First Observations of $\Upsilon(1S) \to \gamma\pi^+\pi^-$ and $\Upsilon(1S) \to \gamma\pi^0\pi^0$

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(Received 5 August 1998)

 0031-9007/99/82(2)/286(5)$15.00

We report on a study of exclusive radiative decays of the $\Upsilon(1S)$ resonance collected with the CLEO II detector operating at the Cornell Electron Storage Ring. We present the first observation of the radiative decays $\Upsilon(1S) \to \gamma\pi^+\pi^-$ and $\Upsilon(1S) \to \gamma\pi^0\pi^0$. For the dipion mass regime $m_{\pi\pi} >$ 1.0 GeV, we obtain $\mathcal{B}(\Upsilon(1S) \to \gamma\pi^+\pi^-) = (6.3 \pm 1.2 \pm 1.3) \times 10^{-5}$ and $\mathcal{B}(\Upsilon(1S) \to \gamma\pi^0\pi^0) = (1.7 \pm 0.6 \pm 0.3) \times 10^{-5}$. [S0031-9007(98)08171-X]

PACS numbers: 13.40.Hq, 13.25.Gv, 13.87.Fh, 14.40.Gx

Although several modes of radiative and hadronic $\Upsilon(1S)$ decays with multiparticle final states have previously been observed, no radiative decays of the $\Upsilon(1S)$ into a photon and two hadrons have yet been reported. Such final states have provided the most direct evidence for two-body radiative J/ψ decays, which are well established [1] at the 10^{-3} level. To extrapolate these to the Υ, the charge coupling to the photon and the mass of the quark propagator predict a suppression of order $[(q_b/q_c)(m_c/m_b)]^2 \sim 1/40$. More sophisticated calculations can be found in the literature [2].

The radiative decays of the $\Upsilon(1S)$ can provide information on exotic states, including weakly interacting massive particles (WIMP's) and axions [3,4]. Radiative decays of the $\Upsilon(1S)$ with charged final state hadrons have been studied by many experimental groups, including ARGUS [5], CLEO [6], and MD-1 [7]. In the CLEO analysis, the decay modes $\Upsilon(1S) \to \gamma X$; $X \to \pi^+\pi^-$, K^+K^-, and $p\overline{p}$ were investigated. As noted in that study [6], the only region of the dipion invariant mass distribution suggestive of an excess above background was in the interval 1.2–1.6 GeV, where ten signal events were counted; the scaled background in the same region corresponded to two events. In this Letter, we extend the previous CLEO analysis, using a new data set and exploiting many improvements in the performance of the CLEO II detector [8]. We also present first results for the all-neutral final state $\Upsilon(1S) \to \gamma\pi^0\pi^0$.

The $\Upsilon(1S)$ signal data ($E_{\rm cm} = 9.46$ GeV) correspond to an integrated luminosity of 78.9 pb^{-1}, collected at the Cornell Electron Storage Ring (CESR). Data taken at $E_{\rm cm} \cong 10.52$ GeV, just below the $\Upsilon(4S)$ resonance, were used to subtract the $e^+e^- \to \gamma X$ events due to non-$\Upsilon(1S)$ production under the resonant $\Upsilon(1S)$ peak; this sample corresponds to an integrated luminosity of 500.4 pb^{-1}. We search for events in both our $\Upsilon(1S)$ (signal) and continuum (background) datasets compatible with the kinematics for the process $\Upsilon(1S) \to \gamma\pi\pi$. Separate event selection criteria are applied for the cases $\Upsilon(1S) \to \gamma\pi^+\pi^-$ and $\Upsilon(1S) \to \gamma\pi^0\pi^0$.

Candidate events for the $\gamma\pi^+\pi^-$ final state are selected as follows. There must be exactly two oppositely charged tracks observed in the detector. If the ratio of a track's associated calorimeter energy to its momentum measured in the drift chambers is greater than 0.85, the track is identified as an electron and the event vetoed from further consideration. At least one of the charged tracks must satisfy the kinematic requirements for muon identification, defined in terms of a track's polar angle (θ) and its momentum (p) as $|\cos\theta| < 0.7$ and $p >$ 1.0 GeV$/c$. Any track satisfying these criteria and also producing associated hits in the muon chambers is identified as a muon, and the event is similarly vetoed. There must be exactly one electromagnetic shower in the good barrel region of the calorimeter ($|\cos\theta| < 0.71$) with energy exceeding $0.4 \times E_{\rm cm}$. This shower must have an energy deposition profile consistent with that of a photon, and also not match, within 15°, the position of any charged track extrapolated into the calorimeter. Additional showers, presumed to be either noise or split-offs from charged tracks propagating into the detection volume of the calorimeter, are allowed provided their measured energies are each less than 500 MeV. The sum of the energy of the highest energy photon candidate plus the energies of the drift chamber tracks must, under the $\pi^+\pi^-$ hypothesis, lie within three standard deviations in energy resolution (σ_E) of $E_{\rm cm}$. Typically, we find $\sigma_E \cong 80$ MeV. The radiative decays $\Upsilon(1S) \to \gamma K^+K^-$ and $\Upsilon(1S) \to \gamma p\overline{p}$, if misinterpreted as $\Upsilon(1S) \to \gamma\pi^+\pi^-$, are more likely to fail this energy-conservation requirement than true $\Upsilon(1S) \to \gamma\pi^+\pi^-$ events. The magnitude of the net momentum vector of the event must be within three standard deviations (σ_p) of zero; σ_p takes into account the resolutions on the two tracks and the high energy photon and is typically 80 MeV$/c$. We require that the opening angle ϕ between the two charged tracks satisfy the condition $\cos\phi > -0.95$.

The momentum of each charged track recoiling against the high energy photon is typically ≈ 2 GeV$/c$, beyond the momentum range for which the CLEO detector can cleanly separate pions from kaons or protons. We therefore require only that the available dE/dx particle identification information be consistent with the pion hypothesis. [We have, nevertheless, performed dedicated searches for $\Upsilon(1S) \to \gamma K^+K^-$ and $\Upsilon(1S) \to \gamma p\overline{p}$. In neither case was a signal observed above background.]

Candidate $\gamma\pi^0\pi^0$ events must have no charged tracks. The requirements on the high-energy photon in the event are identical to the case of $\gamma\pi^+\pi^-$. Neutral pions are defined as combinations of two showers in the electromagnetic calorimeter with an invariant mass within five standard deviations of the nominal π^0 mass. All photons used in π^0 reconstruction must also satisfy a minimum energy requirement ($E_\gamma > 50$ MeV), and have an energy deposition pattern consistent with true photons. The four-momentum conservation requirements are identical to the charged pion case.

We use a GEANT-based [9] detector simulation to determine the efficiency for reconstructing a radiative $\Upsilon(1S)$ event, as a function of dipion mass, for each final state studied. Candidate $\Upsilon(1S) \to \gamma X$ events are generated with a flat distribution over the entire kinematically allowed m_X regime. The recoil X system is decayed isotropically to two pions, which are then propagated through the detector. The overall event selection efficiency (ϵ) for the $\gamma\pi^+\pi^-$ final state varies smoothly from $\epsilon \cong 33\%$ at threshold ($m_{\pi^+\pi^-} = 2m_\pi$) to a maximum of $\epsilon \cong 41\%$ at $m_{\pi^+\pi^-} \cong 2$ GeV. By comparison, the event reconstruction efficiency for the $\gamma\pi^0\pi^0$ final state grows rapidly from zero at threshold to $\epsilon \cong 30\%$ at $m_{\pi^0\pi^0} \cong 1$ GeV and then falls smoothly to $\epsilon \cong 28\%$ at $m_{\pi^0\pi^0} \cong 2$ GeV.

The invariant mass of the recoiling hadrons for candidate events is presented in Fig. 1(a) (charged pions) and Fig. 1(b) (neutral pions), for both the $\Upsilon(1S)$ resonance data and the continuum data. The continuum data have been properly scaled to the $\Upsilon(1S)$ data, taking into account the difference in the luminosity of our signal and background event samples, the expected $1/E_{\rm cm}^2$ energy dependence of the QED cross section, and the relative event selection efficiencies for the $\Upsilon(1S)$ and the continuum data.

Prominent in Fig. 1(a) is a large ρ^0 signal as verified experimentally [5–7] by other analyses. Backgrounds due to $e^+e^- \to \gamma\rho^0$, $\rho^0 \to \pi^+\pi^-$ are expected to dominate the $\gamma\pi^+\pi^-$ analysis. Comparing the acceptance and luminosity-corrected signals observed in both the $\Upsilon(1S)$ and continuum data, we note that the $\gamma\rho^0$ rate observed on the $\Upsilon(1S)$ is consistent with the yield from the continuum data. Subtracting the scaled continuum dipion mass distribution from the resonant $\Upsilon(1S)$ mass distribution in the "ρ-rich region" ($m_{\pi\pi} < 1.0$ GeV), we obtain 1.4 ± 21.0 events, consistent with zero. Also evident is a small enhancement at $m_{\pi\pi} \approx 400$ MeV which is largely from misidentified $e^+e^- \to \gamma\phi$; $\phi \to K^+K^-$ events.

At higher dipion invariant mass, we note a significant excess of events in the $\Upsilon(1S)$ data sample over background in both the $\gamma\pi^+\pi^-$ and the $\gamma\pi^0\pi^0$ final states. Performing a bin-by-bin continuum subtraction, we obtain an excess of 47.0 ± 9.3 (9.0 ± 3.0) events for the $\pi^+\pi^-$ ($\pi^0\pi^0$) data, integrated over $m_{\pi\pi} \geq 1$ GeV. We attribute these excesses to the decays $\Upsilon(1S) \to \gamma\pi^+\pi^-$ and $\Upsilon(1S) \to \gamma\pi^0\pi^0$, respectively. Based on the total number of $\Upsilon(1S)$ events in our sample (1.86×10^6), and correcting for the efficiencies as a function of invariant mass, we obtain $\mathcal{B}(\Upsilon(1S) \to \gamma\pi^+\pi^-) = 6.3 \pm 1.2 \pm 1.3) \times 10^{-5}$ and $\mathcal{B}(\Upsilon(1S) \to \gamma\pi^0\pi^0) = (1.7 \pm 0.6 \pm 0.3) \times 10^{-5}$, for $m_{\pi\pi} \geq 1$ GeV, in which the second error is systematic (to be discussed later).

Whereas the statistics in the background-subtracted $m_{\pi^0\pi^0}$ mass distribution are too poor to show any obvious structure, the excess in the charged dipion mode is apparent in the region $m_{\pi^+\pi^-} \approx 1.0–1.4$ GeV. The most prominent resonance in this mass range observed in radiative J/ψ decays is the $f_2(1270)$ [1], for which $\mathcal{B}[J/\psi \to \gamma f_2(1270)] = (1.38 \pm 0.14) \times 10^{-3}$. If we assume that the excess in this interval is due to $\Upsilon(1S) \to \gamma f_2(1270)$, and neglecting any possible interference effects with other processes producing the $\gamma\pi^+\pi^-$ final state, we can perform a fit to the background-subtracted on-resonance dipion invariant mass spectrum and thereby determine the possible level of $\Upsilon(1S) \to \gamma f_2(1270)$, as shown in Fig. 2. In performing this fit, we use a spin-2 Breit-Wigner signal function with the mean and width parameters fixed to the established [1] $f_2(1270)$ values, over the interval 0.6–1.8 GeV. Such a fit yields 34.8 ± 9.7 events with a χ^2 per degree of freedom of 12.8/23. If, instead, we allow the mass and width

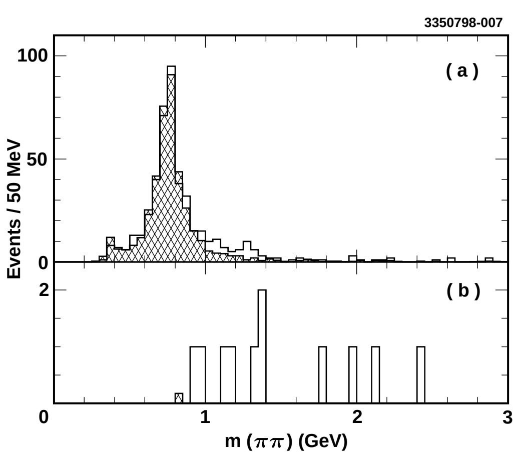

FIG. 1. Dipion invariant mass for the $\Upsilon(1S)$ data, with scaled continuum data (shaded) overlaid, for the final states $\gamma\pi^+\pi^-$ (a) and $\gamma\pi^0\pi^0$ (b).

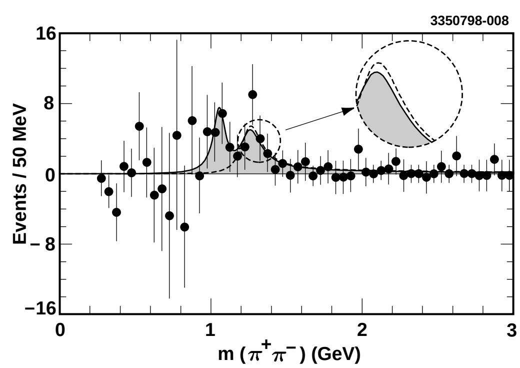

FIG. 2. The dashed line shows a fit of the continuum-subtracted $\Upsilon(1S)$ dipion invariant mass spectrum to a single $f_2(1270)$ only. The solid line (and the shaded region) represents a fit to the $f_2(1270)$ plus a possible second resonance at $m_{\pi^+\pi^-} \approx 1.05$ GeV. Note that the $f_2(1270)$ yield is relatively insensitive to the addition of the second resonance.

to float, we obtain a yield of $30.1^{+9.9}_{-9.3}$ events, with a fitted mass of (1.28 ± 0.02) GeV and a width of (100^{+80}_{-40}) MeV. Assuming no other contributions to the spectrum in Fig. 2, the corresponding efficiency-corrected product of branching fractions would be $\mathcal{B}(\Upsilon(1S) \to \gamma f_2(1270)) \times \mathcal{B}(f_2(1270) \to \pi^+\pi^-) = (4.6 \pm 1.3^{+1.6}_{-1.5}) \times 10^{-5}$, which gives [1] $\mathcal{B}(\Upsilon(1S) \to \gamma f_2(1270)) = (8.1 \pm 2.3^{+2.9}_{-2.7}) \times 10^{-5}$. The likelihood that the excess in this region is due to an upward fluctuation of the background is determined to be less than 0.01%.

If this excess is due to $\Upsilon(1S) \to \gamma f_2(1270)$, then, by isospin, we expect to also observe $\Upsilon(1S) \to \gamma f_2(1270)$, $f_2(1270) \to \pi^0\pi^0$ at half the charged rate. Despite the lack of pronounced $f_2(1270) \to \pi^0\pi^0$ signal, we can compare the $\pi^0\pi^0$ yield with the $\pi^+\pi^-$ yield under the assumption that $\gamma f_2(1270)$ production saturates the $\gamma\pi^0\pi^0$ final state. When compared to the fitted result in the charged dipion case, the excess of 10.8 ± 3.3 events observed is consistent, after the mass-dependent efficiency correction, with the isospin expectation. The probability of the continuum background fluctuating up to the $\pi^0\pi^0$ signal is negligible. Non-f_2 contributions, if any, are difficult to assess given the limited statistics of the signal sample.

Although there is no resonance with $m \approx 1.05$ GeV expected in our sample, we nevertheless note an apparent enhancement in this mass region in Fig. 2. To investigate this further, we have allowed for a second Breit-Wigner in our fit, with the values of mass and width for this second Breit-Wigner allowed to float, but with the f_2 parameters again constrained to the established values (indicated by the solid line in Fig. 2). We then obtain 20.5 ± 12.3 events for this second Breit-Wigner, at a mass of (1.05 ± 0.02) GeV and a fitted width of (100 ± 90) MeV; the putative $f_2(1270)$ yield correspondingly drops to 29.7 ± 11.0 events. The overall χ^2 per degree of freedom in this second fit improves to $6.2/20$. We note that although the level of the excess at 1.05 GeV is at the 1.7 standard deviation level, the likelihood that the excess in the 1.28 GeV mass region is an upward fluctuation of background is still small (less than 0.1%).

We have considered possible contamination to our signal from the process $\Upsilon(1S) \to \gamma\mu^+\mu^-$. This is evaluated by selecting, rather than vetoing, events having a high energy photon and two charged tracks, in which there are hits in the muon chambers matched to at least one of the charged tracks. For such a search, the continuum-subtracted $\Upsilon(1S)$ data yields 18 ± 19 $\Upsilon(1S) \to \gamma\mu^+\mu^-$ event candidates. Knowing that the maximal inefficiency for $\gamma\mu^+\mu^-$ events is 30%, we determine that the contribution from the $\gamma\mu^+\mu^-$ final state to our signal $\Upsilon(1S) \to \gamma\pi^+\pi^-$ sample has a central value less than 5.4 events, and is consistent with zero; we include this in our systematic uncertainty.

The decay $\Upsilon(1S) \to \pi^0\pi^+\pi^-$, although not yet observed, could produce background to the $\gamma\pi^+\pi^-$ final state in those cases in which the π^0 decays either very asymmetrically (resulting in one very high energy shower with energy almost equal to the energy of the parent π^0), or produces a π^0 in which both daughter photons are approximately collinear, and cannot be distinguished. In the latter case, the photon showers overlap and merge into a single detected calorimeter shower. Using requirements identical to those used in the $\gamma\pi\pi$ analysis for the π^0 candidate, the two charged pion candidates, and overall event four-momentum conservation, we have conducted a dedicated search for the decay $\Upsilon(1S) \to \pi^0\pi^+\pi^-$. The resulting upper limit is $\mathcal{B}(\Upsilon(1S) \to \pi^0\pi^+\pi^-) < 1.84 \times 10^{-5}$ at 90% confidence level. Based on this null result and the probability to misinterpret a "merged" π^0 as a single photon, we expect fewer than 3.4 events contamination from the decay $\Upsilon(1S) \to \pi^0\pi^+\pi^-$ in our $\gamma\pi^+\pi^-$ event sample over the entire kinematically allowed dipion invariant mass range. The net contribution from $\Upsilon(1S) \to \pi^0\pi^+\pi^-$ events in which the π^0 decays asymmetrically is determined to be less than 0.7 events.

We note that the two pions produced in $\Upsilon(1S) \to \gamma f_2(1270)$, $f_2(1270) \to \pi^+\pi^-$ will have a characteristic angular distribution, due to the tensor nature of the $f_2(1270)$. We have correspondingly fit the helicity angle distribution (defined as the angle between one of the pions and the dipion parent measured in the dipion rest frame) over the mass interval 1.2–1.4 GeV, after subtracting out the contribution from the $\gamma\rho$ final state. Such a fit gives confidence levels of 48%, 35%, 0.0%, and 0.1% under the tensor, scalar, vector, or axial vector assumptions for the system recoiling against the photon, respectively. Although inconclusive on its own, this spin-parity analysis of the dipion system strongly favors a tensor or scalar assignment for the dipion system, and rules out a vector or axial vector interpretation.

For the measurement $\Upsilon(1S) \to \gamma\pi^+\pi^-$, systematic uncertainties are due primarily to the muon veto used to suppress the $\gamma\mu^+\mu^-$ final state (12% relative error), uncertainties in our total efficiency (5%, arising mainly from event triggering uncertainties), and our uncertainty in the total number of $\Upsilon(1S)$ events (3%). Because we have assumed that the photon angular distribution is isotropic in our Monte Carlo event generator, there is an additional uncertainty (16%) from our extrapolation to the region $|\cos\theta_\gamma| > 0.71$. For the possible $\Upsilon(1S) \to \gamma f_2(1270)$ signal, we have an additional systematic error (20%) due to the fitting procedure used to extract the signal, including the possible effect of the apparent enhancement in the region $m_{\pi^+\pi^-} \approx 1.05$ GeV, and asymmetric uncertainties due to the possible interference between events from the $\Upsilon(1S) \to \gamma f_2(1270)$ excess and $\pi^+\pi^-$ pairs not associated with either the ρ^0 or the resonant enhancement ($^{+20}_{-15}\%$).

For the $\gamma\pi^0\pi^0$ final state, primary uncertainties in our integrated measurement $\mathcal{B}(\Upsilon(1S) \to \gamma\pi^0\pi^0)$ are due to the possible anisotropy of the $\Upsilon(1S) \to \gamma\pi^0\pi^0$ decay (16%), π^0 finding (8%) [10], trigger efficiency (4%), and the number of $\Upsilon(1S)$ events (3%).

In summary, we have made the first observation of the radiative decay $\Upsilon(1S) \to \gamma\pi\pi$ in both the charged and neutral modes. Restricted to $m_{\pi\pi} \geq 1.0$ GeV, we obtain $\mathcal{B}(\Upsilon(1S) \to \gamma\pi^+\pi^-) = (6.3 \pm 1.2 \pm 1.3) \times 10^{-5}$, and $\mathcal{B}(\Upsilon(1S) \to \gamma\pi^0\pi^0) = (1.7 \pm 0.6 \pm 0.3) \times 10^{-5}$.

The $\pi^+\pi^-$ mass and helicity angle distributions are suggestive of $f_2(1270)$ production as a source. Under the $\Upsilon(1S) \to \gamma f_2(1270)$ assumption, the efficiency-corrected product of branching fractions of this enhancement corresponds to $\mathcal{B}(\Upsilon(1S) \to \gamma f_2(1270)) \times \mathcal{B}(f_2(1270) \to \pi^+\pi^-) = (4.6 \pm 1.3^{+1.6}_{-1.5}) \times 10^{-5}$. In the $\pi^0\pi^0$ mode, the net yield relative to the charged mode and the shape of the $\pi^0\pi^0$ mass spectrum are also consistent with $\Upsilon(1S) \to \gamma f_2(1270)$. This is approximately twice the rate that would be expected by the $[(q_b/q_c)(m_c/m_b)]^2$ scaling from $\mathcal{B}[J/\psi \to \gamma f_2(1270)]$.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, the U.S. Department of Energy, Research Corporation, the Natural Sciences and Engineering Research Council of Canada, the A. P. Sloan Foundation, the Swiss National Science Foundation, and the Alexander von Humboldt Stiftung.

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