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

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

I. MOTIVATION

In perturbative QCD, the dominant process of J/ψ and $\psi(2S)$ hadronic decay is $c\overline{c}$ annihilation into three gluons. Since the decay width is proportional to the amplitude of the $c\bar{c}$ wave function at the origin, $|\Psi(0)|^2$, the branching fractions of J/ψ and $\psi(2S)$ decays into light quark states are related as [1]:

$$\frac{B(\psi(2S)\to h)}{B(J/\psi\to h)}=\frac{B(\psi(2S)\to ggg)}{B(J/\psi\to ggg)}$$
$$\simeq\frac{B(\psi(2S)\to e^+e^-)}{B(J/\psi\to e^+e^-)}=(14.6\pm2.2)\%$$

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 The prediction was originally made for the total decay width into three gluons.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 $c\bar{c}$ 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 $\rho\pi$ and $K^*\overline{K}$ — the so called *$\rho\pi$ puzzle*. The BES experiment also reported heavy suppression in the vector plus tensor (VT) final states such as $K^*\overline{K_2^*}$, ρa_2, ωf_2 and $\phi f_2^{'}$ [3].

In perturbative QCD, the radiative J/ψ 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 α_S is replaced by α_{QED} in the cross section formula. It is expected that the "15%" rule should also work for radiative decay modes [4]. Hence the ratio of $B(\psi(2S)\to\gamma X)$ to $B(J/\psi\to\gamma X)$ for different final states X should be roughly 15%. This paper explores the $\psi(2S)$ radiative decays into pairs of pseudoscalars, $\pi\pi$, $K\overline{K}$ and $\eta\eta$, and reports the first branching fraction measurements of $\psi(2S)\to\gamma f_2(1270)$ and $\gamma f_0(1710)$. The branching fractions of χ_{c0} and χ_{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/ψ into $K\overline{K}$, but not in the reaction $K^-p\to KK\Lambda$ by the LASS experiment [5]. The later 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 $e^+e^-\to\psi(2S)$ event [6] 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 $\sigma_p/p=1.7\%\sqrt{1+p^2(\mathrm{GeV/c})}$ 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 $\sigma_E/E=0.22/\sqrt{E(\mathrm{GeV})}$, and spatial resolutions of $\sigma_\phi=4.5$ mrad and $\sigma_\theta=12$ mrad. The BSC is surrounded by a magnetic coil and steel plates (for magnetic flux return). There is a 3-layer μ counter interleaved with the steel plates to identify μ tracks.

The photons used in this analysis are detected as showers in the BSC. Showers within 8^o of each other are regarded as split showers of a single photon candidate and their energies are recombined. For a π^0 or η decaying into two photons, the helicity angle of the decay should be flat and hence $|\cos\theta_{helicity}|<0.99$ 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 μ^+ or μ^- by the μ 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. $\psi(2S)\to\gamma\pi\pi$ ANALYSIS

Here the analysis of decays into both charged and neutral pion pairs, $\psi(2S)\to\gamma\pi^+\pi^-$ and $\psi(2S)\to\gamma\pi^0\pi^0$, 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 ρ signal is observed over a continuous background. These are due to the initial state radiation processes $e^+e^-\to\gamma\rho$ and $e^+e^-\to\gamma\mu^+\mu^-$. These processes are also presented in the $e^+e^-\to\tau\tau$ 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 τ 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 τ 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. 2a shows the result of subtracting the $\tau\tau$ scan histogram normalized to the $\psi(2S)$ from the $\psi(2S)$ histogram.

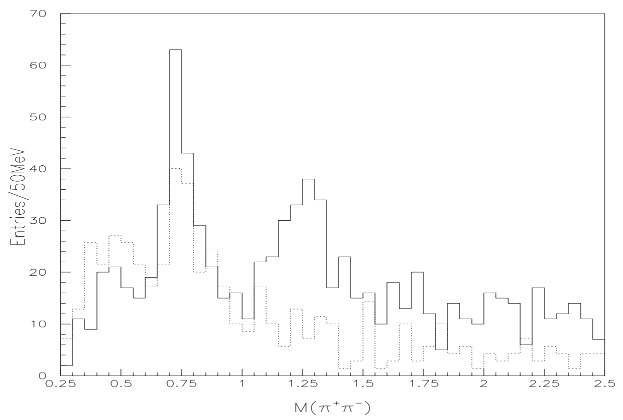

FIG. 1. $M_{\pi^+\pi^-}$ from $\psi(2S)$ data in the solid line histogram and luminosity normalized τ data in the dashed line histogram.

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 π^0 resonances. The combination with the smallest fit χ^2 is selected. A four-constraint fit is also applied on that combination and $|M_{\gamma\gamma} - M_{\pi^0}| < 70MeV$ is required. The resulting mass distribution is shown in Figure 2b.

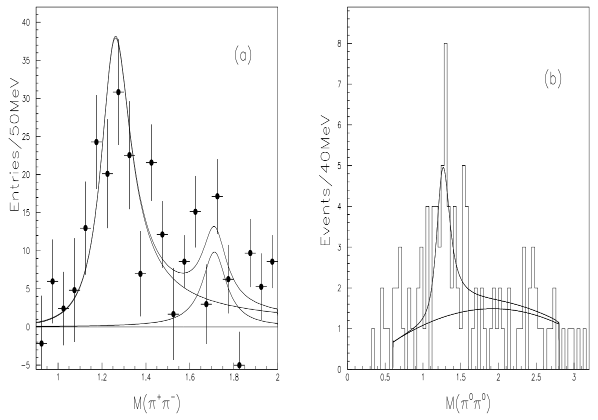

FIG. 2. (a): $M_{\pi^+\pi^-}$ fit result. The data points are obtained from the difference of the two histograms in Fig. 1 (b): $M_{\pi^0\pi^0}$.

In both the $\pi^+\pi^-$ and $\pi^0\pi^0$ invariant mass distributions, clear $f_2(1270)$ signals are observed. Both distributions are fitted with a D-wave Breit-Wigner function with the resonant parameters fixed at the PDG [8] values for the $f_2(1270)$. An S-wave Breit-Wigner with mass and width fixed at the PDG values for the $f_0(1710)$ is included in the mass fitting in the $\gamma\pi^+\pi^-$ channel in order to describe the line shape in that region. A phase space background is included in the $\gamma\pi^0\pi^0$ channel. The fit yields 209.8 ± 24.9 events and 29.9 ± 11.1 events above background as shown in Fig. 2a and Fig. 2b, respectively.

Branching fractions of $B(\psi(2S) \rightarrow \gamma f_2(1270)) = (2.21 \pm 0.26 \pm 0.39) \times 10^{-4}$ from the $\psi(2S) \rightarrow \gamma\pi^+\pi^-$ channel and $B(\psi(2S) \rightarrow \gamma f_2(1270)) = (2.95 \pm 1.10 \pm 1.12) \times 10^{-4}$ from the $\psi(2S) \rightarrow \gamma\pi^0\pi^0$ 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

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

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/ψ decay on PDG. See Table I.

A $f_0(1710)$ signal is observed in the $\pi^+\pi^-$ invariant mass distribution, as shown in Fig. 2a. The number of $f_0(1710)$ events above background is 39.2 ± 10.1. The Monte Carlo determined efficiency for this channel is 45.4%, and the resulting branching fractions are

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

or

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

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 χ_{c0} and χ_{c2} charmonium states. This mass distribution is fitted with two Breit-Wigner resonancess plus a polynomial background function, and 96.9 ± 11.1 and 20.8 ± 5.8 events are obtained for χ_{c0} and χ_{c2}, respectively. The detection efficiencies are 10.5% and 8.2%, and the resulting branching fractions are

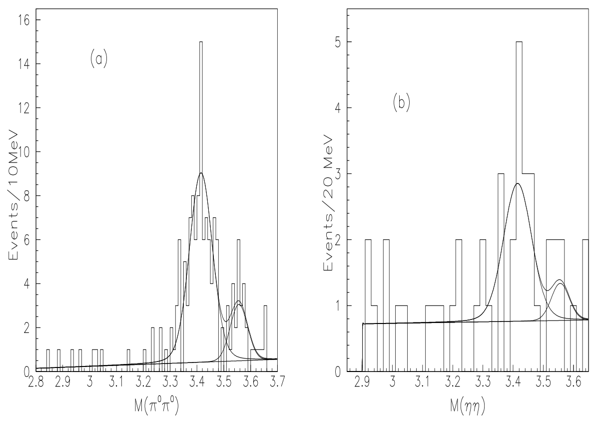

FIG. 3. Invariant mass of (a) $\pi^0\pi^0$ and (b) $\eta\eta$.

$$B(\chi_{c0} \to \pi^0\pi^0) = (2.65 \pm 0.30 \pm 0.58) \times 10^{-3}$$

and

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

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

IV. $\psi(2S) \to \gamma K\overline{K}$ ANALYSIS

Here the analysis of decays into charged and neutral kaon pairs, $\psi(2S) \to \gamma K^+K^-$ and $\psi(2S) \to \gamma K^0_S K^0_S \to \gamma 4\pi^\pm$, is presented. For the $\psi(2S) \to \gamma K^+K^-$ 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 $e^+e^- \to \gamma\phi \to \gamma K^+K^-$ and $e^+e^- \to \gamma\mu^+\mu^-$ are determined using the τ scan data (See Fig. 4). A $f_0(1710)$ signal and a hint of a possible $f_2^{'}(1525)$ signal (Fig. 5) 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 ± 14.4 $f_0(1710)$ events above background. The detection efficiency is 33.6%, giving a branching fraction

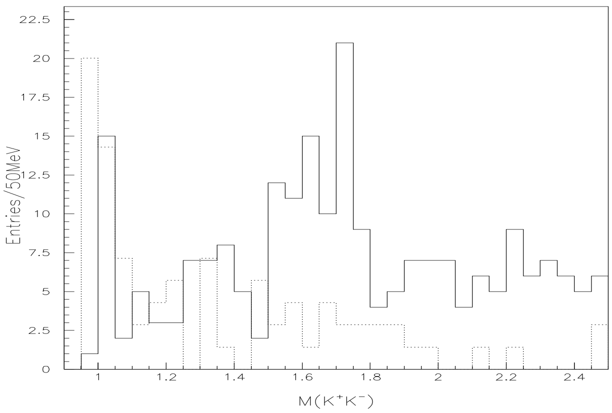

FIG. 4. $M_{K^+K^-}$ from $\psi(2S)$ data in the solid line histogram and luminosity normalized τ data in the dashed line histogram.

$$B(\psi(2S) \to \gamma f_0(1710)) \times B(f_0(1710) \to K^+K^-) = (5.59 \pm 1.12 \pm 0.93) \times 10^{-5}$$

The systematic error includes the uncertainties from varying the cuts and the total number of $\psi(2S)$'s. This result is again consistent with the "15%" rule. See Table I.

For the $\psi(2S) \to \gamma K^0_S K^0_S \to \gamma\pi^+\pi^-\pi^+\pi^-$ channel, events with two positive charged tracks, two negative charged tracks and at least one photon are selected. Both K^0_S vertices are reconstructed and $|M_{\pi^+\pi^-} - M_{K^0_S}|$ must be smaller than 20 MeV. At least one of the combinations must yield a four-constraint fit with χ^2 probability greater than 0.01. If more than one combination survives, the combination with the smallest value of

$$\sqrt{(m_{\pi_1^+\pi_2^-} - m_{K^0_S})^2 + (m_{\pi_3^+\pi_4^-} - m_{K^0_S})^2}$$

is chosen. An S-wave Breit Wigner plus a polynomial background are used to fit the invariant mass distribution shown in Fig. 5b. The fit finds 6.8 ± 3.1 events, or an upper limit of 10.8 events at 90% confidence level. The detection efficiency for this channel is 18.0%. The branching fraction is

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

or

$$< 3.98 \times 10^{-5} \quad (90\% \; C.L.)$$

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

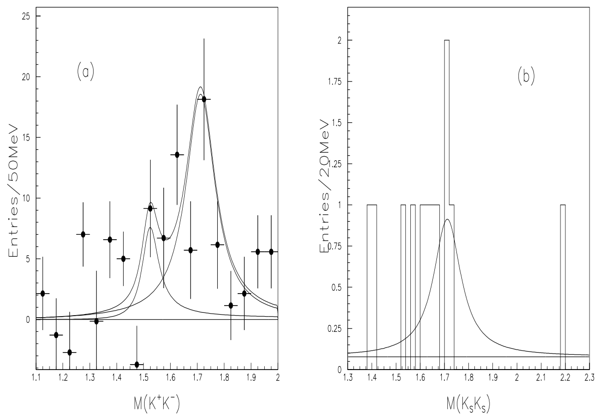

FIG. 5. Invariant mass of (a) K^+K^- and (b) $K^0_S K^0_S$. The data points in (a) are obtained from the difference of the two histograms in Fig. 4.

V. $\psi(2S) \to \gamma\eta\eta$ ANALYSIS

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

$M_{\eta\eta} > 3$ GeV, shown in Fig. 3b, a χ_{c0} signal and a possible χ_{c2} signal are observed. Two Breit-Wigner functions with a polynomial background are used to fit the mass distribution, and 12.7 ± 5.3 events for χ_{c0} and an upper limit of 5.9 χ_{c2} events are found, giving the following branching fractions

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

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

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

Flavor SU(3) symmetry predicts that the branching fractions of χ_{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 $p^{(2s+1)}$, where p is the momentum of the π^0 or η in χ_c's rest frame and s is the spin of the χ_c. Based on the PDG values for the χ_{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 II 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 fractions 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 II to V for the results.

VII. SUMMARY

This paper studies $\psi(2S) \to \gamma\pi^+\pi^-$, $\gamma\pi^0\pi^0$, γK^+K^-, $\gamma K^0_S K^0_S$, $\gamma\eta\eta$ 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 $\gamma K^0_S K^0_S$ 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 χ_{c0} and χ_{c2} decay into $\pi^0\pi^0$, χ_{c0} decay into $\eta\eta$, and an upper limit of the branching fraction of χ_{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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Final state	$B(\psi(2S)\to)(\times10^{-4})$	$B(J/\psi\to)(\times10^{-4})$	$B(\psi(2S))/B(J/\psi)$
$\gamma f_2(1270)$	$2.27\pm0.26\pm0.39$	13.8 ± 1.4	$(16.4\pm1.9\pm2.5)\%$
$\gamma f_0(1710)\to\gamma K^+K^-$	$0.559\pm0.112\pm0.093$	$4.25^{+0.60}_{-0.45}$ [8]	$(13.2\pm2.76^{+2.60}_{-2.88})\%$

TABLE I. Verification of the 15% rule. The value of $B(J/\psi\to\gamma f_0(1710)\to\gamma K^+K^-)$ is obtained from $B(J/\psi\to\gamma f_0(1710)\to\gamma K\overline{K})=8.6^{+1.2}_{-0.9}$ divided by a factor of 2 from iso-spin.

Mode	Number of events from mass fitting	Detection efficiency	Branching Fractions correction factor	Number of events after correction
$\psi(2S)\to\gamma f_2(1270)$ from $\gamma\pi^+\pi^-$	209.8 ± 24.9	43.8%	0.847 ± 0.024	$565.5\pm67.1\pm85.7$
$\psi(2S)\to\gamma f_2(1270)$ from $\gamma\pi^0\pi^0$	29.9 ± 11.1	9.6%	0.827 ± 0.028	$376.7\pm139.9\pm138.1$
$\psi(2S)\to\gamma f_0(1710)\to\gamma\pi\pi$ from $\gamma\pi^+\pi^-$	39.2 ± 10.1	45.4%	1.0 ± 0.0	$86.3\pm22.2\pm35.2$
$\psi(2S)\to\gamma f_0(1710)\to\gamma K^+K^-$	71.9 ± 14.4	33.6%	1.0 ± 0.0	$214.0\pm42.9\pm30.6$
$\psi(2S)\to\gamma f_0(1710)\to\gamma K_S^0K_S^0$	6.8 ± 3.1	18.0%	0.471 ± 0.004	$80.3\pm36.6\pm41.9$

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 $\pi^0\to\gamma\gamma$, $\eta\to\gamma\gamma$, $K_S^0\to\pi^+\pi^-$, $f_2(1270)\to\pi\pi$, etc. They do not include iso-spin factors.

Mode	$B(\times10^{-4})$	$B/B(\psi(2S)\to\pi^+\pi^-J/\psi)(\times10^{-4})$
$\psi(2S)\to\gamma f_2(1270)$ from $\gamma\pi^+\pi^-$	$2.21\pm0.26\pm0.39$	$7.14\pm0.85\pm1.09$
$\psi(2S)\to\gamma f_2(1270)$ from $\gamma\pi^0\pi^0$	$2.95\pm1.10\pm1.12$	$9.52\pm3.53\pm3.49$
$\psi(2S)\to\gamma f_2(1270)$ from $\gamma\pi\pi$	$2.27\pm0.26\pm0.39$	$7.31\pm0.83\pm1.04$
$\psi(2S)\to\gamma f_0(1710)\to\gamma\pi\pi$ from $\gamma\pi^+\pi^-$	$0.338\pm0.087\pm0.141$	$1.09\pm0.28\pm0.44$
$\psi(2S)\to\gamma f_0(1710)\to\gamma K^+K^-$	$0.559\pm0.112\pm0.093$	$1.80\pm0.36\pm0.26$
$\psi(2S)\to\gamma f_0(1710)\to\gamma K_S^0K_S^0$	$0.210\pm0.096\pm0.111$	$0.68\pm0.31\pm0.35$

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

Mode	Number of event from mass fitting	Detection efficiency	Branching Fractions correction factor	Number of events after correction
$\chi_{c0}\to\pi^0\pi^0$	96.9 ± 11.1	10.5%	0.9761 ± 0.0005	$945.4\pm108.3\pm163.8$
$\chi_{c2}\to\pi^0\pi^0$	20.8 ± 5.8	8.2%	0.9761 ± 0.0005	$259.9\pm72.5\pm145.8$
$\chi_{c0}\to\eta\eta$	12.7 ± 5.3	11.9%	0.1547 ± 0.0035	$689.9\pm287.9\pm188.9$
$\chi_{c2}\to\eta\eta$	<5.9	10.5%	0.1547	<363.3

TABLE IV. Numbers of events corrected for efficiency and branching fraction acceptance for χ_c decay.

Mode	$B(\times10^{-3})$	$B\times B(\psi(2S)\to\gamma\chi_{c0,2})(\times10^{-4})$	$B\times B(\psi(2S)\to\gamma\chi_{c0,2})/B(\psi(2S)\to\pi^+\pi^-J/\psi)(\times10^{-4})$
$\chi_{c0}\to\pi^0\pi^0$	$2.65\pm0.30\pm0.58$	$2.47\pm0.28\pm0.49$	$7.96\pm0.91\pm1.38$
$\chi_{c2}\to\pi^0\pi^0$	$0.87\pm0.24\pm0.50$	$0.68\pm0.19\pm0.39$	$2.19\pm0.61\pm1.23$
$\chi_{c0}\to\eta\eta$	$1.94\pm0.81\pm0.59$	$1.80\pm0.75\pm0.52$	$5.81\pm2.42\pm1.59$
$\chi_{c2}\to\eta\eta$	<1.22	<0.95	<3.06

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