Radiative Decay of the $\psi(2S)$ into Two Pseudoscalar Mesons

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Radiative decays of the radically excited charmonium resonance, $\psi(2S)$, into $\pi\pi$, $K\bar{K}$ and $\eta\eta$ final states have been measured in a sample of $3.96 \times 10^6 \psi(2S)$ events collected by the BES collaboration. The branching ratios $B(\psi(2S) \rightarrow \gamma f_2(1270)) = (2.27 \pm 0.26 \pm 0.39) \times 10^{-4}$ and $B(\psi(2S) \rightarrow \gamma f_0(1710)) \times B(f_0(1710) \rightarrow K^+K^-) = (5.59 \pm 1.12 \pm 0.93) \times 10^{-5}$ are obtained. When compared to the corresponding radiative $J/\psi$ decays, the observed $\psi(2S)$ radiative decay rates into $\gamma f_2(1270)$ and $\gamma f_0(1710)$ are consistent with the “15%” rule.

I. MOTIVATION

In perturbative QCD, the dominant process of $J/\psi$ and $\psi(2S)$ hadronic decay is $c\bar{c}$ annihilation into three gluons. Since the decay width is proportional to the amplitude of

1
the $\sigma$ wave function at the origin, $|\Psi(0)|^2$, the branching fractions of $J/\psi$ and $\psi(2S)$ decays into light quark states are related as [4]:

$$\frac{B(\psi(2S) \rightarrow h)}{B(J/\psi \rightarrow h)} = \frac{B(\psi(2S) \rightarrow ggg)}{B(J/\psi \rightarrow ggg)} \approx \frac{B(\psi(2S) \rightarrow e^+e^-)}{B(J/\psi \rightarrow e^+e^-)} = (14.6 \pm 2.2)\%$$

This relation is called the 15% rule. The prediction was originally made for the total decay width into three gluons. Since the partial widths of individual channels involving the initial annihilation of $\sigma$ quarks are also functions of the $|\Psi(0)|^2$, we expect this rule to be generally valid.

Results from the Mark II experiment [2] show that while many of the $\psi(2S)$ hadronic decay channels obey this rule, it is severely violated in vector plus pseudoscalar (VP) final states such as $\rho\tau$ and $K^*\overline{K}$ — the so-called $\rho\tau$ puzzle. The BES experiment also reported heavy suppression in the vector plus tensor (VT) final states such as $K^*\overline{K}$, $\rho\omega$, $\omega\rho_2$, and $\phi_2$ [5].

In perturbative QCD, the radiative $J/\psi$ and $\psi(2S)$ decays should be similar to hadronic decays except instead of decaying into three gluons, the radiative mode decays via two gluons and one photon. Thus one power of the coefficient $\alpha_S$ is replaced by $\alpha_{QED}$ in the cross section formula. It is expected that the “15%” rule should also work for radiative decay modes [6]. Hence the ratio of $B(\psi(2S) \rightarrow \gamma X)$ to $B(J/\psi \rightarrow \gamma X)$ for different final states $X$ should be roughly 15%. This paper explores the $\psi(2S)$ radiative decays into pairs of pseudoscalars, $\pi\pi$, $KK$ and $\eta\eta$, and reports the first branching fraction measurements of $\psi(2S) \rightarrow \gamma f_2(1270)$ and $\gamma f_0(1710)$. The branching fractions of $\chi_{c0}$ and $\chi_{c2}$ decays into $\pi\pi$ and $\eta\eta$ are also reported.

The $f_0(1710)$ has been observed with a large branching ratio in radiative decays of $J/\psi$ into $KK$, but not in the reaction $K^-p \rightarrow KKA$ by the LASS experiment [7]. The latter result excludes $f_0(1710)$ as a conventional $s\bar{s}$ state and makes it a leading glueball candidate. Thus whether $f_0(1710)$ can be seen in the radiative $\psi(2S)$ decays is quite interesting.

II. BES DETECTOR

This study uses a subset of the 3.96 million $e^+e^- \rightarrow \psi(2S)$ event [8] logged by the BES detector operating at the BEPC storage ring. A detailed description of the BES detector can be found elsewhere [9]. It features a 40-layer main drift chamber (MDC) in a 0.4 T solenoidal magnetic field providing a momentum resolution of $\sigma_p/p = 1.7\%\sqrt{1+p^2}(\text{GeV}/c)$ and a $dE/dx$ resolution of 9% for hadron tracks. Outside of the MDC cylinder is an array of 48 scintillation counters of the time-of-flight (TOF) system with a resolution of 450 ps for hadrons. A 24-layer lead-gas barrel electromagnetic shower calorimeter (BSC), outside of the TOF system, provides an energy resolution of $\sigma_E/E = 0.22/\sqrt{E}(\text{GeV})$, and spatial resolutions of $\sigma_\phi = 4.5\, \text{mrad}$ and $\sigma_\theta = 12\, \text{mrad}$. The BSC is surrounded by a magnetic coil and steel plates (for magnetic flux return). There is a 3-layer $\mu$ counter interleaved with the steel plates to identify $\mu$ tracks.

The photons used in this analysis are detected as showers in the BSC. Showers within 8° of each other are regarded as split showers of a single photon candidate and their energies are recombined. For a $\pi^0$ or $\eta$ decaying into two photons, the helicity angle of the decay should be flat and hence $|\cos\theta_{\text{helicity}}| < 0.99$ is required to remove some asymmetric background decays. For charged tracks, only those that fall in the fiducial region $|\cos\theta| < 0.8$ are used. Charged tracks identified as electrons or positrons by the BSC or identified as $\mu^+$ or $\mu^-$ by the $\mu$ counter are rejected. TOF information, $dE/dx$ information and kinematic fitting are used to identify charged particles. Kinematic fits are applied to improve momentum measurements and mass resolutions, as well as to resolve combinatorial ambiguities if more than one combination is possible in the same event.

III. $\psi(2S) \rightarrow \gamma \pi\pi$ ANALYSIS

Here the analysis of decays into both charged and neutral pion pairs, $\psi(2S) \rightarrow \gamma \pi^+\pi^-\text{ and } \psi(2S) \rightarrow \gamma \pi^0\pi^0$, is described. In the charged channel, events are selected with two oppositely charged tracks and at least one photon. Kinematic fit, TOF, and $dE/dx$ information are combined and the probability for the two pions hypothesis should be greater than 1% and should also be greater than the probability for the two kaons hypothesis. The solid-line histogram of Fig. 1 is the $\pi^+\pi^-$ invariant mass distribution below 2.5 GeV. A clear $\rho$ signal is observed over a continuous background. These are due to the initial state radiation processes $e^+e^- \rightarrow \gamma\rho$ and $e^+e^- \rightarrow \gamma\mu^+\mu^-$. These processes are also presented in the $e^+e^- \rightarrow \tau\tau$ scan data taken by BES at $\sqrt{s} = 3.55 - 3.6$ GeV (below $\psi(2S)$ threshold) [10] and the mass distribution from the $\tau\tau$ scan can be used to represent the background in the $\psi(2S)$ sample. The $\pi^+\pi^-$ mass distribution taken from the $\tau$ scan data is shown in Fig. 1 (with the dashed line). The backgrounds are removed by assigning each $\psi(2S)$ event a weight of 1 and each $\tau$ event a weight of $-w$ in the likelihood function for the mass fit. Here $w$ is the ratio of the integrated luminosities of these two data sets. Fig. 2b shows the result of subtracting the $\tau\tau$ scan histogram normalized to the $\psi(2S)$ from the $\psi(2S)$ histogram.
In the neutral mode, events are required to have at least 5 neutral tracks and no charged tracks. A six-constraint fit is made to all possible $\gamma\pi^0\pi^0$ combinations with two $\pi^0$ resonances. The combination with the smallest fit $\chi^2$ is selected. A four-constraint fit is also applied on that combination and $|M_{\gamma\pi^0\pi^0} - M_{\gamma\pi^0}| < 70MeV$ is required. The resulting mass distribution is shown in Figure 2b.

Branching fractions of $B(\psi(2S) \to \gamma f_2(1270)) = (2.21 \pm 0.26 \pm 0.39) \times 10^{-4}$ from the $\psi(2S) \to \gamma\pi^+\pi^-$ channel and $B(\psi(2S) \to \gamma f_2(1270)) = (2.95 \pm 1.10 \pm 1.12) \times 10^{-4}$ from the $\psi(2S) \to \gamma\pi^0\pi^0$ channel are obtained using the total number of $\psi(2S)$ events and detection efficiencies, which are determined from Monte Carlo simulations, of 43.8% and 9.6%, respectively. The combined result from these two channels is

$$B(\psi(2S) \to \gamma f_2(1270)) = (2.27 \pm 0.26 \pm 0.39) \times 10^{-4}.$$  

Here and below, the first error is statistical and the second is systematic. The latter includes uncertainties from varying the cuts, the shape of the background, and the uncertainty from the total number of $\psi(2S)$’s. This result is consistent with the “15%” rule when compared with the corresponding branching fraction from $J/\psi$ decay on PDG. See Table I.

A $f_0(1710)$ signal is observed in the $\pi^+\pi^-$ invariant mass distribution, as shown in Fig. 3a. The number of $f_0(1710)$ events above background is 39.2 $\pm$ 10.1. The Monte Carlo determined efficiency for this channel is 45.4%, and the resulting branching fractions are

$$B(\psi(2S) \to f_0(1710)) \times B(f_0(1710) \to \pi^+\pi^-) = (3.38 \pm 0.87 \pm 1.41) \times 10^{-5}$$

or

$$< 5.50 \times 10^{-5} \ (90\% \ C.L. \ [11])$$

The region with a $\pi^+\pi^-$ invariant mass greater than 3 GeV has been presented elsewhere [12]. The region with a $\pi^0\pi^0$ invariant mass greater than 3 GeV (see Fig. 3a) has signal peaks due to the $\chi_{c0}$ and $\chi_{c2}$ charmonium states. This mass distribution is fitted with two Breit-Wigner resonances plus a polynomial background function, and 96.9 $\pm$ 11.1 and 20.8 $\pm$ 5.8 events are obtained for $\chi_{c0}$ and $\chi_{c2}$, respectively. The detection efficiencies are 10.5% and 8.2%, and the resulting branching fractions are
\[ B(\chi_{c0} \rightarrow \pi^0\pi^0) = (2.65 \pm 0.30 \pm 0.58) \times 10^{-3} \]

and

\[ B(\chi_{c2} \rightarrow \pi^0\pi^0) = (8.7 \pm 2.4 \pm 5.0) \times 10^{-4} \]

The detection efficiencies, branching fraction acceptances, and final results for the decays described in this section are summarized in Tables IV to V.

**IV. \( \psi(2S) \rightarrow \gamma K\bar{K} \) ANALYSIS**

Here the analysis of decays into charged and neutral kaon pairs, \( \psi(2S) \rightarrow \gamma K^+K^- \) and \( \psi(2S) \rightarrow \gamma K^0_SK^0_S \rightarrow \gamma 4\pi^\pm \), is presented. For the \( \psi(2S) \rightarrow \gamma K^+K^- \) channel, cuts similar to those for the \( \gamma \pi^+\pi^- \) analysis are used, but with the requirement that the probability from particle identification for each kaon hypothesis should be greater than 0.01 and should be greater than the probability for the pion hypothesis. QED backgrounds such as \( e^+e^- \rightarrow \gamma \phi \rightarrow \gamma K^+K^- \) and \( e^+e^- \rightarrow \gamma \mu^+\mu^- \) are determined using the \( \tau \) scan data (See Fig. 3). A \( f_0(1710) \) signal and a hint of a possible \( f_2'(1525) \) signal (Fig. 3) are observed. The mass distribution is fitted using S-wave and D-wave Breit-Wigner functions with masses and widths fixed at the PDG values for \( f_0(1710) \) and \( f_2'(1525) \), respectively. The fit yields 71.9 \pm 14.4 \( f_0(1710) \) events above background. The detection efficiency is 33.6\%, giving a branching fraction

\[ B(\psi(2S) \rightarrow \gamma f_0(1710)) \times B(f_0(1710) \rightarrow K^0_SK^0_S) = (2.10 \pm 0.96 \pm 1.11) \times 10^{-5} \]

or

\[ < 3.98 \times 10^{-5} \ (90\% \ C.L.) \]

The detection efficiencies, branching fraction acceptances, and final results for the decays described in this section are summarized in Tables IV to V.

**FIG. 5.** Invariant mass of (a) \( K^+K^- \) and (b) \( K^0_SK^0_S \). The data points in (a) are obtained from the difference of the two histograms in Fig. 4.

**V. \( \psi(2S) \rightarrow \gamma \eta \eta \) ANALYSIS**

Here the analysis of decays into \( \eta \) pairs, \( \psi(2S) \rightarrow \gamma \eta \eta \rightarrow 5\gamma \), is presented. The selection criteria for this channel are similar to those used in the \( \psi(2S) \rightarrow \gamma \pi^0\pi^0 \) channel except that the requirement \( |M_{\gamma\eta} - M_{\eta\eta}| < 70 \ MeV \) is imposed. In the region where \( M_{\eta\eta} < 3 \ GeV \), no \( \eta\eta \) resonant state is observed. In the mass region with

\[ \sqrt{(m_{\pi^+\pi^-} - m_{K^0_S})^2 + (m_{\pi^+\pi^-} - m_{K^0_S})^2} \]
Two Breit-Wigner functions with a polynomial background are used to fit the mass distribution, and 12.7 ± 5.3 events for $\chi_{c0}$ and an upper limit of 5.9 $\chi_{c2}$ events are found, giving the following branching fractions

$$B(\chi_{c0} \to \eta\eta) = (1.94 \pm 0.81 \pm 0.59) \times 10^{-3}$$

$$B(\chi_{c2} \to \eta\eta) < 1.22 \times 10^{-3}$$ (90% C.L.)

The detection efficiencies for these two channels are 11.9% and 10.5%, respectively.

Flavor SU(3) symmetry predicts that the branching fractions of $\chi_{c0}$ decay into $\pi^0\pi^0$ and $\eta\eta$ should be the same except for a phase space factor and a barrier factor of $\rho^{2s+1}$, where $\rho$ is the momentum of the $\pi^0$ or $\eta$ in $\chi_c \to \pi^0\pi^0$'s rest frame and $s$ is the spin of the $\chi_c$. Based on the PDG values for the $\chi_{c0}$, this predicts $B(\chi_{c0} \to \eta\eta)/B(\chi_{c0} \to \pi^0\pi^0) = 0.95$ which is consistent with our measurement of

$$\frac{B(\chi_{c0} \to \eta\eta)}{B(\chi_{c0} \to \pi^0\pi^0)} = 0.73 \pm 0.32 \pm 0.27.$$

The detection efficiencies, branching fraction acceptances, and final results for the decays described in this section are summarized in Tables III to V.

VI. $\psi(2S)$ NORMALIZATION

The total number of $\psi(2S)$ events in the BES data sample is determined from the observed number of cascade decays of $\psi(2S) \to \pi^+\pi^-J/\psi, J/\psi \to X$. The total number of $\psi(2S) \to \pi^+\pi^-J/\psi$ events observed in the full BES data sample is $(1.227 \pm 0.003 \pm 0.017) \times 10^6$ \[6\] \[7\]. The decay branching fraction of $B(\psi(2S) \to \pi^+\pi^-J/\psi) = (31.0 \pm 2.8\%)$ taken from PDG 2000 \[8\] is used to calculate the total number of produced $\psi(2S)$ events in the data sample. This paper provides the ratios of the branching functions and $B(\psi(2S) \to \pi^+\pi^-J/\psi)$ in order to isolate the systematic error caused by the $\psi(2S) \to \pi^+\pi^-J/\psi$ branching fraction. See Tables III to V for the results.

VII. SUMMARY

This paper studies $\psi(2S) \to \gamma\pi^+\pi^-, \gamma\pi^0\pi^0, \gamma K^+K^-, \gamma K^0S\bar{K}^0_S, \gamma\eta\eta$ final states and reports the first measurement of the $\psi(2S) \to \gamma f_2(1270)$ and $\psi(2S) \to \gamma f_0(1710) \to \gamma K^+K^-$ and $\gamma K^0S\bar{K}^0_S$ branching fractions. A clear $f_0(1710)$ signal in $\psi(2S)$ radiative decay into $K^+K^-$ final states is observed. The results are consistent with the “15%” rule.

In addition, this paper reports the first measurement of the branching fractions of $\chi_{c0}$ and $\chi_{c2}$ decay into $\pi^0\pi^0$, $\chi_{c0}$ decay into $\eta\eta$, and an upper limit of the branching fraction of $\chi_{c2}$ decay into $\eta\eta$. The results from $\chi_{c0} \to \pi^0\pi^0$ and $\eta\eta$ are consistent with the prediction by SU(3) flavor symmetry.

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[1] W.S. Hou and A. Soni, Phys. Rev. Lett. 50, 569 (1980); G. Karl and W. Roberts, Phys. Lett. 144B, 243 (1984); S.J. Brodsky et al., Phys. Rev. Lett. 59, 621 (1987); M. Chaichian et al., Nucl. Phys. B323, 75 (1989); S.S Pinsky, Phys. Lett. B 236, 479 (1990); X.Q. Li et al., Phys. Rev. D 55, 1421 (1997); S.J. Brodsky and M. Karliner, Phys. Rev. Lett. 78, 4682 (1997); Y.Q. Chen and E. Braaten, Phys. Rev. Lett. 80, 5060 (1998).

[2] M.E.B. Franklin et al., Phys. Rev. Lett. 51, 11 (1983).

[3] BES Collaboration, J.Z. Bai et al., Phys. Rev. Lett. 81, 5080 (1999).

[4] T. Appelquist, A. De Rújula, H.D. Politzer, S.L. Glashow, Phys. Rev. Lett. 34 (1975) 363; M. Chanowitz, Phys. Rev. D 12 (1975) 918; L. Okun and M. Voloshin, ITEP-95-1976 (unpublished); S.J. Brodsky, T.A. DeGrand, R.R. Horgan, D.G. Coyne, Phys. Lett. 73B (1978) 203; K. Koller and T. Walsh, Nucl. Phys. B410 (1978) 449.

[5] D. Aston et al., Nucl. Phys. B 301 (1988) 525; D. Aston et al., Phys. Lett. B 15 (1988) 199.

[6] The total number of $\psi(2S)$ recorded by the BES detector is determined by the total number of $\psi(2S) \to \pi^+\pi^-J/\psi$ events divided by the PDG branching fraction value for this mode. This total $\psi(2S)$ number is $(3.96 \pm 0.36) \times 10^6$. In this paper, only runs of good quality have been used, corresponding to $3.83 \pm 0.36 \times 10^6 \psi(2S)$ events and $1.188 \pm 0.003 \pm 0.016 \times 10^6 \pi^+\pi^-J/\psi$ events.

[7] BES Collaboration, J.Z. Bai et al., Phys. Rev. D58:092006 (1998).

[8] D.E. Groom et al., Review of Particle Physics, Euro. Phys. Jnl. C15 (2000).
[9] BES Collaboration, J.Z. Bai et al., Nucl. Instrum. Methods Phys. Res., Sect. A 344, 319 (1994).
[10] BES Collaboration, J.Z. Bai et al., Phys. Rev. D 53, 20, (1996).
[11] The 90\%C.L. limits are calculated by increasing the number of events from the fit by 1.28\sigma, where \sigma includes the statistical error and the systematic error added in quadrature.
[12] BES Collaboration, J.Z. Bai et al., Phys. Rev. Lett. 81,3091 (1998).
| Final state | $B(\psi(2S) \rightarrow J/\psi)(\times 10^{-4})$ | $B(\psi(2S)) / B(J/\psi)$ |
|-------------|---------------------------------|-----------------|
| $\gamma f_{2}(1270)$ | 2.27 ± 0.26 ± 0.39 | 13.8 ± 1.4 | (16.4 ± 3.1)% |
| $\gamma f_{0}(1710) \rightarrow \gamma K^+ K^-$ | 0.559 ± 0.112 ± 0.093 | 4.25$^{+0.05}_{-0.04}$ | (13.2$^{+1.2}_{-1.0}$)% |

TABLE I. Verification of the 15% rule. The value of $B(J/\psi \rightarrow \gamma f_{0}(1710) \rightarrow \gamma K^+ K^-)$ obtained from $B(J/\psi \rightarrow \gamma f_{0}(1710) \rightarrow \gamma K^+ K^-) = 8.6_{-0.6}^{+1.2}$ divided by a factor of 2 to account for isospin.

| Mode | Number of events from mass fitting | Detection efficiency | Branching Fractions correction factor | Number of events after correction |
|------|----------------------------------|----------------------|--------------------------------------|----------------------------------|
| $\psi(2S) \rightarrow \gamma f_{2}(1270)$ from $\gamma \pi^+ \pi^-$ | 209.8 ± 24.9 | 43.8% | 0.847 ± 0.024 | 565.5 ± 67.1 ± 85.7 |
| $\psi(2S) \rightarrow \gamma f_{2}(1270)$ from $\gamma \pi^+ \pi^0$ | 29.9 ± 11.1 | 9.6% | 0.827 ± 0.028 | 376.7 ± 139.9 ± 138.1 |
| $\psi(2S) \rightarrow \gamma f_{0}(1710)$ from $\gamma \pi^+ \pi^-$ | 39.2 ± 10.1 | 45.4% | 1.0 ± 0.0 | 86.3 ± 22.2 ± 35.2 |
| $\psi(2S) \rightarrow \gamma f_{0}(1710)$ from $\gamma \pi^+ \pi^0$ | 71.9 ± 14.4 | 33.6% | 1.0 ± 0.0 | 214.0 ± 42.9 ± 30.6 |
| $\psi(2S) \rightarrow \gamma f_{0}(1710)$ from $\gamma K^+ K^-$ | 6.8 ± 3.1 | 18.0% | 0.471 ± 0.004 | 80.3 ± 36.6 ± 41.9 |

TABLE II. Numbers of events before and after correction for efficiency and branching fraction acceptance. Branching fraction acceptance factors include branching fractions from intermediate decays processes such as $\pi^0 \rightarrow \gamma \gamma$, $\eta \rightarrow \gamma \gamma$, $K_S^0 \rightarrow \pi^+ \pi^-$, $f_{2}(1270) \rightarrow \pi \pi$, etc. They do not include iso-spin factors.

| Mode | $B(\times 10^{-4})$ | $B/B(\psi(2S) \rightarrow \pi^+ \pi^- J/\psi)(\times 10^{-4})$ |
|------|---------------------|--------------------------------------------------|
| $\psi(2S) \rightarrow \gamma f_{2}(1270)$ from $\gamma \pi^+ \pi^-$ | 2.21 ± 0.26 ± 0.39 | 7.14 ± 0.85 ± 1.09 |
| $\psi(2S) \rightarrow \gamma f_{2}(1270)$ from $\gamma \pi^+ \pi^0$ | 2.95 ± 1.10 ± 1.12 | 9.52 ± 3.53 ± 3.49 |
| $\psi(2S) \rightarrow \gamma f_{2}(1270)$ from $\gamma \pi^0$ | 2.27 ± 0.26 ± 0.39 | 7.31 ± 0.83 ± 1.04 |
| $\psi(2S) \rightarrow \gamma f_{0}(1710)$ from $\gamma \pi^+ \pi^-$ | 0.338 ± 0.087 ± 0.141 | 1.09 ± 0.28 ± 0.44 |
| $\psi(2S) \rightarrow \gamma f_{0}(1710)$ from $\gamma \pi^+ \pi^0$ | 0.559 ± 0.112 ± 0.093 | 1.80 ± 0.36 ± 0.26 |
| $\psi(2S) \rightarrow \gamma f_{0}(1710)$ from $\gamma K^+ K^-$ | 0.210 ± 0.096 ± 0.111 | 0.68 ± 0.31 ± 0.35 |

TABLE III. Branching fractions and ratios of branching fractions ($B/B(\psi(2S) \rightarrow \pi^+ \pi^- J/\psi)$) for $\psi(2S) \rightarrow \gamma X \rightarrow \gamma PP$ modes ($P$ stands for pseudo-scalar).

| Mode | Number of event from mass fitting | Detection efficiency | Branching Fractions correction factor | Number of events after correction |
|------|---------------------------------|----------------------|--------------------------------------|----------------------------------|
| $\chi_{c0} \rightarrow \pi^0 \pi^0$ | 96.9 ± 11.1 | 10.5% | 0.9761 ± 0.0005 | 945.4 ± 108.3 ± 163.8 |
| $\chi_{c2} \rightarrow \pi^0 \pi^0$ | 20.8 ± 5.8 | 8.2% | 0.9761 ± 0.0005 | 259.9 ± 72.5 ± 145.8 |
| $\chi_{c0} \rightarrow \eta \eta$ | 12.7 ± 5.3 | 11.9% | 0.1547 ± 0.0035 | 689.9 ± 287.9 ± 188.9 |
| $\chi_{c2} \rightarrow \eta \eta$ | < 5.9 | 10.5% | 0.1547 | < 363.3 |

TABLE IV. Numbers of events corrected for efficiency and branching fraction acceptance for $\chi_{c}$ decay.

| Mode | $B(\times 10^{-4})$ | $B \times B(\psi(2S) \rightarrow \gamma \chi_{c0,2})(\times 10^{-4})$ | $B \times B(\psi(2S) \rightarrow \gamma \chi_{c0,2}) / B(\psi(2S) \rightarrow \pi^+ \pi^- J/\psi)(\times 10^{-4})$ |
|------|---------------------|--------------------------------------------------|--------------------------------------------------|
| $\chi_{c0} \rightarrow \pi^0 \pi^0$ | 2.65 ± 0.30 ± 0.58 | 2.47 ± 0.28 ± 0.49 | 7.96 ± 0.91 ± 1.38 |
| $\chi_{c2} \rightarrow \pi^0 \pi^0$ | 0.87 ± 0.24 ± 0.50 | 0.68 ± 0.19 ± 0.39 | 2.19 ± 0.61 ± 1.23 |
| $\chi_{c0} \rightarrow \eta \eta$ | 1.94 ± 0.81 ± 0.59 | 1.80 ± 0.75 ± 0.52 | 5.81 ± 2.42 ± 1.59 |
| $\chi_{c2} \rightarrow \eta \eta$ | < 1.22 | < 0.95 | < 3.06 |

TABLE V. The $\chi_{c}$ decay branching fractions, and ratios of branching fractions for $\chi_{c0,2} \rightarrow \pi^0 \pi^0$ or $\eta \eta$ ($B \times B(\psi(2S) \rightarrow \gamma \chi_{c0,2}) / B(\psi(2S) \rightarrow \pi^+ \pi^- J/\psi)$).