Measurement of the Leptonic Branching Ratios of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$

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Using the CLEO detector at the Cornell Electron Storage Ring, the authors have measured the leptonic branching fractions, $B_{\mu\mu}$, of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ to be $2.7 \pm 0.3 \pm 0.3\%$, $1.9 \pm 1.3 \pm 0.5\%$, and $3.3 \pm 1.3 \pm 0.7\%$, respectively. Combining these values of $B_{\mu\mu}$ with previous measurements of the leptonic widths of these resonances, the authors find the total widths of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ to be $48 \pm 4 \pm 4$, $27 \pm 17 \pm 6$, and $13 \pm 4 \pm 3$ keV.

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The J/ψ and upsilon particles provide a useful testing ground for the study of heavy-quark dynamics. Present theory interprets these resonances as quark-antiquark bound states. The large quark masses permit the use of nonrelativistic quantum mechanical approximations. The branching fraction into muons, $B_{\mu\mu}$, is particularly important since it measures the relative probability for the state to decay via a single photon as compared with decay channels involving gluons. Furthermore, by combining $B_{\mu\mu}$ with the integral of the production cross section across the resonance, one obtains a measurement of the total width of the resonance. Previous experiments have yielded measurements of $B_{\mu\mu}$ for the $\Upsilon(1S)$,[1] and a 90%-confidence-level upper limit for $B_{\mu\mu}$ of the $\Upsilon(2S)$.[2] This work presents a new measurement of $B_{\mu\mu}$ for the $\Upsilon(1S)$ and the first measurement of $B_{\mu\mu}$ for the $\Upsilon(2S)$ and $\Upsilon(3S)$.

The data were taken with the CLEO detector at the Cornell Electron Storage Ring (CESR). The elements of CLEO used in this analysis are described below. A more detailed description of CLEO can be found in Andrews *et al.*[3] The inner tracking detector consists of cylindrical proportional and drift chambers inside a solenoidal magnetic field of 1 m radius. The $\Upsilon(2S)$ data were taken with use of an aluminum coil which produced a 0.42-T field, while the data for the $\Upsilon(1S)$ and $\Upsilon(3S)$ were taken at 1.0 T with a superconducting coil. Outside the solenoid are eight identical octants each containing a time-of-flight system with twelve scintillation counters, followed by shower counters. The time-of-flight system forms a cylindrical array 2.3 m from the beam axis with resolution of 0.4 nsec (rms). The shower-counter system consists of 44 layers of proportional tubes alternated with lead (a total of 11.3 radiation lengths) and has energy resolution $\sigma(E)/E = 17\%/\sqrt{E}$ (E in gigaelectronvolts). The entire octant assembly is enclosed by an iron absorber of 0.5 to 1.0 m thickness. A system of planar drift chambers outside the absorber provides muon identification.

Data were taken at the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$, and in the continuum region above and below the $\Upsilon(3S)$. Because of the different operating conditions of the CLEO detector, the $\Upsilon(2S)$ data were analyzed with a different set of cuts than the $\Upsilon(1S)$ and $\Upsilon(3S)$ data. For the $\Upsilon(1S)$ and $\Upsilon(3S)$, events were classified as μ pairs if (a) there were two tracks in the drift chamber, each with a momentum greater than 58% of the beam energy; (b) less than 4 GeV of energy was deposited in the shower detector; (c) time-of-flight counters in opposite octants measured a time difference less than 5 nsec; and (d) at least one drift-chamber track pointed to orthogonal hit wires in the muon chambers. Cuts b and d eliminate Bhabha scattering events. Cut c reduces the number of cosmic-ray events, since a cosmic ray that traverses the detector and passes near the interaction region has a time difference of ~ 15 nsec. Cut a rejects low-multiplicity hadronic and τ events. Approximately 1000 events which passed the above cuts were scanned in order to estimate the remaining contamination in the μ-pair sample. The background is estimated to be 1% with the dominant source being cosmic-ray events (0.5%).

The $\Upsilon(2S)$ analysis retained cuts b and c but substituted for cuts a and d a strict collinearity cut on the two high-momentum tracks in the event. The noncollinearity angle of the tracks was measured with the shower chambers. The requirement on this angle varied with polar angle θ from less than 26 mrad at $\theta = 57°$ to less than 53 mrad at $\theta = 90°$. Both a physicist and a nonphysicist scanned events which satisfied the above criteria. They demanded that the events contain two high-momentum collinear nonshowering tracks which passed through the interaction region in both the front and side views of the detector. The background in this sample is less than 1%.

The visible μ-pair cross section for the two data sets is shown in Fig. 1. In order to determine $B_{\mu\mu}$ we first obtain $\overline{B}_{\mu\mu} = \Gamma_{ee}/\Gamma_h$, where Γ_h is the width for decay into hadronic final states. When e-μ-τ universality is assumed, we have $B_{\mu\mu} = \overline{B}_{\mu\mu}/(1+3\overline{B}_{\mu\mu})$. $\overline{B}_{\mu\mu}$ is calculated from

$$\overline{B}_{\mu\mu} = (N_R - \epsilon\sigma_{\rm QED}\mathcal{L} - N_F)/\sigma_R\mathcal{L}\epsilon A.$$

Here N_R, $\mathcal{L}$, $\sigma_{\rm QED}$, and σ_R refer respectively to the total number of μ pairs found on the resonance, the accumulated luminosity at the resonance, the nonresonant QED μ-pair cross section[4] at the resonance energy, and the hadronic cross section of the resonance. The factors A and N_F are discussed below.

In the above equation ϵ is the efficiency includ-

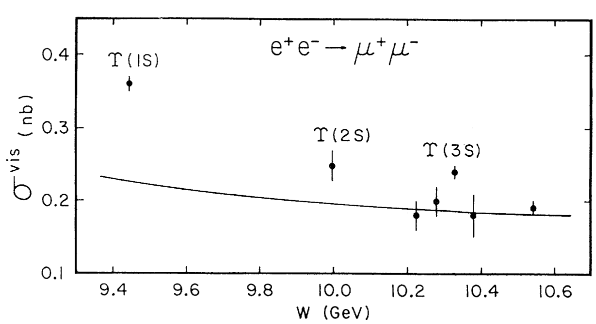

FIG. 1. The visible μ-pair cross section as a function of center-of-mass energy. The curve represents the nonresonant QED contribution to the cross section. The data points and curve are normalized to the $\Upsilon(3S)$ efficiency given in Table I.

ing geometric acceptance for detecting μ-pairs from the nonresonant background at the resonance. The value of ϵ, determined with use of the continuum data near the $\Upsilon(3S)$ or $\Upsilon(4S)$,[5] is just the ratio of detected μ pairs to the number of μ pairs expected from QED over the 4π solid angle. We have also calculated ϵ independently using a Monte Carlo simulation of the CLEO detector. The simulation included the resolution and efficiency of the drift chamber, muon chambers, time-of-flight counters, and shower-chamber system, as well as all geometrical effects but not the trigger efficiency. Events were generated according to the model of Berends and Kleiss, which includes higher-order radiative effects.[4] The trigger-efficiency contribution to ϵ was obtained from a sample of Bhabha events which had an independent trigger by virtue of depositing a large amount of energy in the shower chambers. Bhabha events in which either the positron or electron showed evidence of radiation in the material before the drift chamber (e.g., pair conversion in the beam pipe) were discarded for the efficiency calculation. We find that the two determinations of ϵ agree to within 10%.

The factor A in the above equation accounts for the fact that μ pairs produced by the decay of a narrow resonance tend to be more collinear than continuum μ pairs because of the absence of initial-state radiation. A was calculated by comparison of the acceptance of Monte Carlo μ pairs generated with and without radiative corrections. The large value of A for the $\Upsilon(2S)$ relative to the $\Upsilon(1S)$ and $\Upsilon(3S)$ is due to the tight collinearity cut imposed on the $\Upsilon(2S)$ data. This cut reduces the efficiency for detecting the continuum μ pairs more than the resonant μ pairs.

Finally, N_F is the contribution to the μ-pair sample from other decay modes of the resonance. For the $\Upsilon(1S)$, $N_F=0$. For the $\Upsilon(2S)$ and $\Upsilon(3S)$ the decay modes that result in a $\Upsilon(1S)$ or $\Upsilon(2S)$ in the final state can contribute if the daughter state decays into μ pairs. Using the calculations of Tye[6] for the various unmeasured decay modes and Refs. 1 and 7 for the measured decay modes of the $\Upsilon(2S)$ and $\Upsilon(3S)$, we obtain $N_F=4$ events for the $\Upsilon(2S)$,[8] and 30 events for the $\Upsilon(3S)$.[9] Neglecting this term in the calculation increases the value of $B_{\mu\mu}$ of the $\Upsilon(2S)$ by 12%. The corresponding increase for the $\Upsilon(3S)$ is 16%.

The result of this analysis is summarized in Table I. The systematic errors account for uncertainties in the luminosity, total hadronic cross section, and detector acceptance. The value for $B_{\mu\mu}$ of the $\Upsilon(1S)$ is in agreement with previous measurements and the world average of $3.3\pm0.5\%$.[1,10] Using the calculations of Mackenzie and Lepage[11] we can relate $B_{\mu\mu}$ of the $\Upsilon(1S)$ to the QCD scale parameter $\Lambda_{\overline{MS}}$. Doing so we obtain $\Lambda_{\overline{MS}}=0.12\pm0.02\pm0.02$ GeV. The measured branching ratios at the $\Upsilon(2S)$ and $\Upsilon(3S)$ are in agreement with theoretical estimates[12] of 2%. Combining the above values of $B_{\mu\mu}$, and our value of the modified leptonic widths[13] of the $\Upsilon(1S)$ ($\overline{\Gamma}_{ee}=1.17\pm0.05\pm0.08$ keV), $\Upsilon(2S)$ ($\overline{\Gamma}_{ee}=0.49\pm0.03\pm0.04$ keV), and $\Upsilon(3S)$ ($\overline{\Gamma}_{ee}=0.38\pm0.03\pm$ ±0.03 keV) from Plunkett,[14] we obtain the total widths listed in Table I.

The value of Γ_{tot} for the $\Upsilon(2S)$ allows the determination of the ratio $\Gamma(\Upsilon(2S)\to\Upsilon(1S)\pi\pi)/\Gamma(\psi'\to\psi\pi\pi)$. We use data from the reaction $\psi'\to\psi\pi\pi$,[15] our measurement of $B(\Upsilon(2S)\to\Upsilon(1S)\pi\pi)$,[1] and the value of $\Gamma_{tot}(2S)$. The result is $\Gamma(\Upsilon(2S)\to\Upsilon(1S)\pi\pi)/\Gamma(\psi'\to\psi\pi\pi)=0.071\pm0.046$. From the expected mass-scaling behavior of QCD dipole radiation[16] this ratio is predicted to be 0.11 for vector gluons and close to unity for scalar gluons.[17] Our result is incompatible with the prediction for scalar gluons, but is in agreement with the QCD prediction for vector gluons.

In conclusion we have measured $B_{\mu\mu}$ for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$. Using these values we have determined the total width of each resonance.

TABLE I. Summary of factors used to calculate $B_{\mu\mu}$ for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$. The first error is the statistical uncertainty and the second is the systematic uncertainty. The systematic errors on the luminosity ($\mathcal{L}$) and efficiency (ϵ) are 3.5% and 3.0%, respectively. The total systematic error is determined by combining the errors in quadrature.

	N_R	ϵ	$\mathcal{L}$ (nb^{-1})	σ_{QED} (nb)	σ_R (nb)	A	N_F	$B_{\mu\mu}$ (%)	Γ_{tot} (keV)
$\Upsilon(1S)$	1652	0.27 ± 0.01	3257	1.16	$21.5\pm0.2\pm0.8$	1.15 ± 0.02	0	$2.7\pm0.3\pm0.3$	$48\pm4\pm4$
$\Upsilon(2S)$	176	0.178 ± 0.013	780	1.04	$7.06\pm0.17\pm0.25$	1.37 ± 0.03	4	$1.9\pm1.3\pm0.5$	$27\pm17\pm6$
$\Upsilon(3S)$	1096	0.193 ± 0.011	4690	0.97	$4.81\pm0.07\pm0.18$	1.17 ± 0.03	30	$3.3\pm1.3\pm0.7$	$13\pm4\pm3$

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[8]For the $\Upsilon(2S)$ N_F is dominated by the cascade decay $\Upsilon(2S) \to \Upsilon(1S)\pi\pi$, $\Upsilon(1S) \to \mu\mu$. N_F is calculated as follows:

$$N_F = \sigma_{2S}\mathcal{L}B(\Upsilon(1S)\to\mu\mu)\epsilon_1\{\epsilon_2 B(\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-) + B(\Upsilon(2S)\to\Upsilon(1S)\pi^0\pi^0)\}.$$

Both $B(\Upsilon(1S)\to\mu^+\mu^-)$ $(3.3\pm0.5\%)$ and $B(\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-)$ $(19.1\pm3.1\%)$ are taken from Ref. 1. By isospin invariance $B(\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-) = 2B(\Upsilon(2S)\to\Upsilon(1S)\pi^0\pi^0)$. ϵ_1 (0.17) is the Monte Carlo calculated probability for the process $\Upsilon(2S)\to\Upsilon(1S)\pi\pi$ to be accepted as an event to be scanned. ϵ_2 (0.25) is the fraction of $\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-$ events that would pass the scan and be classified as a μ pair because neither charged pion would be visible in the drift chamber. The luminosity ($\mathcal{L}$) and cross section (σ_{2S}) are given in Table I.

[9]The calculation of N_F for the $\Upsilon(3S)$ proceeds along the same lines as that of the $\Upsilon(2S)$. It is complicated by the fact that many of its decay modes are unknown. In calculating N_F we have only considered decay modes with ≤ 4 charged tracks and assumed an overall detection efficiency of 25%.

[10]With the same data sample used to measure $B_{\mu\mu}$ at the $\Upsilon(1S)$, a comparison of the angular distribution of the $e^+e^-\to e^+e^-$ scattering cross section on and off the $1S$ resonance yielded a measurement of B_{ee}. The value obtained, $3.0\pm0.8\%$, is consistent with $B_{\mu\mu}$ and e-μ universality. M. Ito, Cornell University CLEO Internal Report No. CBX82-71 (unpublished).

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