Inclusive $\chi(2P)$ Production in $\Upsilon(3S)$ Decay

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Using the CsI calorimeter of the CLEO II detector, the spin triplet $\chi_b(2P)$ states are observed in $\Upsilon(3S)$ radiative decays with much higher statistics than seen in previous experiments. The observed mass splittings are not described well by theoretical models, while the relative branching ratios agree with predictions that include relativistic corrections to the radiative transition rates.

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We report the results from a study of the $\chi_b(2\,^3P_J)$ states ($J=0,1,2$) produced in radiative $\Upsilon(3S)$ decay using the new CLEO II detector at the Cornell Electron Storage Ring (CESR). The data consist of 116 pb^{-1} of integrated luminosity collected at the peak of the $\Upsilon(3S)$ resonance. The $\chi_b(2\,^3P_J)$ states are expected to be split into three mass states with J^{PC} quantum numbers 0^{++}, 1^{++}, and 2^{++}. In the strict nonrelativistic potential model these three states are degenerate in mass and the matrix element for the electric dipole transitions $3\,^3S_1 \to \gamma+2\,^3P_J$ is independent of J. The relativistic effects, primarily spin-orbit and tensor interactions, are responsible for spin dependence of the $\chi_b(2\,^3P_J)$ masses and matrix elements for the photon transitions.

The CLEO II detector was designed to detect both charged and neutral particles with high resolution and efficiency. The detector consists of a charged-particle tracking system surrounded by a time-of-flight scintillation system and an electromagnetic shower detector consisting of 7800 thallium-doped CsI crystals [1]. The tracking system, time-of-flight system, and calorimeter are installed inside a 1.5-T superconducting coil. Immediately outside the coil are iron and chambers used for muon detection [2].

The crystals in the barrel portion of the detector point approximately toward the e^+e^- collision point. They have a roughly trapezoidal shape ≈ 5 cm$\times$5 cm at the front and 30 cm (16.2 radiation lengths) in length. The relative calibration of crystals was performed using Bhabha scattering ($e^+e^- \rightarrow e^+e^-$). The energy of the scattered electrons then is the well-known beam energy of 5.18 GeV. We have converted this calibration of electron energy to photon energy using $e^+e^- \rightarrow \gamma\gamma$ events.

We have further corrected the photon energies for small nonlinearities in the energy measurement [3]. An energy-dependent correction factor which multiplies the measured photon energies, $E_{\rm true}/E_{\rm meas}$, is determined from $\pi^0 \rightarrow \gamma\gamma$ events. In Fig. 1 we compare these results with a Monte Carlo simulation and at higher energies with radiative Bhabha events and $e^+e^- \rightarrow \gamma\gamma\gamma$ events. In the energy region around 100 MeV, we find that we need to lower the measured energies by $\approx 1\%$. The error on the absolute energy scale is $\pm 0.5\%$, while the error on the relative energy determination is $\pm 0.1\%$ in the restricted energy region relevant for this analysis.

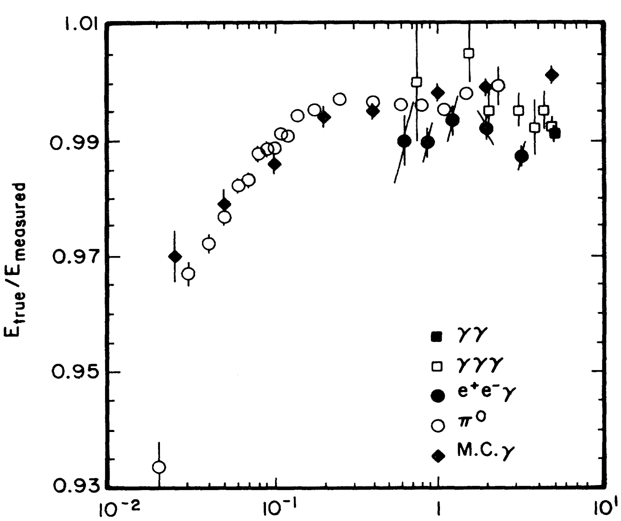

FIG. 1. $E_{\rm true}/E_{\rm meas}$ determined from π^0 decays (open circles), Monte Carlo simulation (diamonds), radiative Bhabha events (solid circles), three-γ events (open squares), and $e^+e^- \rightarrow \gamma\gamma$ events (solid square). The vertical error bar on the radiative Bhabha events gives the statistical error, while the skewed error bar gives a linear combination of the statistical and systematic errors. There is an additional $\pm 0.3\%$ scale error on the π^0 measurements.

Radiative transitions from the $\Upsilon(3S)$ can be studied inclusively by the observation of monochromatic peaks in the photon-energy spectrum. Hadronic events have been selected using criteria based mainly on drift chamber information. We require at least three charged tracks of good quality, a reasonable event vertex, a visible energy (charged and neutral) of at least half the center-of-mass energy, and events not consistent with radiative Bhabhas or beam-wall collisions. We have approximately 700000 observed events, of which 410000 come from $\Upsilon(3S)$ decays and the rest from the continuum, where we use the measured luminosity and cross section [4] to calculate the number of $\Upsilon(3S)$ decays.

For this analysis we use only the barrel portion of the calorimeter which subtends 70.7% of the solid angle. The end plates of the drift chamber, the cables, and other material worsen the resolution substantially in the end-cap regions. Photon candidates are selected from the showers in the barrel by requiring that the shower is not matched to a charged-particle track from the drift chamber and that the shower has a lateral energy distribution consistent with Monte Carlo photons.

The energy spectrum of photon candidates in these events is plotted in Fig. 2(a) for the energy region around 100 MeV. The large background in our sample is mainly due to photons from other processes (mostly π^0 decays) and hadronic showers produced from interactions of hadrons with the crystal nuclei. The curve is a fit by a third-order background polynomial plus three bifurcated Gaussian signal functions whose means are allowed to float. A bifurcated Gaussian has two width parameters, one on the higher side, $\sigma_{\rm high}$, and the other on the lower side, $\sigma_{\rm low}$. We constrain the ratio $\sigma_{\rm high}/\sigma_{\rm low}$ to be the same in each peak. Furthermore, we constrain the average, $\frac{1}{2}(\sigma_{\rm high}+\sigma_{\rm low})$, to have an energy dependence as predicted by Monte Carlo simulation. Thus we are left with two overall width parameters. Assuming that the mass splittings in the $\chi_b(2P)$ system follow the same pattern as in the $\chi_b(1P)$ system [5], the lower-photon-energy line corresponds to the $J=2$ case, with the others following in order of increasing photon energy. The energies E_γ and their errors, determined from the fit, are given in Table I [6]; they are more precise than previous determinations [7]. The background-subtracted spectrum is shown in Fig. 2(b).

The fit gives an energy resolution of $(4.2\pm0.2)\%$ at 100 MeV. The width on the high-energy side is 4.0 MeV and on the low-energy side is 4.3 MeV. This compares well with other crystal-based detectors in this energy region [8].

The γ detection efficiency ϵ_γ is determined by implanting Monte Carlo photons into real hadronic events. We

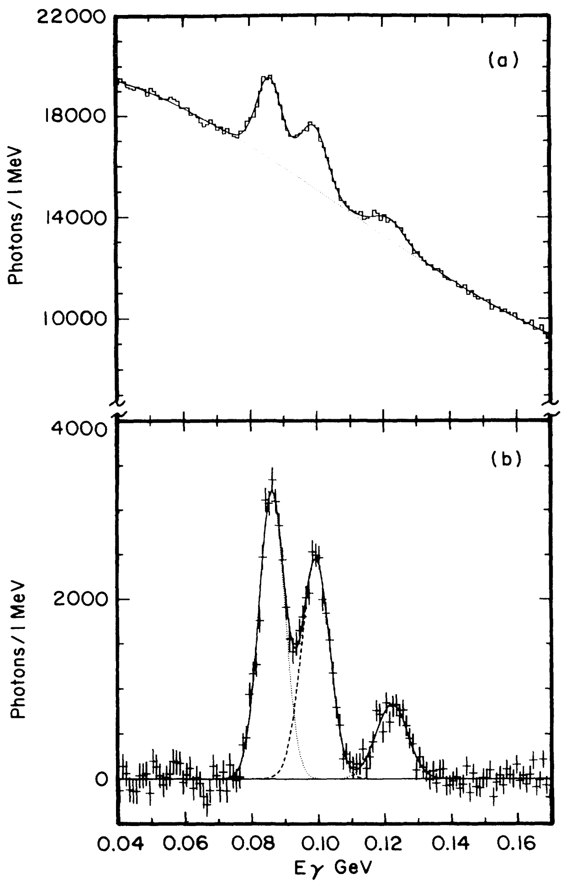

FIG. 2. Inclusive photon spectrum from $\Upsilon(3S)$ decays. (a) The solid curve is a fit with bifurcated Gaussian signal functions plus a third-order polynomial background. The dotted curve shows the background. (b) Background-subtracted spectrum.

find that $\epsilon_\gamma = (53 \pm 3)\%$ for γ's distributed uniformly in solid angle. The γ's in these decays have different angular distributions depending on the χ_b angular momentum. Defining $\cos\theta$ as the angle between the γ and the e^+ beam direction, the angular distribution $dN/d\cos\theta$ varies as $1+\frac{1}{13}\cos^2\theta$, $1-\frac{1}{3}\cos^2\theta$, and $1+\cos^2\theta$, for $J=2$, 1, and 0, respectively. We correct the efficiencies for these distributions.

We have evaluated the J-dependent hadronic-event selection efficiencies by a LUND-based Monte Carlo simulation including our event trigger. Angular momentum and parity considerations lead to the expectation that the $J=0$ and $J=2$ states decay by annihilating into two gluons (gg), while the $J=1$ annihilates into quark and antiquark plus a gluon ($q\bar{q}g$) [9]. We have taken into account that the $J=1$ and $J=2$ states have significant radiative branching ratios to $\Upsilon(2S)$ and $\Upsilon(1S)$ which subsequently decay dominantly into ggg. We find these efficiencies are independent of J at the level of 2%. Note that we do not expect the efficiency for these events to be as low as that for continuum two-jet events because the jets from the χ_b decays will not have a preferred orientation along the e^+e^- beam direction. The branching ratios are given in Table I; the first error is due to statistical uncertainties and other uncertainties which occur when considering the errors on the relative branching ratios, while the second error reflects our uncertainty in the overall scale [10].

TABLE I. Energies and branching ratios of $\Upsilon(3S) \rightarrow \gamma + 2\,^3P_J$.

J	E_γ (MeV)	CLEO II No. of γ	$\mathcal{B}$ (%)
2	$86.4 \pm 0.1 \pm 0.4$	$30\,741 \pm 560$	$13.5 \pm 0.3 \pm 1.7$
1	$99.5 \pm 0.1 \pm 0.5$	$25\,759 \pm 510$	$10.5^{+0.3}_{-0.2} \pm 1.3$
0	$122.3 \pm 0.3 \pm 0.6$	$9\,903 \pm 550$	$4.9^{+0.3}_{-0.4} \pm 0.6$

The widths for the electric dipole transitions $3\,^3S_1 \rightarrow \gamma + 2\,^3P_J$ are given by

$$\Gamma_{E1} = \tfrac{4}{27}\,\alpha e_b^2 E_\gamma^3 (2J+1) \langle 2P|r|3S\rangle^2 , \qquad (1)$$

where α is the electromagnetic coupling constant and e_b is the charge of the b quark, assumed to be $\frac{1}{3}$. Because of the E_γ^3 dependence of Γ_{E1} we compare with the predictions for the matrix elements $\langle 2P|r|3S\rangle$ which are almost independent of the χ_b masses. In the nonrelativistic approximation, $\langle 2P|r|3S\rangle$ is spin independent. Its value depends slightly on the choice of the potential; for example, four papers give nonrelativistic predictions of 2.64 [11], 2.68 [12], 2.66 [13], and 2.75 [14] (in GeV^{-1}) for $\langle 2P|r|3S\rangle$. By averaging over the transitions to all three $\chi_b(2\,^3P_J)$ states and using $\Gamma_{\text{tot}}(3\,^3S_1) = 24.3 \pm 2.9$ keV [15], we find $\langle 2P|r|3S\rangle = 2.6 \pm 0.2\ \text{GeV}^{-1}$. Thus, the data roughly agree with the nonrelativistic prediction confirming that the relativistic effects are small, in contrast with the similar transitions observed in the $c\bar{c}$ system [11]. Most of the relativistic calculations [11-14,16] predict lower rates for the $3\,^3S_1 \rightarrow \gamma + 2\,^3P_J$ transitions. The relativistic corrections are J dependent and are expected to be the largest for $J=0$ because the spin-orbit and tensor forces have the same sign and the largest magnitude [11]. Experimental and theoretical uncertainties in the absolute scale of the transition widths are comparable to the magnitude of the expected relativistic corrections. The ratios of the transition widths for different J can be determined with less uncertainty. Ratios of the quantity $\Gamma_{E1}/E_\gamma^3(2J+1)$ for $J=2$ and $J=0$ relative to $J=1$ which equal ratios of the squared matrix element in Eq. (1) are shown for the data and for various relativistic models in Table II. Our measured ratios deviate significantly from unity, thus disagreeing with the nonrelativistic expectation, and confirming the pattern of the spin dependence predicted in all relativistic calculations.

The splittings of the ^3P_J states are related to the expectation values of the vector (V) and scalar (S) parts of the quark-antiquark potential. If we define $\overline{M}$ as the spin-weighted center of gravity, a as the spin-orbit contribu-

TABLE II. Ratios of $\Gamma_{E1}/E_\gamma^3(2J+1)$.

	Data	Ref. [11]	Ref. [12]	Ref. [13]	Ref. [16]	Ref. [14]
$(J=2)/(J=1)$	$1.17^{+0.03}_{-0.05}$	1.17	1.04	1.12	1.08	1.14
$(J=0)/(J=1)$	$0.74^{+0.05}_{-0.06}$	0.73	0.90	0.86	0.80	0.85

tion, and b as the tensor contribution, the masses are given by [9] $M(\chi_2)=\bar{M}+a-\frac{2}{5}b$, $M(\chi_1)=\bar{M}-a+2b$, and $M(\chi_0)=\bar{M}-2a-4b$. Here a and b are computed as the configuration-space expectation values:

$$\langle V_{\text{spin-orbit}}\rangle = a\langle \mathbf{L}\cdot\mathbf{S}\rangle = \frac{1}{2m_b^2}\left\langle \frac{3}{r}\frac{dV}{dr}-\frac{1}{r}\frac{dS}{dr}\right\rangle\langle \mathbf{L}\cdot\mathbf{S}\rangle ,$$

$$\langle V_{\text{tensor}}\rangle = b\langle S_{12}\rangle = \frac{1}{12m_b^2}\left\langle \frac{1}{r}\frac{dV}{dr}-\frac{d^2V}{dr^2}\right\rangle\langle S_{12}\rangle ,$$

where m_b is the b-quark mass, $\mathbf{L}$ and $\mathbf{S}$ are the total angular momentum and spin of the $q\bar{q}$ pair, and $S_{12}=2[3(\mathbf{S}\cdot\mathbf{r})(\mathbf{S}\cdot\mathbf{r})-\mathbf{S}^2]$. We measure $\bar{M}=10260.1\pm0.7\pm0.7$ MeV, $a=9.4\pm0.2$ MeV, and $b=2.3\pm0.1$ MeV, showing a larger spin-orbit than tensor contribution.

Since the spin-orbit and tensor terms contain different amounts of vector and scalar components, it is convenient to define a parameter R_χ which gives information about the different proportions. R_χ is a function of the masses of the different χ states:

$$R_\chi=\frac{M(\chi_2)-M(\chi_1)}{M(\chi_1)-M(\chi_0)} .$$

A value of R_χ equal to 0.8 corresponds to a potential with no scalar confinement (i.e., Coulomb-type potential). We find $R_{\chi_b(2P)}=0.574\pm0.013\pm0.009$. The systematic error is due to the error in the relative energy calibration added in quadrature with the uncertainty in background shape. This value is smaller than the value for the lower radial excitation of the P wave in the Υ system, $R_{\chi_b(1P)}=0.68\pm0.03$ [17], and higher than the value for the ψ system, $R_{\chi_c(1P)}=0.48\pm0.02$.

Dib, Gilman, and Franzini have studied a general class of potential models and find that R increases from the lowest P states to their radial excitations which is also a feature of the other models [12,18,19]. However, this behavior is sensitive to the Lorentz character of the exchanges between heavy quarks. Our measurement indicates that $R_{\chi_b(2P)}\le R_{\chi_b(1P)}$. There are currently no models which correctly predict both this and the magnitude of R.

The CsI calorimeter gives us the capability of making precision photon-energy measurements with high efficiency. We have measured the photon-energy spectrum from $\Upsilon(3S)\to\gamma\chi_b(2\,^3P_J)$. We find the mass splitting ratio R_χ for these states to be $0.574\pm0.013\pm0.009$. Our measurements of the relative branching ratios confirm the presence of the relativistic effects predicted for these transitions.

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[1] The crystals were manufactured by BDH Ltd., Poole, England (now called Merck Ltd.) and Horiba Ltd., Kyoto, Japan.

[2] E. Blucher *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **249**, 201 (1986); C. Bebek *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **265**, 258 (1988).

[3] The energy correction depends on several factors including shower leakage and the algorithm we use to determine crystal energies. In order to minimize the effects of noise on the resolution we lower the number of crystals summed as the photon energy decreases.

[4] I. C. Brock *et al.*, Phys. Rev. D **43**, 1448 (1991).

[5] T. Skwarnicki *et al.*, Phys. Rev. Lett. **58**, 972 (1987).

[6] The first error for the energy entry is statistical. The second is systematic and results from uncertainties in the absolute energy scale and the background shape. In order to study uncertainties in the background shape we added photons from the decay chain $\Upsilon(3S)\to\Upsilon(2S)X$, $\Upsilon(2S)\to\gamma\chi_b$ explicitly as fixed signals. This shifted the energies by 0.10, 0.07, and 0.05 MeV for $J=0$, 1, and 2, respectively. Varying the relative energy resolution expectation used in the fit did not alter the photon-energy measurements.

[7] M. Narain *et al.*, Phys. Rev. Lett. **66**, 3113 (1991).

[8] The resolutions depend on the event topologies. In hadronic Υ events the Crystal Ball (NaI crystals) and CUSB II (bismuth-germanate crystals) Collaborations find σ's at 100 MeV of 4.8% and 5.5%, respectively. For CUSB see Ref. [7], and for Crystal Ball see R. Nernst *et al.*, Phys. Rev. Lett. **54**, 2195 (1985).

[9] W. Kwong, J. Rosner, and C. Quigg, Annu. Rev. Nucl. Part. Sci. **37**, 325 (1987).

[10] In addition to the statistical error, the first error includes possible distortions of the polynomial background shape due to photons from the decay chain $\Upsilon(3S)\to\Upsilon(2S)X$, $\Upsilon(2S)\to\gamma\chi_b$, and uncertainties from the variation of the relative energy resolution expectation used in the fit. The overall scale error includes uncertainties in photon detection efficiency, the hadronic-event-selection efficiency, and

the integrated luminosity.

[11] R. McClary and N. Byers, Phys. Rev. D **28**, 1692 (1983).

[12] P. Moxhay and J. L. Rosner, Phys. Rev. D **28**, 1132 (1983).

[13] H. Grotch, D. A. Owen, and K. J. Sebastian, Phys. Rev. D **30**, 1924 (1984).

[14] F. Daghighian and D. Silverman, Phys. Rev. D **36**, 3401 (1987).

[15] Particle Data Group, J. J. Hernández *et al.*, Phys. Lett. B **239**, 1 (1990).

[16] H. Ito, Prog. Theor. Phys. **74**, 1092 (1985).

[17] S. Stone, in *Proceedings of the Third Regular Meeting of the Division of Particles and Fields of the APS, Salt Lake City, January 1987,* edited by C. DeTar and J. Ball (World Scientific, Singapore, 1987).

[18] C. O. Dib, F. J. Gilman, and P. J. Franzini, Phys. Rev. D **37**, 735 (1988); this reference also provides a summary of various theoretical predictions for R_χ.

[19] L. P. Fulcher, Phys. Rev. D **37**, 1258 (1988); S. N. Gupta *et al.*, Phys. Rev. D **39**, 974 (1989).