# Observation of New Structure in the $e^+e^-$ Cross Section above the $\Upsilon(4S)$

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Measurements of the $e^+e^-$ cross section above $B\bar{B}$ threshold are reported. Structures are observed which could be the $\Upsilon(5S)$ and $\Upsilon(6S)$ resonances. The masses and widths are given and compared with various potential-model predictions. Average charged multiplicities and inclusive lepton yields are also presented.

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Quarkonium potential models[1] have been successful in predicting the mass splittings and relative yields of the bound $q\bar{q}$ states in the $\Psi$ and $\Upsilon$ systems. However, above open flavor thresholds the theories have not done as well. This is due to the unknown couplings of the many channels that become available once the threshold is crossed. In the $\Upsilon$ system all that is known up to now is that the mass of the first unbound state, the $\Upsilon(4S)$,[2] is lower than that predicted by most models.[1]

We report here on the results of a scan above the $\Upsilon(4S)$ and the discovery of new structure in the total hadronic cross section. The data were obtained from the CLEO magnetic detector operating at the Cornell

 

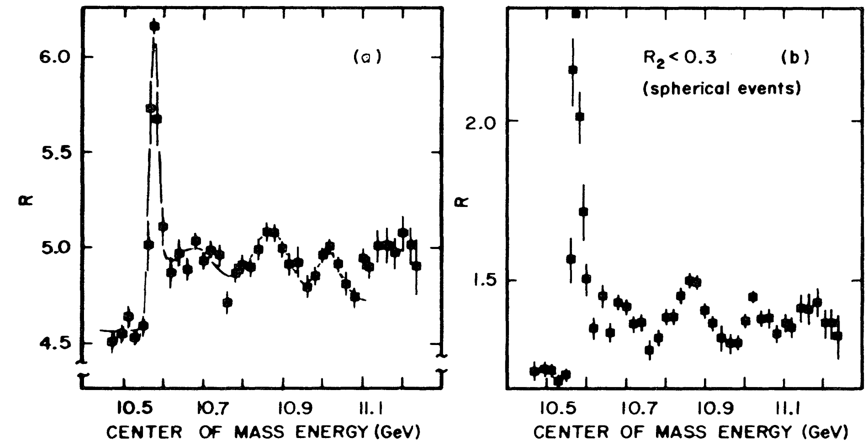


FIG. 1. The corrected $R$ ($\sigma_{had}/\sigma_{\mu\mu}$) vs center-of-mass energy for (a) all events and (b) events with the Fox-Wolfram variable $R_2 < 0.3$. The curve is a fit by four radiative Gaussians.

Electron Storage Ring (CESR). We acquired an integrated luminosity of 40.6 $pb^{-1}$ on the $\Upsilon(4S)$, 19.2 $pb^{-1}$ below the resonance, and 70 $pb^{-1}$ above the $\Upsilon(4S)$ from a center-of-mass energy of 10.6 to 11.2 GeV.

Details of the detector[3] and the hadronic selection[4] criteria have been presented elsewhere. Briefly, we define as hadronic those events with three or more charged tracks which form a vertex near the nominal $e^+e^-$ collision point. The event must also deposit at least 30% of the center-of-mass energy in the detector as either charged or neutral particles. Contamination due to beam-gas events ($<1\%$) is estimated by measuring the number of events outside the beam intersection region. Backgrounds from $\tau^+\tau^-$ production (5%) and two-photon processes (3%) are calculated from Monte Carlo studies.

The detection efficiency for hadronic events is determined by Monte Carlo procedures.[4] We find an average efficiency of $(80 \pm 2)\%$ for two-jet events and $(91 \pm 2)\%$ for $B\bar{B}$ events, where the error is determined by varying the parameters of the Monte Carlo within reasonable bounds.

Figure 1(a) shows our measurement of $R$, the ratio of the total hadronic cross section to the theoretical muon-pair cross section. Backgrounds have been subtracted though, because of the complicated structures observed, radiative effects have not been unfolded. The errors are statistical only; we estimate a systematic uncertainty of 6% in the overall level though the point-to-point systematic error is less than 1%. The energy scale has been determined by recent precise measurements of the $\Upsilon(1S)$ mass.[5] We have corrected for our hadronic detection efficiency by extrapolating the continuum cross section points below the $\Upsilon(4S)$ to the region above it and using our two-jet efficiency for this level. We then corrected the excess in the cross section above this extrapolation by using our $B\bar{B}$ detection efficiency.

Figure 1(b) shows a similar plot with an added cut on the Fox-Wolfram variable[6] $R_2 < 0.3$. This suppresses the less spherical continuum two-jet events. In both plots, besides the obvious $\Upsilon(4S)$,[2] there are clear enhancements around 10.85 and 11.0 GeV. There is also a visible step between the continuum points below the $\Upsilon(4S)$ and the average level above the resonance. These data are in good agreement with those of Lovelock *et al.*[7]

While the quarkonium potential models give predictions for the masses and $e^+e^-$ couplings of the next two excited states, the $\Upsilon(5S)$ and $\Upsilon(6S)$, the coupled-channels models[8] also predict a rich structure

TABLE I. The parameters of the four radiative Gaussians shown in Fig. 1(a). The first is the $\Upsilon(4S)$, the second is a possible threshold effect or $b\bar{b}g$ state, and the last two are identified with the $\Upsilon(5S)$ and $\Upsilon(6S)$ resonances.

| Mass (GeV) | $\Gamma$ (MeV) | $\Gamma_{ee}$ (keV) |
|---|---|---|
| $10.5775 \pm 0.0007 \pm 0.004$ | $20 \pm 2 \pm 4$ | $0.192 \pm 0.007 \pm 0.038$ |
| $10.684 \pm 0.010 \pm 0.008$ | $131 \pm 27 \pm 23$ | $0.20 \pm 0.05 \pm 0.10$ |
| $10.868 \pm 0.006 \pm 0.005$ | $112 \pm 17 \pm 23$ | $0.22 \pm 0.05 \pm 0.07$ |
| $11.019 \pm 0.005 \pm 0.007$ | $61 \pm 13 \pm 22$ | $0.095 \pm 0.03 \pm 0.035$ |

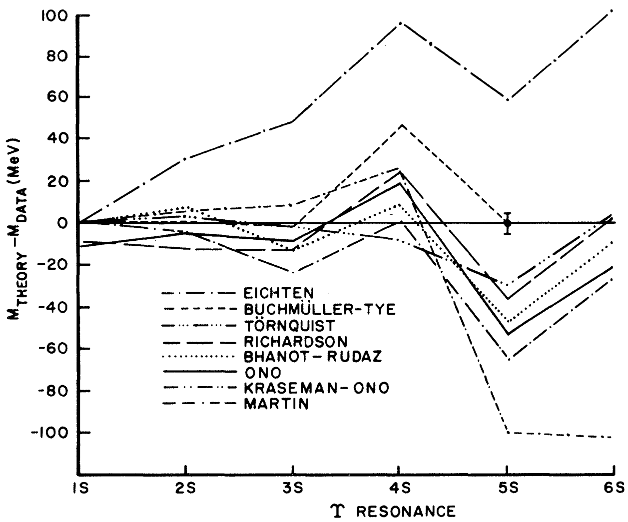


FIG. 2. The difference between the theoretical predictions from Refs. 1 and 8 for the Υ masses and the measured values. The error bar shows the typical experimental uncertainty.

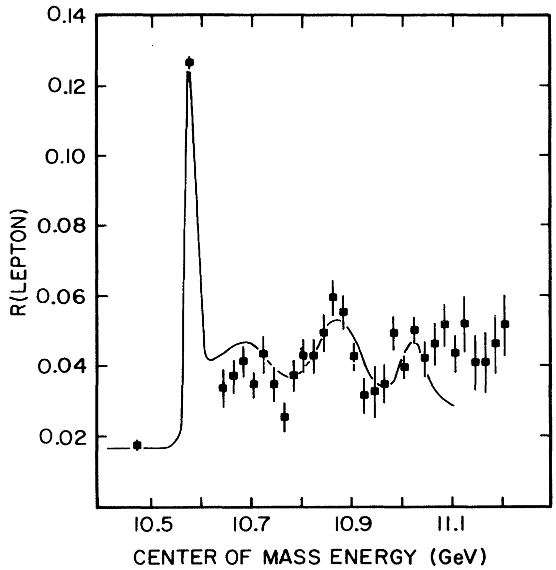


FIG. 3. The visible $R$ for inclusive lepton production vs center-of-mass energy. A cut on the Fox-Wolfram variable $R_2 < 0.3$ has been made. The curve is the same as in Fig. 1(a) normalized to the height of the Υ(4$S$).

in the total cross section due to the turn-on of various exclusive states—e.g., $B\bar{B}$, $B^*\bar{B}$, etc. This complication makes it difficult to identify resonances above $B\bar{B}$ threshold or extract information about them. To parametrize our data, we have fitted the Υ(4$S$) and the structures at higher energy using Gaussians[9] with radiative tails[10] and a single step in $R$.

Recently there has been theoretical interest in the region above the Υ(4$S$) near 10.7 GeV as a place for a possible $b\bar{b}g$ state.[11] We do see structure in this region, but again it is difficult to differentiate between a resonance and a threshold effect.[8] To parametrize the structure, we have also fitted this region using a radiative Gaussian.

Near 11.1 GeV we see a sharp rise in the total cross section and then a leveling off. This could be due to multibody $b\bar{b}$ production, e.g., $B\bar{B}\pi$, etc., or to the production of $P$-wave $B$ mesons.[12] We have not included this region in our fit. The curve in Fig. 1(a) shows the fit to the data.

The resonance parameters derived from the fit are given in Table I, corrected for our detection efficiency on the assumption that the resonances decay to $B\bar{B}$. The second error in the fit parameters is the systematic uncertainty. It is found by varying the binning, the hadronic cuts, and the background shape. We have calculated the partial width to electrons using the standard formula $\Gamma_{ee} = (M^2/6\pi^2)\int \sigma_{\rm had}\, dE$.[13] The results are in essential agreement with those of Lovelock *et al.*[7]; the differences reflect only the dependence on the assumptions made in fitting the two similar data samples.

The two highest-energy structures are near the masses predicted for the Υ(5$S$) and Υ(6$S$). In Fig. 2 we plot the difference between the theoretical predictions[1,8] and the experimental masses assuming that these are indeed the Υ(5$S$) and Υ(6$S$). None of the models correctly predicts both the Υ(5$S$) and Υ(6$S$) masses.

If these structures are unbound $b\bar{b}$ states, they should show evidence of the $b$ quark decay. One example is the production of high-momentum leptons from the $b$ semileptonic decays. Our procedures for detecting leptons have been described before.[14] Figure 3 shows the cross section for lepton production where we have also cut on $R_2 < 0.3$. There is an excess at the same energies as the resonances in the total hadronic cross section. We have superimposed the fit to the total cross section from Fig. 1(a) on the lepton data, normalizing to the height of the Υ(4$S$). A comparison between the data and the curve shows that the decay products of the new structures have the same semileptonic branching ratio within errors as those of the Υ(4$S$).[15]

Other characteristics of $b$-quark decay are a higher charged multiplicity,[16] and a more spherical event shape,[2] than for continuum events. Figures 4(a) and 4(b) show the average charged multiplicity and $1-\langle R_2\rangle$ (which will rise for more spherical events) versus center-of-mass energy. No corrections have been made for detector acceptance. The Υ(4$S$) is clearly visible in both plots, while in Fig. 4(b) there is also evidence for the Υ(5$S$) and Υ(6$S$) resonances.

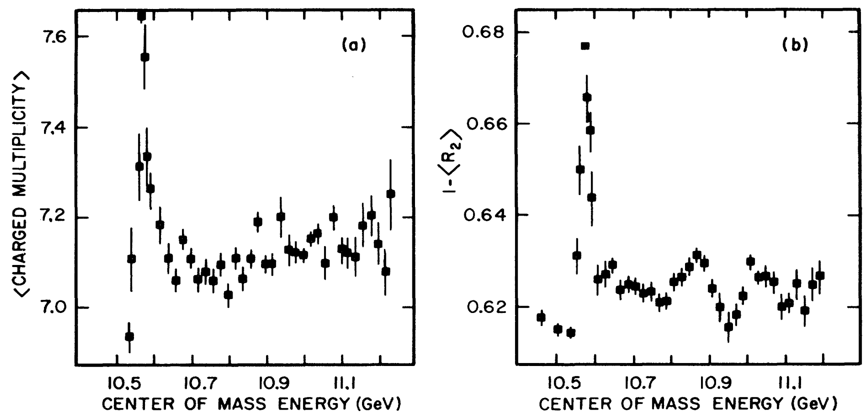


FIG. 4. (a) The average observed charged multiplicity and (b) $1-\langle R_2\rangle$ vs center-of-mass energy.

In both figures there is a clear difference between the levels of the points above the $\Upsilon(4S)$ and the continuum points below the $\Upsilon(4S)$, giving further evidence that a threshold has been crossed.

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