Measurement of the Branching Ratio for Decay of Υ States to $\mu^+\mu^-$

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Using the Columbia University–Stony Brook detector at the Cornell Electron Storage Ring, we have measured $B_{\mu\mu}$, the branching fraction into muons, of the 1*S*, 2*S*, and 3*S* Υ mesons. We obtain $B_{\mu\mu}(1S)=(2.61\pm0.09\pm0.11)\%$, $\Gamma_{tot}(1S)=51.1\pm3.2$ keV, $B_{\mu\mu}(2S)=(1.38\pm0.25\pm0.15)\%$, $\Gamma_{tot}(2S)=42.3\pm9.2$ keV, $B_{\mu\mu}(3S)=(1.73\pm0.15\pm0.11)\%$, and $\Gamma_{tot}(3S)=27.7\pm3.7$ keV. We also derive, from these results, $\alpha_s=0.174$ and $\Lambda_{\overline{MS}}=157$ MeV, where $\overline{MS}$ denotes the modified minimal-subtraction scheme.

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The branching fractions for Υ decay into two muons, $B_{\mu\mu}$, together with the e^+e^- widths and branching ratios for individual channels, allow the determination of total and partial widths. One can then obtain $\Gamma_{ggg}/\Gamma_{\mu\mu}$ and therefore α_s and $\Lambda_{\overline{MS}}$, the coupling constant and the scale parameter of QCD ($\overline{MS}$ denotes the modified minimal-subtraction scheme).

We have measured $B_{\mu\mu}$ for the 1*S* and 3*S* Υ mesons using the Columbia University–Stony Brook (CUSB) II detector at the Cornell Electron Storage Ring. We have also obtained $B_{\mu\mu}$ for the Υ(2*S*) from data collected earlier with the CUSB detector. CUSB II is a high-resolution bismuth germanate (BGO) electromagnetic calorimeter inserted in a NaI array and is described in detail elsewhere.[1] The cylindrical BGO array consists of 36 azimuthal sectors, each covering 10° in ϕ. Each sector is divided into two polar halves, covering 45° to 90° and 90° to 135° in θ. The sectors, 12 radiation lengths (X_0) thick at $\theta=90°$, are subdivided into 5 radial layers, for a total of 360 crystals in the whole array. Between the beam pipe and the BGO cylinder is a small drift chamber. The BGO cylinder is surrounded by a square array of 328 NaI crystals, $8.8X_0$ thick at normal incidence, arranged in 5 radial layers, 32 azimuthal sectors, and 2 polar halves. The NaI array is surrounded by 256 total-absorption lead-glass Cherenkov counters, $7X_0$ thick at normal incidence. Between NaI crystal layers are four proportional chambers with x and y cathode strip readout, used for tracking muons, in r,θ,ϕ. Minimum-ionizing noninteracting particles are identified, by their energy loss, 5 times in BGO, 5 times in NaI, and once in lead glass, crossing ∼2.5 nuclear interaction lengths. The detector covers a solid angle of 66% of 4π. Plastic scintillator counters on four sides of the detector cover ∼29% of the total solid angle. They provide the dimuon trigger and give time-of-flight information for cosmic-ray rejection.

The dimuon trigger for the CUSB-II detector required a coincidence among muon counters on opposite sides of the detector, plus at least 100 MeV in the outer three layers of NaI and BGO. Two minimum-ionizing tracks lose at least 180 MeV in NaI and 190 MeV in BGO. The trigger is 100% efficient for muons crossing the counters and is dominated by soft particles in the counters and the BGO and NaI arrays. Most background is trivially removed on line by requiring that the observed energy signals be consistent with two noninteracting particles with their origin at the interaction point.

These criteria are reapplied in a more refined way in the final analysis mostly to reject a small amount of τ pair contamination. Only events with two muon tracks and no other energy clusters in BGO or NaI are used for the determination of $B_{\mu\mu}$. The remaining background at this level consists of cosmic-ray muons, mostly vertical, in accidental coincidence with the beam bunch crossing time in the trigger window of ∼30 ns. This background is effectively rejected by using muon time of arrival and tracking information.[2] Chamber and timing information are used to require the following.

1. The event origin along the beam direction be within 2σ of the interaction point, where $\sigma=1.3$ cm is the longitudinal rms spread of the luminous region.
2. The difference in time of arrival of the two muons satisfies $\delta t\leq3\sigma_t$, where $\sigma_t=1.1$ ns is the timing resolution. Cosmic rays appear ∼10 ns off time.
3. The event time must be within $2\sigma_t$ of the bunch crossing time.
4. The two muons are collinear within 10°.

Requirements 1 and 2 are somewhat equivalent and, together with requirement 3, effectively entirely remove the cosmic-ray background. Requirement 4 is imposed for computation of the continuum-sample radiative correction. We estimate that the data sample retained for analysis after all the cuts is better than 99.4% pure.

To obtain $B_{\mu\mu}$ we must measure the small increase in muon yield at the resonance peaks with respect to the value in the continuum. This increase is of the order of 10% to 35% for the Υ resonances. Apart from small differences due to radiative corrections muons from $e^+e^- \to \mu^+\mu^-$ and from $e^+e^- \to \Upsilon \to \mu^+\mu^-$ have the same angular distribution; therefore, most systematic uncertainties in determining the dimuon yield at the Υ's and in the continuum cancel.

Assuming lepton universality, we write $B_{\mu\mu} = 1/(3+1/\bar{B}_{\mu\mu})$, where $\bar{B}_{\mu\mu} = \Gamma(\Upsilon\to\mu\mu)/\Gamma(\Upsilon\to \text{hadrons}) = N(\Upsilon\to\mu\mu)/N(\Upsilon\to\text{hadrons})$ and N is the number of events. Since at resonance one measures the yield from Υ decay *plus* continuum, knowledge of the increase ΔR in $R\equiv\sigma_{\text{had}}/\sigma_{\mu\mu}$ is necessary.

We can write $\bar{B}_{\mu\mu}$ as

$$\bar{B}_{\mu\mu} = \left(\frac{N_1/\mathcal{L}_1}{N_2/\mathcal{L}_2} - 1\right)\frac{\epsilon_C}{\epsilon_R}\frac{1}{\Delta R},$$

where $N_1/\mathcal{L}_1$ is the number of dimuons counted at resonance, of mass $\sqrt{s_1}$, per unit integrated luminosity, and $N_2/\mathcal{L}_2$ is the continuum ratio, measured at an energy $\sqrt{s_2}$, scaled by s_2/s_1. The energy-scaled ratio $(N_1/\mathcal{L}_1)/(N_2/\mathcal{L}_2)$ is given directly by $(N_{\mu\mu}/N_{\text{Bha}})_1/(N_{\mu\mu}/N_{\text{Bha}})_2$, where N_{Bha} is the observed number of large-angle Bhabha scattering events in the detector.[3] ϵ_C/ϵ_R is the ratio of the efficiencies for detecting continuum dimuon events and $\Upsilon\to\mu\mu$ events, whose value is 0.910 ± 0.014. This is calculated from the Monte Carlo calculations of Berends and Kleiss[4] and is due to initial-state radiation. We use as the "continuum" sample data taken just below the Υ(4S) as well as at the Υ(4S) peak, since $B_{\mu\mu}(4S)\sim10^{-5}$.[5] ΔR is obtained from the hadronic and Bhabha yields measured at the resonance peaks, accounting for efficiencies and the ratio of Bhabha to dimuon yields. Additional small corrections (e.g., for $\tau\bar{\tau}$ contamination) are applied. All efficiencies and corrections are obtained from our detector simulation Monte Carlo program.

For excited Υ's, feed-down also gives muon pairs. One such reaction is $\Upsilon^i\to\chi^j\gamma\to\Upsilon^k\gamma\gamma\to\gamma\gamma\mu\mu$. The number of the above events with both photons missing the detector and the acollinearity of the muons less than 10° is negligible. Similarly we find[6] that the contribution from $\Upsilon(3S)\to\Upsilon(2S,1S)\pi\pi\to\mu\mu\pi\pi$ is also negligible. The rarity of such events is verified from a search of dimuon events with additional energy in the calorimeter. Most of the data were taken over a 21-month period. We collected ~400000 Υ(3S) for a total luminosity of 86 pb^{-1}. In just a few weeks we obtained almost as many Υ(1S) ~400000 from 22 pb^{-1}. The rest of the running, ~330 pb^{-1}, was on or just below the Υ(4S). Our results for the four data sets are summarized in Table I. The error on ΔR is dominated by systematics, is the only error shown in the table, and is fully reflected in the systematic errors below. We also include results from data taken at the Υ(2S) with the CUSB detector, corresponding to ~200000 produced Υ(2S).[7]

TABLE I. Experimental results.

	$N_{\mu\mu}$	ΔR	N_{Bha}
	CUSB II data		
Υ(1S)	8274	17.0 ± 0.6	256870
Υ(3S)	18757	5.2 ± 0.2	806444
Υ(4S)	44002	···	2083446
Continuum	20589	···	982627
	CUSB data		
Υ(2S)	6202	7.14 ± 0.8	276627
Continuum	4771	···	236842

From Table I we obtain

$$B_{\mu\mu}(1S) = (2.61\pm0.09\pm0.11)\%,$$

$$B_{\mu\mu}(2S) = (1.38\pm0.25\pm0.15)\%,$$

$$B_{\mu\mu}(3S) = (1.73\pm0.15\pm0.11)\%,$$

where the first error is statistical and the second is systematic. The systematic error accounts for uncertainties in hadronic and dimuon efficiency calculations and in the normalization of different data samples. These results are to be compared with previous measurements of $(2.62\pm0.16)\%$ (Ref. 5) for the Υ(1S), $(0.9\pm0.6\pm0.6)\%$ (Ref. 8) and $(1.8\pm0.8\pm0.5)\%$ (Ref. 9) for the Υ(2S),[10] and $(1.6\pm0.4)\%$ (Ref. 5) for the Υ(3S). Our results for $B_{\mu\mu}$ combined with the new averages for $(1-3B_{\mu\mu})\Gamma_{ee}$ of 1.23 ± 0.04 keV for the 1S, 0.56 ± 0.03 keV for the 2S,[11] and $\Gamma_{ee}(3S)=0.48\pm0.04$ keV[12] determine the Υ's total widths to be

$$\Gamma_{\text{tot}}(1S) = 51.1\pm3.2\ \text{keV},$$

$$\Gamma_{\text{tot}}(2S) = 42.3\pm9.2\ \text{keV},$$

$$\Gamma_{\text{tot}}(3S) = 27.7\pm3.7\ \text{keV}.$$

$B_{\mu\mu}$ can also be used, along with the measured transition branching ratios, to obtain Γ_{ggg} from the relation

$$\frac{\Gamma_{ggg}}{\Gamma_{\mu\mu}} = \frac{1}{B_{\mu\mu}}(1-B_{\gamma gg}-B_{\pi\pi}-B_{E1})-3-R,$$

where $R=3.48\pm0.04\pm0.16$.[11] $B_{\gamma gg}$ is the branching fraction into a photon and two gluons. This branching ratio has been measured for the Υ(1S) and Υ(2S)[13] and is of the order of 3% of B_{ggg} which we will assume to be also true for the Υ(3S). For the $\pi\pi$ and electric dipole or $E1$ transitions we use the measured $B_{\pi\pi}$ (Refs. 5 and 6) and B_{E1} (Ref. 14) branching ratios to obtain

$$F_1 = \frac{\Gamma_{ggg}(1S)}{\Gamma_{\mu\mu}(1S)} = 30.9^{+1.3+1.6}_{-1.2-1.5},$$

$$F_2 = \frac{\Gamma_{ggg}(2S)}{\Gamma_{\mu\mu}(2S)} = 32.5^{+8.6+5.6}_{-5.9-4.5},$$

$$F_3 = \frac{\Gamma_{ggg}(3S)}{\Gamma_{\mu\mu}(3S)} = 30.5^{+3.7+2.9}_{-3.1-2.6}.$$

In the following, for simplicity, we shall use $F_1 = 30.9 \pm 2.0$, $F_2 = 32.5 \pm 8.7$, and $F_3 = 30.5 \pm 4.4$, where the errors have been combined in quadrature and geometrically averaged. The ratio $\Gamma_{ggg}/\Gamma_{\mu\mu}$, up to terms next to leading order, is given by[15,16]

$$\Gamma_{ggg}/\Gamma_{\mu\mu} = 5773\alpha_s^3[1 + c(\mu)(\alpha_s/\pi)] .$$

The energy scale μ is not defined in the theory and $c(\mu)$ has a strong dependence on the scale, casting doubt on the validity of the perturbative expansion. It should be noted, however, that through $B_{\mu\mu}$ we measure α_s^3. This implies that the effect of the first-order radiative corrections on the determination of α_s is of the order of $c(\mu)/3$. Following Kwong *et al.*,[17] we write $c(\mu) = 0.43 - 12.5\ln(\mu/m_q)$, where m_q is the mass of the bound quarks. In the Υ's case, $m_q = m_b = 4.9$ GeV.[17] Choosing, as in Ref. 17, $\mu = m_b$, gives $c = 0.43$, which affects the determination of α_s by less than 1%. For 3.3 GeV $< \mu <$ 7.8 GeV, the overall effect of the next-to-leading term is to change the value of α_s by $\sim \pm 10\%$, an amount, unfortunately, much larger than the experimental errors. For $\mu = m_b$ we obtain

$$\alpha_s(m_b) = 0.1736 \pm 0.0037 ,$$

$$\alpha_s(m_b) = 0.176 \pm 0.016 ,$$

$$\alpha_s(m_b) = 0.1728 \pm 0.0083 ,$$

$$\langle \alpha_s(m_b) \rangle_\Upsilon = 0.1736 \pm 0.0033 ,$$

from the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, respectively, the last entry being the weighted average of the three measured values. We also obtain the corresponding values of the QCD scale parameter in the $\overline{\text{MS}}$[18] scheme

$$\Lambda_{\overline{\text{MS}}} = 157 \pm 13 \text{ MeV} ,$$

$$\Lambda_{\overline{\text{MS}}} = 167 \pm 58 \text{ MeV} ,$$

$$\Lambda_{\overline{\text{MS}}} = 154 \pm 29 \text{ MeV} ,$$

$$\langle \Lambda_{\overline{\text{MS}}} \rangle_\Upsilon = 157 \pm 12 \text{ MeV} .$$

These determinations compare favorably with the values of $\alpha_s(m_b) = 0.179 \pm 0.009$ and $\Lambda_{\overline{\text{MS}}} = 175 \pm 32$ MeV of Ref. 17 and with the value $\Lambda_{\overline{\text{MS}}} = 137 \pm 25$ MeV given by Duke and Roberts.[19] The errors for α_s given above do not, however, include theoretical uncertainties. Using for instance the range in energy scale given above as a guess of these uncertainties would result in

$$\langle \alpha_s(m_b) \rangle_\Upsilon = 0.1736 \pm 0.0033 \pm 0.0173 ,$$

$$\langle \Lambda_{\overline{\text{MS}}} \rangle_\Upsilon = 157 \pm 12 \pm 60 \text{ MeV} ,$$

where the second error is due to the lack of theoretical guidance on how to fix the energy scale, clearly indicating the necessity for higher-order calculations.

Factorization requires that all annihilation processes scale in the same ratio from any Υ to any other.[20] This implies that $B_{\mu\mu}(2S,3S) = B_{\mu\mu}(1S)[1 - B_{\text{NA}}(2S,3S)]$, where B_{NA} is the branching ratio for all decay channels of the excited Υ's with no annihilation of the $b\bar{b}$ quark pair. From our value of $B_{\mu\mu}(\Upsilon)$ given here and the value of B_{NA} obtained from the results of Refs. 5, 6, and 14 we obtain $B_{\mu\mu}(\Upsilon(3S)) = 0.0171 \pm 0.0011$ and $B_{\mu\mu}(\Upsilon(2S)) = 0.0144 \pm 0.0010$, in excellent agreement with the measured values.

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[1]J. Lee-Franzini, Nucl. Instrum. Methods Phys. Res., Sect. A **263**, 35 (1988).

[2]T. Kaarsberg *et al.*, Phys. Rev. D **35**, 2265 (1987).

[3]At resonance the Bhabha yield is obtained by counting large angle e^+e^- events and subtracting the contribution from $\Upsilon \rightarrow e^+e^-$.

[4]F. A. Berends and R. Kleiss, Nucl. Phys. **B178**, 141 (1981); F. A. Berends and R. Kleiss, Nucl. Phys. **B177**, 237 (1981).

[5]Particle Data Group, G. P. Yost *et al.*, Phys. Lett. B **204**, 1 (1988).

[6]T. Bowcock *et al.*, Phys. Rev. Lett. **58**, 307 (1987).

[7]C. Klopfenstein *et al.*, Phys. Rev. Lett. **51**, 160 (1983).

[8]H. Albrecht *et al.*, Z. Phys. C **28**, 45 (1985).

[9]P. Haas *et al.*, Phys. Rev. D **30**, 1996 (1984).

[10]We do not use the average in Ref. 5 in this case since it is totally dominated by our preliminary result as reported at conferences.

[11]Z. Jakubowski *et al.*, Z. Phys. C **40**, 49 (1988).

[12]We use the data from Ref. 5, corrected, as discussed in Ref. 11, for the improper radiative corrections used and the new value of $B_{\mu\mu}$ reported here.

[13]R. D. Schamberger *et al.*, Phys. Lett. **138B**, 225 (1984); H. Albrecht *et al.*, Phys. Lett. B **199**, 291 (1987).

[14]J. Lee-Franzini, in Proceedings of the 1987 International Symposium on Lepton-Photon Interactions edited by W. Bartel and R. Rückl [Nucl. Phys. B (Proc. Suppl.) **3**, 139 (1988)].

[15]R. Barbieri, R. Gatto, R. Kögler, and Z. Kunszt, Phys. Lett. **57B**, 455 (1975).

[16]P. B. Mackenzie and G. P. Lepage, Phys. Rev. Lett. **47**, 1244 (1981).

[17]W. Kwong, P. B. Mackenzie, R. Rosenfeld, and J. L. Rosner, Phys. Rev. D **37**, 3210 (1988).

[18]W. A. Bardeen, A. J. Buras, D. W. Duke, and T. Muta, Phys. Rev. D **18**, 3998 (1978).

[19]D. W. Duke and R. G. Roberts, Phys. Rep. **120**, 275 (1985).

[20]P. Franzini and J. Lee-Franzini, Phys. Rep. **81**, 239 (1982); Annu. Rev. Nucl. Part. Sci. **33**, 21 (1983).