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Radiative Decays of the $\Upsilon(1S)$ to $\gamma\pi^0\pi^0$, $\gamma\eta\eta$ and $\gamma\pi^0\eta$

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Abstract

We report on a study of exclusive radiative decays of the $\Upsilon(1S)$ resonance into the final states $\gamma\pi^0\pi^0$, $\gamma\eta\eta$ and $\gamma\pi^0\eta$, using 1.13 fb^{-1} of e^+e^- annihilation data collected at $\sqrt{s} = 9.46\,\text{GeV}$ with the CLEO III detector operating at the Cornell Electron Storage Ring. In the channel $\gamma\pi^0\pi^0$, we measure the branching ratio for the decay mode $\Upsilon(1S) \to \gamma f_2(1270)$ to be $(10.5 \pm 1.6\ (\text{stat})\ {}^{+1.9}_{-1.8}\ (\text{syst})) \times 10^{-5}$. We place upper limits on the product branching ratios for the isoscalar resonances $f_0(1500)$ and $f_0(1710)$ for the $\pi^0\pi^0$ and $\eta\eta$ decay channels. We also set an upper limit on the $\Upsilon(1S)$ radiative decay into $\pi^0\eta$.

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Radiative decays of quarkonia, where one of the three gluons arising from the quark-antiquark annihilation is replaced by a photon leaving two gluons to form bound states, are thought to be a glue-rich environment that may lead to the production of glueballs and gluonic-mesonic states rather than ordinary mesons [1, 2]. Lattice gauge theory calculations [3, 4] predict that the lightest glueball should have $J^{PC} = 0^{++}$ and that its mass should be in the range of 1.45 to 1.75 GeV/c^2, with decay into two pseudo-scalars ($J^{PC} = 0^{-+}$) expected to dominate. Unfortunately, the identification of a scalar glueball among the many established scalar resonances is difficult, as they have the same quantum numbers and similar decay modes and may mix. The triplet of f_0 states are likely candidates for the superposition of quark states and a scalar glueball state. Many of the lattice QCD models predict the decay ratios (e.g., $\eta\eta/\pi\pi$, $\eta\eta/K\bar{K}$) for a glueball and for scalar resonances [5], and this is a possible tool to distinguish among them.

Most of the information on radiative decays of quarkonia has centered on J/ψ decays [6–10], leading to a list of two-body decay branching ratios. The establishment of a corresponding list for $\Upsilon(1S)$ decays is desirable and would not only deepen our understanding of $c\bar{c}$ and $b\bar{b}$ quarkonia, but could also contribute to the identification of a scalar glueball state or shed new light on its mixing with ordinary nearby meson states.

Recently, radiative decays into two charged particles have been studied by the CLEO III collaboration [11]. The analysis included a measurement of the decay rate into $f_2(1270)$, a confirmation of its spin, and a measurement of its helicity distribution. In this analysis, we use the same CLEO III $\Upsilon(1S)$ data sample to perform a complementary study of all-neutral decays. Although these final states are subject to poorer resolution and efficiency than those with charged particles, they have the advantage of having no background from QED final states such as $\gamma\rho$. Furthermore, they allow the search for states decaying into $\eta\eta$ and $\pi^0\eta$. Resonant production in the latter mode would be a signature of unexpected physics.

The analysis presented here uses data collected by the CLEO III detector configuration [12, 13] at the Cornell Electron Storage Ring (CESR). The vital component for this analysis is the CsI(Tl) calorimeter, which has a resolution of 1.5%(2.2%) for 1 GeV(5 GeV) photons, typical of the photons studied here. We search for radiative $\Upsilon(1S)$ decays in the modes $\Upsilon(1S) \to \gamma\pi^0\pi^0$, $\gamma\eta\eta$ and $\gamma\pi^0\eta$. The $\Upsilon(1S)$ data ($\mathrm{E_{cm}} = 9.46$ GeV) sample consists of an integrated luminosity of 1.13 fb^{-1}, corresponding to $(21.2 \pm 0.2(\mathrm{syst})) \times 10^6$ $\Upsilon(1S)$ decays [14].

Candidate events for the individual final states ($\gamma\pi^0\pi^0$, $\gamma\eta\eta$ and $\gamma\pi^0\eta$) are selected in a similar fashion, using the following basic selection criteria. An event must have no charged tracks and exactly one electromagnetic shower in the barrel ($|\cos\theta| < 0.75$, where θ represents the polar angle) or the endcap region ($0.82 < |\cos\theta| < 0.93$) of the calorimeter with an energy exceeding 4 GeV, together with at least four other photons in the event. All combinations of two photons (excluding the photon that has $E > 4$ GeV) in the event are then combined to form π^0 and η candidates. To be selected, an event must have two pairs of photons satisfying the requirement

$$\sqrt{P_1^2(\pi_1^0/\eta_1) + P_2^2(\pi_2^0/\eta_2)} < 5,$$

with P_1 and P_2 being the pulls, defined as:

$$P(\pi^0/\eta) = \left[m_{\gamma\gamma} - m(\pi^0/\eta)\right]/\sigma_{\gamma\gamma},$$

where $m_{\gamma\gamma}$ is the $\gamma\gamma$ invariant mass, $m(\pi^0/\eta)$ is the known π^0 or η mass, [15] and $\sigma_{\gamma\gamma}$ is the

$\gamma\gamma$ mass resolution, with typical values of 5 - 7 MeV/c^2. The π^0 and η candidates are then kinematically constrained to their masses, $m(\pi^0)$ and $m(\eta)$.

To study the event-selection criteria and measure their efficiencies, we use a Monte Carlo simulation consisting of an event generator [16] and a GEANT-based [17] detector-response simulation. For each final state, $\Upsilon(1S) \to \gamma X$, events are generated with $X = f_2(1270)$, $f_0(1500)$ and $f_0(1710)$, using a Breit-Wigner line-shape and the PDG mass and width [15]. We do not search for the $f_0(1370)$ as it overlaps completely in mass with the $f_2(1270)$ due to its large instrinsic width.

A 4-momentum cut and an asymmetry cut are then used to further select candidate events. For the $\gamma\pi^0\pi^0$ final-state selection, the allowed region for the 4-momentum is bounded by the following three conditions: $|\vec{p}| = -0.30 - 1.20\ \Delta E$, $|\vec{p}| = 0.25 - 0.80\Delta E$, and $|\vec{p}| = 1.10 + 0.50\ \Delta E$, where ΔE is the difference between the reconstructed event energy and the center-of-mass energy ($\mathrm{E_{cm}}$) in GeV and $|\vec{p}|$ is the magnitude of the reconstructed total event momentum in GeV/c. These cuts include the $\Delta E - |\vec{p}|$ area where the 4-momentum is conserved for the entire event and increase the efficiency by, in addition, including the region where the single, recoiling photon is reconstructed with too low an energy. For the latter, the 4-momentum is not conserved for the entire event but only for the intermediate resonance X in the decay chain $\Upsilon(1S) \to \gamma X \to \gamma\pi^0\pi^0$. These cuts are illustrated in Figure 1. We define a 4-momentum allowed region for the $\gamma\eta\eta$ final state selection in a similar manner.

A source of background originates from combining a wrong pair of photons to form a π^0 or η candidate. Real π^0 and η mesons decay isotropically and their angular distributions are flat. However, the π^0 and η candidates which originate from a wrong photon combination do not have a flat distribution in this variable and can largely be removed by a cut which uses the polar $\Delta\theta$ and azimuthal $\Delta\varphi$ angle differences between the two photons from a decay candidate. For the $\gamma\pi^0\pi^0$ final state the asymmetry requirement is $\sqrt{\Delta\theta^2 + \Delta\varphi^2} < 40°$, while for the $\gamma\eta\eta$ final state it is $\sqrt{\Delta\theta^2 + \Delta\varphi^2} < 60°$.

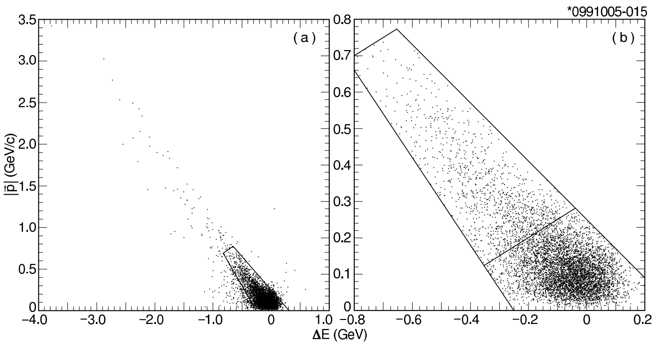

FIG. 1: Illustration of the chosen 4-momentum distribution cuts on a larger (a) and smaller (b) scale, using Monte Carlo events for the decay channel $\Upsilon(1S) \to \gamma f_2(1270) \to \gamma\pi^0\pi^0$. The slanted line in the lower right part of (b) divides the selected events roughly into two categories: the lower area where the 4-momentum is conserved for the entire event; the upper area where the 4-momentum is conserved for the intermediate resonance but not for the entire event. The remaining events outside the selected area in (a) have an energy loss from more than one photon and, hence, are excluded from the selection.

Comparison of the invariant $\pi^0\pi^0$ and $\eta\eta$ mass spectra from the Monte Carlo simulation reveals significant differences in the mass and width values from the ones used at the generator level. These differences are parametrized in the form of Gaussian resolution functions off-set from zero. The mass shift is an artifact of the shower reconstruction in the calorimeter of such fast π^0 and η mesons, when the showers tend to overlap. For example, the resolution function for the decay $f_2(1270) \to \pi^+\pi^-$ is a Gaussian function with $\sigma =$ 27 MeV/c^2 and an offset of -20 MeV/c^2.

We determine the selection efficiency for each of the resonances individually. The event selection efficiencies are summarized in Table 1. The uncertainties shown are statistical only.

Resonance	Reconstruction Efficiency in %	
	$\gamma\pi^0\pi^0$	$\gamma\eta\eta$
$f_2(1270)$	16.4 $\pm$ 0.2	10.2 $\pm$ 0.2
$f_0(1500)$	20.4 $\pm$ 0.3	9.1 $\pm$ 0.2
$f_0(1710)$	20.6 $\pm$ 0.3	8.6 $\pm$ 0.2

TABLE I: Reconstruction efficiencies for various intermediate resonances in the $\gamma\pi^0\pi^0$ and $\gamma\eta\eta$ final states.

The major background contribution in our signal region originates from non-resonant processes. CLEO's sample of data collected in the continuum below the $\Upsilon(1S)$ (192pb^{-1}) is too small to perform a continuum subtraction. Hence, we parametrize the background using a threshold function of the form

$$F(x) = N \cdot (x - T) \cdot e^{c_1(x-T)\ +\ c_2(x-T)^2},$$

where x is the $\pi^0\pi^0$ invariant mass, N is a scale factor, T is the mass threshold, and c_1, c_2 are free parameters. This functional form is a good fit to the spectrum obtained from a large Monte Carlo data sample of continuum events, and also to continuum events taken at energies near the $\Upsilon(4S)$.

Figure 2 shows the final $\pi^0\pi^0$ and $\eta\eta$ invariant mass spectra. The $\pi^0\pi^0$ invariant mass distribution is dominated by the isoscalar resonance $f_2(1270)$. The $\eta\eta$ invariant mass distribution, Figure 2(b), has only two events, which is too few to show any resonant structure.

The Monte Carlo signal events for the processes $\Upsilon(1S) \to \gamma\ X \to \gamma\pi^0\pi^0/\eta\eta$ are produced with a decay angle distribution which is characteristic of the spin of the final state (*i.e.*, $J = 0$ for $f_0(1500)$ and $J = 2$ for $f_2(1270)$). However, the generation does not take into account the correct helicity distribution for the $f_2(1270)$ since this distribution depends on the specific decay channel and can only be determined from the data itself. The method to obtain the correct helicity-angle distributions is described in detail in [11] and results in a helicity correction factor which takes into account decay-dependent efficiency corrections and the helicity substructure for the final state resonance. For this analysis, we use the helicity substructure, which is independent of the charge of the pions, determined in [11], as this is more precise than the one we can determine using the decay into $\pi^0\pi^0$. We obtain a correction factor for the $f_2(1270)$ of 0.66 $\pm$ 0.04, where the uncertainty is statistical only. This factor multiplies the efficiency stated in Table I.

To determine the branching ratio for $\Upsilon(1S) \to \gamma f_2(1270)$, we fit the invariant $\pi^0\pi^0$ mass distribution with a spin-2 Breit-Wigner line-shape of fixed mass and width, convolved with the resolution function derived from Monte Carlo studies as previously described, together with the threshold function. Integrating the Breit-Wigner line-shape fit from 0.28 to 3.0 GeV/c^2 gives 67.9 $\pm$ 10.2 events for the $f_2(1270)$.

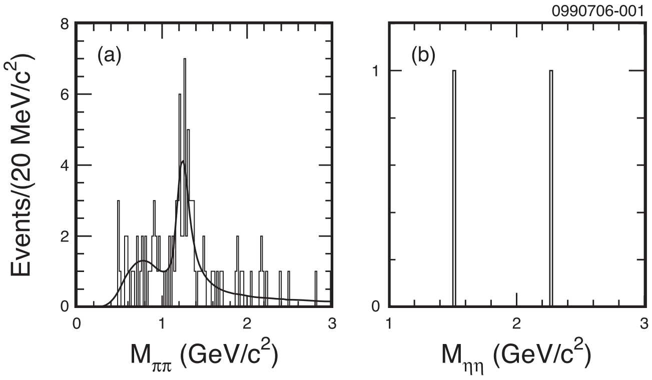

FIG. 2: The (a) $\pi^0\pi^0$ invariant mass distribution, and (b) $\eta\eta$ invariant mass distribution, from the $\Upsilon(1S)$ data sample. The line shows the fit described in the text.

With the results from this line-shape fit, the efficiency from Table I, and the helicity-correction factor, we determine the product branching ratio for the $f_2(1270)$ to be:

$$\mathcal{B}(\Upsilon(1S) \to \gamma f_2(1270)) \cdot \mathcal{B}(f_2(1270) \to \pi^0\pi^0) = (3.0 \pm 0.5) \times 10^{-5},$$

where the error is statistical only.

We determine a systematic uncertainty on this branching ratio of $\pm17\%$. The largest contribution to this error originates from uncertainties in the line-shape fit and the threshold function used for the background parametrization. Other contributions include systematic uncertainties in the π^0 reconstruction and in the 4-momentum cut. Taking into account the isoscalar nature of the $f_2(1270)$ and the branching ratio of $\mathcal{B}(f_2(1270) \to \pi\pi) = 0.847^{+0.025}_{-0.012}$ [15], we determine an overall $\Upsilon(1S)$ radiative decay branching ratio to $f_2(1270)$ of:

$$\mathcal{B}(\Upsilon(1S) \to \gamma f_2(1270)) = (10.5 \ \pm 1.6 \text{ (stat) } {}^{+1.9}_{-1.8} \text{ (syst)}) \times 10^{-5}.$$

To set upper limits on the branching ratios for other likely resonances in the $\gamma\pi^0\pi^0$ final state, we include an additional spin-dependent Breit-Wigner line-shape in the $f_2(1270)$ branching ratio fit, with a line-shape determined from our Monte Carlo studies. We fix the area of the additional Breit-Wigner and then repeat the fit using different values for the number of events. We then plot the number of events versus their likelihood from the fit, numerically integrate the area under the curve and determine the number of events where 90% of the physically allowed area is covered. This number represents the upper limit at the 90% confidence level (C.L.), which we find to be 6.9 events for the $f_0(1500)$ and to be 6.6 events for the $f_0(1710)$. Using the branching ratio $\mathcal{B}(f_0(1500) \to \pi\pi) = 0.349 \pm 0.023$ [15], and incorporating the systematic uncertainties ($\approx$6%) in the efficiencies by smearing the probability density function, we determine the 90% C.L. upper limit branching ratio for the $f_0(1500)$ to be

$$\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1500)) < 1.5 \times 10^{-5},$$

and the product branching ratio for the $f_0(1710)$ to be

$$\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1710)) \cdot \mathcal{B}(f_0(1710) \to \pi^0\pi^0) < 1.4 \times 10^{-6}.$$

As we see no evidence of any resonant structure in the $\eta\eta$ invariant mass distribution we measure upper limit branching ratios for the $f_0(1500)$ and $f_0(1710)$. For this determination we use the simple method of event counting. The final invariant mass plot has negligible background and, hence, we assume both events are from the $\Upsilon(1S) \to \gamma\eta\eta$ final state. Therefore, the number of events follows a Poisson distribution. For the $f_0(1500)$ we find 1 event in the mass interval of 1 full-width around its mass and 0 events for the $f_0(1710)$, which translates into 90% C.L. upper limits of 3.9 and 2.3 events, respectively.

The systematic uncertainty for the $f_0(1500)$ and the $f_0(1710)$ is $\approx$ 30%. The largest contributions to these uncertainties originate from the 4-momentum requirement, and the η asymmetry cut, which are on the order of 20%. Combining the statistical and systematical uncertainties, we determine the 90% C.L. upper limit on the product branching ratio for the $f_0(1500)$ to be:

$$\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1500)) \cdot \mathcal{B}(f_0(1500) \to \eta\eta) < 3.0 \times 10^{-6},$$

and for the $f_0(1710)$ to be:

$$\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1710)) \cdot \mathcal{B}(f_0(1710) \to \eta\eta) < 1.8 \times 10^{-6}.$$

In the decay $\Upsilon(1S) \to \gamma X$, if we assume that the γ is produced directly and is not the product of an intermediate virtual particle, the resonance X must be an iso-scalar. In this case, if X is conventional meson state, it can only decay into a pair of pseudo-scalars ($J^P = 0^-$) each with $I = 0$ (*e.g.*, $\eta\eta$), or $I = 1$, *e.g.*, $\pi\pi$. Observation of a resonance in $\pi^0\eta$ could therefore be an indication that the photon in this case is the result of enhanced production via an intermediate hadron, or alternatively the result of an unexpectedly large I=0 component of the $\pi^0\eta$ final state.

Following the same analysis chain as detailed above and using the same $\vec{p}, \Delta E$ region as for the $\pi^0\pi^0$ case, we find no events in our signal region for this decay. Hence, we determine an upper limit for the branching ratio $\Upsilon(1S) \to \gamma\pi^0\eta$.

We use the same method as for the upper limit determination in the $\Upsilon(1S) \to \gamma\eta\eta$ final state. To measure the reconstruction efficiency for any exotic-state mass, we generate Monte Carlo events of the type $\Upsilon(1S) \to \gamma\pi^0\eta$ with a flat $\pi^0\eta$ invariant mass distribution between 0.7 and 3 GeV/c^2, and use the lowest efficiency found in the entire mass distribution of (4.8 $\pm$ 0.5)%; The efficiency is relatively flat over the mass interval of interest.

Having no events in the data over the mass range of 0.7 to 3.0 GeV/c^2 corresponds to a 90% C.L. upper limit of 2.3 events. Combining this with a systematic error of $^{+24}_{-14}$%, due to the same sources of uncertainty as with the previous 2 analyses, we determine the 90% C.L. upper limit for the branching ratio to be:

$$\mathcal{B}(\Upsilon(1S) \to \gamma\pi^0\eta) < 2.4 \times 10^{-6}.$$

In summary, we have analyzed 1.13 fb^{-1} of data from the CLEO III detector at the $\Upsilon(1S)$ for resonances in the radiative decay channels $\Upsilon(1S) \to \gamma\pi^0\pi^0$, $\gamma\eta\eta$ and $\gamma\pi^0\eta$.

In the decay channel $\gamma\pi^0\pi^0$, we measure a branching ratio value for the isoscalar resonance $f_2(1270)$ of $\mathcal{B}(\Upsilon(1S) \to \gamma f_2(1270)) = (10.5 \pm 1.6 \ ^{+1.9}_{-1.8}) \times 10^{-5}$. This is in excellent agreement with the same branching ratio obtained from the charged final state $\gamma\pi^-\pi^+$, using the same CLEO III data set: $\mathcal{B}(\Upsilon(1S) \to \gamma f_2(1270)) = (10.2 \ \pm 0.8 \ \pm 0.7) \times 10^{-5}$ [11]. It also agrees within the uncertainties with the earlier CLEO II result of $(8.1 \ \pm 2.3 \ \pm 2.7) \times 10^{-5}$, based on the decay channel $\gamma\pi^-\pi^+$ [18]; this earlier measurement had no correction for the helicity distribution, and the large systematic uncertainty reflected this fact.

In addition, we determine 90% C.L. upper limits for the isoscalar resonances $f_0(1500)$ and $f_0(1710)$ decaying into $\pi\pi$, as well as a 90% C.L. upper limit for the decay $\Upsilon(1S) \to$

$\gamma f_0(1500)$. Based on the scalar-glueball mixing matrix from [5], QCD factorization model calculations in [2] predict branching ratios for the $f_0(1500)$ and $f_0(1710)$ to be $\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1500)) \approx 42-84\times 10^{-5}$ and $\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1710))\cdot\mathcal{B}(f_0(1710) \to \pi^0\pi^0) \approx 6-12\times 10^{-6}$. Our measurements of $\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1500)) < 1.5 \times 10^{-5}$ and $\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1710)) \cdot \mathcal{B}(f_0(1710) \to \pi^0\pi^0) < 1.4 \times 10^{-6}$ are much smaller than these predictions.

In the $\gamma\eta\eta$ decay channel, no resonant structures are observed. Therefore, we determine a 90% C.L. upper limit on the branching ratios for the isoscalar resonances $f_0(1500)$ and $f_0(1710)$ decaying into $\eta\eta$ as $\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1500)) \cdot \mathcal{B}(f_0(1500) \to \eta\eta) < 3.0 \times 10^{-6}$ and $\mathcal{B}(\Upsilon(1S) \to \gamma f_0(1710)) \cdot \mathcal{B}(f_0(1710) \to \eta\eta) < 1.8 \times 10^{-6}$.

The search for states in the $\gamma\pi^0\eta$ decay channel does not show any evidence of a signal. We determine a 90% C.L. upper limit on the branching ratio for the decay $\Upsilon(1S) \to \gamma\pi^0\eta$ for any intermediate state with a mass between 0.7 and 3.0 GeV/c^2 to be $\mathcal{B}(\Upsilon(1S) \to \gamma\pi^0\eta) < 2.4 \times 10^{-6}$.

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