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

G. Eigen, G. Blanar,[a] H. Dietl, E. Lorenz, F. Pauss, and H. Vogel
Max-Planck-Institut für Physik, D-8000 Munich 40, Federal Republic of Germany

and

T. Böhringer,[b] P. Franzini, K. Han, G. Mageras, D. Peterson, E. Rice, and J. K. Yoh[c]
Columbia University, New York, New York 10027

and

S. W. Herb
Cornell University, Ithaca, New York 14853

and

J. E. Horstkotte, C. Klopfenstein, J. Lee-Franzini, R. D. Schamberger, M. Sivertz, L. J. Spencer, and P. M. Tuts
The State University of New York at Stony Brook, Stony Brook, New York 11794

and

R. Imlay, G. Levman, W. Metcalf, and V. Sreedhar
Louisiana State University, Baton Rouge, Louisiana 70803

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Evidence is presented for the production of χ_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 $2\,^3P$ $b\bar{b}$ (χ_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 for 80% of the data-taking period. The trigger required a coincidence of opposite muon counters and at least 100 MeV deposited in the CD. The solid-angle acceptance is 32% of 4π sr with ~ 60% backed up by a muon filter consisting of drift chambers and 80 cm of iron.

Tracking information in the CD is provided by four planes of cathode-readout proportional chambers, each with two views. The total material traversed by a photon in the beam pipe and chambers is about 0.06 radiation length. Information on the position of γ showers is obtained from the shower centroid in the NaI and/or lead glass and from three layers of proportional chambers interleaved between the NaI layers of the CD.

The energy resolution for photons in the CD was calculated as a function of energy by means of the electron-gamma shower Monte Carlo (MC) code[2] accounting for intrinsic NaI and lead-glass resolution, inactive material, and geometry. The result is $\sigma(E)/E \sim 3.9\%/E^{0.25}$ (E in gigaelectronvolts), and reproduces both our Bhabha event resolution and the distribution of reconstructed π^0's.[1]

The energy calibration of the calorimeter was obtained by use of ^{137}Cs and ^{60}Co sources mounted on each crystal. Any change in the calibration by more than 2% was automatically corrected. A MC-derived correction factor (1.15 at 100 MeV weakly energy dependent) was used to compensate for inactive material. Bhabha events were used as a cross check at 5 GeV.

The data correspond to integrated luminosities of 14.2 pb^{-1} at the Υ'' and 4.4 pb^{-1} in the continuum around the Υ''. We observe 37 300 hadronic Υ'' decays which correspond to 55 700 produced Υ''.

Candidates were first selected by a computer scan. The events were required to have either a Bhabha-like electron pair or a muon pair, i.e., a pair of nearly collinear tracks showing no nuclear interaction in the NaI or lead glass, and penetrating the muon filter if pointing to it (11 out of the 18 events). In addition ≥ 2 γ-shower candidates of at least 7 MeV were required. These events were then hand scanned for two and only two clean γ showers together with the electron or muon pair. Finally we required (1) acollinearity of the electron (muon) pair less than 17° (15°), (2) a minimum γ energy of 50 MeV, (3) a summed energy between 150 and 1200 MeV for the two γ showers, and (4) shower centroids at least 23° (10°) away from the electron (muon) tracks. In order to reduce background from double-bremsstrahlung processes at least one γ had to be more than 45° away from the electrons.

The analysis presented here includes the following categories of events: (1) both electrons and both γ's in the CD, (ii) both electrons in the end caps and both γ's in the CD, and (iii) muons in the muon trigger sector and at least one γ in the CD. Because of limited statistics, we computed acceptances assuming that the γ's are produced isotropically in the laboratory frame which is a good approximation within our solid angle.[3] A $1+\cos^2\theta$ distribution is used for the lepton pair from Υ' or Υ decay. We obtain acceptances of 17% (12%) for events with final-state electrons (muons). The trigger efficiencies are > 99% and ~ 94%, respectively.

For the $\gamma\gamma ee$ events all kinematic quantities are measured. These events are subjected to a kinematic [four-constraint (4C)] fit. The reconstructed invariant e^+e^- mass is shown in Fig. 1. The resolution is dominated by the electron energy measurement and not identical to the one in Fig. 2(b). The pronounced peaks at the Υ and Υ' mass clearly establish the existence of double radiative transitions.[4] Figures 2(a) and 2(b) show scatter plots of the raw data of the higher-energy γ versus the lower-energy γ for the muon and the electron samples. The regions for the transitions to the Υ or Υ' are indicated as solid lines, including Doppler broadening. The dotted lines indicate $\pm 2\sigma$ bands of our energy resolution.

The data cluster around 100 MeV for the lower-energy γ and around 230 and 770 MeV for the higher-energy γ, in both the muon- and electron-pair samples. The natural explanation is that these events result from radiative cascade decays with intermediate χ_b' production, $\Upsilon'' \to \gamma\chi_b' \to \gamma\gamma\Upsilon'$ or $\Upsilon'' \to \gamma\chi_b' \to \gamma\gamma\Upsilon$. From the observation of γ's of about 100 MeV in the transition to both the Υ and the Υ' we unambiguously determine the

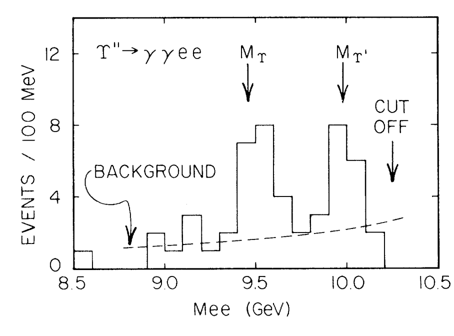

FIG. 1. Invariant e^+e^- mass from $\gamma\gamma e^+e^-$ events.

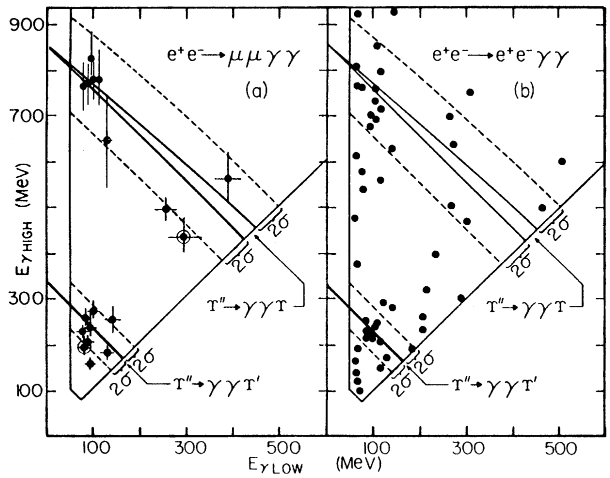

FIG. 2. Scatter plot of the lower vs the higher-energy photon, (a) from $\Upsilon'' \rightarrow \gamma\gamma\mu\mu$, (b) from $\Upsilon'' \rightarrow \gamma\gamma ee$. The two circled data points denote events with the higher-energy γ in a detector region of slightly degraded energy resolution.

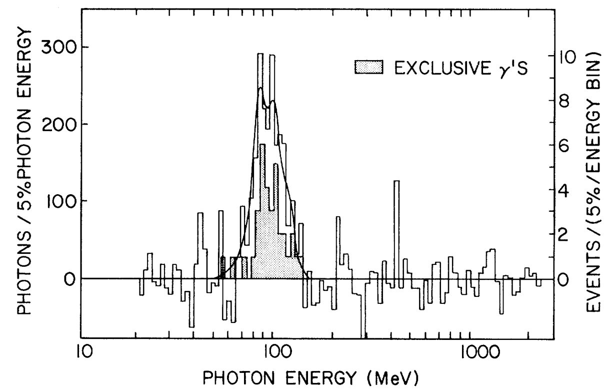

FIG. 3. Comparison of unconstrained exclusive γ spectrum for 50 MeV $< E_{\gamma \mathrm{low}} <$ 170 MeV (shaded area) with inclusive γ spectrum after background subtraction.

χ_b' masses to be approximately 100 MeV below the Υ'' mass. In Fig. 3 the exclusive spectrum of the low-energy γ's inside the 2σ bands is superimposed on the background-subtracted inclusive γ spectrum from Ref. 1. Both spectra peak around 100 MeV and strengthen the evidence for the existence of P-wave $b\bar{b}$ bound states.

Two different background processes may contaminate the $\gamma\gamma\mu\mu$ sample. The reaction $e^+e^- \rightarrow \tau^+\tau^- \rightarrow (\mu\nu\bar{\nu})(\rho\nu) \rightarrow \mu\pi\gamma\gamma$ can result in events with one genuine muon, two γ's, and a charged pion misidentified as a muon. From a MC simulation we predict 1 ± 1 background events in the entire data sample of Fig. 2(a). As a cross check we search for $\gamma\gamma\mu\mu$ candidates in the continuum data. No event was found. Another background source is the reaction $\Upsilon'' \rightarrow \pi^0\pi^0\Upsilon'(\Upsilon) \rightarrow \gamma\gamma\gamma\gamma\mu\mu$, where two out of the four γ's go undetected. From our measured branching ratios for hadronic $\pi^+\pi^-$ transitions,[5] we expect 1 ± 1 event in the entire scatter plot. Therefore within the 2σ bands the $\Upsilon'' \rightarrow \gamma\gamma\mu\mu$ sample is basically background free.

The dominant background in the $\gamma\gamma ee$ sample results from double-bremsstrahlung Bhabha events. This QED background peaks at the tip of the scatter plot and along the 50-MeV boundary because of the steep energy dependence ($\sim 1/E$ for each photon). The background inside the 2σ bands of Fig. 2(b) has been estimated by (i) extrapolation from the 2σ–4σ bands with the assumption of a smooth behavior, (ii) analysis of continuum data with the same scanning criteria, where data were averaged over the 6σ bands to compensate for the luminosity ratio, and (iii) simulation of double-bremsstrahlung events from 5000 single radiative Bhabha events. Assuming the validity of the soft-photon approximation, we randomly combined two single radiative Bhabha events and analyzed them with the above criteria. This method predicts 21 background events outside the 2σ bands of Fig. 2(b) versus 24 observed and 9 versus 10 in the continuum sample. The analysis results in the following background estimate:

	In $\pm 2\sigma$ band		In $\pm 2\sigma$ band and $70 < E_{\mathrm{low}} < 130$ MeV	
	$\Upsilon'' \rightarrow \Upsilon'\gamma\gamma$	$\Upsilon'' \rightarrow \Upsilon\gamma\gamma$	$\Upsilon'' \rightarrow \Upsilon'\gamma\gamma$	$\Upsilon'' \rightarrow \Upsilon\gamma\gamma$
(i)	4 ± 2	6 ± 2.5	2 ± 1.5	1 ± 1
(ii)	4 ± 2	4 ± 2	1.7 ± 0.9	1.7 ± 0.9
(iii)	3 ± 0.8	2 ± 0.5	1.4 ± 0.4	1 ± 0.3

Method (i) slightly overestimates the background because of spillover of genuine events into the 2σ–4σ bands.

In order to estimate the position of the χ_b' levels the data inside the 2σ bands from the $\gamma\gamma\mu\mu$ and $\gamma\gamma ee$ sample have been combined. In Fig. 4 we show the energy spectrum for the lower-energy γ after the $\gamma\gamma$ energy sum has been constrained to the appropriate mass differences corrected for recoil (326

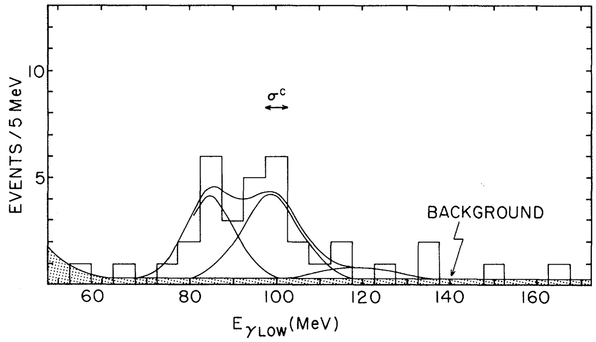

FIG. 4. The lower-energy photon spectrum from a constrained $\gamma\gamma$ fit for $\Upsilon'' \to \gamma\gamma ee$ and $\Upsilon'' \to \gamma\gamma\mu\mu$. The estimated background is shown as shaded area. σ^c denotes the resolution.

or 858 MeV), weighting the individual energies according to the resolution. Constraining the $\gamma\gamma$ energy reduces possible small errors in the absolute energy scale to ≤ 2 MeV and improves the resolution by about 10%. Three lines, corresponding to $J = 0, 1, 2$, are expected for the χ_b' states (2^3P_J) with a total splitting between 30 and 60 MeV.[6] We do not observe a distinctive line splitting. This can be explained either by the splitting being < 35 MeV or by at least one of the lines being suppressed in the cascade decay. A fit with a single line broadened by the resolution of 6.5% yields a low confidence level of $< 3\%$ and a mass of 94 ± 2 MeV. It is predicted[7] that the cascade transition rates via the $2\,^3P_0$ state to Υ' and Υ are much smaller than those via $2\,^3P_1$ and $2\,^3P_2$. Cutting at $E_\gamma < 114$ MeV and fitting for two Gaussians of $\sigma = 6.5\%$ gives $E_2 = 84 \pm 3$ MeV and $E_1 = 99 \pm 2$ MeV. Attributing the three events above 114 MeV to the $2\,^3P_0$ state gives $E_0 = 119 \pm 5$ MeV. The confidence level for this three-line description, shown in Fig. 4, is 45%. The statistical errors given are diagonal and do not include position/area coupling between adjacent peaks.

The total number of $\gamma\gamma\mu\mu$ and $\gamma\gamma ee$ events observed within the area of $\pm 2\sigma$ and $70 < E_{\rm low} < 130$ MeV is 14 (15) for the transition via χ_b' to the Υ' (Υ). The corresponding total numbers of background events are 1.7 and 1.3, respectively. Taking into account all corrections and using the muonic branching ratios[8] of Υ' and Υ, we derive the following sums of product branching ratios for intermediate χ_b' production:

$$\sum_{i=1}^{3} R(\Upsilon'' \to \gamma_i \chi_{bi}')R(\chi_{bi}' \to \gamma\Upsilon') = (5.9 \pm 2.1)\%,$$

$$\sum_{i=1}^{3} R(\Upsilon'' \to \gamma_i \chi_{bi}')R(\chi_{bi}' \to \gamma\Upsilon) = (3.6 \pm 1.2)\%,$$

In the region $(E_{\rm low}, E_{\rm high}) \sim (400, 500)$ MeV in Figs. 2(a) and 2(b) which corresponds to the transition via the χ_b ($1\,^3P$) to the Υ, we see eight events while 3.3 background events are expected. From this, we give an upper limit

$$\sum_{i=1}^{3} R(\Upsilon'' \to \gamma_i \chi_{bi})R(\chi_{bi} \to \gamma\Upsilon) < 3\%$$

(90% confidence level).

In conclusion, we have observed evidence for χ_b' production in the exclusive channels $\Upsilon'' \to \gamma\chi_b' \to \gamma\gamma(\Upsilon'$ or $\Upsilon)$, with Υ' (Υ) decaying into a $\mu^+\mu^-$ or e^+e^- pair. Both the χ_b' mass and the transition rates are in qualitative agreement with theoretical calculations.[6,7] The present statistics do not allow an unambiguous determination of the fine splitting.

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[a]Present address: LeCroy Corp., Spring Valley, N.Y. 10977.

[b]Present address: CERN, CH-1211 Geneva, Switzerland.

[c]Present address: Fermi National Accelerator Laboratory, Batavia, Ill. 60510.

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