Masses, Widths, and Leptonic Widths of the Higher Upsilon Resonances

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The masses, total widths, and leptonic widths of three triplet *s*-wave $b\bar{b}$ states $\Upsilon(4S)$, $\Upsilon(5S)$, and $\Upsilon(6S)$ are determined from measurements of the e^+e^- annihilation cross section into hadrons for $10.55 < W < 11.25$ GeV. The resonances are identified from potential model results and their properties are obtained with the help of a simplified coupled-channels calculation. We find $M(4S) = 10.577$ GeV, $\Gamma(4S) = 25$ MeV, $\Gamma_{ee}(4S) = 0.28$ keV; $M(5S) = 10.845$ GeV, $\Gamma(5S) = 110$ MeV, $\Gamma_{ee}(5S) = 0.37$ keV; $M(6S) = 11.02$ GeV, $\Gamma(6S) = 90$ MeV, $\Gamma_{ee}(6S) = 0.16$ keV.

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We report new measurements of the e^+e^- annihilation cross section into hadrons, performed between July 1983 and 1984, when Cornell Electron Storage Ring delivered 123 pb^{-1} of integrated luminosity in the energy region $10.60 < W < 11.25$ GeV. The fourth Υ, $\Upsilon(4S)$ of mass 10.577 GeV, has a width of ≈ 20 MeV, indicating that it lies above the *b*-flavor threshold. Its resonance shape, however, was not well known.[1] Two or three additional triplet S states ($n = 5, 6, 7$) are expected to exist, in the energy region studied, with mass spacings of the order of 200 MeV.[2] Some data were also collected on the continuum below the $\Upsilon(4S)$ and at the $\Upsilon(4S)$ peak showing very good consistency with larger previous data sets.

Figure 1(a) shows R_{vis} versus W, where vis stands for visible, i.e., uncorrected for detection efficiency, as observed with the Columbia University–Stony Brook (CUSB) detector, where R is defined as $\sigma(e^+e^- \to \mathrm{hadrons})/\sigma_{\mu\mu}$. CUSB is a purely calorimetric detector, composed of NaI crystals and Pb glass blocks, with excellent hadron identification and energy resolution. Details of detector, trigger, and hadronic criteria can be found elsewhere.[3,4] Hadronic final states from resonance decays have lower thrust than continuum events, especially for resonances above threshold which decay into pairs of B mesons. Figure 1(b) shows R_{vis} for the same data after applying a thrust cut[5] which retains 70% of the resonance events and 34% of the continuum events. Both figures show complex and very similar structure of approximately the same magnitude, thus proving that the excess hadronic yield above the $\Upsilon(4S)$ is due to resonance decays. Table I gives a summary of the data. The features in R are reflected in the fractional yields of resonant events versus W. These yields are obtained

TABLE I. Summary of data.

Region (GeV)	$\int L\,dt$ (nb^{-1})	Hadronic events	Resonant events	Resonant fraction
10.44 – 10.54	3141	5699	0	0.000
10.54 – 10.60	6057	10893	3169	0.225
10.60 – 10.67	8828	15717	1127	0.067
10.67 – 10.73	15154	26681	2122	0.074
10.73 – 10.77	6909	12049	561	0.045
10.77 – 10.83	12896	22271	1833	0.076
10.83 – 10.93	25374	43185	4600	0.096
10.93 – 10.99	7616	12765	502	0.038
10.99 – 11.06	25284	41939	3761	0.082
11.06 – 11.25	21073	31283	2940	0.079

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by subtracting the value of R_{vis} below the flavor threshold.[4] The hadronic-event efficiencies are 69% and 58%, respectively, for resonance decays and continuum events. Both efficiencies are constant to better than 1% throughout the energy range studied.

$R(W)$ above threshold has a rather complicated behavior. A shoulder is present on the tail of the $\Upsilon(4S)$ of approximately 0.2 in R. A "large" peak is observed at ≈ 10.9 GeV, preceded and followed by flat regions and dips. Just above 11.0 GeV a second peak is possibly present and finally R appears to level out at a value of $R_{vis} \approx 2.5$. This behavior of R, from below the $\Upsilon(4S)$ to 11.25 GeV, cannot be fitted with three Gaussian (or Breit-Wigner) functions, corresponding to the $4S$ and the expected $5S$ and $6S$ $b\bar{b}$ states. The very gross features of our data can be accomodated by four Gaussians corresponding to two resolved resonances, the shoulder of the $4S$, and part of the cross section above 10.05 GeV. However, the confidence level ($\chi^2 = 158$ for 46 degrees of freedom) of such a fit is very poor and there is no physical explanation for the shoulder of the $4S$ nor the rise in cross section at high W. A good fit ($\chi^2 = 44.6$ for 46 degrees of freedom) to the data can be obtained with seven radiatively corrected[6] Gaussians plus a smooth step in R, as suggested by the data and required by the presence of six thresholds and the decay-amplitude zeros, as explained later. The results of this fit are given in Table II. When the appropriate Gaussians are added as indicated in the table, the effective leptonic widths obtained are in agreement with the results of Besson *et al.*[7]

The observed structure of the cross section is predicted by the coupled-channels model.[8,9] Eichten has applied this model to the Υ family and calculated the decay amplitudes of the first four Υ's.[10] We have used a simplified version of the coupled-channels model of Eichten *et al.*,[8] to identify the origin of the various components in the cross section observed in the region from $W = 10.55$ to $W = 11.05$ GeV. We assume that four triplet S-wave states ($4S$, $5S$, $6S$, $7S$) decay mostly into the six two-body channels: $B\bar{B}$, $B\bar{B}^* + B^*\bar{B}$, $B^*\bar{B}^*$, $B_s\bar{B}_s$, $B_s\bar{B}_s^* + B_s^*\bar{B}_s$ and $B_s^*\bar{B}_s^*$, where B^*'s are excited B's and B_s's are bound $(b\bar{s})$ states. This assumption becomes inadequate at energies where decay channels such as $B\bar{B} + n\pi$ become important. We account for them by a smooth step in R as in the previous fit. The decay amplitudes of the resonances in momentum space and the wave functions at the origin, $\psi_{nS}(0)$, are extrapolated from Refs. 10 and 8, respectively. No S-D mixing is assumed and the relative contributions from $B\bar{B}$, $B\bar{B}^*$, and $B^*\bar{B}^*$ are weighted by statistical factors.[11] The mass of the B has been measured to be 5.2725 GeV.[12] The masses of B^*'s and B_s's are obtained from $M(B^*) - M(B) = 55$ MeV, $M(B_s) - M(B) = 103$ MeV, and $M(B_s^*) - M(B_s) = 50$ MeV.[13] These values are in agreement with simple scaling arguments. Masses and total widths of the resonances were varied as allowed

TABLE II. Seven-Gaussian fit results.

Gaussian	Mass[a] (GeV)	Γ[a] (MeV)	Γ_{ee} (keV)
1	10.579 ± 0.001	25 ± 2.6	0.185 ± 0.024
2	10.63	82	0.114 ± 0.016
3	10.70	61	0.083 ± 0.009
(2+3)			(0.197 ± 0.018)
4	10.79	61	0.102 ± 0.010
5	10.86	47	0.115 ± 0.009
6	10.91	59	0.076 ± 0.010
(4+5+6)			(0.293 ± 0.018)
7	11.02	66	0.113 ± 0.008

[a]The central positions and widths were fixed for Gaussians 2–7 because of the very large correlations between these parameters.

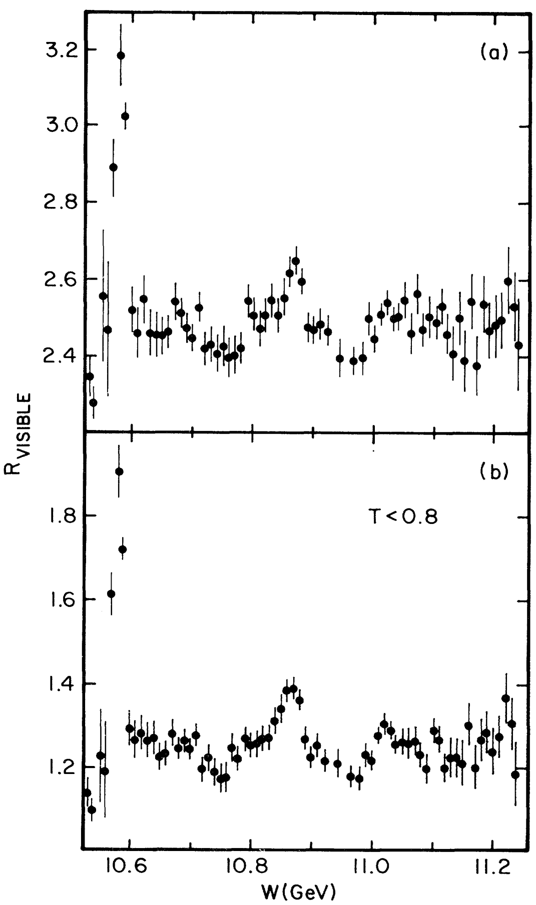

FIG. 1. (a) R_{vis} $\{\sigma(e^+e^- \rightarrow \text{hadrons})/\sigma_{\mu\mu}\}$ as a function of c.m. energy, W, as measured by CUSB. Note highly suppressed zero. (b) Same as (a) with thrust cut; see text for details.

by the data and within the range suggested by potential models. The following values were used. $\Upsilon(4S)$: $M=10.5774$ GeV, $\Gamma=25$ MeV; $\Upsilon(5S)$: $M=10.845$ GeV, $\Gamma=110$ MeV; $\Upsilon(6S)$: $M=11.02$ GeV, $\Gamma=90$ MeV; $\Upsilon(7S)$: $M=11.20$ GeV, $\Gamma=100$ MeV; step in R: $\Delta R=0.18$, turning on smoothly at 11.075 GeV. The computed contribution to R is corrected for finite machine-energy spread, radiative effects,[6] and detection efficiency.

The results of the calculation, show superimposed on the data in Fig. 2, reproduce the main features remarkably well (the excess cross section at $W\approx 10.7$ GeV may be due to D-wave states). The thrust-cut data of Fig. 1(b) are equally well described by this calculation. Table III gives the properties of the $\Upsilon(4S)$, $\Upsilon(5S)$, and $\Upsilon(6S)$. The quoted error on each parameter reflects the freedom in changes which can be tolerated by the comparison with the data. Figure 3(a) shows the contributions of the four resonances to the cross section for two-body final states. Most of the cross section in the energy region 10.7 to 10.95 GeV is due to the presence of the $\Upsilon(5S)$, while the $\Upsilon(7S)$ contributes practically nil. The complex structure seen is due to the radial nodes of the Υ's wave functions and the six two-body thresholds in an energy interval of ≈ 300 MeV. Similar complexity is obtained by Tornqvist, using a pair creation model.[9] The contributions from B mesons (solid curve) and strange B mesons (dashed curve) are shown in Fig. 3(b). The narrow peak at 10.8 GeV is mostly due to $B_s^*\bar{B}_s^*$ production. This could be verified experimentally, given enough statistics, by looking for increased strange-particle yield.

The relative population of ground-state B mesons to states containing one excited B, and to states containing two excited B's, in the energy region 10.73–10.93 GeV, is 0.19:0.32:0.49. For the assumed hyperfine splitting, excited B mesons decay via emission of an ≈ 50 MeV photon. From our calculation we expect a yield of 1.3 photons per resonant event in the $5S$ region. There is at present preliminary evidence for this.[14]

In conclusion, most of the structure seen in the energy interval between 10.75 and 10.95 GeV is due to the fifth $\Upsilon\ {}^3S_1$ state, $\Upsilon(5S)$. Its mass value is within 50 MeV of most predictions, for example, Ref. 10, and

TABLE III. Summary of resonance properties.

Resonance	Mass (GeV)	Γ (MeV)	Γ_{ee} (keV)
$\Upsilon(4S)$	10.5774 ± 0.001	25 ± 2.5	0.283 ± 0.037
$\Upsilon(5S)$	10.845 ± 0.020	110 ± 15	0.365 ± 0.070
$\Upsilon(6S)$	11.02 ± 0.03	90 ± 20	0.156 ± 0.040

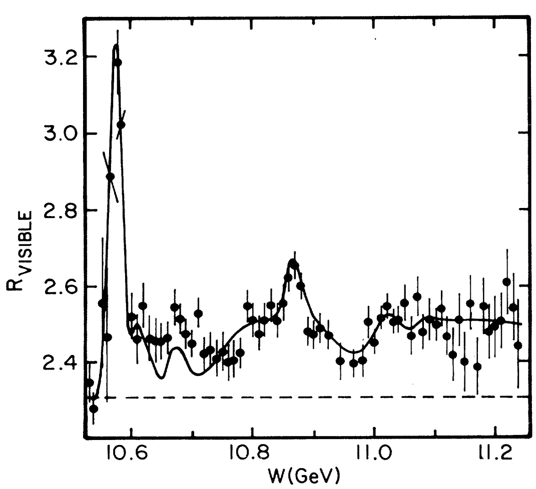

FIG. 2. Model calculation superimposed on data.

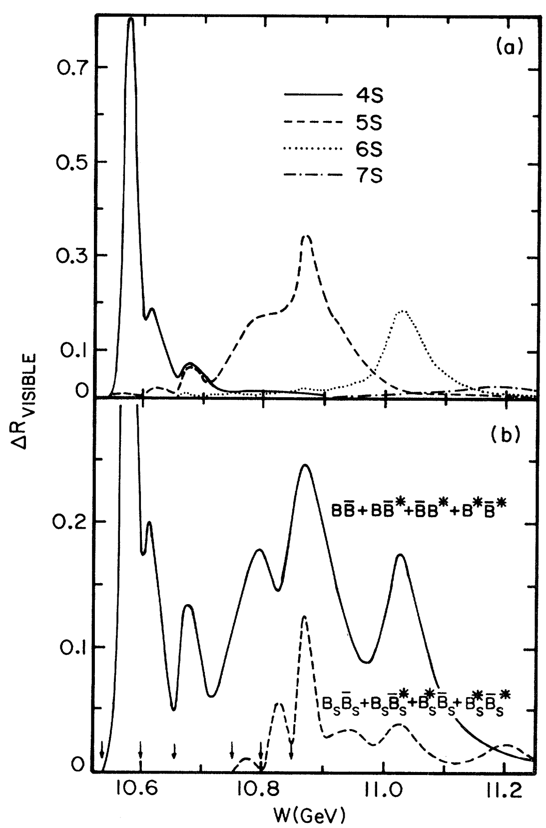

FIG. 3. (a) Contributions of the four Υ's to R, for two-body decays. (b) Contribution to R from B mesons (solid curve) and strange B mesons (dashed curve). Arrows indicate thresholds: $B\bar{B}$(10.545 GeV), $B\bar{B}^*$(10.600 GeV), $B^*\bar{B}^*$(10.655 GeV), $B_s\bar{B}_s$(10.751 GeV), $B_s\bar{B}_s^*$(10.801 GeV), $B_s^*\bar{B}_s^*$(10.851 GeV).

is within 5 MeV of a recent calculation.[9] Its large leptonic width (0.365 keV) indicates that it is coupled to many decay channels and that the simple relation between Γ_{ee} and $|\psi(0)|^2$ is considerably modified.[8] Similarly most of the cross section excess around 10.6 GeV is due to $\Upsilon(4S)$ decays into excited B's resulting in $\Gamma_{ee}(4S) \approx 280$ eV.

The identification of the next resonance as the sixth upsilon is more tenuous. From a theoretical standpoint one expects the next higher triplet state to be about 200 MeV above the $\Upsilon(5S)$. Experimentally, there is a relatively sharp rise in the cross section around 11 GeV. Both the empirical fit and the model calculation can accomodate its presence nicely. However, since it is located at an energy where multiparticle (rather than two-body) final states are expected to give sizable contributions, this interpretation is not unique. Perhaps the best way to state the situation is this: If the peak at 11.02 is the $\Upsilon(6S)$, its parameters are those given in Table III. Our findings for the higher Υ resonances are in substantial agreement with those of Besson *et al.*[7]

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