CLEO CONF 03-06
LP-121

Observation of the Hadronic Transitions $\chi_{b1,2}(2P) \to \omega \Upsilon(1S)$ *

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(Dated: July 15, 2003)

Abstract

The CLEO Collaboration has observed the first hadronic transition among bottomonium ($b\bar{b}$) states other than the dipion transitions among vector states, Υ(nS)$\to\pi\pi\Upsilon$(mS). In our study of Υ(3S) decays, we find a significant signal for Υ(3S)$\to\gamma\omega\Upsilon$(1S) that is consistent with radiative decays Υ(3S)$\to\gamma\chi_{b1,2}(2P)$, followed by $\chi_{b1,2}(2P)\to\omega\Upsilon$(1S). The branching ratios we obtain are $\mathcal{B}(\chi_{b1}(2P)\to\omega\Upsilon(1\mathrm{S})) = 1.63^{+0.35}_{-0.31}{}^{+0.16}_{-0.15}\%$ and $\mathcal{B}(\chi_{b2}(2P)\to\omega\Upsilon(1\mathrm{S})) = 1.10^{+0.32}_{-0.28}{}^{+0.11}_{-0.10}\%$, in which the first error is statistical and the second is systematic.

*Submitted to XXI International Symposium on Lepton and Photon Interactions at High Energies, August 11-16, 2003, Fermi National Accelerator Laboratory, Batavia, IL

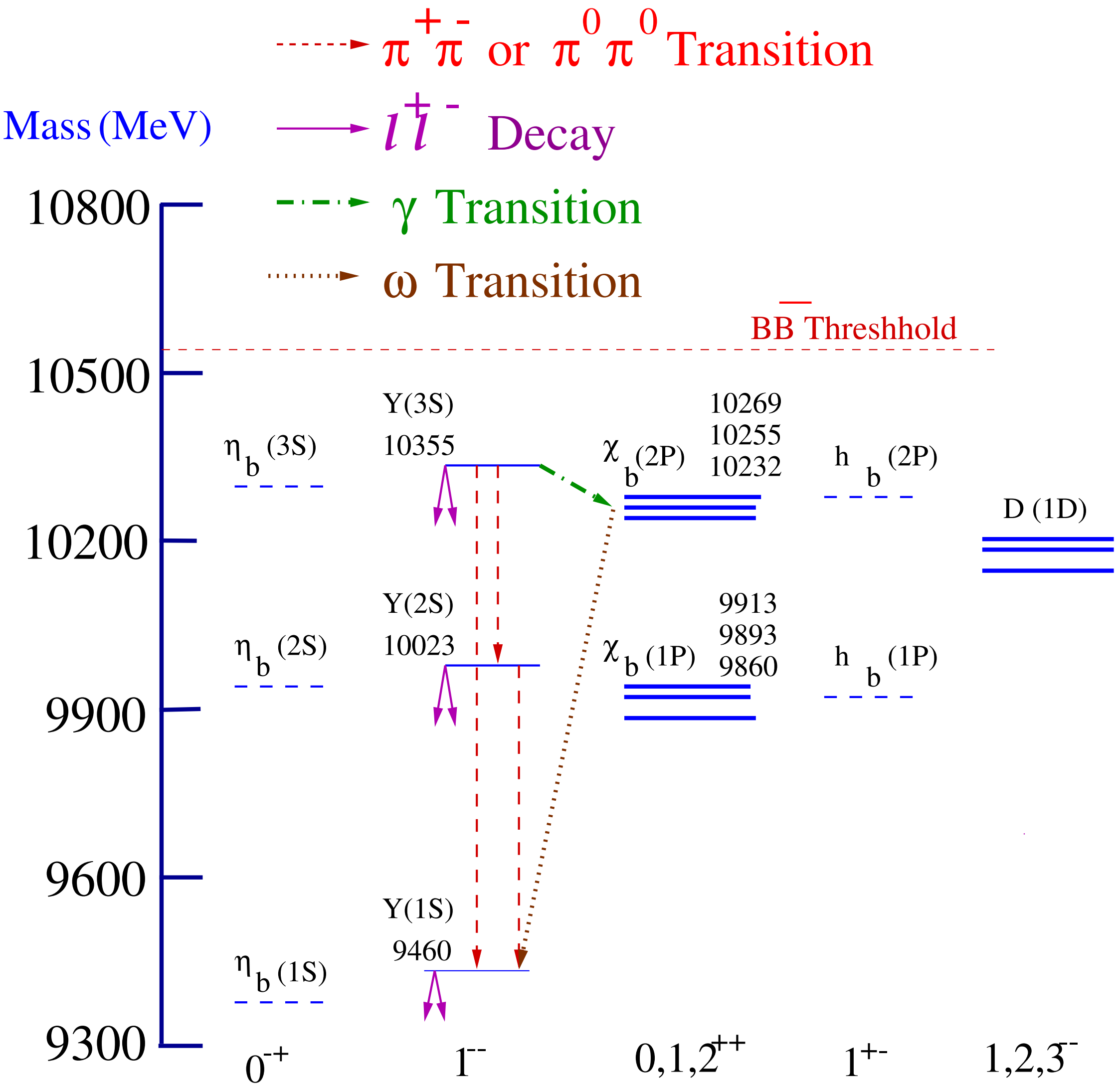

FIG. 1: The spectrum of bottomonium states. Dilepton decays of the vector states are denoted by the solid lines, while dipion transitions are denoted by dashed lines. The radiative decay $\Upsilon(3S)\to\chi_b(2P)$ is indicated by the dot-dashed line, and the decay $\chi_b(2P)\to\omega\Upsilon(1S)$ by the dotted line.

The only hadronic decays of bottomonia that have been experimentally observed to date are the $\pi\pi$ ($\pi\pi \equiv \pi^+\pi^-$ and $\pi^0\pi^0$) transitions among vector bottomonium states. [1] Figure 1 illustrates the bottomonium spectrum and transitions. Although there is extensive literature describing hadronic transitions among bottomonium states [2], nearly all of it is directed toward understanding the various $\pi\pi$ transitions. [2] While the $\pi\pi$ transitions do provide important information about strong interaction dynamics in heavy quark systems, the investigation of other hadronic decay modes (i.e. involving η, ω or multiple π) should offer a different perspective. The analysis of heavy quarkonium hadronic transitions is one of few possible laboratories for the study of the physics of the soft gluon emission and hadronization process that governs such decays. In this letter, we describe the evidence for observation of new hadronic transitions, $\chi_{b1,2}(2P)\to\omega\Upsilon(1S)$.

The data set analyzed for the purposes of this paper consists of $(5.81 \pm 0.12) \times 10^6 \Upsilon(3S)$

decays observed with the CLEO III detector at the Cornell Electron Storage Ring. The CLEO III detector is described in Ref. [3]. Charged particle tracking is done by the 47-layer drift chamber and a four-layer silicon tracker which reside in a 1.5T solenoidal magnetic field. Photons are detected using an electromagnetic calorimeter (CC) consisting of 7784 CsI(Tl) crystals distributed in a barrel geometry. The particle-identification capabilities of the CLEO-III detector are not used in the present analysis.

The final state of $\gamma\pi^+\pi^-\pi^0\ell^+\ell^-$ can be selected in a straightforward manner. Events with two high momentum charged tracks ($p > 4$ GeV) and two or three charged low momentum tracks ($0.12 < p < 0.75$ GeV) are considered. The low momentum tracks are required to come from the interaction region using criteria obtained by studying charged pion tracks in a sample of events from the kinematically similar decay Υ(2S)$\to\pi^+\pi^-\Upsilon$(1S).

We require events to contain a Υ(1S) candidate by requiring that the two high momentum tracks in the event have an invariant mass consistent with the Υ(1S) mass ($9.3 - 9.6$) GeV. We make no cuts on the track quality variables for the lepton candidate tracks, nor do we require them to satisfy lepton-identification criteria. The invariant mass requirement alone provides a nearly background free sample, and imposition of lepton-identification criteria only leads to larger systematic errors and reduced signal efficiency without much improvement in signal quality.

We require events to have three or four showers in the CC that are not matched to charged tracks. Two of these showers must form an invariant mass within 3σ of the nominal π^0 mass. In the further analysis, we utilize the momentum for this π^0 candidate obtained from a mass-constrained kinematic fit. In addition to the two showers that correspond to the π^0, events must contain an isolated photon candidate, between 50 and 250 MeV in energy, that does not form an invariant mass within 8 MeV $\approx 1.5\sigma$ of the π^0 mass with any other shower. Further, the polar angle (θ) of the third shower is restricted to $|\cos\theta| < 0.804$, the angular region in which CLEO's energy resolution is sufficiently good to resolve the photons for the signal channels of interest. Finally, we allow events to contain up to one additional shower in the range $|\cos\theta| < 0.804$.

In addition, we allow for the possibility of one spurious charged track candidate in addition to the four "signal" tracks. Such spurious tracks may arise from failures in pattern recognition and from delta rays. Spurious showers may arise from synchrotron radiation from the $e^\pm$ beams or as a result of random noise in the CC. If a given event yields more than one candidate due to the presence of an additional shower or track, we choose the candidate for which the sum of energies of all final state particles is nearest $M(\Upsilon(3\text{S}))$.

Because there is no phase space for a pair of kaons for decays in which a Υ(1S) is present, we assume that the low momentum charged tracks are due to $\pi^\pm$. The invariant mass of the $\pi^+\pi^-\pi^0$ combination, plotted in Figure 2, shows a clear enhancement at the mass of ω, $M(\omega) = 0.782$ GeV.

Finally, to complete the reconstruction of the full decay chain, $\Upsilon(3\text{S})\to\gamma\omega\Upsilon(1\text{S})\to\gamma\pi^+\pi^-\pi^0\ell^+\ell^-$, we require that the χ^2 be less than 10 for a kinematic fit of $\pi^+\pi^-\pi^0$ constrained to the ω mass, and subsequently that the mass recoiling against the kinematically fitted ω and γ candidates lie within $^{+25}_{-20}$ MeV of $M(\Upsilon(1\text{S})) = 9.460$ GeV.

The simplest explanation for the observed events is the decay sequence $\Upsilon(3\text{S})\to\gamma\chi_{bJ}(2P)$, with $\chi_{bJ}(2P)\to\omega\Upsilon(1\text{S})$. Transitions through $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$ only are allowed by energy conservation. $\chi_{b0}(2P)$ lies below threshold for decay to $\omega\Upsilon(1\text{S})$. In principle a transition through the $\eta_b(3S)$ state (see Figure 1) is possible, but this state has never been observed, and, furthermore, the energy of the photon in the decay $\Upsilon(3\text{S})\to\gamma\eta_b(3S)$ is expected to be

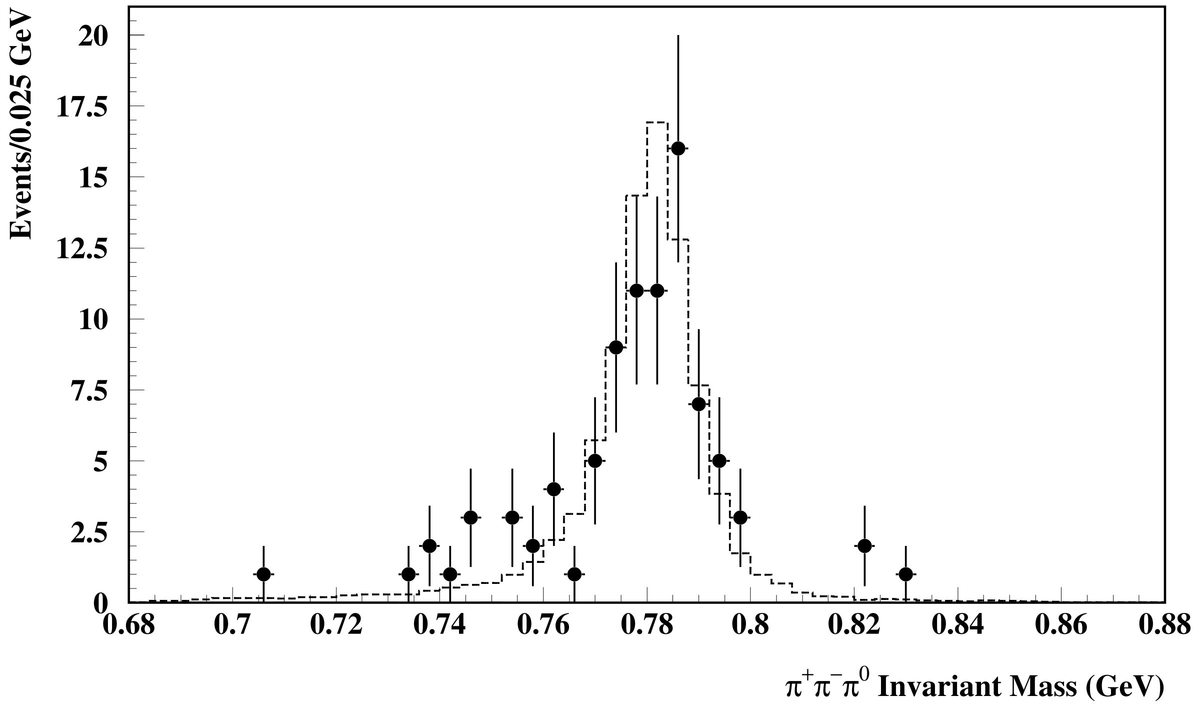

FIG. 2: $\pi^+\pi^-\pi^0$ invariant mass, for data events subject to final analysis cuts with the exception of the cut on the χ^2 of the kinematic fit to ω. The overlaid histogram shows signal Monte Carlo events (normalized to the same total number) and indicates the good reproduction by the Monte Carlo of the shape and location of the ω peak.

below the range of observed energies in the data. We also neglect as highly improbable the possibility that the ω is emitted directly in a transition from Υ(3S) to a heretofore unknown state, which then decays radiatively to Υ(1S).

Backgrounds from ordinary *udsc* quark production are extremely small because of the presence of the $\Upsilon(1\mathrm{S})\to\ell^+\ell^-$ decay in the signal sample. The only significant source of background Υ(1S) expected is known cascades from Υ(3S). The final state of $\gamma\pi^+\pi^-\pi^0\Upsilon(1\mathrm{S})$ may be reached through:

$$\begin{aligned}\Upsilon(3\mathrm{S}) &\to \gamma\chi_b(2P),\ \chi_b(2P)\to\gamma\Upsilon(2\mathrm{S}),\ \Upsilon(2\mathrm{S})\to\pi^+\pi^-\Upsilon(1\mathrm{S})\\ \Upsilon(3\mathrm{S}) &\to \pi^0\pi^0\Upsilon(2\mathrm{S}),\ \Upsilon(2\mathrm{S})\to\pi^+\pi^-\Upsilon(1\mathrm{S}).\end{aligned}$$

In the first case, this final state can be produced by the addition of a spurious shower in the calorimeter. In the second case, it may be reached by loss of one of the γ from one of the π^0 due to acceptance or energy threshold.

Backgrounds produced through either of these two processes may be removed by excluding events in which the mass recoiling against the two charged pions in the Υ(3S) reference frame is consistent with the hypothesis that the $\pi^+\pi^-$ system is recoiling against Υ(2S) in the process $\Upsilon(3\mathrm{S})\to X+\Upsilon(2\mathrm{S})\to X+\pi^+\pi^-\Upsilon(1\mathrm{S})$ (between 9.78 and 9.81 GeV).

Two other decay sequences can yield the final state of $\gamma\pi^+\pi^-\pi^0\Upsilon(1S)$: the decay $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$, with the $\Upsilon(2S)$ decaying either to $\pi^0\pi^0\Upsilon(1S)$, or to $\gamma\chi_b(1P)$ followed by $\chi_b(1P)\to\gamma\Upsilon(1S)$. In each of these cases, however, the $\pi^\pm$ are too soft to produce spurious ω candidates for the signal decay chain.

In order to evaluate residual background, we generated a GEANT [4] Monte Carlo sample for the channel $\Upsilon(3S)\to\gamma\chi_b(2P)$, $\chi_b(2P)\to\gamma\Upsilon(2S)$, $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$, corresponding to 21.5 ± 3.1 million $\Upsilon(3S)$ decays, or 4.53 ± 0.65 times our data set. The uncertainty on the equivalent number of $\Upsilon(3S)$ decays is due to the error on the branching ratios needed to convert our number of generated events to the equivalent number of $\Upsilon(3S)$ decays. This Monte Carlo sample produced one event that satisfied our selection criteria. We therefore expect $1/(4.53 \pm 0.65) = 0.22 \pm 0.03$ events due to this source. We also generated a Monte Carlo sample of $\Upsilon(3S)\to\pi^0\pi^0\Upsilon(2S)$, $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$, corresponding to 538^{+107}_{-77} million $\Upsilon(3S)$ decays, or 113^{+23}_{-16} times our data set. From this sample, a total of nine events passed our selection. In our data set, we thus expect $9/(113 \pm {}^{+23}_{-16}) = 0.08 \pm 0.01$ events due to this source. To account for the residual background, we subtract the expected contribution of 0.30 events from the observed yield. We conservatively set a systematic error of ± 0.30 events due to this subtraction.

To evaluate the signal detection efficiency, we generated 150,000 signal Monte Carlo events for each of $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$, proceeding through the sequence $\Upsilon(3S)\to\gamma\chi_{b1,2}(2P)\to\gamma\omega\Upsilon(1S)\to\gamma\pi^+\pi^-\pi^0\ell^+\ell^-$, and utilizing PDG average values for the $\chi_{b1,2}(2P)$ and $\Upsilon(nS)$ masses, and with a uniform angular distributions for the $\Upsilon(3S)\to\gamma\chi_{b1,2}(2P)$ and $\Upsilon(1S)\to\ell^+\ell^-$ decays. The analysis cuts described above have been applied to these samples, and we obtain $\epsilon(\chi_{b2}(2P)) = (6.23 \pm 0.06)\%$ and $\epsilon(\chi_{b1}(2P)) = (6.81 \pm 0.07)\%$, including all selection criteria, acceptance and trigger efficiencies. The efficiencies have been corrected for the known angular distributions of the $E1$ transitions $\Upsilon(3S)\to\gamma\chi_{b1,2}(2P)$. We apply an additional relative systematic error of ${}^{+0}_{-3}\%$ to the efficiency in order to account for the possibility that the $\Upsilon(1S)$ retains the initial polarization of the $\Upsilon(3S)$.

In Figure 3 we present a scatter plot of the recoil mass against $\omega\gamma$ vs. dilepton invariant mass for all events subject to all the cuts discussed above, except those on the variables plotted, in order to emphasize the clarity of the signal. The final E_γ spectrum is shown in Figure 4. The observed yield has possible contributions from both decay sequences involving $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$ intermediate states.

To obtain branching fractions for the $\chi_{b2}(2P)$ and $\chi_{b1}(2P)$ transitions, we perform a maximum likelihood fit of the E_γ spectrum. The expected photon spectra for $\Upsilon(3S)$ transitions to $\chi_{b2}(2P)$ and $\chi_{b1}(2P)$ were obtained from the signal Monte Carlo samples, and the observed E_γ spectrum was then fit to normalized Monte Carlo lineshapes with intensities (or yields) for $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$ as the free parameters. We obtain yields of $32.6^{+6.9}_{-6.1}$ and $20.1^{+5.8}_{-5.1}$ events, respectively. These yields have statistical significances of 10.2σ and 5.2σ, respectively. The histogram resulting from the best fit is shown superimposed on the data in Figure 4.

We subtract the expected background contribution of a total of 0.30 events, subtracting from each yield a fraction of this total background equal to the ratio of the fitted yield to the sum of the two yields.

We thus obtain the following product branching ratios, using the detection efficiency and number of $\Upsilon(3S)$ discussed above:

$$\mathcal{B}(\Upsilon(3S)\to\gamma\chi_{b1}(2P)) \times \mathcal{B}(\chi_{b1}(2P)\to\omega\Upsilon(1S))$$

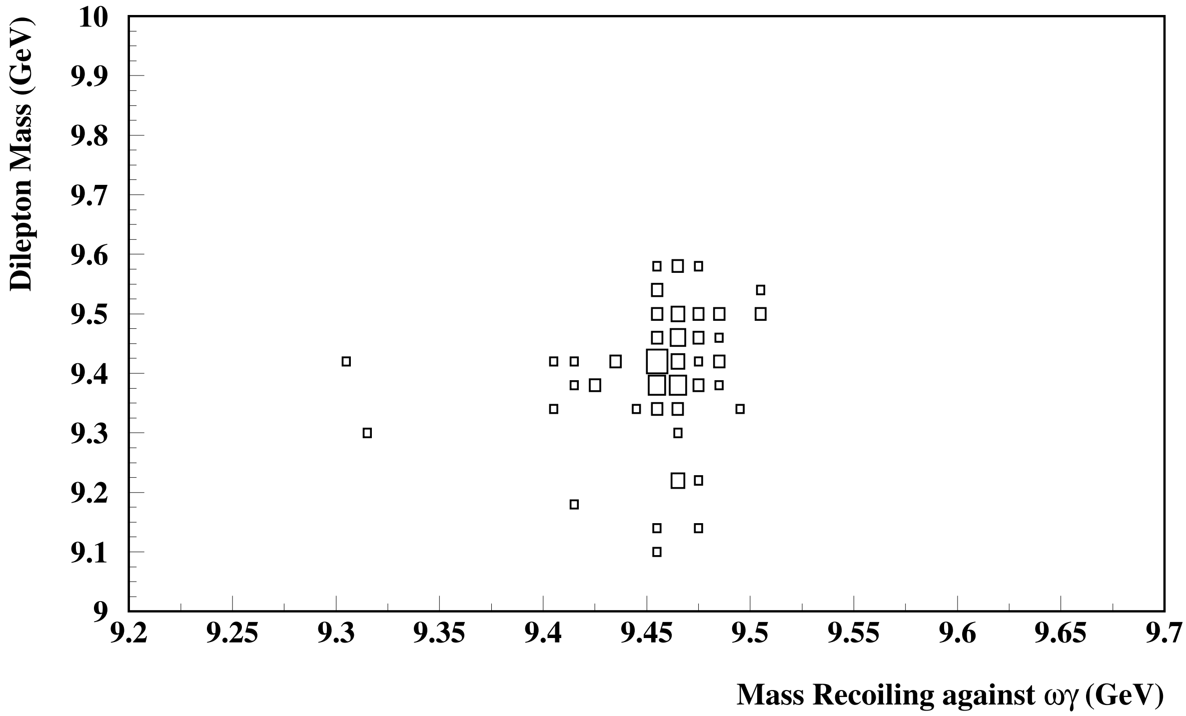

FIG. 3: Plot of recoil mass versus dilepton mass, for data events subject to the final set of cuts, with the exception of the cuts on the two variables plotted.

$$
\begin{aligned}
&\times\mathcal{B}(\omega\to\pi^+\pi^-\pi^0)\times\mathcal{B}(\Upsilon(1\mathrm{S})\to\ell^+\ell^-)\\
&\qquad = 0.82^{+0.17}_{-0.15}\pm 0.06\times 10^{-4},\ \text{and} \qquad (1)\\
&\mathcal{B}(\Upsilon(3\mathrm{S})\to\gamma\chi_{b2}(2P))\times\mathcal{B}(\chi_{b2}(2P)\to\omega\Upsilon(1\mathrm{S}))\\
&\times\mathcal{B}(\omega\to\pi^+\pi^-\pi^0)\times\mathcal{B}(\Upsilon(1\mathrm{S})\to\ell^+\ell^-)\\
&\qquad = 0.55^{+0.16}_{-0.14}\pm 0.04\times 10^{-4}, \qquad (2)
\end{aligned}
$$

in which the first error is statistical and the second is the systematic error.

The statistical error of nearly 20% is the dominant source of error. Systematic error contributions to the above product of branching ratios are the following: 2% for the uncertainty in the number of $\Upsilon(3\mathrm{S})$, 1% per charged track (a total of 4%) for track finding, 5% for π^0 reconstruction, 2% for radiative γ reconstruction, 1% for Monte Carlo statistics, $^{+3}_{-0}$% for the assumption of uniform $\Upsilon(1\mathrm{S})\to\ell^+\ell^-$ angular distribution, and 1% for background subtraction. These contributions, added in quadrature, result in an overall relative systematic error of $^{+7.7}_{-7.1}$.

Using the present world average branching fractions for $\Upsilon(3\mathrm{S})\to\gamma\chi_{b1,2}(2P)$, $\Upsilon(1\mathrm{S})\to\ell^+\ell^-$ (taken to be twice that of $\Upsilon(1\mathrm{S})\to\mu^+\mu^-$), and $\omega\to\pi^+\pi^-\pi^0$ from Ref. [5], we thus obtain

$$\mathcal{B}(\chi_{b1}(2P)\to\omega\Upsilon(1\mathrm{S})) = 1.63^{+0.35+0.16}_{-0.31-0.15}\%\ \text{and} \qquad (3)$$

$$\mathcal{B}(\chi_{b2}(2P)\to\omega\Upsilon(1\mathrm{S})) = 1.10^{+0.32+0.11}_{-0.28-0.10}\%, \qquad (4)$$

in which the errors quoted are statistical and systematic, respectively. The systematic

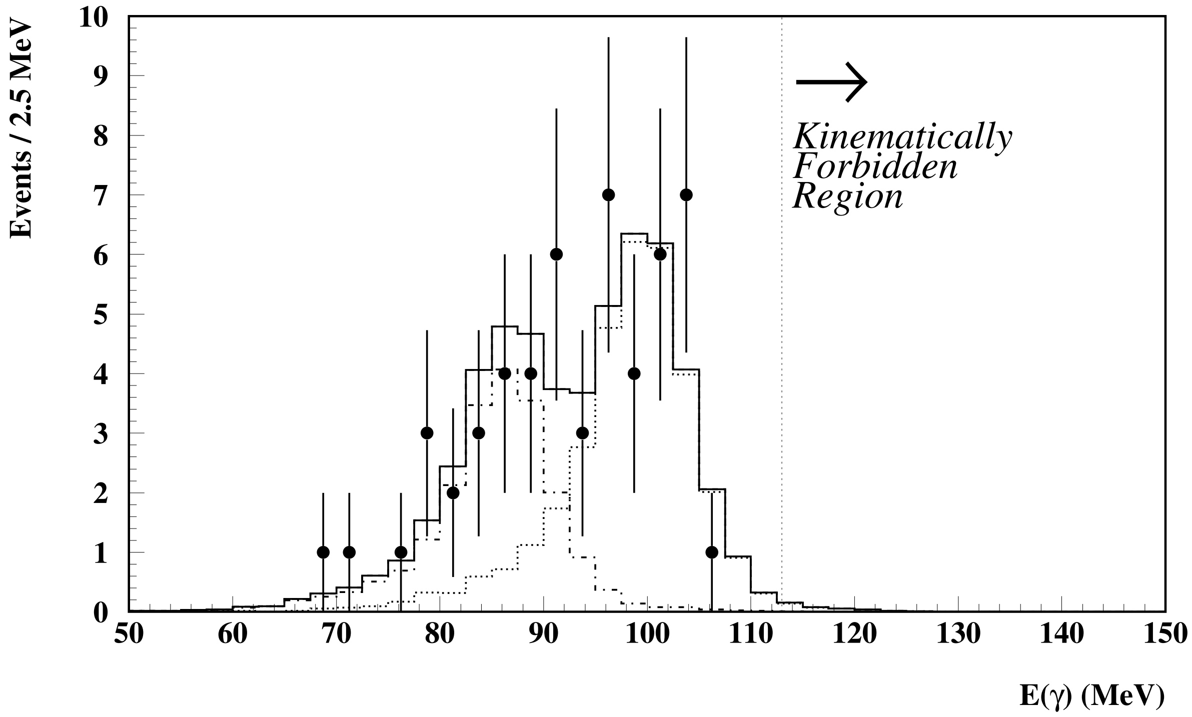

FIG. 4: Fitted photon energy spectrum for the final selection of events. The solid histogram shows contributions for both $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$, while the dotted and dashed histograms show the individual $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$ contributions, repsectively. The dotted line indicates the region above which γ energies are disallowed for lack of phase space. The small leakage of the histogram for the $\chi_{b1}(2P)$ Monte Carlo sample into the kinematically disallowed region is due to the finite detector resolution.

errors on include the experimental errors on the branching ratios for $\Upsilon(3S)\to\gamma\chi_{b1,2}(2P)$, $\omega\to\pi^+\pi^-\pi^0$ and $\Upsilon(1S)\to\ell^+\ell^-$, which contribute an additional systematic error of 5.9%.

We may also calculate the ratio of $\chi_{b2}(2P)$ to $\chi_{b1}(2P)$ branching ratios, for which systematic errors discussed above cancel almost entirely. We obtain this through a maximum likelihood fit to the E_γ spectrum, in which the two free parameters are the sum of yields and the ratio of $\chi_{b2}(2P)$ to $\chi_{b1}(2P)$ yields. When this fit is performed, we obtain a sum of yields equal to $52.4^{+7.5}_{-6.9}$ and a ratio of $0.62^{+0.27}_{-0.20}$. In order to convert the ratio of yields to the ratio of branching ratios, we multiply the yield ratio by a factor of $\epsilon(\chi_{b1}(2P))/\epsilon(\chi_{b2}(2P))$.

$$\begin{aligned}\mathcal{B}(\chi_{b2}(2P)\to\omega\Upsilon(1S)))/\mathcal{B}(\chi_{b1}(2P)\to\omega\Upsilon(1S)) &= 0.62^{+0.27}_{-0.20}\times\frac{\epsilon(\chi_{b1}(2P))}{\epsilon(\chi_{b2}(2P))}\\ &= 0.62^{+0.27}_{-0.20}\times\frac{(6.81\pm0.07)\%}{(6.23\pm0.06)\%} = 0.67^{+0.30}_{-0.22}. \end{aligned} \tag{5}$$

The only systematic errors which do not cancel in this ratio are the small uncertainties in efficiency and $\Upsilon(3S)\to\gamma\chi_{b1,2}(2P)$ branching ratios. These are entirely negligible compared to the output error from the maximum likelihood fit.

In Ref. [6], Voloshin predicts on the basis of S-wave phase space factors, that the ratio of partial widths $\Gamma(\chi_{b2}(2P)\to\omega\Upsilon(1S))/\Gamma(\chi_{b1}(2P)\to\omega\Upsilon(1S))$ should be approximately 1.4. The ratio of full widths $\Gamma(\chi_{b2}(2P))/\Gamma(\chi_{b1}(2P))$ lies in the range of 1/(1.5-1.25), using world average measurements of $\mathcal{B}(\chi_{b1,2}(2P)\to\gamma\Upsilon(1S,2S))$ and theoretical predictions for the rates $\Gamma(\chi_{b1,2}(2P)\to\gamma\Upsilon(1S,2S))$. Thus the branching ratios $\mathcal{B}(\chi_{b1,2}(2P)\to\omega\Upsilon(1S))$ are expected to be approximately equal. Our measurement is rough agreement with this expectation.

Furthermore, Gottfried [7] predicted that, due to the non-Abelian nature of strong interactions, $\Delta L = 1$, $\Delta S = 0$ hadronic transitions ought to have sizeable widths. Our observation provides experimental evidence for his statement.

We have made the observation of the first hadronic decay modes involving non-vector $b\bar{b}$ states, thanks to the large statistical advantage of the CLEO-III $b\bar{b}$ data set over all previous data sets. The discovery came in the phase-space limited channels $\chi_{b1,2}(2P)\to\omega\Upsilon(1S)$, and the ratio of the measured branching ratios for the two transitions are in rough agreement with theoretical expectations based on S-wave phase space factors. The observation of these decays supports the prediction that such transitions should have significant rates.

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, the Research Corporation, and the Texas Advanced Research Program.

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[1] See, for example, F. Butler *et al.*, Phys. Rev. D **49**, 40 (1994), I. Brock *et al.*, Phys. Rev. D **43**, 1448 (1991), J. Green *et al.*, Phys. Rev. Lett. **49**, 617 (1982), Q. Wu *et al.*, Phys. Lett. B **301** 307 (1993) and G. Mageras *et al.*, Phys. Lett. B **118** 453 (1982).

[2] T. M. Yan, Phys. Rev. D **22**, 1652 (1980), Y. P. Kuang and T. M. Yan, Phys. Rev. D **24**, 2874 (1981); M. Voloshin and V. Zakharov, Phys. Rev. Lett. **45**, 688 (1980); V. A. Novikov and M. A. Shifman *Zeit. Phys.* C **8** (1981) 43; M. E. Peskin, in "Dynamics and Spectroscopy at High Energy", Proceedings of the Eleventh SLAC Summer Institute on Particle Physics, SLAC Report 267, 1984; P. Moxhay, Phys. Rev. D **39**, 3497 (1989); H-Y. Zhou and Y.-P. Kuang, Phys. Rev. D **44**, 756 (1991); G. Bélanger, T. DeGrand and P. Moxhay, Phys. Rev. D **39**, 257 (1989); S. Chakravarty and P. Ko, Phys. Rev. D **48**, 1205 (1993); S. Chakravarty, S. M. Kim and P. Ko, Phys. Rev. D **50**, 389 (1994); T. Komada, M. Ishida and S. Ishida, Phys. Lett. B **508** 31 (2001); T. A. Lähde and D. O. Riska, hep-ph/0112131.

[3] CLEO Collaboration, CLNS-94-1277; D. Peterson *et al.*, *Nucl. Instr. Meth.* **A478** 142 (2002).

[4] R. Brun *et al.*, GEANT 3.15, CERN Report No. DD/EE/84-1 (1987).

[5] Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. D **66**, 1 (2002).

[6] M. Voloshin, *hep-ph/0304165.*

[7] K. Gottfried, Phys. Rev. Lett. **40**, 598 (1978).