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Measurement of the Branching Ratios for $J/\psi \to \gamma\pi^0$, $\gamma\eta$, $\gamma\eta' \to 3\gamma$ on the BES

The BES Collaboration

Bai Jingzhi, Bian Jianguo, Chai Zhengwei, Chen Guangpei, Chen Hongfang[1], Chen Jiangchuan, Chen Shaomin, Chen Yaqing, Chen Yu, Chen Yuanbo, Cheng Baosen, Cui Xiangzong, Ding Huiliang, Du Zhizhen, Fan Xiaoling, Fang Jian, Gao Cuishan, Gao Meili, Gao Shuqi, Gu Jianhui, Gu Shudi, Gu Weixin, Gu Yifan, Guo Yanan, Han Shiwen, Han Ying, He Jingtang, He Ju, He Mao[2], Hu Guiyun, Hu Jingliang, Hu Qionghui, Hu Tao, Hu Xiaoqing, Huang Xiuping, Huang Yinzhi, Jiang Chunhua, Jin Shan, Jin Yan, Kang Shuhui, Ke Zunjian, Lai Yuanfen, Lan Huibin, Lang Pengfei, Li Jin, Li Peiqin, Li Qun, Li Rubai, Li Wei, Li Weidong, Li Weiguo, Li Xinhua, Li Xiaonan, Lin Shuzi, Liu Huaimin, Liu Jing, Liu Jinghua, Liu Qi, Liu Rongguang, Liu Yan, Liu Zhenan, Lü Feng, Lü Junguang, Lu Jianye, Luo Shuanqun, Luo Yong, Ma Aimin, Ma Encheng, Ma Jimao, Mao Huishun, Mao Zepu, Meng Xiangcheng, Ni Huiling, Nie Jing, Qi Nading, Qu Yunhe, Qiu Jinfa, Que Youkun, Rong Gang, Shao Yuying, Shen Benwei, Shen Dingli, Shen Hong, Shen Xiaoyan, Sheng Huayi, Shi Huanzhang, Song Xiaofei, Sun Fang, Sun Hansheng, Sun Shijun, Tan Yiping, Tang Suqiu, Tian Jianling, Tong Guoliang, Wang Feng, Wang Jufang, Wang Linzhou, Wang Lingshu, Wang Man, Wang Meng, Wang Peiliang, Wang Ping, Wang Shaomin, Wang Taijie, Wang Yunyong, Wei Chenglin, Wu Yougeng, Xi Deming, Xia Xiaomi, Xie Peipei, Xiong Weijun, Xu Guofa, Xu Rongsheng, Xu Zhijing, Xue Shengtian, Yan Jie, Yan Wuguang, Yang Changyou, Yang Chunmin, Yang Jie, Yang Xiaofeng, Ye Minghan, Ye Shizhang, Ye Shuwei[1], Yi Kai, Yu Chuansong, Yu Chunxu, Yu Zhitang, Yu Zhongqiang, Yuan Changzheng, Zhang Bingyun, Zhang Changchun, Zhang Dahua, Zhang Dehong, Zhang Huiling, Zhang Jian, Zhang Jiawen, Zhang Lin, Zhang Liangsheng, Zhang Qinjian, Zhang Shaoqiang, Zhang Xueyao[2], Zhang Yu, Zhang Yueyuan, Zhao Dixin, Zhao Haiwen, Zhao Jingwei, Zhao Meng, Zhao Weiren, Zheng Jianping, Zheng Linsheng, Zheng Zhipeng, Zhou Guangpu, Zhou Huashi, Zhou Li, Zhou Yuehua, Zhu Guoyi, Zhu Qiming, Zhu Yongsheng, Zhu Yucan, and Zhuang Baoan

(Institute of High Energy Physics, The Chinese Academy of Sciences, Beijing, China)
[1](Department of Modern Physics, University of Science and Technology of China, Hefei, China)
[2](Department of Physics, Shandong University, Jinan, China)

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Decays of the J/ψ resonance into the three-photon final state are investigated. Branching ratios for the decays of $J/\psi \to \gamma\pi^0$ and $J/\psi \to \gamma\eta'$ are determined to be $Br(J/\psi \to \gamma\pi^0) = (4.6 \pm 1.1) \times 10^{-5}$ and $Br(J/\psi \to \gamma\eta') = (4.12 \pm 0.82) \times 10^{-3}$. The ratio of the two decay widths, $\Gamma(J/\psi \to \gamma\eta') / \Gamma(J/\psi \to \gamma\eta)$, is 4.79 ± 0.85. This value agrees well with the predictions of the two theoretical models.

Key words: J/ψ, radiative decay, three-photon final state, branching ratio.

The measurement was done with the Beijing Spectrometer (BES) [1] at the Beijing Electron Positron Collider (BEPC). The BES trigger system has successfully implemented the neutral trigger, so the events with pure photons final states can be acquired. Since 1989, the BES has collected about 7 million produced J/ψ events with the neutral trigger mode. The corresponding on-line integrated luminosity is about 3.67 pb^{-1}. Analyzing the J/ψ radiative decays with three-photon final states $J/\psi \to \gamma\pi^0, \gamma\eta, \gamma\eta' \to 3\gamma$, the branching ratios for $J/\psi \to \gamma\pi^0$ and $J/\psi \to \gamma\eta'$ and the ratio of two decay widths $\Gamma(J/\psi \to \gamma\eta') / \Gamma(J/\psi \to \gamma\eta)$ were obtained.

The BES is a large general-purpose solenoidal detector and consists of the following parts: the central drift chamber (CDC), the main drift chamber (MDC), the time of flight counters (TOF), the shower counter (SC), and the muon chamber. Photons from J/ψ decay are mainly detected and measured by the barrel shower counter (BSC) [2]. The BSC is made up of 24 layers of self-quenching streamer (SQS)-mode sampling tubes. There are 560 cells in each layer. In order to reduce the number of readout channels, signals from the anode wire are combined together into 6 layers of the readout channel. The solid angle coverage is $80\% \times 4\pi$. From the Bhabha events, the shower position resolution at the z direction and the angular resolution in the x-y plane is determined to be $\sigma_z = 3.6$ cm and $\sigma_\phi = 7.9$ mrad, respectively, and the energy resolution is $\Delta E / E = 22\% / \sqrt{E}$ (E in GeV). A 100 (50) MeV photon is detected with 100% (65%) efficiencies.

In the data acquisition process on BES, the trigger system [3] selects events in real time to retain all good events while rejecting backgrounds. The trigger criteria for pure neutral events are: no charged track in MDC; the total energy deposited in the BSC is greater than a high threshold (about 0.95 GeV); the total energy deposited in any of two adjacent cells is greater than the radial condition threshold; no hits in the innermost layer of the muon counters to reject the cosmic ray background.

1. THEORETICAL PREDICTION

The decay rate of $J/\psi \to \gamma P$ [4] (P is a pseudoscalar meson) can be calculated using the QCD perturbation theory

$$\Gamma(J/\psi \to \gamma P) = \frac{1}{6}\left(\frac{2}{3}\right)^2 \alpha_s^4 \alpha Q_c^2 \frac{1}{M_\psi^3}\left(\frac{4R_\psi(0)}{\sqrt{4\pi M_\psi}}\right)^2\left(\frac{4R_P(0)}{\sqrt{4\pi M_P}}\right)^2 x|H^P(x)|^2 , \tag{1}$$

here $R_\psi(0)$ and $R_P(0)$ are the wave functions of the J/ψ and pseudoscalar meson with mass M_P at the origin. Q_c is the charge of the charm quark. The reduced pseudoscalar helicity amplitude $H^P(x)$ depends on $x = 1 - (M_P / M_\psi)^2$, numerically $x|H^P(x)| \approx 55$ for $J/\psi \to \gamma\eta'$. $R_\psi(0)$ and $R_P(0)$ can be calculated based on the decay widths of $J/\psi \to e^+e^-$ and $P \to \gamma\gamma$, respectively. Using the lowest order QCD equation for $J/\psi \to \gamma\eta'$, the decay width is 213 eV.

The vector meson dominance model (VMD) [5] predicts $\Gamma(J/\psi \to \gamma\pi^0) \approx 1$ eV, by assuming the coupling between the photon and ρ^0 in the decay $J/\psi \to \rho^0\pi^0$. The decays of $J/\psi \to \gamma\eta$ and $J/\psi \to \gamma\eta'$ have been measured by several experiments. It was found that η' is produced in radiative J/ψ decays with a rather large branching fraction. The Crystal Ball group [6] obtained the ratio $\Gamma(J/\psi \to \gamma\eta') / \Gamma(J/\psi \to \gamma\eta) = 4.7 \pm 0.6$. This fact cannot be explained very well by the u, d, and s quark contents of η and η'. In order to tackle the large ratio $\Gamma(\gamma\eta')\,\Gamma(\gamma\eta)$, two kinds of theoretical models have been built. The η, η', and η_c admixture model [7] allows a small mixture of η and η' to the wave function of the η_c. In turn the η and η' obtain some $c\bar{c}$ components in their wave functions. The η' has more $SU(3)$ singlet component than η, so it could have a larger mixture of the $c\bar{c}$ component and hence a larger production rate from J/ψ decay. This model predicts $\Gamma(\gamma\eta') / \Gamma(\gamma\eta) = 3.9$. The η, η' and $\iota(1440)$ admixture model [8] assumes that $\iota(1440)$ is a 0^{-+} meson, its main component is glueball, and therefore there is a glueball component in η and η'. This model, by considering the contribution from glueball component, predicts $\Gamma(\gamma\eta') / \Gamma(\gamma\eta) = 5.1$. A study of the $\eta-\eta'$ system in the radiative J/ψ decays is therefore of considerable interest.

2. DATA ANALYSIS

Data taken at the J/ψ energy region was processed and sorted out to the zero-prong data sample after filtering, calibration, and reconstruction. For the physics analyses, the pre-selection process is essential to reject the background. The pre-selection for the sample of neutral events satisfy the following conditions: the number of hit wires in the MDC is less than 10, the number of hits in the μ chamber is less than 8, the number of neutral clusters in the BSC is between 3 and 8, the total energy deposited in BSC is in the range of 2.0 to 4.0 GeV, and the momentum of each event measured by BSC should be smaller than 1.0 GeV/c.

From the pre-selected data set, we obtain the events of 3 photon final states by following these further requirements:

(1) For each event there should be exactly three good neutral clusters satisfying the following: the energy deposited in BSC for each cluster is greater than 0.15 GeV, $|\cos\theta| < 0.8$ where θ is the polar angle of each cluster, the total hit layers in BSC for each cluster should be greater than 1 and the first hit layer should be less than the 4th layer. From the study of the Monte Carlo simulation, if two neutral clusters with energy E_1, E_2 satisfy $E_1 < 0.2 \times (E_1 + E_2)$ and $|\Delta\theta| + |\Delta\phi| < 8°$, the neutral cluster with energy E_1 is considered as a split-off from E_2 cluster and is therefore abandoned. (ϕ denotes the azimuthal angle with beam direction as z axis.)

(2) The acollinearity angle between the direction of photon production and the direction of shower development should be less than 16°.

(3) In order to reject the background from events with 5γ and 7γ final states, the total energy deposited in BSC of the three candidate photons should be greater than 2.4 GeV. Three clusters are also required on the same plane, the criterion $|n_1 \cdot (n_2 \times n_3)| < 0.06$ is used, where n_1, n_2, and n_3 is the unit vector pointing in the direction of the corresponding cluster.

(4) A minimal acollinearity angle between two photons greater than 6° is required to discriminate against events of the type $e^+e^- \to \gamma\gamma$, where the spray from one of the photons fakes a third low energy photon. The Monte Carlo simulation indicates that this cut will not remove the events of $J/\psi \to \gamma\pi^0$, $\gamma\eta$, and $\gamma\eta' \to 3\gamma$.

(5) Finally, events are 4C kinematically fit to obtain better mass resolution and to suppress backgrounds further by the requirement $\chi^2 < 14$.

With energies of photons from the 4C-fit, the events are shown in the Dalitz plot in Fig. 1. Three bands at the masses of π^0, η, and η' are clearly seen. The lowest photon pair mass is plotted in Fig. 2 after the cut on the highest photons pair mass is less than 2.8 GeV/c^2, and clear signals at the mass of π^0, η, and η' are superimposed on the smoothly varying background.

Table 1
Fitting results of the lowest pair mass spectrum.

	π^0	η	η'
Events	40 ± 8	361 ± 17	99 ± 13
Mass (GeV)	0.137 ± 0.003	0.548 ± 0.001	0.958 ± 0.003

The invariant mass spectrum in the region from 0.04 GeV/c^2 to 1.24 GeV/c^2 is fit by the maximum-likelihood function with a linear function for background and three Gaussian functions for the three peaks. The fit masses of π^0, η, and η' and the corresponding event numbers are listed in Table 1. The fit masses are in good agreement with data from PDG96 [9].

The number of produced J/ψ events which are obtained using the neutral trigger mode can be calculated using the decay J/$\psi \to \gamma\eta \to 3\gamma$ by the following equation,

$$N_{J/\psi} = \frac{N_\eta}{\varepsilon \times Br(J/\psi \to \gamma\eta) \times Br(\eta \to \gamma\gamma)}, \tag{2}$$

where $N_\eta = 361 \pm 17$ is the observed J/$\psi \to \gamma\eta \to 3\gamma$ event number, and ε is selection efficiency for J/$\psi \to \gamma\eta \to 3\gamma$. The Monte Carlo simulation shows that ε is 14.9% with a relative error 6.2%. PDG96 gives $Br(J/\psi \to \gamma\eta) = (8.6 \pm 0.8) \times 10^{-4}$. $Br(\eta \to \gamma\gamma) = (39.25 \pm 0.31) \times 10^{-2}$. Because the measurement error of $Br(\eta \to \gamma\gamma)$ is very small, its contribution to the error of $N_{J/\psi}$ can be ignored. Besides $Br(\eta \to \gamma\gamma)$, the other three quantities in Equation (2) are measured by different methods, so they are independent each other. The total number of $N_{J/\psi}$ is determined to be $(7.18 \pm 0.87) \times 10^6$.

From the Monte Carlo simulation, the event selection efficiencies for J/$\psi \to \gamma\pi^0 \to 3\gamma$ and J/$\psi \to \gamma\eta' \to 3\gamma$ are 12.3% and 15.8% with relative errors of 5.7% and 6.6%, respectively.

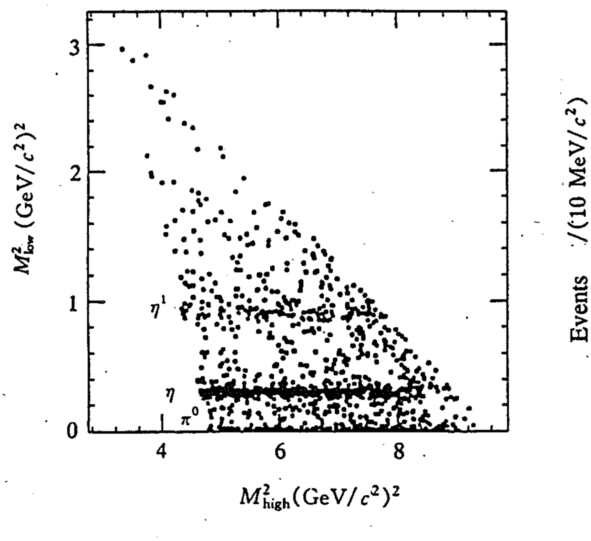

Fig. 1
The Dalitz plot for J/$\psi \to 3\gamma$.

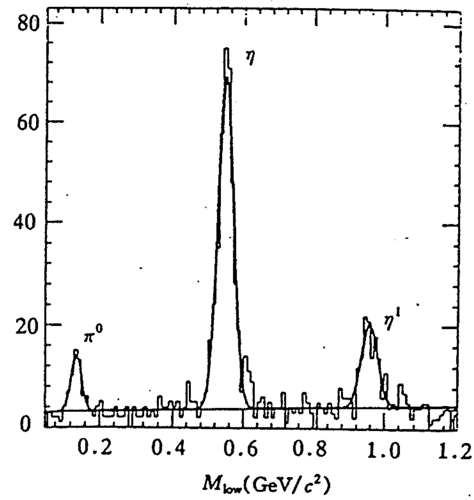

Fig. 2
The lowest pair mass spectrum.

Normalizing to the total number of produced J/ψ events and using branching fractions of $Br(\eta' \to \gamma\gamma)$ and $Br(\pi^0 \to \gamma\gamma)$ from PDG96, the branching ratios,

$$Br(J/\psi \to \gamma\pi^0) = (4.6 \pm 1.1) \times 10^{-5} ;$$
$$Br(J/\psi \to \gamma\eta') = (4.12 \pm 0.82) \times 10^{-3} ,$$

are obtained. These results are in good agreement with PDG96 values $(3.9 \pm 1.3) \times 10^{-5}$ and $(4.31 \pm 0.30) \times 10^{-3}$, respectively.

The ratio of the decay widths of $J/\psi \to \gamma\eta'$ and $J/\psi \to \gamma\eta$, which is determined by events for $\gamma\eta'$ and $\gamma\eta$ as well as the event selection efficiencies, is independent of the produced J/ψ events number. The ratio is obtained as

$$\frac{\Gamma(J/\psi \to \gamma\eta')}{\Gamma(J/\psi \to \gamma\eta)} = 4.79 \pm 0.85 .$$

Similarly

$$\frac{\Gamma(J/\psi \to \gamma\pi^0)}{\Gamma(J/\psi \to \gamma\eta)} = 0.053 \pm 0.012 .$$

3. DISCUSSION

Based on about 7 million produced J/ψ events taken with the neutral trigger mode, the neutral events with three-photon final state from J/ψ decays have been selected. Clear signals of π^0, η, and η' are found in the two-photon invariant mass spectrum. The branching ratio of $J/\psi \to \gamma\eta'$ is $(4.12 \pm 0.82) \times 10^{-3}$, corresponding to the partial decay width of 358 ± 75 eV, which is consistent with the prediction of the QCD perturbation theory. The branding ratio of $J/\psi \to \gamma\pi^0$ is found to be $(4.6 \pm 1.1) \times 10^{-5}$, corresponding to the partial decay width of 4.0 ± 1.0 eV. This result agrees roughly with the value predicted from the VMD.

In the decays of $J/\psi \to \gamma\eta'$ and $J/\psi \to \gamma\eta$ with the three-photon final state, η' was observed to produce with a rather larger branching fraction. The model of admixtures of η, η' and η_c (mixture of η, η' and $\iota(1440)$) gives that the ratio of the decay widths of $J/\psi \to \gamma\eta'$ and $J\psi \to \gamma\eta$ is 3.9 (5.1). Within the experimental error, our result is consistent with predictions of both models. If utilizing $\eta' \to \gamma\gamma$, $\eta' \to \pi^+\pi^-\eta$, and $\eta' \to \gamma\rho^0$ decay modes to measure $J/\psi \to \gamma\eta'$, the accuracy can be improved significantly.

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