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

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The existence of P-wave $b\bar{b}$ bound states χ_b' is demonstrated by observation of photons from the transition $\Upsilon'' \to \gamma + \chi_b'$ in the inclusive photon spectrum from Υ'' decays. The center of gravity of the observed photon energies is 98 MeV and the branching ratio for the transition of the Υ'' to the χ_b' states is $(34 \pm 3)\%$ (statistical).

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The discovery[1] of the J/ψ and its explanation by Appelquist and Politzer as the bound state of a charmed quark and antiquark[2] opened a new field of experimental and theoretical physics, the spectroscopy of heavy "quarkonia."[3] The discovery of four Υ states[4-6] has further enriched this field by the addition of a fifth quark, the b quark, of mass ~ 5 GeV. In typical quarkonium potentials the bound $b\bar{b}$ quarks are considerably less relativistic than the lighter $c\bar{c}$ quarks and the $b\bar{b}$ states are therefore more amenable to calculations by nonrelativistic potential methods.[7,8] In any model of quark-antiquark bound systems one expects the existence of singlet and triplet S-wave, P-wave, etc., states. Most of these states have been found in "charmonium."[9] Only triplet S states are typically produced in e^+e^- annihilations. Other states can be reached via electromagnetic or hadronic transitions.

We report in the following the first evidence for the existence of P-wave $b\bar{b}$ states, obtained from the observation of a strong, quasimonochromatic photon signal in Υ'' decays. We interpret this signal as being due to the electric dipole ($E1$) radiative transition $3^3S_1(b\bar{b}) \to \gamma + 2^3P_J(b\bar{b})$ because (i) the large observed branching ratio is in good agreement with calculations for the above transition and incompatible with a two- or more-step decay, (ii) the observation of $\Upsilon'' \to \gamma\gamma\Upsilon'$ and $\Upsilon'' \to \gamma\gamma\Upsilon$ establishes that the observed signal is due to direct Υ'' decay (see following Letter), (iii) the relative intensities of the three lines are consistent with transitions to a triplet P state, and (iv) the good agreement between measured photon energy and potential-model calculations is evidence for transitions to the first excited P-wave state, 2^3P_J or χ_b'. After discussing the evidence for the photon signal we will therefore analyze our results in terms of $E1$ transitions to $2^3P_J(b\bar{b})$ and compare our results with theoretical calculations.

During a run of ~ 14 pb^{-1} at the Cornell Electron Storage Ring, the Columbia University–Stony Brook detector (described in Refs. 6 and 10) collected 64 689 hadronic events at the Υ'' peak, of which 37 298 are resonance decays. In addition we have collected 40 491 events at the Υ peak of which 34 674 are resonance decays, and 31 486 continuum events around the Υ''. We present in the following the search for photons in hadronic events and the determination of energy resolution and efficiency for photon recovery.

The central part of the detector covers about 60% of 4π sr in 32 azimuthal sectors each divided into two polar halves and six radial layers; fiducial cuts in azimuth reduce this to 48% of 4π sr. The efficiency for finding photons is low because of the high multiplicity of Υ'' decays, typically eight charged particles and eight photons from four π^0's, with an average of 11.5 clusters per hadronic event observed in the central detector. These high multiplicities result in overlaps between two-photon showers or between shower and charged particle. The segmentation of the detector allows construction of transverse and longitudinal shape criteria, which are used to identify photons and to reduce overlaps. Determination of the photon-finding–code efficiency, described below, gives an overall efficiency for 100-MeV photons due to solid angle and reconstruction of ~ 17% and an energy resolution for the reconstructed photons of ~ 8.5% (rms).

Figure 1(a) shows the inclusive photon spectrum observed at the Υ'' peak, and Figs. 1(b) and 1(c) show the spectra in the continuum and at the Υ, respectively. An obvious excess around 100 MeV is observed in the Υ'' spectrum. The Υ and continuum spectra can be combined to produce an estimate of the photon spectrum for the Υ'' in the absence of $E1$ lines. In a previous study of

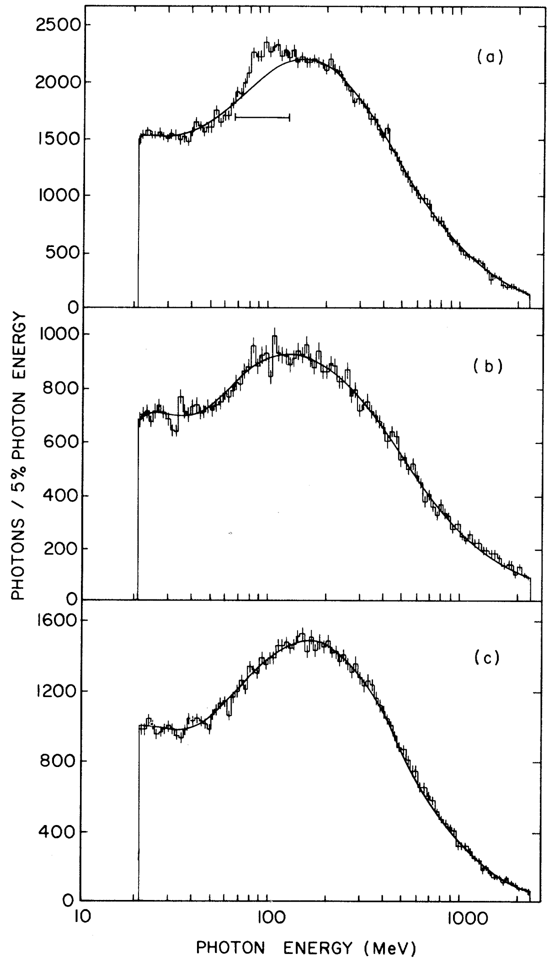

FIG. 1. The observed inclusive photon spectrum from (a) Υ'' region, (b) continuum, and (c) Υ region. The bin size is 5% in $\Delta E/E$. The region excluded in the polynomial fit is indicated by the horizontal line in (a) (see text).

the thrust distribution[11] of the three Υ's and the continuum we have shown that the observed thrust distribution for Υ'' is well reproduced by a linear combination of the distributions for Υ and continuum. This thrust analysis gave in fact the first evidence for $E1$ transitions.[11] The same combination of Υ and continuum photon spectra, normalized by event count, is the predicted Υ'' photon spectrum. The curve shown in Fig. 1(a) is constructed by these means from the polynomial fits to the data shown in Figs. 1(b) and 1(c). The agreement is very good except around 100 MeV, where we observe an excess of about 2200 photons above a background of 37 500 counts in the region indicated in Fig. 1(a) (69 to 130 MeV). The signal is slightly larger than 11 standard deviations.

Having established the statistical significance of the signal we prefer to obtain the net $E1$ signal in a model-independent way, by fitting the background in the Υ'' spectrum itself. A fit of a ninth degree polynomial (10 parameters) to the entire Υ'' photon spectrum gives a χ^2 of 148 for 86 degrees of freedom corresponding to a confidence level of $\sim 6\times10^{-5}$, where most of the contribution comes from a region around the 100-MeV enhancement. Excluding from the fit a region of thirteen bins around the enhancement lowers χ^2 to 77 for 73 degrees of freedom, resulting in a net excess of 2150 counts, in good agreement with the previous result. The subtracted photon spectrum is shown in Fig. 2(a). This method of subtraction is extremely stable versus changes of the excluded region. The subtracted signal shows a very steep rise and fall compared to its width of ~ 45 MeV. In general one expects the triplet P-wave states to show a fine-structure splitting which has been estimated to be in the range of 30 to 60 MeV.[12] The shape of the observed enhancement is inconsistent with its being due to a single line; however, the three possible lines are not resolved.

The intensity and position of the three lines can be obtained from knowledge of the photon energy resolution function. We obtain the resolution function by Monte Carlo (MC) methods and confirm its correctness by reconstructing π^0's. Photon showers generated using the electron-gamma shower MC code are randomly superimposed on hadronic events which are then processed through the same photon-finding code. Fluctuations in the energy lost (15% on average at 100 MeV) in inactive material dominate our resolution around 100 MeV. Using the same fitting procedure we obtain the photon energy resolution, shown in Fig. 2(b), and the overall recovery efficiency. We note that this method is slightly pessimistic since a little extra energy is added to the events (3.3% on average). The validity of this procedure has been checked by studying π^0's. The diphoton mass spectrum for hadronic events shows a clean π^0 signal, due largely to photons in the 50- to 300-MeV range. The same MC program has been used to generate photons from π^0 decays which again have been added to real events. The excellent agreement of the mass spectra for real and MC π^0's confirms our ability to obtain correctly the photon energy resolution function. The position of the π^0 peak requires a correction of $\sim 3\%$ upwards of the energy calibra-

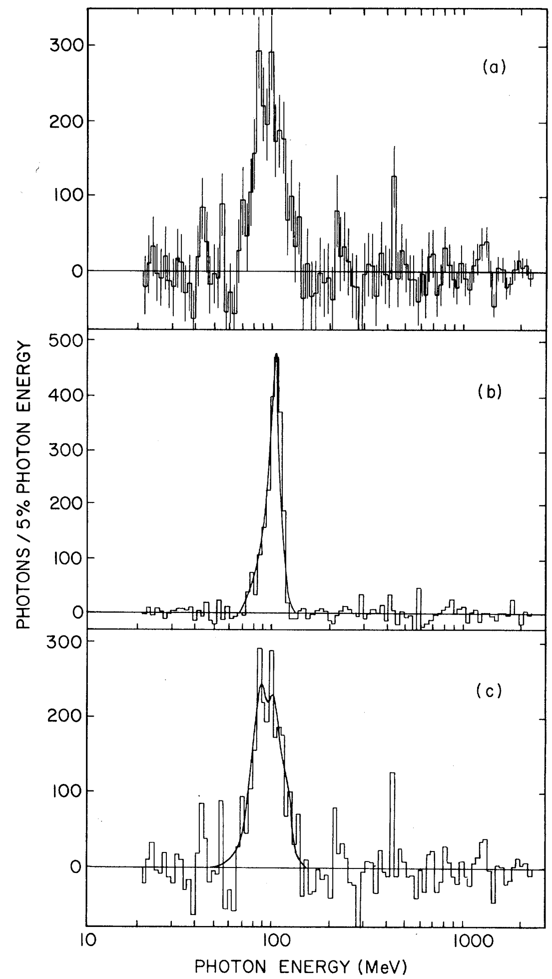

FIG. 2. (a) The subtracted photon signal for $\Upsilon'' \to \chi_b' + \gamma$, as described in the text. (b) The experimental photon energy resolution function. The continuous line is a fit with two Gaussians of widths 6.7% and 12.5% of the peak position, the wider Gaussian displaced down by 10% and contributing 35% to the total area. (b) Fit of three lines to the subtracted photon spectrum; see text.

tion obtained from radioactive sources and the MC study of photon recovery.

Using the resolution function thus obtained we fit the subtracted photon spectrum to three lines of arbitrary intensity and position. The result of the fit, which gives a χ^2 of 16.0 for 14 degrees of freedom, is shown in Fig. 2(c). A fit with two lines is worse and a fit with only one line has a confidence level of less than 10^{-5}. Table I gives the results of the three-line fit and Table II those for the two-line fit. The fine-structure splittings obtained from the three-line fit are 15 and 18 MeV. The center of gravity of the signal is 98

TABLE I. Results of a fit of the subtracted photon signal with three lines.

Final state	Photon energy (MeV)	$\Gamma/k^3(2j+1)$ (norm. to $^3P_1$)
$^3P_2$	84.4 ± 2.0	0.95 ± 0.3
$^3P_1$	99.5 ± 3.2	1.0
$^3P_0$	117.2 ± 5.0	1.03 ± 0.5
Center of gravity	$= 97.7 \pm 1.0$ MeV	$\chi^2 = 16.0$ for 14 d.o.f.[a]

[a]Degrees of freedom.

TABLE II. Results of a fit with only two lines.

Line	Photon energy (MeV)	Γ (norm. to line 2)
1	86.3 ± 1.2	1.0 ± 0.2
2	105.7 ± 1.5	1.0
Center of gravity	$= 96.3 \pm 1.0$ MeV	$\chi^2 = 23.7$ for 16 d.o.f.[a]

[a]Degrees of freedom.

MeV computed from the measured energies and 93 MeV computed from the fitted line positions with $2j+1$ weights. This last value is in good agreement with calculations of the 3^3S-2^3P splitting in Refs. 8, 14, and 15 which give respectively 84, 100, and 100 MeV. Table I gives the intensities of the three lines divided by the factor $k^3(2j+1)$ appropriate to $E1$ transitions (k is the photon momentum) and arbitrarily normalized to 1.0 for the middle line. The equalities of the normalized intensities is evidence that we observe transition to P-wave states. We wish to emphasize that there are strong correlations between positions and intensities of the various lines which are not reflected in the diagonal errors given in the tables; we estimate an additional systematic error of about 4 MeV for the fine-structure splittings.

From the recovery efficiency, the number of Υ'' events above continuum, and the observed excess we obtain a branching ratio for $3^3S \rightarrow 2^3P$ $E1$ transitions of 0.34 ± 0.03 with an estimated systematic uncertainty of 0.03. Combining this result with the values of the leptonic width of the Υ'' and of $B_{\mu\mu}$,[16] and the hadronic cascade branching ratio,[17] we can compute the partial width for $E1$ transitions for which we obtain $\Gamma(E1) = 6.5 \pm 0.8$ keV, with an additional systematic uncertainty of 0.6 keV. This value is in good agreement with calculations in Refs. 8, 14, and 15 which give, respectively, 6, 6.2, and 7 keV for the $E1$ rate of $3^3S \rightarrow 2^3P$, with $k = 93$ MeV, as given above.

In conclusion, we have demonstrated the existence of bound P-wave states in the Υ family, in particular the first excited ^3P states. In addition we have measured their center of gravity, the fine-structure splitting (under the assumption that we observe all three lines), and the partial width for $E1$ transitions, which appears to agree better with potential model calculations in the Υ family than for the ψ case.[18] These results are in excellent agreement with the evidence for the existence of the χ_b' mesons obtained from the study of exclusive channels as reported in the following Letter.

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Evidence for $\chi_b{}'$ Production in the Exclusive Reaction $\Upsilon'' \to \gamma\chi_b{}' \to (\gamma\gamma\Upsilon' \text{ or } \gamma\gamma\Upsilon)$

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Evidence is presented for the production of $\chi_b{}'$ states ($2\,{}^3P$) in the reaction $\Upsilon''\to\gamma\chi_b{}'\to\gamma\gamma\Upsilon'$ (or $\gamma\gamma\Upsilon$) with subsequent decay of the Υ' (Υ) into e^+e^- or $\mu^+\mu^-$. The data were obtained with the nonmagnetic CUSB detector at the Cornell e^+e^- storage ring. Observed were 14 (15) events consistent with the transition to the Υ' (Υ) with an estimated background of 1.7 (1.3) events. The lower-energy photons cluster around 100 MeV, implying $M(\Upsilon'')-M(\chi_b{}')\sim 100$ MeV. A single-line interpretation of the lower-energy photon spectrum is disfavored.

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In the preceding paper[1] we present evidence for $E1$ transitions from Υ'' to $2\,{}^3P$ $b\bar{b}$ ($\chi_b{}'$) states. These states can subsequently decay by a second $E1$ transition into lower lying ${}^3S$ states. We present the results of a search for such double transitions using the reactions $e^+e^-\to\Upsilon''\to\gamma\gamma\Upsilon'$ and $e^+e^-\to\Upsilon''\to\gamma\gamma\Upsilon$ with the Υ' (Υ) decaying into an e^+e^- or $\mu^+\mu^-$ pair.

The data were obtained with the CUSB detector[1] at the Cornell Electron Storage Ring. Electron and photon energies are measured in the central detector (CD) calorimeter covering $\sim 60\%$ of 4π and also in two end caps of 84 NaI crystals each, giving a total solid-angle coverage of $\sim 90\%$ of 4π sr. The relevant trigger conditions for $ee\gamma\gamma$ events are >900 MeV energy deposited in the outer three layers of NaI in the CD, or >1.5 GeV in each end cap and >50 MeV in the CD. Scintillation counters were recently added outside the CD, allowing us to trigger on muon pairs, operational

