$ with $\eta_c \rightarrow \gamma\gamma$, are also described. Previous searches for $\omega$ and $J/\psi$...
decay to $3\gamma$ have yielded branching fraction upper limits of $1.9 \times 10^{-4}$ and $5.5 \times 10^{-5}$, respectively [5]. As with $o$-Ps, C-parity symmetry suppresses vector quarkonia decays to an even number of photons, and two-photon decays are forbidden by Yang’s theorem [6]. Ref. [7] reports the limit $B_{\gamma\gamma} < 2.2 \times 10^{-5}$ at 90% confidence level (C.L.). Five-photon decays are suppressed by an additional factor of (at least) $\sim \alpha^2$; cf. $B(o\text{-}Ps \to 5\gamma) \sim 2 \times 10^{-6}$ [8].

Ignoring QCD corrections altogether, Ref. [4] predicts $B_{3\gamma}/B_{\ell\ell} = \alpha/14$, $B_{3\gamma}/B_{\gamma\gamma} = (\alpha/\alpha_s)^2/3$ and $B_{3\gamma}/B_{\pi\pi} = (\alpha/\alpha_s)^3$. Using the precisely measured $B_{\ell\ell}$ [5] in the first prediction implies $B_{3\gamma} \approx 3 \times 10^{-5}$. The latter two suffer the uncertainty of what value of $\alpha_s$ to employ at the charmed quark mass scale [2]. Assuming $\alpha_s(m_c^2) = 0.3$ and inserting the result from a recent CLEO measurement [9] ($B_{\gamma\gamma} = 0.09$ and $B_{3\gamma} = 0.66$) into the latter two predictions gives $B_{3\gamma} = (0.9–1.6) \times 10^{-5}$. The first-order perturbative QCD corrections [4] to these estimates are large, so these predictions should only be considered as approximate.

Events were acquired at the CESR $e^+ e^-$ collider with the CLEO detector [10], mostly in the CLEO-c configuration (95%) with the balance from CLEO III. The dataset corresponds to $27 \times 10^6$ produced $\psi(2S)$ mesons and $(9.59 \pm 0.07) \times 10^6$ $\psi(2S) \to \pi^+ \pi^- J/\psi$ decays [11]. Event selection requires the tracking system to find exactly two oppositely charged particles, corresponding to the $\pi^+ \pi^-$ recoiling from the $J/\psi$, and that the calorimeter have at least 2, 3, 4, 5, and 3 photon showers for the $J/\psi \to \gamma \gamma$, 3$\gamma$, 4$\gamma$, 5$\gamma$, and $\gamma \eta_c(\to \gamma \gamma) \gamma$ samples, respectively. Photon candidates must have energy exceeding 36 MeV and, with respect to any shower associated with one of the charged pions, either be located (a) more than 30 cm away, or (b) between 15 and 30 cm from it and have a photonlike lateral shower profile. We require that photon candidates not be located near the projection of either pion’s trajectory into the calorimeter nor be aligned with the initial momentum of either pion within 100 mrad.

A two-step kinematic fit first constrains the beam spot and the two charged pion candidates to a common vertex, and then the vertexed $\pi^+ \pi^-$ and the most energetic $n$ photon candidates to the $\psi(2S)$ mass [5] and initial three-momentum, including the effect of the $\sim 3 \text{ mrad}$ crossing angle between the $e^+$ and $e^-$ beams. Tight quality restrictions are applied to the vertex ($X^2/d.o.f. < 3$) and four-momentum ($X^2/d.o.f. < 3$) fits. The mass recoiling against the $\pi^+ \pi^-$ must lie inside a window around the $J/\psi$ mass, $M(\pi^+ \pi^- - \text{recoil}) = 3087–3107$ MeV. Non-$J/\psi$ backgrounds are estimated by keeping a separate tally of events with $M(\pi^+ \pi^- - \text{recoil})$ inside 2980–3080 MeV or 3114–3214 MeV, ranges which together are 10 times wider than the signal window.

Events with any of the photon pairs in the mass windows $0.10–0.16$ GeV, $0.50–0.60$ GeV, or $0.90–1.00$ GeV are rejected to eliminate contributions from decays with $\eta^0$'s, $\eta$'s, or $\eta'$'s, the dominant sources of photons in $J/\psi$ decays. For the $3\gamma$ selection only, we require all photon pair masses be less than 2.8 GeV to eliminate potential contamination from $\eta_c \to \gamma \gamma$. This requirement effectively restricts the smallest energy photon to have energy exceeding 200 MeV. For the $4\gamma$ and $5\gamma$ samples only, the smallest energy energy must be above 120 MeV, and all lateral shower profiles must be photonlike. This last restriction on shower shape avoids feed-up from $J/\psi \to \gamma \eta_c(\to \gamma \gamma)$, $\gamma \pi^0 \to \gamma \gamma$ events with one or more photon conversions between the tracking chambers and the calorimeter: in such cases the two showers from the conversion $e^+$ and $e^-$ overlap one another, thereby distorting both of their lateral profiles. For the $\gamma \eta_c$ channel only, we restrict the

![Graphical representation](image-url)
search region to large $M(\gamma\gamma)_{lg}$ and small $M(\gamma\gamma)_{sm}$, which are, respectively, the largest and smallest of the three two-photon mass combinations in the event. The signal region is chosen this way so as to keep backgrounds small. Specifically, the signal box is defined, in units of GeV, by $0.16 < M(\gamma\gamma)_{sm} < 0.48$, $2.985 < M(\gamma\gamma)_{lg} + 0.0935M(\gamma\gamma)_{sm} < 3.040$.

Signal and background decay modes are modeled with Monte Carlo (MC) samples that were generated using the EVTGEN event generator [12], fed through a GEANT-based [13] detector simulation, and then exposed to event selection criteria. For $J/\psi \rightarrow n\gamma$ signal decays, final state photon momenta are distributed according to phase space. For $J/\psi \rightarrow 3\gamma$, the lowest order matrix element for ortho-positronium [14] is used as an alternate; compared to phase space, it modestly magnifies the configurations that are two-body-like and those with three nearly equal-energy photons (at the expense of topologies lying between these two extremes). For the process $J/\psi \rightarrow \gamma\eta_c$, an $\eta_c$ mass and width of 2979.8 and 27 MeV, respectively, are used (both are close to the PDG values [5]) to generate a Breit-Wigner $\gamma\gamma$-mass distribution; alternate widths from 23–36 MeV and different line shapes [15] are explored as systematic variations.

Distributions in $M(\gamma\gamma)_{sm}$ vs $M(\gamma\gamma)_{lg}$ and $M(\pi^+\pi^- - \text{recoil})$ for the $J/\psi \rightarrow 3\gamma$ and $J/\psi \rightarrow \gamma\eta_c(\gamma\gamma)$ samples are shown for data, signal MC samples, and likely background decays in Figs. 1 and 2, respectively.

In all modes, non-$J/\psi$ backgrounds are small and are subtracted statistically using $M(\pi^+\pi^- - \text{recoil})$ sidebands in the data. We determine the backgrounds from $J/\psi$ decays with an exhaustive study of Monte Carlo samples. Decays with $J/\psi \rightarrow \gamma f_J$ (where $f_J$ signifies any of the many isoscalar mesons in the mass range from 600–2500 MeV), followed by $f_J \rightarrow \gamma\gamma$ pose a negligible threat for any of the target modes because the product branching fractions are extremely small (e.g., $\approx 2 \times 10^{-8}$ for $J/\psi \rightarrow \gamma f_J(1270)$, $f_J(1270) \rightarrow \gamma\gamma$). The predominant source of backgrounds to the $3\gamma$ sample is the $\gamma\pi^0\pi^0$ final state.
This type of event can survive the selection by having both \( \pi^0 \) decay axes nearly parallel to their lines of flight, such that one photon of each pair has very low energy in the laboratory frame, and is therefore nearly irrelevant to conservation of four-momentum. An analysis by BES [16] found that the largest sources of \( J/\psi \rightarrow \gamma \pi^0 \pi^0 \) are from \( J/\psi \rightarrow \gamma f_J \) decays, specifically through \( f_2(1270) \) and \( f_0(2050) \), followed in importance by \( f_0(1710) \), \( f_0(1500) \), and a number of much smaller contributions from nearby resonances. However, not all relevant product branching fractions for \( J/\psi \rightarrow \gamma f_J, f_J \rightarrow \pi^0 \pi^0 \) have been measured, those that are measured have large uncertainties, and interference effects among overlapping \( f_J \) may not be small. A method to normalize \( \gamma \pi^0 \pi^0 \) other than using measured branching fractions is employed to reduce systematic uncertainty. The \( \chi^2/\text{d.o.f.} \) distribution for \( \gamma \pi^0 \pi^0 \) decays has a characteristic shape, nearly independent of \( \pi^0 \pi^0 \) mass, as shown in Fig. 3: the region \( \chi^2/\text{d.o.f.} = 5 \rightarrow 20 \), where almost no signal is present, is used to establish the level of \( J/\psi \rightarrow \gamma \pi^0 \pi^0 \). Figure 4 shows the \( \chi^2/\text{d.o.f.} \) distribution from data, MC signal and MC background and the small contribution from non-\( J/\psi \) decays obtained from the \( M(\pi^+ \pi^- - \text{recoil}) \) sidebands. The 142 data events with \( \chi^2/\text{d.o.f.} = 5 \rightarrow 20 \) contain \( J/\psi \rightarrow 3\gamma \) signal (3.4 events), non-\( J/\psi \) background (3.2), and, using known branching fractions, \( J/\psi \rightarrow \omega \eta, \eta \rightarrow \gamma \gamma \) (1.7), \( J/\psi \rightarrow \gamma \eta, \eta \rightarrow \gamma \gamma \) (1.2), \( J/\psi \rightarrow \eta \gamma, \eta \rightarrow \gamma \gamma \) (1.2), \( J/\psi \rightarrow \gamma \gamma \), \( \gamma \rightarrow \gamma \gamma \) (0.6), and \( J/\psi \rightarrow \pi^0 \gamma \) (0.2). The remainder (130.5 events) serves to normalize the \( \gamma \pi^0 \pi^0 \) background component, which has a relative 8% statistical uncertainty. With this normalization of the major background in \( J/\psi \rightarrow 3\gamma \), the 37 observed data events are attributed to signal (24.2 events), non-\( J/\psi \) background (9.0), and \( J/\psi \) background (11.9).

As a cross check on the \( 3\gamma \) background normalization, we perform a maximum likelihood fit to data in the entire \( J/\psi \rightarrow 3\gamma \chi^2\text{d.o.f.} = 0 \rightarrow 30 \) region with the combination of shapes from MC of \( \gamma \pi^0 \pi^0 \) and \( 3\gamma \) signal with floating normalizations for each, and a fixed \( J/\psi \)-sidebands contribution from data, scaled by a factor of 0.1. Using this method with different sources of the \( \gamma \pi^0 \pi^0 \) taken one at a time as 100% of the background results in an average signal size of 23.3 events (with variation from 22.8 to 24.1), which is 0.9 events smaller than our nominal technique. Based on these numbers we assign a systematic error of 0.9 events, or \( \approx 5\% \) relative, for signal extraction and background estimation for \( J/\psi \rightarrow 3\gamma \).

The \( \chi^2/\text{d.o.f.} \) fit just described is repeated with the \( 3\gamma \) signal shape weight fixed to zero. The likelihood difference with respect to the nominal fit provides a measure of the statistical significance of the signal. This significance varies from 5.9\( \sigma \) to 6.6\( \sigma \) when using any one of the backgrounds \( \gamma f_2(1270), \gamma f_0(1500), \gamma f_0(1710), \gamma f_0(2050), \gamma \pi^0 \pi^0 \) (phase space) as the sole contributor to the background shape.

MC studies indicate the following primary sources of backgrounds for the other modes: for the \( 2\gamma \) sample, \( J/\psi \rightarrow \gamma \pi^0 \) (3.3 events) and \( \gamma \eta, \eta \rightarrow \gamma \gamma \) (2.7); for the

| Signal candidates (events) | 2\( \gamma \) | 3\( \gamma \) | 4\( \gamma \) | 5\( \gamma \) | \( \gamma \eta \), \( \gamma \eta \rightarrow \gamma \gamma \) |
|---------------------------|-----------|-----------|-----------|-----------|---------------------------------|
| **Background (events)**    |           |           |           |           |                                 |
| \( J/\psi \) backgrounds   | 6.2       | 11.9      | 3.2       | 0.5       | 0.8                             |
| Non-\( J/\psi \) backgrounds | 0.9   | 0.9       | 0.5       | 0         | 0                               |
| Background sum (events)    | 7.1       | 12.8      | 3.7       | 0.5       | 0.8                             |
| Statistical significance (\( \sigma \)) | 1.1    | 6.3       | 1.0       | 0.0       | 1.0                             |
| Net yield (68\% C.L. interval) (events) | 19 \( ^{+4.7}_{-1.6} \) | 24.2 \( ^{+7.2}_{-0.6} \) | 13 \( ^{+2.4}_{-1.3} \) | 0 \( ^{+1.2}_{-0.7} \) | 1.2 \( ^{+2.8}_{-1.1} \) |
| UL @ 90\% C.L.             | <7.7      | <33.5     | <6.0      | <2.3      | <4.7                             |
| Efficiency (%)             | 19.2      | 21.8      | 8.71      | 1.90      | 10.9                            |

**Systematic errors (%)**

| Matrix element | 0 | 15 | 15 | 15 | 15 |
|-----------------|---|----|----|----|----|
| \( J/\psi \) background | 15 | 5 | 10 | 0 | 15 |
| \( \pi^+ \pi^- J/\psi \) counting | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Detector modeling | 4.5 | 6.4 | 8.3 | 10 | 6.4 |
| \( \Gamma(\eta_c) \) | 0 | 0 | 0 | 0 | 12 |
| Quadrature sum (%) | 16 | 17 | 20 | 18 | 25 |
| \( \mathcal{B}(J/\psi \rightarrow X) \times 10^{-6} \) | 12 \( \pm 3 \pm 2 \) | 1.2 \( ^{+2.7}_{-1.1} \pm 0.3 \) |
| UL on \( \mathcal{B}(J/\psi \rightarrow X) \) @ 90\% C.L. \( \times 10^{-6} \) | <5 | <19 | <9 | <15 | <6 |
events observed on a background of 12.8. Statistics domi-
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[1] S. G. Karshenboim, Int. J. Mod. Phys. A 19, 3879 (2004); S. Asai et al., arXiv:0805.4672v1.
[2] M. B. Voloshin, arXiv:0711.4556v3 [Prog. Part. Nucl. Phys. (to be published)].
[3] A. Petrelli et al., Nucl. Phys. B514, 245 (1998).
[4] W. Kwong, P. B. Mackenzie, and J. L. Rosner, Phys. Rev. D 37, 3210 (1988).
[5] W.-M. Yao et al. (Particle Data Group), J. Phys. G 33, 1 (2006) and 2007 partial update for 2008.
[6] C. N. Yang, Phys. Rev. 77, 242 (1950); L. Landau, Dokl. Akad. Nauk SSSR 60, 207 (1948) [Phys. Abstracts A 52, 125 (1949)].
[7] M. Ablikim et al. (BES Collaboration), Phys. Rev. D 76, 117101 (2007).
[8] T. Matsumoto et al., Phys. Rev. A 54, 1947 (1996); 56, 1060(E) (1997).
[9] D. Besson et al., (CLEO Collaboration), arXiv:0806.0315v1 [Phys. Rev. D (to be published)].
[10] Y. Kubota et al. (CLEO Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 320, 66 (1992); M. Artuso et al., Nucl. Instrum. Methods Phys. Res., Sect. A 554, 147 (2005); D. Peterson et al., Nucl. Instrum. Methods Phys. Res., Sect. A 478, 142 (2002); CLEO-c/ESR-c Taskforces & CLEO-c Collaboration, Cornell University LEPP Report No. CLNS 01/1742 2001 (unpublished).
[11] H. Mendez et al. (CLEO Collaboration), Phys. Rev. D 78, 011102(R) (2008).
[12] D. J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A 462, 152 (2001).
[13] R. Brun et al., GEANT 3.21, CERN Program Library Long Writeup W5013 1993 (unpublished).
[14] A. Ore and J. L. Powell, Phys. Rev. 75, 1696 (1949); G. S. Adkins, Phys. Rev. A 72, 032501 (2005).
[15] R. E. Mitchell et al. (CLEO Collaboration), arXiv:0805.0252v1.
[16] M. Ablikim et al. (BES Collaboration), Phys. Lett. B 642, 441 (2006).