Observation of the Lowest P-Wave $b\bar{b}$ Bound States

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In a continuing study of the spectroscopy of the $b\bar{b}$ bound quark systems the discovery of the lowest P-wave bound states by observation of photons from the decays $2^3S_1(b\bar{b}) \to \gamma + 1^3P_J(b\bar{b})$ and $1^3P_J(b\bar{b}) \to \gamma + 1^3S_1(b\bar{b})$ is reported. The photons are observed as narrow enhancements in the inclusive photon spectrum from Υ' decays. The center of gravity of the ^3P_J states (χ_b), the fine-structure splitting, and the branching ratios for the two transitions are given.

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The interpretation of the Υ vector mesons as bound $^3S_1$ states of a $b\bar{b}$ quark pair results in the prediction of other states, in particular ^3P_J $b\bar{b}$ states (χ_b). These states can be reached via electric dipole ($E1$) transitions from the Υ's. We have recently reported the observation of the 2^3P_1 $b\bar{b}$ state from a sample of 38 000 Υ'' decays and measured a branching ratio (BR) of 35% for $\Upsilon(3S) \to \gamma + 2^3P_J$.[1,2] The decay $\Upsilon(2S) \to \gamma + 1^3P_J$ is more difficult to observe because the BR for $E1$ transitions of the $\Upsilon(2S)$ is expected to be smaller from scaling arguments while the decay $\Upsilon(2S) \to 2\pi^0 + \Upsilon(1S)$ with a BR of 10%[3] is an additional background.

In the period of our present run the Cornell Electron Storage Ring (CESR) delivered an integrated luminosity of 30 pb^{-1} at the north area, where the Columbia University–Stony Brook detector (CUSB) is located. CUSB is a segmented electromagnetic calorimeter, consisting mostly of NaI crystals and Pb-glass blocks, with high efficiency for hadronic e^+e^- annihilations (~80%) and photon showers (~13%). During our run we collected 230 000 hadronic events at the Υ' peak of which 153 000 are resonance decays. We also collected 4 400 hadronic events in the continuum and 12 900 events at the Υ peak of which 10 700 are resonance decays. The methods used to identify photons and to obtain the overall photon recovery efficiency and the energy resolution are similar to those of Ref. 1. The only differences are as follows: (i) The inactive material in the NaI array was reduced by removing the four "strip chambers" between its layers (~1.5 g/cm^2). This slightly improves the resolution for low-energy photons. (ii) The efficiency for finding hadronic events was increased by ~30%. (iii) The photon search code was tightened, resulting in a uniform efficiency of 0.13 between 80 and 500 MeV, with a resolution $\sigma/E = 3.6\%/E^{1/4}$, E in gigaelectronvolts. Both efficiency and resolution are obtained by Monte Carlo (MC) calculations as in Ref. 1 and experimentally verified (Ref. 1 and see below). The energy scale for photons is established by continuously calibrating the NaI crystals with 0.66-, 1.17-, and 1.33-MeV γ lines from radioactive sources while taking data, and MC calculations of the energy loss in inactive materials. The Pb-glass is calibrated with Bhabha scattering events and

MC calculations of shower development. Finally a precision determination of the energy scale is obtained from a sample of events of the type $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^0\pi^0 \rightarrow 4\gamma + e^+e^-$ or $\mu^+\mu^-$.[4] In this way we obtain that our energy scale is low by (2.0 ± 0.7)% and all energies have therefore been corrected by a factor 1.02. These events also prove the correctness of the MC resolution calculations.

The inclusive photon spectrum obtained at the $\Upsilon(2S)$ peak is shown in Fig. 1(a). Some structure is visible around 125 MeV, which is not present in the spectra from Υ decays and continuum events from the present run and in the larger Υ and continuum samples of Ref. 1. Figure 1(b) shows for comparison the spectrum from a reanalysis of the Υ'' data[1] with the present methods, where the photon signal from the Υ'' appears at lower energy and no structure is visible around 400 MeV.

In order to extract the signals in the 125-MeV region we fitted the photon spectrum in the region 65–280 MeV with a cubic polynominal plus three Gaussians of free position and area and fixed width $\sigma/E = 6\%$. The value of χ^2 for this fit is 22.6 for 21 degrees of freedom. The cubic polynominal is required to match polynomial fits to the remainder of the photon spectrum, with two bins around 430 MeV (where a signal is expected and observed) excluded. This fit, excluding the contributions of the three Gaussians, is shown as the solid line in Fig. 1(a); the corresponding fit for the $\Upsilon(3S)$ case is shown in Fig. 1(b), from which results in good agreement with Ref. 1 are obtained. This procedure properly accommodates photons from $\pi^0\pi^0$ decays of the $\Upsilon(2S)$. The difference between the measured spectrum and the fit is shown in Fig. 2(a). The prominent features of the spectrum in Fig. 2(a) are a broad signal with structure in the 90–160 MeV region (3110 ± 323 counts) and a statistically significant narrow peak (833 ± 166 counts) at ~427 MeV. This peak has an rms spread of (4.5 ± 0.4)%, in excellent agreement with the MC calculation of 4.4%, again confirming the correctness of the computed resolution. This peak is also consistent with the merging of two lines at 442 and 422 MeV, with a ~1.2% Doppler broadening. The results of the fit described above are that the enhancement is due to three photon lines smeared by our resolution, centered at ~108, 128, and 149 MeV. These three lines and the one at 427 MeV are shown in Fig. 2(b). Fits with only the cubic polynomial give confidence levels of ~10^{-4} while fits with two lines give two equivalent solutions, both at <1% confidence levels, with peak positions at ~105, 125 or 125, 145 MeV, for $0.04 < \sigma/E < 0.1$.

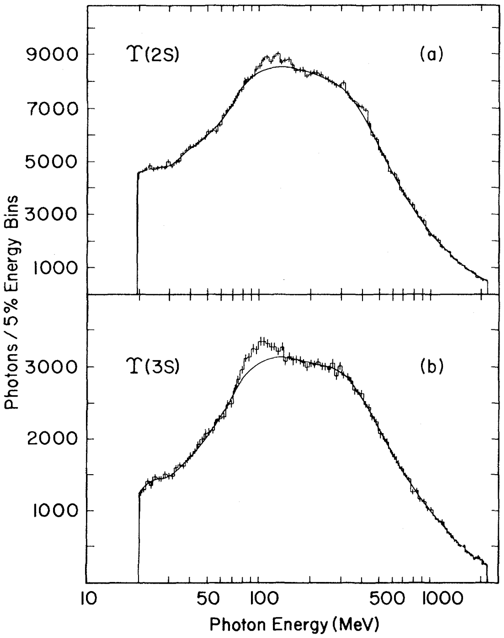

FIG. 1. The observed inclusive photon spectrum (a) at the $\Upsilon(2S)$ from 153 000 resonance decays and 77 000 continuum hadronic events; (b) at the $\Upsilon(3S)$ from 48 000 resonance decays and 38 000 continuum hadronic events. See text for continuous lines.

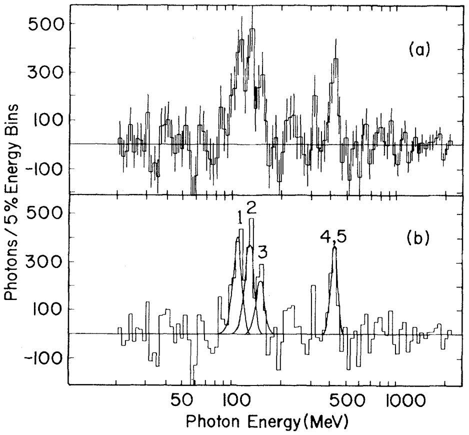

FIG. 2. (a) The subtracted photon signal at the $\Upsilon(2S)$, as described in the text. (b) Fit with four Gaussians of $\sigma/E = 3.6\%/E^{1/4}$, E in gigaelectronvolts, to the subtracted spectrum. The numbers identify the photon lines as defined in Fig. 3.

If we assume that the photon signals observed

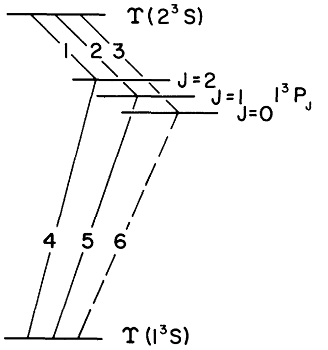

FIG. 3. Schematic level diagram indicating the $E1$ photon transitions between $\Upsilon(2S)$, 1^3P_J, and $\Upsilon(1S)$.

correspond to $\Upsilon(2S) \to \gamma_1 + X$, followed by $X \to \gamma_2 + \Upsilon(1S)$, then we expect that the sum $E_{\gamma 1} + E_{\gamma 2} + E_{\text{recoil}}$ is equal to $M(\Upsilon') - M(\Upsilon)$. If X is identified with the three 1^3P_J states, as we will argue later, it is expected (and observed in the exclusive channels[4]) that the products of BR's for the decays $\Upsilon(2S) \to \gamma + 1^3P_J$ and $1^3P_J \to \gamma + \Upsilon(1S)$ are in the ratio of 2:5:~0 for $J = 2$, 1, and 0, respectively, and that the three observed lines at 108, 128, and 149 MeV correspond to decays to $J = 2$, 1, and 0 states, respectively, while the 427-MeV line is due to decays of the $J = 2, 1$ states. The energy sum rule above gives $(108 \times 2 + 128 \times 5)/7 + 427 + 10.5 = 560$ MeV (10.5 MeV is the total recoil energy), to be compared with the Υ'-Υ mass difference of 560.8 ± 0.4 MeV.[5] From the excess photons observed in the 90–160 MeV region we obtain $R(\Upsilon(2S) \to \gamma + {}^3P_J) = (15.5 \pm 2.5)\%$ (+5%, −2.5% estimated systematic uncertainty due to the fitting procedure) and for the 427-MeV signal $R(\Upsilon(2S) \to \gamma + {}^3P) \times R({}^3P \to \gamma + \Upsilon(1S)) = (4 \pm 1)\%$, confirming that the low-energy photons are from the parent $\Upsilon(2S)$ state and the high-energy photons are from subsequent decays. From a study of exclusive channels we find (3.6 ± 0.9)% for the same product of BR's.[4] The 1^3P_J center of gravity (COG) is 9900 ± 3 MeV, in excellent agreement with potential model predictions.[6,7] A level diagram is shown in Fig. 3. (Line 6 is expected to be suppressed.[8]) The partial widths for $E1$ transitions are proportional to $k^3(2J+1)$, where k is the photon momentum. Table I gives the measured line energies and the BR's and reduced widths for the first three lines, the last obtained by dividing by the $k^3(2J+1)$ factor and normalizing to 1 for the middle line. The experimental results are in good agreement with the assumption of $E1$ transitions and with results from the exclusive-channels search.[4] Combining the exclusive BR measurements with the present results we obtain the entries in Table I for the decays from the 1^3P_J states to the $\Upsilon(1S)$.

The results presented above for the 1^3P_J states are summarized in Table II together with those for the 2^3P_J and theoretical predictions from potential models.[6,7] The partial widths for $E1$ transitions are obtained using our BR's and the best value for $R(\Upsilon \to \mu\mu)$ of (2.8 ± 0.3)%.[9] The agreement between theory and experiments is excellent both for the ${}^3P$ COG's and the partial widths for $E1$ transitions. The position of the 1^3P_J COG is in disagreement however with QCD sum-rule calculations.[10] With respect to the fine structure our results expressed in terms of

$$r = [M(J=2) - M(J=1)]/[M(J=1) - M(J=0)]$$

are $r(1P) = 0.93 \pm 0.1(\pm 0.2)$ and $r(2P) = 0.85 \pm 0.1$ (±0.3), where the errors in parentheses are an estimate of the uncertainties due to the fitting procedure. Theoretical predictions range from 0.45 to 1.1 for $1P$ and 0.5 to 1.0 for $2P$.[7] Our results at present do not allow us to draw conclu-

TABLE I. Photon energies, BR's, and reduced widths for the four observed lines as described in the text and illustrated in Fig. 3.

Line	Energy (MeV)	$\Upsilon' \to \gamma_i + 1^3P$ BR (%)	Reduced width	$1^3P \to \gamma_i + \Upsilon$ BR (%)
1	$108.2 \pm 0.3(\pm 2)$[a]	6.1 ± 1.4	1.04 ± 0.3	
2	$128.1 \pm 0.4(\pm 3)$	5.9 ± 1.4	1	
3	$149.4 \pm 0.7(\pm 5)$	3.5 ± 1.4	1.13 ± 0.5	
4	$427.0 \pm 1.0(\pm 8)$[b]			20 ± 5
5				47 ± 18
1 + 2 + 3		$15.5 \pm 2.5\,(^{+5}_{-2})$		

[a] Errors in parentheses are estimates of systematic uncertainties.
[b] Observed average of lines 4 and 5.

TABLE II. Comparison of experimental results with potential model calculations (Refs. 6 and 7). See the text for the derivation of experimental partial widths.

	Experiment		Calculations	
State	COG (MeV)	Γ_{E1}[a] (keV)	COG (MeV)	Γ_{E1}[b] (keV)
1^3P_J	9900 ± 3	4.9 ± 1.0	9888–9924	3.1–4.4
2^3P_J	10256 ± 5	8.4 ± 1.4	10242–10271	4.8–7.6

[a] Systematic errors not included.

[b] Computed from measured photon energies.

sions with respect to the different assumptions used by various authors.

The results for the BR's for $1^3P_{2,1} \to \gamma + \Upsilon(1S)$ are also in agreement with potential model calculations[8] in conjunction with the two-gluon widths of the $J = 2, 0$ states computed from the formulas of Barbieri *et al.*,[11] which give $R(1^3P_2 \to \gamma\Upsilon(1S)) = (15 \pm 4)\%$ and $R(1^3P_1 \to \gamma\Upsilon(1S)) = (40 \pm 10)\%$.

In conclusion, the present results, together with our results of Refs. 1, 2, and 4, give a fairly complete picture of the triplet P-wave $b\bar{b}$ states. Most $E1$ transitions between these states and the upsilons have been observed. The fine structure of the 1^3P_J states is almost resolved in this experiment while it could only be inferred in the case of the 2^3P_J states. The agreement with theory is excellent in the context of nonrelativistic potential models.

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[1] K. Han *et al.*, Phys. Rev. Lett. 49, 1612 (1982).

[2] G. Eigen *et al.*, Phys. Rev. Lett. 49, 1616 (1982).

[3] G. Mageras *et al.*, Phys. Rev. Lett. 46, 1115 (1981); J. Mueller *et al.*, Phys. Rev. Lett. 46, 1181 (1981).

[4] F. Pauss *et al.*, Cornell University Report No. CUSB 02-83, 1983 (to be published).

[5] A. S. Artamonov *et al.*, J. Phys. (Paris), Colloq. 43, C3-789 (1982), report the value 9459.7 ± 0.6 MeV for the Υ mass. For a compilation of the other Υ masses in this scale, see P. Franzini and J. Lee-Franzini, Annu. Rev. Nucl. Part. Sci. 33, 1 (1983).

[6] W. Buchmüller and S.-H. H. Tye, Phys. Rev. D 24, 132 (1981); E. Eichten *et al.*, Phys. Rev. D 21, 203 (1980); K. H. Krasemann and S. Ono, Nucl. Phys. B154, 283 (1979); A. Martin, Phys. Lett. 93B, 338 (1980), and 100B, 511 (1981); C. Quigg and J. L. Rosner, Phys. Rev. D 23, 2625 (1981).

[7] W. Buchmüller, in *New Flavours: Proceedings of the Second Moriond Workshop, Les Arcs Savoie, France, January 1982*, edited by J. Tran Than Van and L. Montanet (Editions Frontieres, Gif-sur-Yvette, France, 1982), p. 91; E. Eichten and F. Feinberg, Phys. Rev. D 23, 2724 (1981); S. N. Gupta *et al.*, Phys. Rev. D 26, 3305 (1982); A. Khare, Phys. Lett. 93B, 385 (1981); K. H. Krasemann, CERN Report No. TH-3036, 1981 (unpublished); R. McClary and N. Byers, University of California, Los Angeles Report No. UCLA-82-TEP-12, 1982 (to be published); P. Moxhay and J. L. Rosner, Enrico Fermi Institute Report No. 83-15, 1983 (to be published).

[8] Y. P. Kuang and T. M. Yan, Phys. Rev. D 24, 1874 (1981); P. Moxhay and J. L. Rosner, private communication, and Ref. 6.

[9] D. Andrews *et al.*, Phys. Rev. Lett. 50, 807 (1983); we use the value of this paper, averaged with the previous measurements quoted therein.

[10] M. B. Voloshin, Moscow Institute of Theoretical Experimental Physics Report No. ITEP-21, 1980 (to be published); R. Bertlmann, CERN Report No. TH-3192, 1981 (to be published).

[11] R. Barbieri, R. Gatto, and R. Kögerler, Phys. Lett. 60B, 183 (1976); R. Barbieri, R. Gatto, and E. Remiddi, Phys. Lett. 61B, 465 (1976).