Search for the Decay $\Upsilon(1S) \to \gamma\eta'$

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We report on a search for the radiative decay $\Upsilon(1S) \to \gamma\eta'$ in 61.3 pb^{-1} of data taken with the CLEO II detector at the Cornell Electron Storage Ring. Three decay chains were investigated, all involving $\eta' \to \pi^+\pi^-\eta$, followed by $\eta \to \gamma\gamma$, $\eta \to \pi^0\pi^0\pi^0$, or $\eta \to \pi^+\pi^-\pi^0$. We find no candidate events in any of the three cases and set a combined upper limit of 1.6×10^{-5} at 90% C.L., significantly smaller than the previous limit. We compare our result to other radiative Υ decays, to radiative J/ψ decays, and to theoretical predictions.

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The only measurement of a two-body radiative $\Upsilon(1S)$ decay is the CLEO analysis [1] of $\Upsilon \to \gamma\pi\pi$, which was consistent with radiative $f_2(1270)$ production. In contrast, many such radiative decays have been measured for the J/ψ system [2], including the decay to $\gamma\eta'$ at 3 times the rate to $\gamma f_2(1270)$. Such radiative decays provide a "glue-rich" environment, which could mean a large valence gluonic component to the η' wave function. Unexpectedly large rates [3] are also observed in decays such as $B \to \eta' K^{(*)}$.

In addition, there have been several theoretical predictions for the $\gamma\eta'$ final state that involve nonrelativistic [4] or light-cone [5] approaches, with the η' produced by highly virtual gluons, or that involve extended vector meson dominance [6]. There has also been theoretical work on the related process $\Upsilon \to \gamma\eta$ [7] and comparisons of the $\gamma\eta$ and $\gamma\eta'$ final states in J/ψ decay [8]. Further, there have been suggestions [8,9] that the decay $J/\psi \to \gamma\eta^{(\prime)}$ might be dominated by a strong anomaly, whereas this mechanism is suppressed for the radiative Υ decays because of the more massive constituent quarks.

In this Letter we report on a search for the decay $\Upsilon \to \gamma\eta'$ and we compare this decay mode to the $f_2(1270)$ final state in Υ decay, to the η' radiative decay in J/ψ decay, and to the theoretical predictions.

Our analysis used 61.3 pb^{-1} of data recorded at the $\Upsilon(1S)$ resonance ($\sqrt{s} = 9.46$ GeV) with the CLEO II detector [10] operating at the Cornell Electron Storage Ring (CESR). This corresponds to the production of $N_\Upsilon = (1.45 \pm 0.03) \times 10^6$ $\Upsilon(1S)$ mesons [1]. In addition, 189 pb^{-1} taken near in time to this $\Upsilon(1S)$ data but at energies just below the $\Upsilon(4S)$ were used for comparison to the four-quark continuum. The momenta and ionization loss (dE/dx) of charged tracks were measured in a 6-layer straw-tube chamber, a 10-layer precision drift chamber, and a 51-layer main drift chamber, all operating in a 1.5 T solenoidal magnetic field. Photons were detected using the high-resolution electromagnetic calorimeter consisting of 7800 CsI crystals. The Monte Carlo simulation of the detector response was based upon GEANT [11], and simulation events were processed in an identical fashion to data.

Our search for $\Upsilon \to \gamma\eta'$ involved the decay $\eta' \to \pi^+\pi^-\eta$, followed by $\eta \to \gamma\gamma$, $\eta \to \pi^0\pi^0\pi^0$, or $\eta \to \pi^+\pi^-\pi^0$. In order to maximize detection efficiency and minimize possible systematic biases, we employed a minimal number of selection criteria. Combinatoric background is largely suppressed by requiring reconstruction of the three mesons: η, η', and Υ.

Events were required to have the proper number of quality tracks of appropriate charges and at least three calorimeter energy clusters (which may or may not be associated with the tracks), of which one had to correspond to an energy of at least 4 GeV and be in the barrel fiducial volume ($|\cos\theta| < 0.71$). In addition, we required that the events pass trigger requirements [12] that were highly efficient and could be reliably simulated.

For reconstructing π^0 candidates, the photons had to have minimum depositions of 30 (50) MeV in the barrel (end cap) regions and could not be associated with any charged track; in addition, at least one of the two photons had to be in the barrel region. (The end cap region is defined as $0.85 < |\cos\theta| < 0.95$; the region between this and the barrel fiducial region is not used due to its poor resolution.) The $\gamma\gamma$ invariant mass had to be within 50 MeV ($\sim\pm 9\sigma_\pi$) of the known π^0 mass [2]; such candidates were then kinematically constrained to that mass. The photon candidates used in reconstructing the η in $\gamma\gamma$ and the parent Υ in $\gamma\eta'$ had to deposit a minimum of 60 (100) MeV in the barrel (end cap) calorimeter regions, could not be identified as a fragment of a charged track deposition, and had to have a lateral profile consistent with that of a photon.

Next, η candidates were built from $\gamma\gamma$, $\pi^0\pi^0\pi^0$, or $\pi^+\pi^-\pi^0$. Simulation events were used to determine the detector mass resolution for each of these modes: $\sigma_\eta =$ 13.4, 9.4, and 8.2 MeV, respectively. This was confirmed by measurements of resolution functions using independent data samples. Candidates had to be within $\pm 3\sigma_\eta$ of the known η mass. In the case of the $\pi^0\pi^0\pi^0$ final state, no photon could be common to more than one π^0 combination.

Two oppositely charged tracks were then added to the η candidate to form η' candidates that were required to have an invariant mass of $939 < m_{\pi\pi\eta} < 981$ MeV; this corresponds to greater than $3\sigma_{\eta'}$ for all three decay chains. In the case of $\eta \to \gamma\gamma$, a charged track was rejected if its momentum, p, from the drift chamber matched its energy, E, as measured in the calorimeter as $0.85 < E/p < 1.05$; this further suppressed QED backgrounds in this mode.

Finally, Υ candidates were formed by adding the high energy photon ($E > 4$ GeV) to the η' candidate, being sure that this photon was not already used in reconstructing the event. To be considered, such a candidate had to have an invariant mass within ± 300 MeV of $\sqrt{s} = m_\Upsilon$, which is roughly 3 times the detector resolution as obtained from our simulations. Although, in general, multiple candidates per event were not restricted, there were two exceptions: (i) in the case of $\eta \to \pi^0\pi^0\pi^0$, if two η candidates shared more than four photons, the candidate with the better combined χ^2 for mass fits to the three π^0 candidates was accepted and (ii) in the case of $\eta \to \pi^+\pi^-\pi^0$, if two candidates for the neutral pion shared a daughter photon, the one with the better fit to the π^0 mass was taken.

After these highly efficient procedures were applied, we found *no* candidates in either the Υ or continuum data samples.

From Monte Carlo simulations, the overall efficiencies, ϵ_i, were determined to be $(31.8 \pm 1.8)\%$, $(15.0 \pm 1.6)\%$, and $(21.1 \pm 1.4)\%$ for the decay chains ending in $\eta \to \gamma\gamma$, $\eta \to \pi^0\pi^0\pi^0$, and $\eta \to \pi^+\pi^-\pi^0$, respectively. The uncertainties here include the statistics of the Monte Carlo samples and our estimates on possible systematic biases, which we discuss below. Including the branching fractions for the η' and η decays [2] and their uncertainties gave $\mathcal{B}(\eta' \to \eta\pi^+\pi^-) \cdot \sum[\epsilon_i \mathcal{B}_{\eta,i}] = (9.7 \pm 0.5)\%$.

The major sources of possible systematic bias in our efficiency calculation from modeling are shown in Table I. We correct our efficiency due to the angular distribution of the high energy photon not being isotropic as in our simulation. There is a systematic uncertainty introduced here ($\pm 2.2\%$, estimated from detailed simulation studies) because the efficiency is not exactly uniform for $|\cos\theta| < 0.71$ nor exactly zero for $|\cos\theta| > 0.71$. Uncertainties in charged track reconstruction ($\pm 0.5\%$ per track), reconstruction of π^0 and η mesons from photons [13] ($\pm 3\%$ per meson), and trigger effects ($\pm 2.5\%$) were determined from previous detailed CLEO studies of low multiplicity τ-pair and $\gamma\gamma$ events. Our ability to model the E/p requirement in the $\gamma\gamma$ final state was assessed using charged pions from K_S decays and assigned a 2.1% uncertainty. Detector stability was monitored by comparing the reconstruction efficiencies for the η, η', and Υ as a function of time; only in the final state $\pi^+\pi^-\pi^0$ was any variation noted, for which we have assigned a 3% uncertainty. Shower leakage and other calorimeter effects make the mass distribution for Υ candidates asymmetric; based on CLEO experience with exclusive radiative B meson decays [14] we have assigned a 2% uncertainty regarding our ability to model these effects. These uncertainties were added in quadrature, along with the statistical uncertainty associated with the size of Monte Carlo samples, to obtain the overall systematic uncertainty in the efficiencies.

Given that we found zero candidates we applied a frequentist approach [15],

$$N_{\text{true}} = N_\Upsilon \mathcal{B}(\Upsilon \to \gamma\eta')\mathcal{B}(\eta' \to \eta\pi^+\pi^-) \sum[\epsilon_i \mathcal{B}_{\eta,i}], \tag{1}$$

implying that the mean actual number of $\gamma\eta'$ events, N_{true}, is less than 2.3 at 90% C.L. To include systematic effects, we performed a large number of "toy" Monte Carlo experiments in which we used values of N_{true} distributed in accordance with Poisson statistics and used values of efficiencies, branching fractions, and N_Υ distributed as Gaussian functions with their associated uncertainties. From the resulting distributions we found 90% C.L. limits for $\mathcal{B}(\Upsilon \to \gamma\eta')$ of 2.9×10^{-5}, 7.6×10^{-5}, and 7.5×10^{-5} for the final η states of $\gamma\gamma$, $\pi^0\pi^0\pi^0$, and $\pi^0\pi^+\pi^-$, respectively. For the sum of the three modes we found

$$\mathcal{B}(\Upsilon \to \gamma\eta') < 1.6 \times 10^{-5}, \tag{2}$$

again at 90% C.L. Without systematic uncertainties the limit decreases by less than 1% of its value. Our result can be compared to the previous Crystal Ball limit [16] of 1.3×10^{-3}.

To show that we could use our data to observe known final states that have high energy photons and a small number of charged tracks, we first reproduced the $\gamma\pi^+\pi^-$ spectrum previously reported by CLEO [1]. We observed the same features at similar magnitudes as that study, as demonstrated in Fig. 1. We also applied our same selection criteria, with the exception of requiring a high energy photon, to data samples taken at the Υ and at or near the $\Upsilon(4S)$ and found π^0, η, and η' candidates at the expected rates [2]. An example of this is shown in Fig. 2 for the final stage $\eta \to \gamma\gamma$, which is the mode dominating our limit.

To compare our result to other radiative decays we use the established J/ψ branching fractions [2] and the

TABLE I. Systematic uncertainty contributions, as relative percentages, to the efficiency for the studied decay modes. The combined uncertainties were obtained using quadrature addition.

Uncertainty source	$\gamma\gamma$	$\pi^0\pi^0\pi^0$	$\pi^0\pi^+\pi^-$
Fiducial requirements	2.2	2.2	2.2
Track reconstruction	1	1	2
η, π^0 reconstruction from $\gamma\gamma$	3	9	3
Trigger simulation	2.5	2.5	2.5
E/p criterion	2.1	⋯	⋯
Reconstruction stability	⋯	⋯	3
Υ mass distribution	2	2	2
Monte Carlo statistics	1.9	3.5	2.5
Combined uncertainty	5.8	10.4	6.7

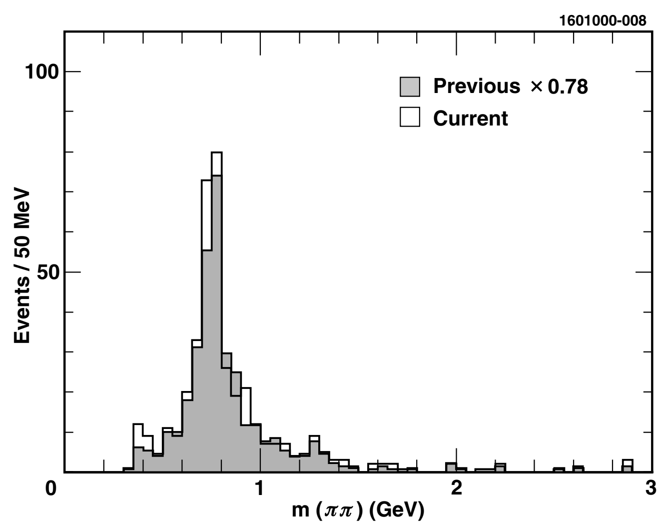

FIG. 1. Mass spectrum for $\gamma\pi^+\pi^-$ events for data collected at the $\Upsilon(1S)$ resonance from this analysis and the prior CLEO analysis, which has been scaled by 0.78 so that both represent the same integrated luminosity.

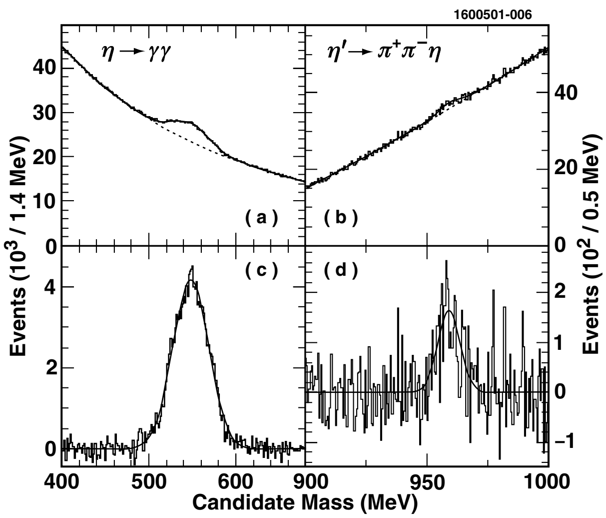

FIG. 2. The $\eta \rightarrow \gamma\gamma$ and $\eta' \rightarrow \pi^+\pi^-\eta$ (with $\eta \rightarrow \gamma\gamma$) invariant mass distributions from data taken at or near the $\Upsilon(4S)$. The upper plots (a) and (b) give the invariant mass distributions (histograms), which are each fit with the sum (solid lines) of a polynomial background (dashed lines) and a Gaussian signal. The lower plots (c) and (d) show the distributions after subtraction of the polynomial background, along with the Gaussian fits. The scales on the right are for plots (b) and (d).

prior CLEO work [1] for $\Upsilon \rightarrow \gamma\pi^+\pi^-$. For the latter, we assume the enhancement at 1270 MeV is all attributable to f_2 production and that $\mathcal{B}(f_2 \rightarrow \pi^+\pi^-)$ is 2/3 of 84.7% to obtain $\mathcal{B}(\Upsilon \rightarrow \gamma f_2) = (8.2 \pm 3.6) \times 10^{-5}$. We then form the ratio $R(V) = \mathcal{B}(V \rightarrow \gamma\eta')/\mathcal{B}(V \rightarrow \gamma f_2)$ and calculate $R(J/\psi) = 3.1 \pm 0.4$ whereas we obtain a 90% C.L. limit of $R(\Upsilon) < 0.26$. Here we have made no attempt to consider possible correlations between the measurements forming the ratios. Clearly the situation is different for J/ψ and $\Upsilon(1S)$.

The models of Körner, Kühn, Krammer, and Schneider [4,5] use highly virtual gluons to form the final state mesons; these models predict $\mathcal{B}(\Upsilon \rightarrow \gamma\eta') = 20 \times 10^{-5}$ but are sensitive to the running of α_s between the charm and bottom mass scales. The recent compilations [2] of α_s would tend to lower this prediction [17] to $(5\text{–}10) \times 10^{-5}$, still significantly larger than our new limit. The Intemann model [6], using extended vector meson dominance, gives bounds of $5.3 \times 10^{-7} \leq \mathcal{B}(\Upsilon \rightarrow \gamma\eta') \leq 2.5 \times 10^{-6}$, with the limits corresponding to the amplitudes from the virtual vector mesons interfering destructively or constructively. Although one of the experimental values used as input to the theory is outdated, it is clear that our experiment does not have the sensitivity to test this prediction. Using nonrelativistic quantum chromodynamics matrix elements for the Υ and twist-2 and twist-3 amplitudes for the gluons, Ma [7] obtains the related branching fraction $\mathcal{B}(\Upsilon \rightarrow \gamma\eta) \approx 1.2 \times 10^{-7}$, again below our present sensitivity.

A more robust prediction of the model of Körner *et al.* is for the double ratio of rates (this ratio is constructed from Table IV of Ref. [4]), which is independent of α_s:

$$\mathcal{R} = \frac{\mathcal{B}(\Upsilon \rightarrow \gamma\eta')}{\mathcal{B}(\Upsilon \rightarrow \gamma f_2)} \times \frac{\mathcal{B}(J/\psi \rightarrow \gamma f_2)}{\mathcal{B}(J/\psi \rightarrow \gamma\eta')} = \frac{0.11}{0.24} = 0.46\,.$$

Using our result, we obtain an upper limit of 0.09 for this double ratio at 90% C.L.; the probability that our result is consistent with 0.46 is 0.6%.

In summary, we have searched for the decay $\Upsilon \rightarrow \gamma\eta'$ with the decay mode $\eta' \rightarrow \eta\pi^+\pi^-$ and three decay modes of the η. Using simple, loose selection criteria, we found no candidates and set the 90% C.L. limit of $\mathcal{B}(\Upsilon \rightarrow \gamma\eta') < 1.6 \times 10^{-5}$. This is significantly small when compared to other radiative decays of heavy vector mesons and smaller than theoretical predictions that use highly virtual gluons in forming final state mesons.

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