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

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Abstract

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

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 the Υ(nS) states [1]. In Fig. 1 we show the spectrum of bottomonium states below open bottom threshold.

Hadronic transitions among heavy quarkonia are generally understood to proceed by the emission of soft gluons, and subsequent hadronization of the gluons. 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.

Most theoretical work dedicated to these transitions has been built around a multipole expansion of the color field, an idea first proposed by Gottfried and Yan [2]. A fairly substantial literature exists which attempts to describe in detail the $\pi\pi$ transitions that have been observed [3]. While these 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.

In the multipole expansion model, a hadronic transition involving ω requires three gluons in an $E1 * E1 * E1$ configuration [4]. For such a purely electric coupling, Voloshin [5] has recently predicted roughly equal rates for the decay of the two states $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$ to $\omega\Upsilon(1S)$. In this Letter, we report on the observation of the transitions $\chi_{b1,2}(2P) \to \omega\Upsilon(1S)$.

The data set consists of $(5.81 \pm 0.12) \times 10^6 \Upsilon(3S)$ decays observed with the CLEO III [6] detector at the Cornell Electron Storage Ring. Charged particle tracking is done by the 47-layer drift chamber and a four-layer silicon tracker which reside in a 1.5 T solenoidal magnetic field. Photons are detected using an electromagnetic calorimeter consisting of 7784 CsI(Tl) crystals distributed in a projective barrel geometry. The particle-identification capabilities of the CLEO III detector are not used in the present analysis.

Events consistent with the final state of $\gamma\pi^+\pi^-\pi^0\ell^+\ell^-$ are selected by requiring two high momentum charged tracks ($p > 4$ GeV/c) and two or three charged low momentum tracks ($0.12 < p < 0.75$ GeV/c). 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 $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$.

We require events to contain an $\Upsilon(1S)$ candidate by requiring that the two high momentum tracks in the event have an invariant mass in the range 9300 to 9600 MeV, consistent with the $\Upsilon(1S)$ mass. 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 uncertainties and reduced signal efficiency without much improvement in signal quality.

We require events to have three or four showers in the calorimeter, each of which has $E > 30$ MeV, and is not matched to any charged track. Two of these showers must form an invariant mass within three standard deviations (3σ) of the known π^0 mass. These candidates are kinematically constrained to the known π^0 mass, in order to improve the momentum resolution of the π^0 candidates. 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 (1.5σ) of the π^0 mass with any other shower. Furthermore we require that the polar angle (θ) of the third shower satisfy $|\cos\theta| < 0.804$, the angular region in which CLEO's energy resolution is best. 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 or from

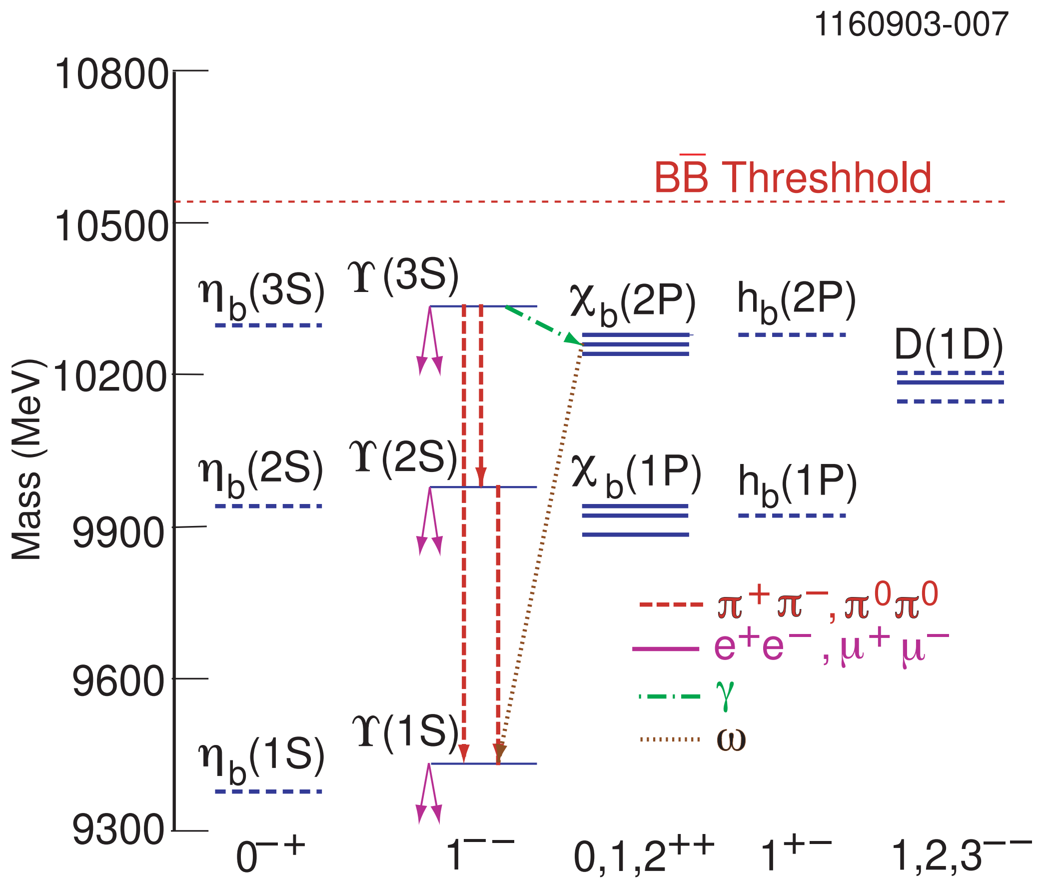

FIG. 1: The spectrum of bottomonium states below open bottom threshold. Dilepton decays of the $J^{PC} = 1^{--}$ states are denoted by the solid lines, while dipion transitions are denoted by dashed lines. The radiative decay $\Upsilon(3S)\to\gamma\chi_{b1,2}(2P)$ is indicated by the dot-dashed line, and the decay $\chi_{b1,2}(2P)\to\omega\Upsilon(1S)$ by the dotted line.

delta rays. Spurious showers may arise from synchrotron radiation from the $e^{\pm}$ beams or as a result of random noise in the calorimeter. 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 $M(\Upsilon(3S))$.

Because there is no phase space for a pair of kaons for decays in which a $\Upsilon(1S)$ is present, we assume that the low momentum charged tracks are pions. The invariant mass of the $\pi^+\pi^-\pi^0$ combination, plotted in Fig. 2, exhibits a clear enhancement at the mass of ω, $M(\omega) = 0.783$ GeV [7].

To complete the reconstruction of the full decay chain, $\Upsilon(3S)\to\gamma\omega\Upsilon(1S)\to\gamma\pi^+\pi^-\pi^0\ell^+\ell^-$, we require that the $\chi^2/d.o.f.$ be less than two 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 candidate and the photon lies within $^{+25}_{-20}$ MeV of $M(\Upsilon(1S)) = 9.460$ GeV [7].

The simplest explanation for the observed events is the decay sequence $\Upsilon(3S)\to\gamma\chi_{b1,2}(2P)$, with $\chi_{b1,2}(2P)\to\omega\Upsilon(1S)$. The lowest mass $\chi_{bJ}(2P)$ state, $\chi_{b0}(2P)$, lies below threshold for decay to $\omega\Upsilon(1S)$. In principle a transition through the $\eta_b(3S)$ state (see Fig. 1) is possible, but this state has never been observed, and, furthermore, the energy

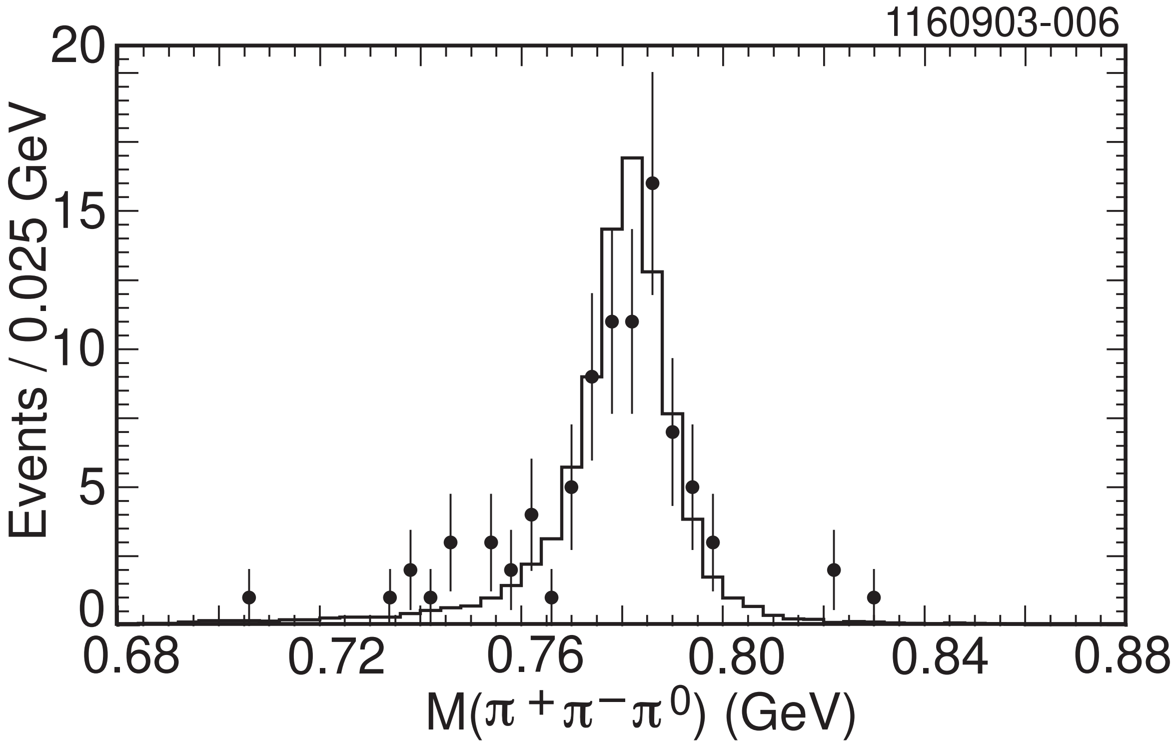

FIG. 2: The $\pi^+\pi^-\pi^0$ invariant mass, for data events subject to final analysis cuts with the exception of the cut on the $\chi^2/d.o.f.$ of the kinematic fit to ω. The overlaid histogram shows signal Monte Carlo events (normalized to the same total number) and indicates the good reproduction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

of the photon in the decay $\Upsilon(3\mathrm{S})\to\gamma\eta_b(3S)$ is expected to be below the range of observed energies in the data.

Backgrounds from ordinary *udsc* quark pair 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 $\Upsilon(1\mathrm{S})$ expected is known cascades from $\Upsilon(3\mathrm{S})$. The final state of $\gamma\pi^+\pi^-\pi^0\Upsilon(1\mathrm{S})$ may be reached through:

$$\Upsilon(3\mathrm{S})\to\gamma\chi_b(2P),\ \chi_b(2P)\to\gamma\Upsilon(2\mathrm{S}),\ \Upsilon(2\mathrm{S})\to\pi^+\pi^-\Upsilon(1\mathrm{S})$$
$$\text{or}\ \ \Upsilon(3\mathrm{S})\to\pi^0\pi^0\Upsilon(2\mathrm{S}),\ \Upsilon(2\mathrm{S})\to\pi^+\pi^-\Upsilon(1\mathrm{S}).$$

In the first case, the final state of interest 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 photon from one of the neutral pions due to acceptance or energy threshold.

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

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

In order to evaluate residual background, we generated a GEANT [8] Monte Carlo sample for the channel $\Upsilon(3S)\to\gamma\chi_{b1,2}(2P)$,$\chi_{b1,2}(2P)\to\gamma\Upsilon(2S)$, $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$, 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 0.22 ± 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 540^{+110}_{-80} 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 0.08 ± 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 ϵ, we generated 150,000 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 uniform angular distributions for the $\Upsilon(3S)\to\gamma\chi_{b1,2}(2P)$ and $\Upsilon(1S)\to\ell^+\ell^-$ decays. The masses for all particles in the decay chain were taken from Ref. [7].

The analysis cuts described above are applied to these samples, and we obtain $\epsilon(\chi_{b1}(2P)) = (6.81\pm0.07)\%$ and $\epsilon(\chi_{b2}(2P)) = (6.23\pm0.06)\%$, including all selection criteria, acceptance and trigger efficiencies. 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 order to illustrate the purity of the signal, in Fig. 3, we present a scatter plot of the mass recoiling against the $\omega\gamma$ system versus the dilepton invariant mass for all events subject to all the cuts discussed above, except those on the variables plotted. The final E_γ spectrum is shown in Fig. 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, obtained by comparing the likelihood of our final fitted yield to those of fits with zero signal events. The histogram resulting from the best fit is shown superimposed on the data in Fig. 4.

The expected background contribution of 0.30 events is subtracted from the fitted yield by assuming that it scales as the ratio of the individual yields to the total yield.

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

$$\begin{aligned}
&\mathcal{B}(\Upsilon(3S)\to\gamma\chi_{b1}(2P)) \times \mathcal{B}(\chi_{b1}(2P)\to\omega\Upsilon(1S)) \\
&\quad\times\mathcal{B}(\omega\to\pi^+\pi^-\pi^0) \times \mathcal{B}(\Upsilon(1S)\to\ell^+\ell^-) \\
&\quad= (0.82^{+0.17}_{-0.15}\pm0.06)\times10^{-4}, \text{ and} \qquad (1)\\
&\mathcal{B}(\Upsilon(3S)\to\gamma\chi_{b2}(2P)) \times \mathcal{B}(\chi_{b2}(2P)\to\omega\Upsilon(1S)) \\
&\quad\times\mathcal{B}(\omega\to\pi^+\pi^-\pi^0) \times \mathcal{B}(\Upsilon(1S)\to\ell^+\ell^-) \\
&\quad= (0.55^{+0.16}_{-0.14}\pm0.04)\times10^{-4}, \qquad (2)
\end{aligned}$$

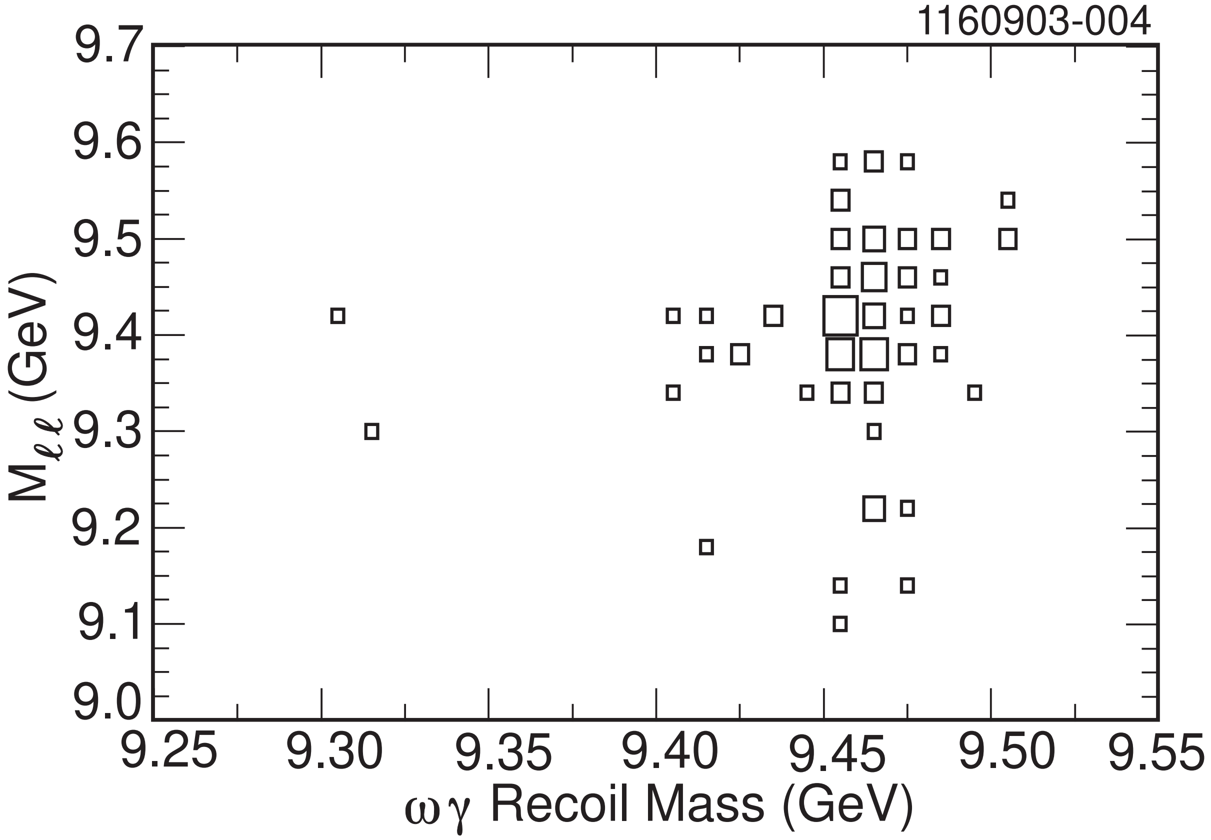

FIG. 3: Plot of recoil mass versus dilepton mass, for data events subject to the final set of cuts, with the exception of the cuts on the two variables plotted. The number of events represented by each square range from one to four.

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

The statistical error of nearly 20% is dominant. Systematic error contributions to the above product of branching ratios are the following: 2% uncertainty in the number of Υ(3S), 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 $\Upsilon(1S)\to\ell^+\ell^-$ 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 [7] for $\Upsilon(3S)\to\gamma\chi_{b1,2}(2P)$, $\Upsilon(1S)\to\ell^+\ell^-$ (taken to be twice that of $\Upsilon(1S)\to\mu^+\mu^-$), and $\omega\to\pi^+\pi^-\pi^0$, we obtain

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

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

The systematic errors include the additional uncertainty 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 at the level of 5.9%.

We may also calculate the ratio of $\chi_{b2}(2P)$ to $\chi_{b1}(2P)$ branching ratios, for which several of the systematic errors discussed above cancel. 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

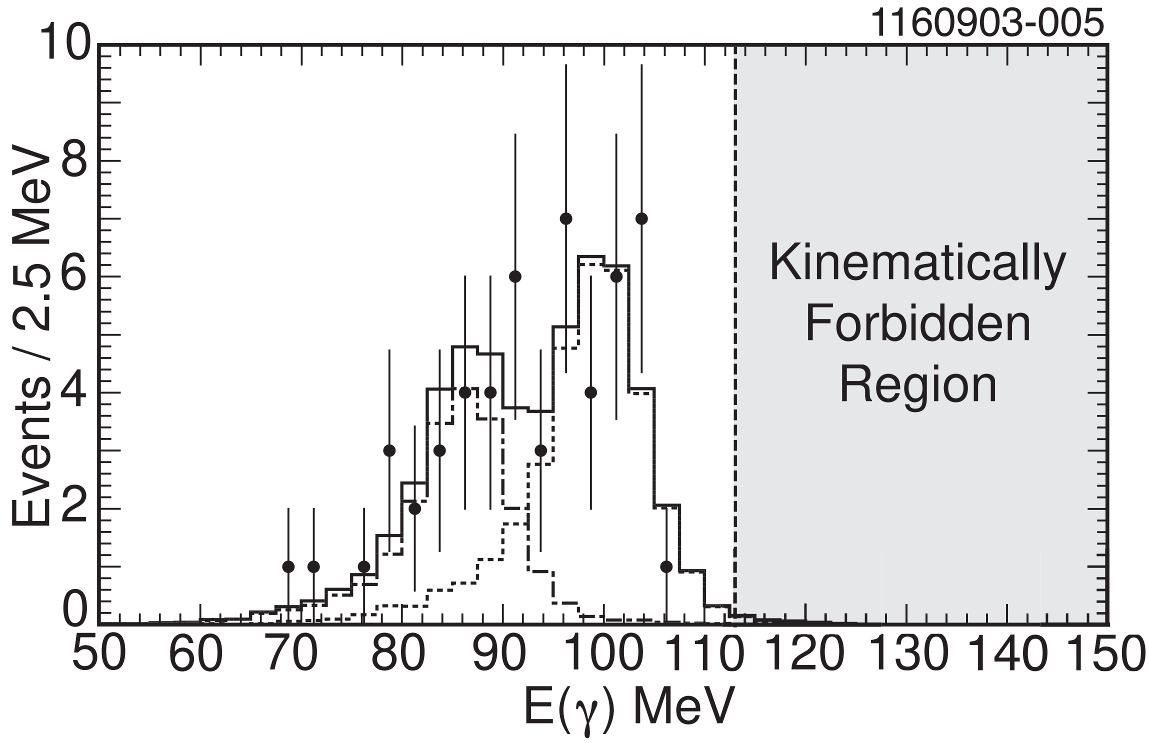

FIG. 4: Fitted photon energy spectrum for the final selection of events. The solid histogram shows contributions for both $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$, while the dotted and dashed histograms show the individual $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$ contributions, repsectively. The dotted line indicates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

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 $\epsilon(\chi_{b1}(2P))/\epsilon(\chi_{b2}(2P))$.

$$\mathcal{B}(\chi_{b2}(2P)\to\omega\Upsilon(1S)))/\mathcal{B}(\chi_{b1}(2P)\to\omega\Upsilon(1S)) \tag{5}$$
$$= 0.67^{+0.30}_{-0.22}. \tag{6}$$

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 statistical error from the maximum likelihood fit.

In Ref. [5], Voloshin predicts on the basis of S-wave phase space factors, for $E_1 * E_1 * E_1$ gluon configurations expected by the multipole expansion model [4], that $\Gamma(\chi_{b2}(2P)\to\omega\Upsilon(1S))/\Gamma(\chi_{b1}(2P)\to\omega\Upsilon(1S)) \approx 1.4$. The ratio of full widths $\Gamma(\chi_{b2}(2P))/\Gamma(\chi_{b1}(2P))$ lies in the range of 1.25-1.5, using world average measurements of $\mathcal{B}(\chi_{b1,2}(2P)\to\gamma\Upsilon(1S,2S))$ and theoretical predictions for the rates $\Gamma(\chi_{b1,2}(2P)\to\gamma\Upsilon(1S,2S))$ [9]. Thus the branching ratios $\mathcal{B}(\chi_{b1,2}(2P)\to\omega\Upsilon(1S))$ are expected to be approximately equal. Our measurement is in agreement with this expectation.

In summary, we have made the observation of the first hadronic decay modes involving non-vector $b\bar{b}$ states using a sample of $(5.81 \pm 0.12) \times 10^6\Upsilon(3S)$ decays collected by CLEO III. The discovery comes in the phase-space limited channels $\chi_{b1,2}(2P)\to\omega\Upsilon(1S)$. We find that the ratio of the measured branching ratios for the two transitions are in agreement with theoretical expectations based on S-wave phase space factors for multipole expansions.

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