Inclusive radiative $\psi(2S)$ decays

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Using e^+e^- collision data taken with the CLEO-c detector at the Cornell Electron Storage Ring, we have investigated the direct photon spectrum in the decay $\psi(2S) \to \gamma gg$. We determine the ratio of the inclusive direct photon decay rate to that of the dominant three-gluon decay rate $\psi(2S) \to ggg$ ($R_\gamma \equiv \Gamma(\gamma gg)/\Gamma(ggg)$) to be $R_\gamma(z_\gamma > 0.4) = 0.070 \pm 0.002 \pm 0.019 \pm 0.011$, with z_γ defined as the scaled photon energy relative to the beam energy. The errors shown are statistical, systematic, and that due to the uncertainty in the input branching fractions used to extract the ratio, respectively.

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I. INTRODUCTION

Theoretical approaches to heavy quarkonia radiative decays were developed shortly after the discovery of charmonium [1]. Predictions for the direct photon energy spectrum of quarkonia were originally based on decays of orthopositronium into three photons, leading to the expectation that the direct photon momentum spectrum should rise linearly with $z_\gamma(\equiv E_\gamma/E_{\text{beam}})$ to the kinematic limit ($z_\gamma \to 1$). Phase space considerations lead to a slight enhancement exactly at the kinematic limit [2,3]. Garcia and Soto (GS) [4] have performed the most recent calculation of the expected direct photon spectrum in charmonium decays, using an approach similar to that applied by the same authors for the case of $\Upsilon(1S) \to \gamma gg$ [5]. They model the endpoint region by combining nonrelativistic QCD (NRQCD) with soft collinear-effective theory (SCET), which facilitates calculation of the spectrum of the collinear gluons resulting as $z_\gamma \to 1$. At lower momenta (defined as $z_\gamma \lesssim 0.4$), the so-called "fragmentation" photon component, due to photon radiation off final-state quarks, must be directly calculated. In general (unfortunately), the intermediate z_γ regime over which calculations are considered reliable for the $\psi(2S)$ overlaps poorly with the higher z_γ kinematic regime to which we have the best experimental sensitivity.

Since the quantum numbers of the gluon system allow both color-octet and color-singlet contributions, these must both be explicitly calculated and summed. Of particular relevance to this analysis is the possibility that, in the context of the GS calculation, the contribution due to the octet matrix element can result in a suppression of the ratio of direct photon to three-gluon widths ("R_γ") for the $\psi(2S)$ compared to the J/ψ. Since the NRQCD matrix element appears in the denominator of R_γ and not in the numerator (up to order v^2 in quark velocity), a larger value of this matrix element leads to a reduced value of R_γ.

For direct radiative decays, given a particular photon energy, theory prescribes the angular distribution $dN/d\cos\theta_\gamma$ for the decay of a vector into three massless vectors (with θ_γ defined as the polar angle relative to the e^+ beam axis). Köller and Walsh considered the angular spectrum in detail [6], demonstrating that, if the parent is polarized along the beam axis, as the momentum of the most energetic primary (photon or gluon) in $c\bar{c} \to \gamma gg$ or $c\bar{c} \to ggg$ approaches the beam energy, the event axis increasingly tends to align with the beam axis. They parametrized the angular distribution as $dN/d\cos\theta_\gamma \propto 1 + \alpha(z_\gamma)\cos^2\theta_\gamma$; as $z_\gamma \to 1$, $\alpha \to 1$. We note that, according to the Köller-Walsh prescription, the value of α for intermediate z_γ values, where most of the events occur, is relatively small (≈ 0.2). Only for $z_\gamma \geq 0.9$ is the forward peaking of the photon angular distribution noticeable.

Although inclusive radiative decays of radially excited bottomonia have been experimentally investigated [7], there have been no corresponding measurements for the case of the charmonium. That one previous measurement of the direct photon spectrum in excited bottomonia [$\Upsilon(2S)$ and $\Upsilon(3S)$] found good agreement in both shape and normalization with the comparable spectrum measured for the $\Upsilon(1S)$ ground state.

II. DATA SETS AND EVENT SELECTION

The CLEO-c detector is essentially identical to the previous CLEO III detector, with the exception of a modified innermost charged particle tracking system. Elements of the detector, as well as performance characteristics, are described in detail elsewhere [8–10]. Over the kinematic regime of interest to this analysis, the electromagnetic shower energy resolution is approximately 2%. The tracking system, RICH particle identification system, and electromagnetic calorimeter are all contained within a 1 T superconducting solenoid.

The primary data used in this analysis consist of 27.4 M events collected on the $\psi(2S)$ resonance at a center-of-mass energy $E_{\rm cm} = 3686$ MeV, over three distinct running periods. To reduce uncertainties from event-finding efficiencies, we require a minimum of one charged track found in the event. Except for this charged multiplicity requirement, all event selection criteria, photon definitions, and the generation of background estimators are identical to those detailed in our previous analyses of Υ [7] and J/ψ [11] data. We therefore present only an abbreviated discussion below.

Events containing two tracks loosely consistent with leptons and identified topologically as (radiative) Bhabha or (radiative) muon pair events are explicitly rejected from consideration as candidate radiative decays, as are events consistent with the "1 vs 3" prong four charged-track event topology often characteristic of τ-pair production. We additionally reject events which have a single, well-identified electron or muon charged track. Photons are defined as showers detected in the barrel ($|\cos\theta_\gamma| \leq 0.8$) electromagnetic calorimeter with energy deposition characteristics consistent with those expected for true photons, and which are well-isolated from both charged tracks as well as other showers.

III. ANALYSIS

To obtain R_γ, we must determine separately the number of direct photon events and the number of three-gluon events. Since approximately 4/5 of all $\psi(2S)$ decays are either hadronic or radiative transitions to lower-mass charmonium states, the relative signal to background (primarily due to $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$) is therefore expected to be considerably reduced compared to the corresponding J/ψ analysis. Moreover, there is a large direct photon background from the J/ψ itself, which is determined from data and directly subtracted. Note that, for the $\psi(2S)$, there is also a high-energy enhancement due to radiative continuum processes, such as $e^+e^- \to \gamma\rho$, which were not present in the tagged J/ψ analysis. Continuum contributions were circumvented in the previous $J/\psi \to \gamma gg$ analysis [11] using the tagged process $\psi(2S) \to \pi\pi J/\psi$; $J/\psi \to \gamma X$. This continuum contribution (including initial state radiation [CO ISR]) to the observed inclusive photon energy spectrum at $E_{\rm cm} = 3686$ MeV is directly determined (and subsequently subtracted) using data taken at center-of-mass energies 15 MeV below the $\psi(2S)$ resonance mass. There is also a correction due to the radiative return to the J/ψ, which subsequently decays into γgg, and is implicitly included in our continuum subtraction.

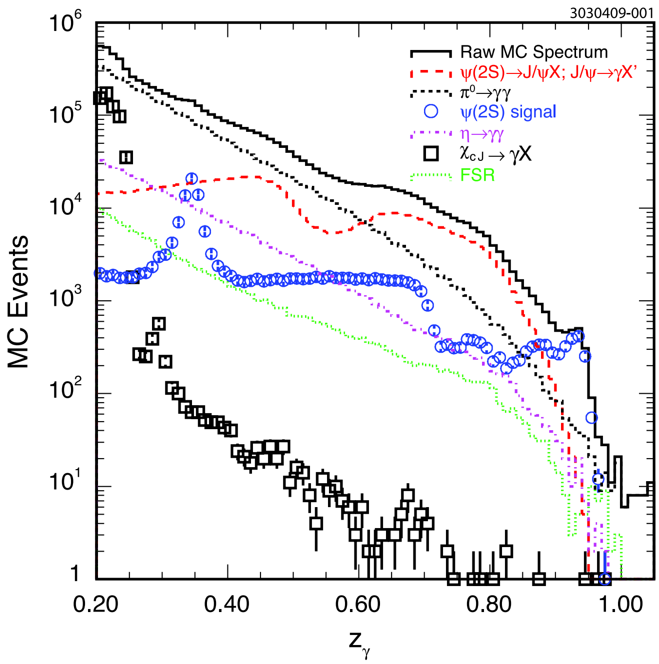

FIG. 1 (color online). MC simulation of expected backgrounds to direct photon signal. In addition to the signal of interest, also shown are contributions from $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, the cascade process, $\psi(2S) \to J/\psi X$; $J/\psi \to \gamma X'$, photons from inclusive χ_c decays, and final state radiation (FSR).

A. Background estimation

Monte Carlo (MC) simulations are used as a guide to the expected composition of the raw, observed $E_{cm} = 3686$ MeV photon momentum spectrum. The MC prediction for the background to the direct photon candidate spectrum, broken down by parent type and source, is shown in Fig. 1. The primary background arises from the cascade process, $\psi(2S) \to J/\psi X$; $J/\psi \to \gamma X'$. This component can be extracted from the data itself using events tagged via $\psi(2S) \to J/\psi \pi^+\pi^-$. We combine all oppositely signed charged pion candidates, and calculate the mass recoiling against the dipion system. The photon spectrum (after a very small sideband subtraction in J/ψ recoil mass) observed in events having a missing mass consistent with the J/ψ is interpreted as the cascade contribution. We scale this observed spectrum up to the total number of $\psi(2S) \to J/\psi X$ events by the ratio $\mathcal{B}(\psi(2S) \to J/\psi X)/(\mathcal{B}(\psi(2S) \to J/\psi \pi^+\pi^-)\epsilon_{\pi^+\pi^-})$, with $\mathcal{B}(\psi(2S) \to J/\psi X)/\mathcal{B}(\psi(2S) \to J/\psi \pi^+\pi^-) = 1.784 \pm 0.003 \pm 0.02$ [12], and $\epsilon_{\pi^+\pi^-}$ defined as the reconstruction efficiency for two transition pions, estimated from MC simulations to be 0.63 ± 0.02. In principle, this cascade photon spectrum depends on the Q value of the specific $\psi(2S) \to J/\psi X$ transition process; in practice, the smearing of the photon spectrum due to this variation is negligibly small.

IV. $\pi^0 \to \gamma\gamma$ AND $\eta \to \gamma\gamma$ BACKGROUNDS

After subtracting the cascade contribution, the dominant nondirect photon background arises primarily from $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ decays. To model the production of π^0 and η daughter photons, two different estimates were employed in this analysis as well, which we now enumerate. The variation between the results obtained with these estimators will later be included in our tabulation of systematic errors.

A. Pseudophotons

First, as in our previous J/ψ analysis [11], we take advantage of the expected similar kinematic distributions between charged and neutral pions, as dictated by isospin symmetry. Although isospin invariance will break down both when there are decay processes which are not isospin-symmetric (e.g., $\psi \to \gamma\eta$) or when the available fragmentation phase space is comparable to M_π, we expect isospin invariance to be reliable in the intermediate-energy regime (e.g., recoil masses of order 2 GeV). There should therefore be approximately half as many neutral pions as charged pions for pions produced in fragmentation. We observe agreement with this expectation to within ~10% over most of the kinematic regime relevant for this analysis.

A pseudophoton background spectrum is generated as follows. Each charged track passing quality requirements and having particle identification information consistent with pions is decayed isotropically in its rest frame into two daughter photons. To simulate the spectrum observed in data, we then boost the daughter photons into the lab frame according to the measured charged pion four-momentum. The photon-finding efficiency from Monte Carlo simulations is then used to determine the fraction of the generated pseudophotons which contribute to the observed neutral spectrum. Using this procedure, we not only simulate backgrounds from $\pi^0 \to \gamma\gamma$ decays, but also compensate for $\eta \to \gamma\gamma$, by selecting the appropriate parent mass with a frequency prescribed by MC simulations.

1. Cross-check of the pseudophoton approach

In addition to the agreement observed between the "true" and pseudophoton reconstructed π^0 yields, as detailed in the J/ψ analysis [11], our large $\psi(3770)$ sample affords an additional check of our pseudophoton approach. Since the $D\bar{D}$ mode is kinematically allowed for the $\psi(3770)$, the direct photon partial width for that resonance should be immeasurably small. We have therefore compared the inclusive photon spectra from the $\psi(3770)$ with our estimated pseudophoton background. Figure 2(a) shows this direct comparison; Fig. 2(b) shows the residuals after subtracting both continuum initial state radiation, and the estimated pseudophoton background (scaled by an

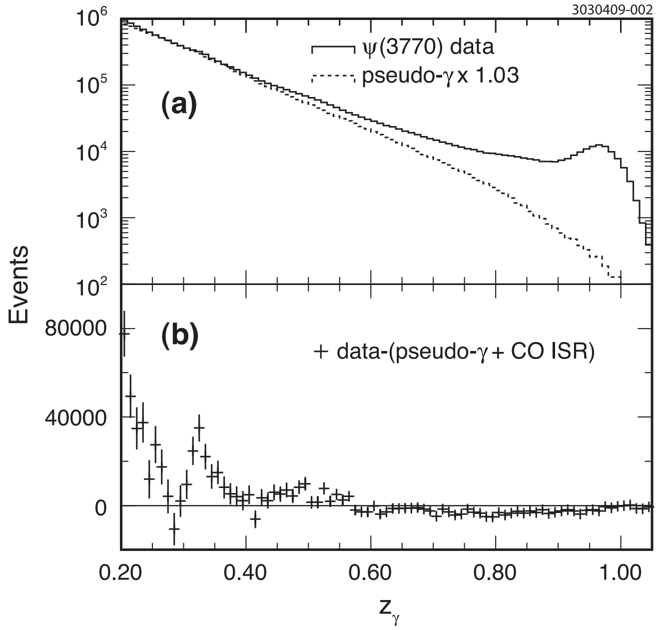

FIG. 2. (a) $\psi(3770)$ data and pseudophoton background estimate. (b) data minus both the pseudophoton and the continuum initial state radiation (CO ISR) spectra. The prominent peak at $z_\gamma \sim 0.32$ corresponds to radiative return to the J/ψ resonance.

empirical factor of 1.03 needed to achieve saturation for $z_\gamma \geq 0.4$) from the inclusive $\psi(3770)$ spectrum. Note the conspicuous presence of the photon line at $z_\gamma \sim 0.32$ in the lower, background-subtracted spectrum, which results from the radiative return to the J/ψ resonance. (Since our continuum data are taken at a center-of-mass energy approximately 100 MeV below the $\psi(3770)$ resonance, the radiative return peak in the much lower-statistics continuum data is expected to appear at $z_\gamma \sim 0.28$.) Aside from that feature, the residuals in the background-subtracted spectrum are generally featureless. To set the scale, the efficiency-corrected $z_\gamma \geq 0.4$ yield after subtraction (~ 26 K photons) deviates from zero by 1.3% relative to the initial candidate photon count in the same kinematic interval (~ 2.1 M photons) prior to subtraction. We will later use this 1.03 scale factor as a basis for estimating the uncertainty in the background normalization for the $\psi(2S) \to \gamma gg$ analysis.

B. Background estimate from an exponential fit

As with the $\Upsilon \to \gamma gg$ analysis [7], we also fit the inclusive photon spectrum to a smooth exponential curve, in the "control" interval $0.27 \leq z_\gamma \leq 0.32$ and extrapolate that curve into the higher-photon energy region as a background estimator. To the extent that the control region contains signal, the exponential may result in an oversubtraction after extrapolation into the high-z_γ regime, and therefore, ultimately, an underestimate of R_γ. To assess this bias, we have applied the exponential subtraction technique to Monte Carlo simulations; we find that the oversubtraction is approximately 9% for $z_\gamma \geq 0.4$. By comparison, the pseudophoton subtraction, applied to Monte Carlo simulations, results in an oversubtraction of less than 5%. We will later consider these deviations as implicit in our background systematic uncertainty estimate.

V. EFFICIENCIES

A. Trigger, event, and photon-finding efficiency

Based on MC simuations, the trigger efficiency for events containing a high-energy photon and at least one charged track is estimated to be 99.3%. In general, the pattern of satisfied trigger criteria for MC simulations shows adequate agreement with data. The largest event-selection inefficiencies are incurred by the requirements that the event pass the lepton veto, and that the event contain at least one well-measured charged track. Within the limited fiducial acceptance of the barrel calorimeter ($\sim 80\%$ of 4π) our photon identification algorithms are approximately 86% efficient, with inefficiencies incurred by imposition of a photon isolation requirement and a shower shape requirement. However, the net photon-finding efficiency is reduced by event-finding requirements. Figure 3 presents our "smoothed" net direct photon reconstruction efficiency, as a function of z_γ. Loss of efficiency at low z_γ is attributed to higher multiplicity events having higher likelihood of one track being mistakenly labeled a lepton. Loss of efficiency at high z_γ is attributed to reduced charged multiplicity recoiling against high-energy photons (and therefore greater likelihood of failing the minimum charged multiplicity requirement), as well as increased forward peaking of photons towards the beampipe.

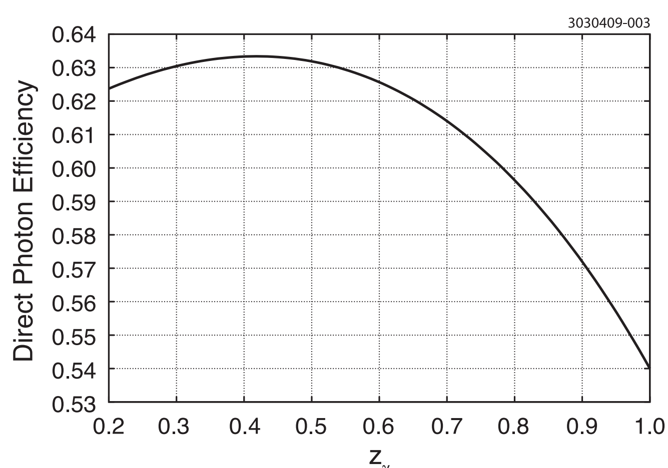

FIG. 3. $\psi(2S) \to \gamma X$ detection efficiency, as a function of scaled photon energy, from MC simulations (includes losses due to fiducial acceptance). Note the suppressed zeroes.

VI. FITS AND SIGNAL EXTRACTION

After imposing our event selection and photon selection criteria, we determine the yield in the direct photon energy spectrum. Given the limited statistics, we do not perform a two-dimensional analysis in both z_γ and $\cos\theta_\gamma$, as was possible for the J/ψ analysis. Figure 4 shows the raw data, and the components used to extract the signal, for the pseudophoton subtraction scheme.

Figure 5 overlays the signal resulting from the two different subtraction schemes. Our final numerical results are based on this figure. The total yield is obtained by integrating the point-to-point yields, and adding the individual point-to-point errors in quadrature to obtain the quoted statistical error. Also shown in Fig. 5(b) is the MC signal spectrum, which illustrates the relative scale of our inclusive signal yield relative to the prominent $\psi(2S) \to \gamma\eta_c$ peak at $z_\gamma \sim 0.34$. The $\Upsilon(1S)$ spectrum is presented for comparison only.

A. Comment on exclusive modes

Excluding electromagnetic transitions to other charmonium states (e.g., $\psi(2S) \to \gamma\eta_c$), two-body radiative exclusive modes should, in principle, be included in our total γgg rate. Although individual photon lines cannot be resolved in our analysis, we note that this analysis yields a branching fraction estimate for $\psi(2S) \to \gamma X$ ($M_X \leq$ 1.5 GeV) consistent with the tabulated Particle Data Group (PDG) [13] world average.

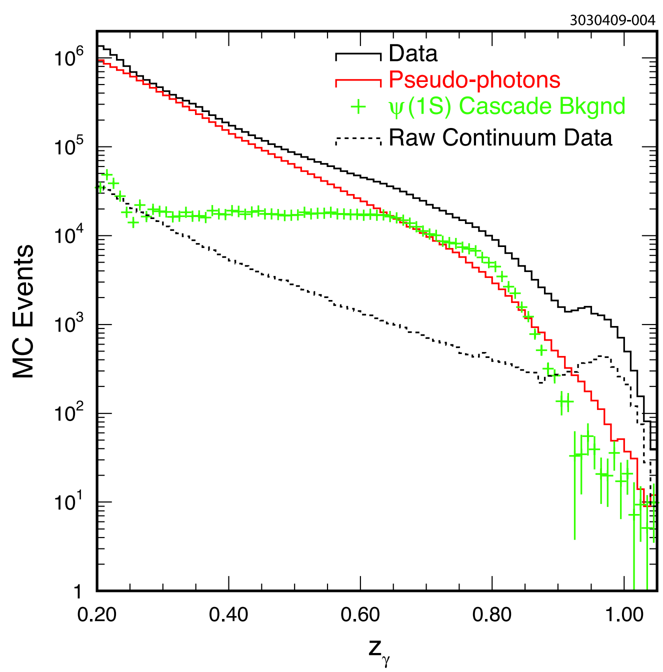

FIG. 4 (color online). Raw photon momentum spectrum, ψ(2S) data, and background estimated using pseudophoton subtraction scheme.

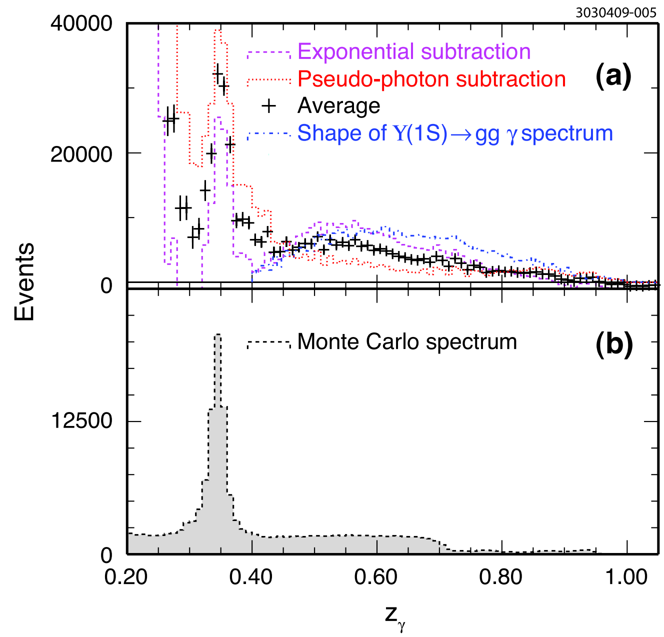

FIG. 5 (color online). (a) $\psi(2S) \to \gamma X$ signal spectra, resulting after applying different subtraction schemes. (b) Monte Carlo simulated $\psi(2S) \to \gamma X$ signal spectrum.

B. Extraction of R_γ

1. Direct ratio determination

To determine R_γ, we first directly take the ratio: $(N^{\rm obs}_{\gamma gg}/\epsilon_{\gamma gg})/N_{ggg}$. The number of ggg events is obtained knowing the effective ψ(2S) cross section, as tabulated elsewhere [12] and subtracting off the branching fractions to $\chi_{c,J}$, J/ψ, η_c, dileptons [12], $q\bar{q}$, and also the sought-after direct photon branching fraction (requiring an iteration). We estimate 2.9×10^6 three-gluon events in our sample.

2. Normalization to $\psi(2S) \to \gamma\eta_c$

Prominent in both the Monte Carlo simulations and data points in Fig. 5 is the photon line due to $\psi(2S) \to \gamma\eta_c$. We can also obtain an estimate of R_γ by normalizing the observed photon yield for $z_\gamma \geq 0.4$ to the photon yield observed corresponding to the decay $\psi(2S) \to \gamma\eta_c$, peaking in the interval $0.32 \leq z_\gamma \leq 0.38$. This photon yield is obtained by fitting the putative $\psi(2S) \to \gamma\eta_c$ line to a double Gaussian photon signal (based on the signal shape observed in [14]) and a smooth lower-order Chebyshev polynomial background. In this case, the absolute-photon finding largely cancels; we must correct, however, by the different angular distributions for the processes $\psi(2S) \to \gamma\eta_c$ and $\psi(2S) \to \gamma gg$, since the latter is less forward-peaked than for the η_c transition. Defining $\epsilon_{\cos\theta}$ as the angular acceptance for $\psi(2S) \to \gamma\eta_c$ relative to $\psi(2S) \to \gamma gg$ (≈ 0.88), the value R_γ obtained by normalizing to the observed number $N^{\rm obs}_{\gamma\eta_c}$ of $\psi(2S) \to \gamma\eta_c$ events can there-

TABLE I. Inputs to calculations and extracted signal results. Note that the branching fractions to the χ_{cJ} states have had cascades to the J/ψ ($\chi_{cJ} \to J/\psi\gamma$) removed to avoid double-counting, as indicated.

Quantity	Value	Comment
Number $\psi(2S)$ decays produced	27.4 M	CLEO-2008
$\mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi)$	$(35.4 \pm 0.5)\%$	CLEO-2008
$\mathcal{B}(\psi(2S) \to J/\psi X)/\mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi)$	$1.784 \pm 0.003 \pm 0.02$	CLEO-2008
$\mathcal{B}(\psi(2S) \to e^+e^-)$	$(0.765 \pm 0.017)\%$	PDG08
$\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$	$(0.76 \pm 0.08)\%$	PDG08
$\mathcal{B}(\psi(2S) \to \tau^+\tau^-)$	$(0.3 \pm 0.04)\%$	PDG08
$\mathcal{B}(\psi(2S) \to \gamma^* \to \text{hadrons})$	$(1.75 \pm 0.14)\%$	PDG08
$\mathcal{B}(\psi(2S) \to \gamma\chi_{c0}) \times (1 - \mathcal{B}(\chi_{c0} \to \gamma J/\psi))$	$[(9.42 \pm 0.31) \times 0.99]\%$	PDG08
$\mathcal{B}(\psi(2S) \to \gamma\chi_{c1}) \times (1 - \mathcal{B}(\chi_{c1} \to \gamma J/\psi))$	$[(9.2 \pm 0.4) \times 0.66]\%$	PDG08
$\mathcal{B}(\psi(2S) \to \gamma\chi_{c2}) \times (1 - \mathcal{B}(\chi_{c2} \to \gamma J/\psi))$	$[(8.69 \pm 0.35) \times 0.8]\%$	PDG08
$\mathcal{B}(\psi(2S) \to \gamma\eta_c)$	$(0.43 \pm 0.06)\%$	CLEO
f_z	0.725	$z_\gamma \geq 0.4$ fraction of entire γgg spectrum
N_{ggg}	2.9 M	
$N_\gamma(z_\gamma \geq 0.4)$	162 K	pseudophoton subtraction
$N_\gamma(z_\gamma \geq 0.4)$	232 K	exponential subtraction
$R_\gamma(z_\gamma \geq 0.4)$	$(5.65 \pm 0.03)\%$	pseudophoton subtraction
$R_\gamma(z_\gamma \geq 0.4)$	$(8.34 \pm 0.04)\%$	exponential subtraction
$N_{\gamma\eta_c}$	130 K	from fit to photon line (averaged plot)
$R_\gamma(z_\gamma \geq 0.4)$	$(7.07 \pm 0.8)\%$	normalized to $\mathcal{B}(\psi(2S) \to \gamma\eta_c)$

fore be written as

$$\mathcal{B}(\psi(2S) \to \gamma\eta_c) \times (N^{\rm obs}_{\gamma gg}/(N^{\rm obs}_{\gamma\eta_c}/\epsilon_{\cos\theta}))/\mathcal{B}(\psi(2S) \to ggg),$$

with $\mathcal{B}(\psi(2S) \to ggg)$ the fraction of $\psi(2S)$ events decaying via the three-gluon mode, and $\mathcal{B}(\psi(2S) \to \gamma\eta_c) = (4.3 \pm 0.6) \times 10^{-3}$ [14]. We note that there is an inherent uncertainty of $\approx 14\%$ in this value, resulting from the limited statistical precision of the prior CLEO $\mathcal{B}(\psi(2S) \to \gamma\eta_c)$ measurement.

Numerical inputs used to derive the desired ratio R_γ are presented in Table I. For internal consistency, we use the most recent CLEO values for $\psi(2S) \to J/\psi X$ transition branching fractions. In the last column, we list the explicit source of the ingredient branching fractions. The CLEO-2008 results are from Ref. [12], the PDG averages are from Ref. [13], and the CLEO result for $\psi(2S) \to \gamma\eta_c$ is from Ref. [14]. Averaging the last three R_γ lines in Table I, we obtain $R_\gamma(z_\gamma > 0.4) = 0.070 \pm 0.002 \pm 0.019 \pm 0.011$, with statistical, systematic, and branching-ratio uncertainties shown, limited to $z_\gamma \geq 0.4$.

VII. SYSTEMATIC ERRORS

We identify and estimate systematic errors in our R_γ determination as follows.

(1) Given the fact that the signal-to-noise ratio is so small, it is important to evaluate the sensitivity to the background scale. We have correspondingly evaluated the change in R_γ when the background estimators are individually toggled in normalization by 3% (typical of the normalization uncertainty in previous Υ and ψ analyses and consistent with Fig. 2). For $\pm 3\%$ variation of the pseudophoton and exponential normalizations, we find fractional R_γ variations of order 20%. We can independently assess the uncertainty in the background normalization by taking the difference between the exponential and pseudophoton extracted R_γ values (19%). Conservatively taken together, we quote a total background normalization uncertainty of 27%. This is by far our largest single systematic error.

(2) Extrapolation of direct photon spectrum to $z_\gamma \leq 0.4$: Although this obviously does not enter directly into the calculated yield for $z_\gamma \geq 0.4$, this quantity does enter in the calculation of R_γ. Since R_γ is defined relative to the three-gluon yield, we must subtract the entire estimated γgg rate, including the unseen portion below $z_\gamma = 0.4$, to estimate the fraction of direct $\psi(2S)$ decays proceeding through ggg-only. We estimate this error as half the total difference between the fractional yield for $z_\gamma \leq 0.4$ expected in an $\Upsilon(1S)$-like direct photon spectrum (28%), vs the extreme case of a linear extrapolation to $z_\gamma = 0$ (40%), or 6%. However, since this enters as second-order in the value of R_γ, this contribution to the total systematic error in R_γ is only $\approx 1\%$.

(3) Angular distribution uncertainties: Although we have not performed a two-dimensional fit, we have

compared the obtained values of R_γ over high- $(0.4 \leq |\cos\theta_\gamma| \leq 0.8)$ and low- $(0.4 \geq |\cos\theta_\gamma|)$ polar angle regimes. We find a difference of 4.4% between these two cases, and assign a corresponding error of 2.2%.

(4) The contribution to the signal due to nonphoton showers, based on MC tagging studies, is estimated to be 4% (the total of the K_L^0 plus antineutron contribution, as indicated by MC studies) after applying all cuts. Note that these contributions are largely subsumed into our exponential background subtraction.

(5) The trigger efficiency systematic error in the ratio is $\leq 1\%$.

(6) Photon-finding efficiency uncertainty contribution to the ratio is estimated at 2%.

(7) The uncertainty contribution due to the limited precision of $\mathcal{B}(\psi(2S) \to J/\psi X)$ is estimated at 2%.

(8) The uncertainty in the three-gluon event-finding efficiency results in a systematic error of 2%.

(9) In principle, the $J/\psi \to \gamma gg$ cascade photon spectrum, which is calculated from the observed $\psi(2S) \to \psi\pi^+\pi^-; J\psi \to \gamma X'$ spectrum, can differ from the cascade spectrum for different cascade processes, with different typical boosts. For a mean dipion mass of 400 MeV, the J/ψ recoil momentum is approximately 390 MeV/c; for a cascade transition through χ_{cJ} (i.e. $\psi(2S) \to \gamma\chi_{cJ}$; $\chi_{cJ} \to \gamma J/\psi$), assuming that the two transition photons are uncorrelated in angle, the average daughter J/ψ momentum is about 10 MeV/c higher. For our purposes, we consider this effect negligible.

(10) We include (separately) an error of 15% based on the difference in results obtained using CLEO-only values vs the most recently compiled values from the Particle Data Group as branching fraction inputs.

Systematic errors are summarized in Table II.

TABLE II. Systematic errors.

Source	$\delta R_\gamma/R_\gamma$ (%)
Background normalization	27
$z_\gamma \to 0$ extrapolation	1
Angular distribution uncertainties	2.2
K_L^0+ antineutron contamination	4
Trigger efficiency	1
Photon-finding	2
$\psi(2S) \to J/\psi X$ normalization	2
Three-gluon event efficiency	2
Input branching fractions	15
Total Systematic Error	$\pm 27 \pm 15$

VIII. COMPARISON TO J/ψ

Our expectation is that the ratio of partial widths $\Gamma(\gamma gg)/\Gamma(ggg)$ should be the same for the $\psi(2S)$ as for the J/ψ. This expectation is satisfied for the case of the Υ system. We have calculated $R_\gamma(\psi(2S))/R_\gamma(J/\psi)$, although we note that since the two signal extraction techniques are very different, the dominant systematic errors are largely uncorrelated for both numerator and denominator, so therefore, there is no cancellation of common systematic errors in this quotient. Restricted to the interval $z_\gamma \geq 0.4$, the ratio of γgg partial widths for the $\psi(2S)$ compared to the J/ψ is 0.69 ± 0.20. Assuming that the direct photon momentum spectral shape for the $\psi(2S)$ is similar to the J/ψ, the fraction of photons in the region $z_\gamma \leq 0.4$ is approximately 28% of the entire spectrum, corresponding to a momentum-integrated value of $R_\gamma = 0.097 \pm 0.026 \pm 0.010$, again about 2/3 the value obtained at the J/ψ. (If instead, we extrapolate linearly from $z_\gamma = 0.4$ to $z_\gamma = 0.0$, this ratio of widths increases by approximately 10%.) Although this low value in comparison to the J/ψ may seem surprising, such apparent anomalies [15] are not uncommon when ratios of $\psi(2S)/J/\psi$ partial widths are taken. The well-known vector-pseudoscalar (VP) suppression observed in $\psi(2S)$ exclusive hadronic decays [16] can be considerably more dramatic, as is the recently documented dearth of radiative $\psi(2S)$ decays to η and η' [15] relative to those from J/ψ. We note that the ratio of dileptonic to three-gluon widths (B_{ll}/B_{ggg}) is also considerably smaller for the $\psi(2S)$ compared to the J/ψ.

IX. SUMMARY

We have made the first measurement of the direct photon spectrum in $\psi(2S)$ decays, obtaining an inclusive rate (relative to three-gluon decays) approximately 2/3 that obtained at the J/ψ, and suggesting larger $\psi(2S)$ corrections, possibly due to closer proximity to $D\bar{D}$ threshold. Although theoretical predictions for this value are somewhat scarce, we note that this is now one of several apparent anomalies observed in ratios of widths between the $\psi(2S)$ and the J/ψ. This study completes the set of R_γ measurements for all bound Υ and J/ψ (nS) states of heavy quarkonia below open flavor threshold. It is hoped that further theoretical study will elucidate this result.

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