Evidence for $B_s^{(*)}\bar{B}_s^{(*)}$ Production at the $\Upsilon(5S)$ Resonance

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We use data collected by the CLEO III detector at the Cornell Electron Storage Ring to measure the inclusive yields of D_s mesons as $\mathcal{B}(\Upsilon(5S) \to D_s X) = (44.7 \pm 4.2 \pm 9.9)\%$ and $\mathcal{B}(\Upsilon(4S) \to D_s X) = (18.1 \pm 0.5 \pm 2.8)\%$. From these measurements, we make a model dependent estimate of the ratio of $B_s^{(*)}\bar{B}_s^{(*)}$ to the total $b\bar{b}$ quark pair production of $(16.0 \pm 2.6 \pm 5.8)\%$ at the $\Upsilon(5S)$ energy.

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An enhancement in the total e^+e^- annihilation cross section into hadrons was discovered at the Cornell Electron Storage Ring (CESR) long ago [1,2] and its mass measured as 10.865 ± 0.008 GeV. This effect was named the $\Upsilon(5S)$ resonance. Theoretical models [3–5] predict the different relative decay rates of $\Upsilon(5S)$ into combinations of $B^{(*)}\bar{B}^{(*)}$ and $B_s^{(*)}\bar{B}_s^{(*)}$, where $(*)$ indicates the possible presence of a B^* meson. This original $\sim$116 pb^{-1} of data failed to reveal if B_s mesons were produced. It is important to check the predictions of these and other models; furthermore, e^+e^- "B factories" could exploit a possible B_s yield here as they have done for B mesons on $\Upsilon(4S)$.

In this Letter, we examine D_s yields, because, in a simple spectator model, B_s decays into D_s nearly all the time. Since the $B \to D_s X$ branching ratio has already been measured to be $(10.5 \pm 2.6 \pm 2.5)\%$ [6], we expect a large difference between the D_s yields at $\Upsilon(5S)$ and $\Upsilon(4S)$ that can lead to an estimate of the size of the $B_s^{(*)}\bar{B}_s^{(*)}$ component at $\Upsilon(5S)$. When we discuss $\Upsilon(5S)$ here, we mean any production above what is expected from continuum production of quarks lighter than b at an e^+e^- center-of-mass energy of 10.865 GeV. The CLEO III detector is equipped to measure the momenta and directions of charged particles, identify charged hadrons, detect photons, and determine with good precision their directions and energies. It has been described in detail previously in Refs. [7,8].

In this analysis, we use 0.42 fb^{-1} of integrated luminosity taken at the $\Upsilon(5S)$ peak in February 2003. We also use 6.34 fb^{-1} of integrated luminosity collected on $\Upsilon(4S)$ and 2.32 fb^{-1} of data taken in the continuum 40 MeV in the center-of-mass energy below $\Upsilon(4S)$. These data were accumulated between August 2000 and June 2001. The detector hardware was not changed over the entire time period. Efficiencies are carefully monitored and did not change measurably between data sets.

We look for D_s candidates through the reconstruction of three charged tracks in hadronic events via the $D_s^+ \to \phi\pi^+$ decay mode. Here and elsewhere in this Letter, mention of one charge implies the same consideration for the charge-conjugate mode. Requiring the Fox-Wolfram shape parameter R_2 [9] to be less than 0.25 suppresses continuum background events which are less isotropic than b-quark events.

Pairs of oppositely charged tracks were considered candidate decay products of a ϕ if at least one of the tracks is identified as a kaon and if the invariant mass of the K^+K^- system is within ± 10 MeV$/c^2$ of the nominal ϕ mass. A third track was combined with the K^+K^- system to form a D_s candidate without using particle identification.

The Ring Imaging Cherenkov (RICH) of the CLEO III detector is used for track momenta larger than 0.62 GeV$/c$. Information on the angle of the detected Cherenkov photons is translated into a likelihood of a given photon being due to a particular particle analyzed with a specific mass hypothesis. Contributions from all photons associated with a particular track with one mass hypothesis are then summed to form an overall likelihood denoted as $\mathcal{L}_i$ for each "i" particle hypothesis.

To utilize the information on the ionization loss in the drift chamber of the CLEO III detector, dE/dx, we calculate the differences between the expected and the observed ionization losses divided by the error for the pion and kaon hypotheses, called σ_π and σ_K.

Particle identification (PID) information arises from both RICH and dE/dx in the following manner: (a) If neither RICH nor dE/dx information is available, then the track is accepted. (b) If dE/dx is available and RICH is not, then we insist that kaon candidates have $\mathrm{PID}_{dE} = \sigma_\pi^2 - \sigma_K^2 > 0$. (c) If RICH information is available and dE/dx is not available, then we require that $\mathrm{PID}_{\mathrm{RICH}} = -2\log(\mathcal{L}_\pi) + 2\log(\mathcal{L}_K) > 0$ for kaons. (d) If both dE/dx and RICH information are available, we require that $(\mathrm{PID}_{dE} + \mathrm{PID}_{\mathrm{RICH}}) > 0$ for kaons.

To suppress combinatoric backgrounds, we take advantage of the polarization of the ϕ, as it is a vector particle while the other particles in this decay are spinless. The expected distribution from real ϕ decays varies as $\cos^2\theta_h$, where θ_h is the angle between the D_s and the K^+ momenta measured in the ϕ rest frame while combinatoric backgrounds tend to be flat. Thus, we require $|\cos\theta_h|$ to be larger than 0.3.

For $\phi\pi^+$ combinations satisfying the previous requirements, we look for D_s candidates having a momentum less than half of the beam energy. Instead of momentum, we choose to work with the variable x, which is the D_s momentum divided by the beam energy, to remove differences caused by the change of the beam energies between continuum data taken just below $\Upsilon(4S)$, at $\Upsilon(4S)$, and at $\Upsilon(5S)$. The $\phi\pi$ invariant mass distributions for $x < 0.5$ are shown in Fig. 1.

We fit the invariant mass of the $\phi\pi^\pm$ candidates in 10 different x intervals (from 0 to 0.5) for data taken at the $\Upsilon(4S)$ peak, at the continuum below $\Upsilon(4S)$, and at the $\Upsilon(5S)$ peak.

The invariant mass distribution in each x interval of the $\Upsilon(4S)$ data set was fitted to a Gaussian signal shape and a linear background. The width of each Gaussian was allowed to float. The corresponding distributions at the other energies were similarly fitted but with the corresponding Gaussian widths fixed to those determined at $\Upsilon(4S)$. The raw D_s yields are listed in the second, third, and fourth columns in Table I.

The number of D_s candidates is determined by subtracting the scaled four-flavor (u, d, s, and c quarks) continuum data below $\Upsilon(4S)$ from the $\Upsilon(4S)$ and the $\Upsilon(5S)$ data. To determine the scale factors, S_{nS}, we account for both the ratio of luminosities and the s dependence of the continuum cross section using

$$S_{nS} = \frac{L_{nS}}{L_{\mathrm{cont}}}\left(\frac{E_{\mathrm{cont}}}{E_{nS}}\right)^2, \qquad (1)$$

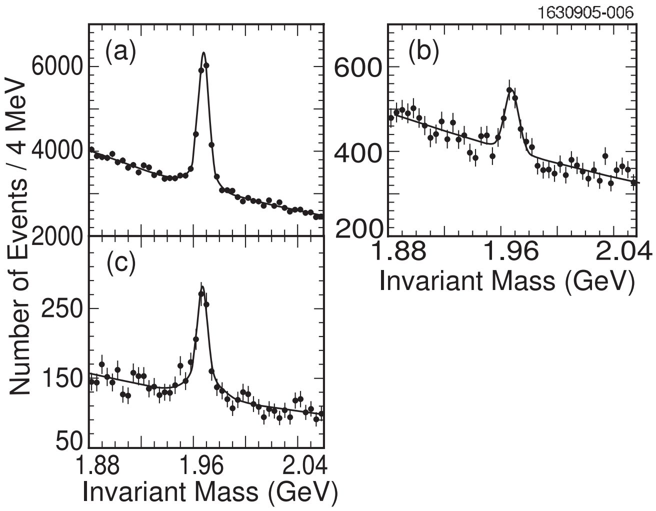

FIG. 1. The invariant mass distributions of the D_s candidates with $x < 0.5$ from: (a) the $\Upsilon(4S)$ on-resonance data, (b) the continuum below the $\Upsilon(4S)$ resonance data, and (c) the $\Upsilon(5S)$ on-resonance data.

where L_{nS}, $L_{\rm cont}$, E_{nS}, and $E_{\rm cont}$ are the collected luminosities and the center-of-mass energies at $\Upsilon(nS)$ and at the continuum below $\Upsilon(4S)$. We find: $S_{4S} = 2.712 \pm 0.001 \pm 0.043$ and $S_{5S} = (17.15 \pm 0.01 \pm 0.24) \times 10^{-2}$.

The second (systematic) error on these scale factors is determined by using the number of charged tracks in the $0.6 < x < 0.8$ interval. The lower limit is determined by the maximum value tracks from $B\bar{B}$ events can have, including smearing due to the measuring resolution, and the upper limit is chosen to eliminate radiative electromagnetic processes. Because tracks should be produced only from continuum events, we suppress beam-gas and beam-wall interactions and photon pair and τ pair events using strict cuts on track multiplicities, event energies, and event shapes. [Since particle production may be larger at the higher $\Upsilon(5S)$ energy than the continuum below $\Upsilon(4S)$, we apply a small multiplicative correction of $(0.6 \pm 1.1)\%$, as determined by Monte Carlo simulation to the relative track yields.] We find that the scale factors using this track counting method are 2.668 ± 0.007 and $(17.085 \pm 0.207) \times 10^2$, for S_{4S} and S_{5S}, respectively, and use the difference as the systematic error.

The total number of hadronic events above the four-flavor continuum are $N^{\rm Res}_{\Upsilon(4S)}$ equals $(6.43 \pm 0.01 \pm 0.41) \times 10^6$ and $N^{\rm Res}_{\Upsilon(5S)}$ equals $(0.130 \pm 0.001 \pm 0.022) \times 10^6$. The 6.4% and 17.5% systematic errors here are due to the 1.6% and 1.4% systematic errors on S_{4S} and S_{5S} scale factors, respectively.

The branching ratio of $\Upsilon(nS) \to D_s X$ in each ith x interval is given by

$$\mathcal{B}^i(\Upsilon(nS) \to D_s X) = \frac{1}{N^{\rm Res}_{\Upsilon(nS)} \mathcal{B}(D_s \to \phi\pi) \mathcal{B}(\phi \to K^+K^-)} \times \left(\frac{N^i_{\Upsilon(nS)}}{\epsilon^i}\right), \quad (2)$$

where $N^i_{\Upsilon(nS)}$ are the continuum subtracted on resonance D_s yields. $\mathcal{B}(\phi \to K^+K^-)$ is taken as 49.1% [6]. The reconstruction efficiency ϵ^i is taken to be the same at both resonances. This is reasonable because our tracking and particle identification efficiencies are carefully monitored and did not change significantly between data sets. Specifically, our Monte Carlo simulations of the D_s reconstruction efficiencies include time dependent effects of dead channels and individual hit efficiencies in both the tracking and RICH systems. A comparison of the simulations at both energies shows changes in the reconstruction efficiency between the two energies of <2%.

The results are listed in Table I. We show in Fig. 2 the x distribution of the inclusive D_s yields from $\Upsilon(4S)$ and $\Upsilon(5S)$ decays, continuum subtracted and efficiency corrected.

TABLE I. The x dependent D_s yields from the $\Upsilon(nS)$ data, the continuum below $\Upsilon(4S)$, the $\Upsilon(nS)$ continuum subtracted data, $N^i_{\Upsilon(nS)}$, the efficiency ϵ^i, and the partial branching ratios $B^i_{nS} = \Upsilon(nS) \to D_s X$, for ns equal to $4S$ and $5S$. The errors are statistical only.

$x^i(\lvert p\rvert/E$ beam)	ON $\Upsilon(4S)$	ON $\Upsilon(5S)$	Continuum	$N^i_{\Upsilon(4S)}$	$N^i_{\Upsilon(5S)}$	$\epsilon^i(\%)$	$B^i_{4S}(\%)$	$B^i_{5S}(\%)$
0.00–0.05	44.4 ± 15.7	1.0 ± 3.2	0.0 ± 0.0	44.4 ± 15.7	1.0 ± 3.1	28.9	0.11 ± 0.04	0.1 ± 0.4
0.05–0.10	317.6 ± 39.6	13.3 ± 8.1	20.7 ± 12.0	261.4 ± 51.2	9.7 ± 8.3	23.9	0.8 ± 0.2	1.4 ± 1.2
0.10–0.15	583.6 ± 53.9	30.4 ± 10.4	21.6 ± 15.3	524.9 ± 68.1	26.7 ± 10.7	24.7	1.5 ± 0.2	3.8 ± 1.5
0.15–0.20	845.5 ± 59.0	54.4 ± 13.0	41.7 ± 18.5	732.3 ± 77.5	47.2 ± 13.3	25.4	2.1 ± 0.2	6.5 ± 1.8
0.20–0.25	1206.4 ± 60.6	57.6 ± 12.7	40.2 ± 18.3	1097.4 ± 78.2	50.7 ± 13.0	27.7	2.8 ± 0.2	6.4 ± 1.7
0.25–0.30	2028.6 ± 63.8	104.1 ± 14.0	70.3 ± 18.0	1838.0 ± 80.3	92.0 ± 14.3	28.6	4.6 ± 0.2	11.3 ± 1.8
0.30–0.35	2233.7 ± 60.7	86.7 ± 12.1	57.0 ± 16.2	2079.2 ± 74.9	76.9 ± 12.4	29.4	5.0 ± 0.2	9.2 ± 1.5
0.35–0.40	660.8 ± 37.9	53.8 ± 9.4	75.0 ± 14.5	457.4 ± 54.6	41.0 ± 9.7	30.4	1.1 ± 0.1	4.7 ± 1.1
0.40-0.45	233.5 ± 25.9	22.6 ± 6.7	73.4 ± 12.9	34.3 ± 43.3	10.1 ± 7.0	31.4	0.1 ± 0.1	1.1 ± 0.8
0.45–0.50	245.8 ± 22.2	14.8 ± 5.6	86.0 ± 12.1	12.6 ± 39.5	0.1 ± 6.0	32.4	0.03 ± 0.09	0.0 ± 0.6

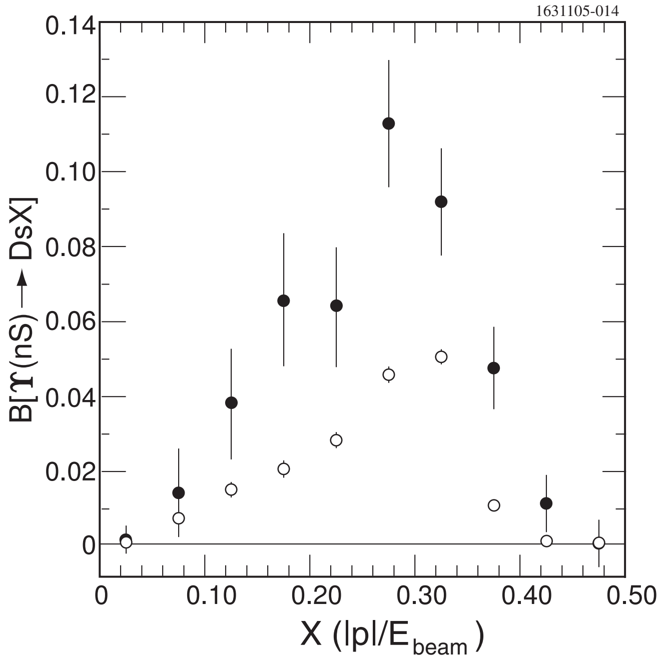

FIG. 2. Branching rate as a function of x from $\Upsilon(5S)$ decays (solid circles) and from $\Upsilon(4S)$ decays (open circles).

The total production rate is found by summing the partial production rates. The product of the D_s production rate at $\Upsilon(4S)$ and $\mathcal{B}(D_s \to \phi\pi)$ is

$$\mathcal{B}(\Upsilon(4S) \to D_s X) \times \mathcal{B}(D_s \to \phi\pi) = (8.0 \pm 0.2 \pm 0.9) \times 10^{-3}, \quad (3)$$

which is in a good agreement with previous measurements [6], while at $\Upsilon(5S)$

$$\mathcal{B}(\Upsilon(5S) \to D_s X) \times \mathcal{B}(D_s \to \phi\pi) = (19.8 \pm 1.9 \pm 3.8) \times 10^{-3}. \quad (4)$$

Many systematic errors cancel in the ratio of decay rates. Thus,

$$\frac{\mathcal{B}(\Upsilon(5S) \to D_s X)}{\mathcal{B}(\Upsilon(5S) \to D_s X)} = 2.4 \pm 0.3^{+0.6}_{-0.3}, \quad (5)$$

directly demonstrates, at 5.6 standard deviation significance, a much larger yield of D_s at $\Upsilon(5S)$ than at $\Upsilon(4S)$.

We use $\mathcal{B}(D_s \to \phi\pi^+) = (4.4 \pm 0.5)\%$, which is the weighted average of the $(3.6 \pm 0.9)\%$ Particle Data Group value [6] and the recent measured value of $(4.8 \pm 0.6)\%$ [10], although the latter value is at the 90% C.L. upper limit found previously [11]. We find

$$\mathcal{B}(\Upsilon(4S) \to D_s X) = (18.1 \pm 0.5 \pm 2.8)\%, \quad (6)$$

and, consequently,

$$\mathcal{B}(B \to D_s X) = (9.0 \pm 0.3 \pm 1.4)\%. \quad (7)$$

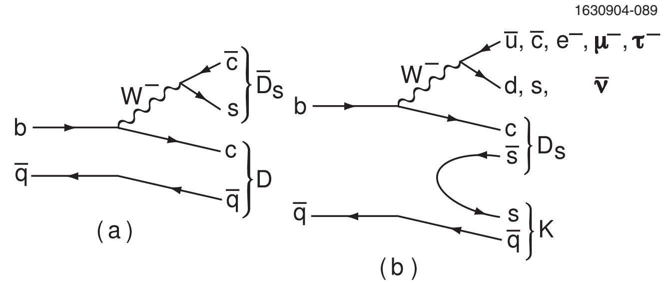

FIG. 3. Dominant decay diagrams for a B meson into D_s mesons (q is either a u or d quark).

In addition, we find

$$\mathcal{B}(\Upsilon(5S) \to D_s X) = (44.7 \pm 4.2 \pm 9.9)\%. \quad (8)$$

From these results, we estimate the size of the $B_s^{(*)}\bar{B}_s^{(*)}$ component at $\Upsilon(5S)$ in a model dependent manner. Here we start with the knowledge that an equal admixture of B^o and B^+ mesons decay into the sum of D^o and D^+ mesons roughly 100% of the time [6]. Thus, we expect B_s mesons to decay into D_s mesons also about 100% of the time. In what follows, we estimate our own theoretical corrections to this number.

We know that the branching fraction $\mathcal{B}(B \to D_s X) = (9.0 \pm 0.3 \pm 1.4)\%$ comes either from the $W^- \to \bar{c}s$ process, shown in Fig. 3(a), or from the $b \to c$ piece if it manages to create an $s\bar{s}$ pair through fragmentation; see Fig. 3(b).

Similarly, the production of D_s mesons from B_s decay arises from two dominant processes. Figure 4(a) shows the simple spectator process that is expected to produce D_s mesons nearly all the time; here the primary $b \to c$ transition has the charm quark pairing with the spectator antistrange quark. Figure 4(b) shows the subset of process (a) where $W^- \to \bar{c}s$ and these two quarks form a color singlet pair. The chances of this occurring should be similar to the chance of getting an upper vertex D_s in B decay [Fig. 3(a)], i.e., a D_s along with a D.

We can use data to help estimate the size of these processes. First let us consider the diagram shown in Fig. 4(a). The nearly 100% probability that this process will produce D_s mesons is reduced if the $c\bar{s}$ pair fragments

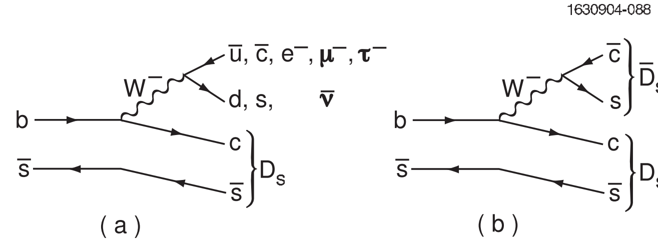

FIG. 4. Dominant decay diagrams for a B_s meson into D_s mesons.

into a kaon plus a D instead of a D_s by producing an additional $u\bar{u}$ or $d\bar{d}$ pair. We do not actually know the size of this fragmentation, though it is clear that producing a light quark-antiquark pair ($d\bar{d}$ or $u\bar{u}$) is easier than $s\bar{s}$. We estimate that the reduction in D_s yield due to this fragmentation is a $(-15 \pm 10)\%$ effect. Next we estimate the size of the process depicted in Fig. 4(b). The $B \to DD_s$ modes have branching fractions that sum to about 5%. There are some additional decays due to $B \to D^{**}D_s$ and $B \to DD_{sJ}^{(*)}$ decays that also contribute D_s mesons. We add these and estimate an extra $(7 \pm 3)\%$ of D_s mesons in B_s decays produced by the diagram in Fig. 4(b). Taking into account all these contributions, we derive a model dependent estimate of $(100 + 7 - 15)\% = 92\%$. Therefore, we use $\mathcal{B}(B_s \to D_s X) = (92 \pm 11)\%$.

We can estimate now the fraction of $\Upsilon(5S)$ that decays into $B_s^{(*)}\bar{B}_s^{(*)}$, which we denote as f_s. The D_s yields at $\Upsilon(5S)$ come from two sources, B and B_s mesons. The equation linking them is

$$\mathcal{B}(\Upsilon(5S) \to D_s X)\mathcal{B}(D_s \to \phi\pi^+)/2 = f_s \mathcal{B}(B_s \to D_s X)\mathcal{B}(D_s \to \phi\pi^+) + \frac{(1 - f_s)}{2}\mathcal{B}(\Upsilon(4S) \to D_s X)\mathcal{B}(D_s \to \phi\pi^+), \tag{9}$$

where the product branching fractions $\mathcal{B}(\Upsilon(5S) \to D_s X)\mathcal{B}(D_s \to \phi\pi^+)$ and $\mathcal{B}(\Upsilon(4S) \to D_s X)\mathcal{B}(D_s \to \phi\pi^+)$ are given by Eqs. (4) and (3), respectively. Therefore, at the $\Upsilon(5S)$ energy, we obtain the $B_s^{(*)}\bar{B}_s^{(*)}$ ratio to the total $b\bar{b}$ quark pair production above the four-flavor (u, d, s, and c quarks) continuum of

$$f_s = \mathcal{B}(\Upsilon(5S) \to B_s^{(*)}\bar{B}_s^{(*)}) = (16.0 \pm 2.6 \pm 5.8)\%. \tag{10}$$

The systematic errors in this analysis are dominated by the 1.6% relative error on S_{4S} and 1.4% on S_{5S} scale factors which contribute large components (6.4% and 17.5%) to the error on the number of hadronic events above continuum at $\Upsilon(4S)$ and $\Upsilon(5S)$. There is also a contribution from the 11.3% error on the $B_s \to D_s X$ branching fraction estimate and a contribution from the 11% error on the absolute $D_s \to \phi\pi$ branching fraction. An additional component comes from a 6.4% error on the D_s detection efficiency, which includes a 2% error on the tracking efficiency and a 2% error on the particle identification, both per track. We also have a 5% error on the yields due to the fitting method. The total systematic error is obtained by summing all entries in quadrature.

In conclusion, we have measured the inclusive yields of D_s mesons as $\mathcal{B}(\Upsilon(5S) \to D_s X) = (44.7 \pm 4.2 \pm 9.9)\%$ and $\mathcal{B}(\Upsilon(4S) \to D_s X) = (18.1 \pm 0.5 \pm 2.8)\%$. The ratio

$$\frac{\mathcal{B}(\Upsilon(5S) \to D_s X)}{\mathcal{B}(\Upsilon(4S) \to D_s X)} = 2.4 \pm 0.3^{+0.6}_{-0.3} \tag{11}$$

provides the first statistically significant evidence (5.6σ) of substantial production of B_s mesons at the $\Upsilon(5S)$ resonance. Using a model dependent estimate of $\mathcal{B}(B_s \to D_s X)$, we find that the $B_s^{(*)}\bar{B}_s^{(*)}$ ratio to the total $b\bar{b}$ quark pair production above the four-flavor (u, d, s, and c) continuum at the $\Upsilon(5S)$ energy is

$$f_s = \mathcal{B}(\Upsilon(5S) \to B_s^{(*)}\bar{B}_s^{(*)}) = (16.0 \pm 2.6 \pm 5.8)\%. \tag{12}$$

Several phenomenological models predict the decay rates of $\Upsilon(5S)$ into combinations of $B^{(*)}\bar{B}^{(*)}$ and $B_s^{(*)}\bar{B}_s^{(*)}$, though here we are concerned only with the relative B_s fraction f_s. The unitarized quark model estimates [3] and the predictions of Martin and Ng [4] are about 30%, both somewhat larger than our measurement. Byers and Eichten [5] present two models, both giving $f_s < 20\%$, in good agreement with our finding.

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