

*Physics*

*Physics Research Publications*

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*Purdue University*

*Year 2011*

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$\Gamma(1S) \rightarrow \gamma f(2)'(1525);$   
 $f(2)'(1525) \rightarrow (KSKS0)\text{-}K\text{-}0$  decays

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$\Upsilon(1S) \rightarrow \gamma f_2'(1525); f_2'(1525) \rightarrow K_S^0 K_S^0$  decays

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(Received 4 January 2011; published 23 February 2011)

We report on a study of exclusive radiative decays of the  $\Upsilon(1S)$  resonance into a final state consisting of a photon and two  $K_S^0$  candidates. We find evidence for a signal for  $\Upsilon(1S) \rightarrow \gamma f_2'(1525); f_2'(1525) \rightarrow \gamma K_S^0 K_S^0$ , at a rate  $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma f_2'(1525)) = (4.0 \pm 1.3 \pm 0.6) \times 10^{-5}$ , consistent with previous observations of  $\Upsilon(1S) \rightarrow \gamma f_2'(1525); f_2'(1525) \rightarrow K^+ K^-$ , and isospin. Combining this branching fraction with existing branching fraction measurements of  $\Upsilon(1S) \rightarrow \gamma f_2'(1525)$  and  $J/\psi \rightarrow \gamma f_2'(1525)$ , we obtain the ratio of branching fractions:  $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma f_2'(1525))/\mathcal{B}(J/\psi \rightarrow \gamma f_2'(1525)) = 0.09 \pm 0.02$ , approximately consistent with expectations based on soft-collinear effective theory.

DOI: 10.1103/PhysRevD.83.037101

PACS numbers: 13.40.Hq

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A particularly interesting class of  $\Upsilon(1S)$  decays are the radiative decays, which could show evidence for the same type of two-body resonance production as has been observed in  $J/\psi$  decay. The most naive arguments simply scale the charge-dependence of the coupling and the mass dependence of the propagator in the associated amplitude,

leading to bottomonium/charmonium radiative widths varying as  $[(q_b/q_c)(m_c/m_b)]^2 \approx 1/36$ . The ratio of the full widths of the (1S) charmonium vs bottomonium states (93 keV/54 keV) [1] implies radiative bottomonium branching fractions approximately 4–5% of that of the corresponding charmonium state. This naive expectation is consistent with measurements of radiative decays into spin-zero mesons (e.g.,  $\gamma\eta^{(\prime)}$ ), although considerably smaller than measurements for decays into spin-two mesons (e.g.,  $\gamma f_2$ ).

A comprehensive calculation using soft-collinear effective theory (SCET) and nonrelativistic QCD has been implemented to calculate the ratio of ‘nonexotic’ branching fractions  $\mathcal{B}(Y(1S) \rightarrow \gamma f_2)/\mathcal{B}(J/\psi \rightarrow \gamma f_2)$  [2]. That theory calculation gives a predicted ratio of (0.13–0.18), slightly larger than the currently measured value for the  $f_2'(1525)$  ( $0.08 \pm 0.03$  [1]), but not inconsistent with extant data, given the large errors. The CLEO Collaboration has previously presented results on exclusive radiative decays into two charged tracks [3], as well as the final states  $\gamma\pi^0\pi^0$  and  $\gamma\eta\eta$  [4]. We now supplement those measurements and searches with a study of decays into a photon plus two  $K_S^0$ , with  $K_S^0 \rightarrow \pi^+\pi^-$ .

The CLEO III detector was operated as a general purpose solenoidal magnet spectrometer and calorimeter. Approximately  $10 \text{ fb}^{-1}$  of data were collected in the region of the  $Y(4S)$ , supplemented by  $1 \text{ fb}^{-1}$  samples of data around each of the narrow, lower-mass resonances. The analysis described herein is based on a sample of  $21.2 \times 10^6$   $Y(1S)$  events, plus  $10.2 \times 10^6$  events taken on the continuum, just below the  $Y(4S)$  resonance.

Elements of the detector, as well as performance characteristics relevant to this analysis are described in detail elsewhere [5–7]. Particularly important in defining the candidate signal sample for this signal topology is photon detection and energy resolution. For photons in the central ‘‘barrel’’ region of the CsI electromagnetic calorimeter, at energies greater than 2 GeV, the energy resolution is approximately 1–2%. The tracking system used to identify the charged pion candidates, the RICH particle identification system, and the electromagnetic calorimeter are all contained within a 1 Tesla superconducting coil. Neutral  $K_S^0$  candidates are identified by CLEO’s standard reconstruction software as oppositely-signed charged pion pairs with a common origin point away from the primary vertex and have an invariant mass within  $12 \text{ MeV}/c^2$  of the nominal  $K_S^0$  mass. Di-pion candidates within  $24 \text{ MeV}/c^2$  of the nominal  $K_S^0$  mass, and not in the signal region, are defined as ‘‘sideband’’  $K_S^0$  candidates and are retained for background evaluation. In our candidate event sample, there is one unique combination of the four daughter pions which satisfy these mass and vertex requirements.

To obtain our candidate event sample, we select those events containing four charged tracks (with total charge

zero) that combine to form two  $K_S^0$  candidates. We allow a maximum of one ‘‘extra’’ charged track in the event, which is ignored in subsequent analysis. Each  $K_S^0$  candidate must have an invariant mass within three units of the experimental mass resolution of the nominal  $K_S^0$  mass, corresponding to approximately  $12 \text{ MeV}/c^2$ . Charged pion  $K_S^0$  decay candidates are required to have  $dE/dx$  information consistent with that expected for charged pions, within 3 standard deviations in energy deposition resolution. To suppress possible QED contamination, we require that the four charged tracks must be inconsistent with an  $e^+e^- \rightarrow \tau\tau$  ‘‘1-prong vs 3-prong’’ charged-track topology and also have no charged-track positively identified as an electron or muon. Beyond the inner tracking chambers, we require one high-energy electromagnetic shower observed in the barrel calorimeter which does not match (within 0.1 radians) the position of any charged track extrapolated beyond the drift chamber into the barrel calorimeter. Finally, the sum of the observed photon energy plus the energies of the drift chamber tracks (assumed to be pions) must lie within 120 MeV (roughly, 2.5 standard deviations) of the total center-of-mass energy. The magnitude of the total event momentum must be within  $120 \text{ MeV}/c$  of the expected value of zero, as well.

For our event candidates, we observe a cluster of events that conserve overall four-momentum with an approximate energy difference resolution of 100 MeV, as shown in the invariant mass vs energy difference plot (Fig. 1).

After imposing energy and momentum conservation requirements, the  $f_2'(1525) \rightarrow K_S^0 K_S^0$  candidate signal is shown in Fig. 2. We note the absence of any signal in events selected from either  $K_S^0 K_S^0$  sidebands, or data taken from the continuum in the vicinity of the  $Y(4S)$  resonance. Extrapolated to the resonant  $Y(1S)$  sample, we can attribute a maximum of two of the observed resonant events to the underlying continuum, with no obvious peaking under the  $f_2'(1525)$ . Defining the  $K_S^0$  sidebands as the region from  $12 \rightarrow 24 \text{ MeV}/c^2$  from the nominal  $K_S^0$  mass, we obtain an

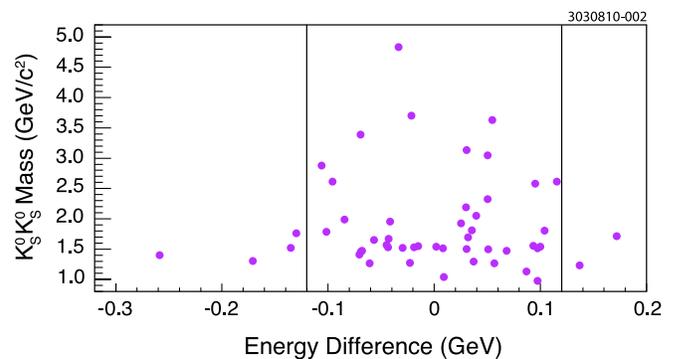


FIG. 1 (color online).  $K_S^0 K_S^0$  invariant mass vs (Total visible energy—center-of-mass energy) for events satisfying overall momentum conservation. Acceptance region is bounded by vertical lines.

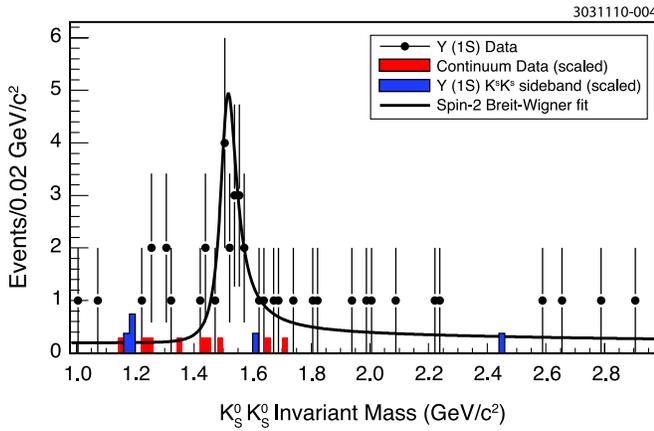


FIG. 2 (color online). Invariant mass of  $K_S^0 K_S^0$  candidates for events satisfying all energy, momentum, and photon selection requirements, showing signal as well as background estimators from the continuum and also  $K_S^0$  sidebands. Also overlaid is the fit to the relativistic, spin-2 Breit-Wigner signal shape. Sideband and continuum contributions have not been explicitly subtracted, and are implicitly included in our background parametrization.

extrapolated yield of  $\approx 3$  such sideband contributions in the entire  $K_S^0 K_S^0$  invariant mass interval. We scale this value by a factor of  $1/3$  to extrapolate the sideband (assumed flat over the region of interest) yield to the signal, giving a maximum net contribution of one event, with no evident peaking under the  $f_2'(1525)$ .

To ensure that the observed signal is not a misreconstruction of the known decay  $Y(1S) \rightarrow \gamma 4\pi$ , we have run our reconstruction code on a sample of simulated Monte Carlo  $Y(1S) \rightarrow \gamma 4\pi$  events, statistically equivalent to the number expected in data, for which the 4 pions are distributed according to a simplistic phase space model. Doing so, we observe 3 events which are reconstructed as  $K_S^0 K_S^0$ , with no peaking in the candidate signal region. In general, asymmetric  $\pi^0$  decays can lead to a topology with a highly energetic photon and a much smaller energy photon which can go undetected. This leads to concerns about possible contamination from hadronic decays of the type  $Y(1S) \rightarrow \pi^0 f_2'(1525)$ . However, this decay violates  $C$  parity and therefore cannot contribute to the background.

We have fit the candidate signal, after applying all candidate and event selection requirements to a relativistic, spin-2 Breit-Wigner signal plus a flat background (Fig. 2). The likelihood fit yield, with mass and width constrained to the Particle Data Group (PDG) values ( $M = (1525 \pm 5)$  MeV and  $\Gamma = (73 \pm 6)$  MeV, respectively [1]) corresponds to  $N_{\text{sig}} = 16.6 \pm 5.3$  signal events. Inclusion of possible  $f_2(1270) \rightarrow K_S^0 K_S^0$  and  $f_0(1710) \rightarrow K_S^0 K_S^0$  components gives yields for those two resonances statistically consistent with zero and results in a variation in the central value for the  $f_2'(1525)$  signal of less than 4%. The efficiency for the decay chain  $Y(1S) \rightarrow \gamma f_2'(1525); f_2'(1525) \rightarrow K_S^0 K_S^0$

is assessed with 10 000 dedicated Monte Carlo simulated events, and estimated to be  $18.5 \pm 0.4\%$  (statistical error only), not including branching fractions.

Systematic errors are estimated as follows: a) photon-finding efficiency uncertainty (2%), b)  $K_S^0 K_S^0$  detection efficiency (8%), c) total number of  $Y(1S)$  events (2%), d) efficiency uncertainty due to component branching fraction errors and limited Monte Carlo statistics (4%), and e) fitting systematics. This last systematic uncertainty is determined as follows: the difference between the area found using a relativistic, spin-2 Breit-Wigner in data (our default parametrization) is 7% smaller in data with parameters fixed according to the Particle Data Group  $f_2'(1525)$  parameters vs floated parameters. The difference between using a second-order vs a first-order Chebyshev polynomial background results in an additional 9% variation in fitted area. As mentioned above, adding possible  $Y(1S) \rightarrow \gamma f_2(1270)$  and  $Y(1S) \rightarrow \gamma f_0(1710)$  structure to our fit changes the fitted  $f_2'(1525)$  area by less than 4%. Taken together in quadrature, we assess a total systematic uncertainty of 14% (relative).

We translate our fit yield into a branching fraction by knowing  $\mathcal{B}(f_2' \rightarrow K\bar{K}) = (0.888 \pm 0.031)$ , the fraction of  $K\bar{K}$  which is  $K_S^0 K_S^0$  ( $1/4$ ), the branching fraction  $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-) = (0.6920 \pm 0.0005)$ , and the Monte Carlo efficiency of 18.5%, giving a total efficiency of  $\epsilon_{\text{tot}} = (0.888 \pm 0.031) \times 0.25 \times (0.6920 \pm 0.0005)^2 \times (0.185 \pm 0.004)$ . Combining our signal yield of  $N_{\text{sig}}$  events and the total efficiency ( $(19.7 \pm 0.7) \times 10^{-3}$ ) with the total number of  $Y(1S)$  events ( $21.2 \times 10^6$ ) yields a final branching fraction estimate of  $\mathcal{B}(Y(1S) \rightarrow \gamma f_2'(1525)) = (4.0 \pm 1.3 \pm 0.6) \times 10^{-5}$ , compared with the previous CLEO branching fraction measurement of  $(3.7_{-0.7}^{+0.9} \pm 0.8) \times 10^{-5}$ , based on the  $\gamma K^+ K^-$  final state [3]. Comparing the likelihood of the fit result to the likelihood obtained when the signal yield is set to zero, we find  $-2 \ln(\Delta \mathcal{L})$  corresponds to a statistical significance of  $4.0\sigma$ . In this expression,  $\Delta \mathcal{L}$  is the difference in likelihood between the two fits. Within errors, we find good agreement between the values derived from the charged vs neutral kaon decay modes.

In summary, we have observed exclusive radiative decays of the  $Y(1S)$  meson into the  $\gamma K_S^0 K_S^0$  final state. A large  $f_2'(1525)$  signal is observed in the di- $K_S^0$  mass spectrum, with a branching fraction  $\mathcal{B}(Y(1S) \rightarrow \gamma f_2'(1525)) = (4.0 \pm 1.3 \pm 0.6) \times 10^{-5}$ , consistent with previous measurements of  $Y(1S) \rightarrow \gamma f_2'(1525)$  [1];  $f_2'(1525) \rightarrow K^+ K^-$ . Although no predictions for this final state, *per se*, exist in the literature, we can nevertheless compare our calculated branching fraction, relative to the analogous branching fraction for  $J/\psi$  decays, with the predictions from SCET [2]. Combining our current result with the previous result for  $Y(1S) \rightarrow \gamma f_2'(1525) \rightarrow \gamma K^+ K^-$ , we obtain an updated estimate  $\mathcal{B}(Y \rightarrow \gamma f_2'(1525)) = (3.8 \pm 0.9) \times 10^{-5}$ . The ratio of experimental branching fractions:

$R_2 \equiv \mathcal{B}(Y(1S) \rightarrow \gamma f_2) / \mathcal{B}(J/\psi \rightarrow \gamma f_2) = 0.08 \pm 0.02$  for the  $f_2'(1525)$ , consistent with both the experimental results for the  $f_2(1270)$  ( $R_2 = 0.071 \pm 0.008$ ) [1], as well as the predictions of SCET, assuming that the SCET calculation can be applied to both  $f_2$  and the radial  $f_2'$  excitation. The equality of these ratios for the  $f_2(1270)$  and the  $f_2'(1525)$  is consistent with the naive expectation from SU(3) symmetry.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. D. Cronin-Hennessy thanks the A.P. Sloan Foundation. This work was supported by the National Science Foundation, the U.S. Department of Energy, the Natural Sciences and Engineering Research Council of Canada, and the U.K. Science and Technology Facilities Council.

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