1. INTRODUCTION

The $\Upsilon(5S)$ was discovered about 20 years ago in $e^+e^-$ collisions at CLEO [1] and CUSB [2]. Its mass is $(10865 \pm 8)$ MeV, about 300 MeV higher than the $\Upsilon(4S)$ resonance, and its width of $(110 \pm 13)$ MeV is about five times larger than the $\Upsilon(4S)$ resonance. Its production cross-section was measured to be about $0.3$ nb, about ten times lower than the $\Upsilon(4S)$ cross-section. Owing to its mass, the $\Upsilon(5S)$ can decay to a variety of final states containing $B$ and $B_s^0$ mesons. The accessible $B$-meson final states include: $BB$, $B^*\bar{B}$, $B^*\bar{B}^*$, $BB\pi$, $B^*\bar{B}\pi$, $B^*\bar{B}\pi$ and $BB\pi\pi$; final states with $B_s^0$ are: $B_s^0\bar{B}_s^0$, $B_s^0\bar{B}_s^0$, and $B_s^0\bar{B}_s^0$. Further study of the $\Upsilon(5S)$ is of great interest because of its being a potentially large source of $B_s^0$ mesons at an $e^+e^-$ machine. If suitably large samples can be collected, their study would provide a complementary probe of CP violation and rare decays to LHCb. Studies involving rare decays, particularly those with soft photons, and untagged time-dependent and time-independent measurements, which provide access to the width difference between the $B_s^0$ mass eigenstates, $\Delta \Gamma_s$, offer complementary information to measurements at hadron machines [3]. Because of the small Lorentz boost at the $\Upsilon(5S)$ and the large value of the mixing frequency, $\Delta m_s$ [4], time-dependent CP violation measurements in mixing are not possible.

Until recently, there existed only weak limits on the production rate of $B_s^0$ at the $\Upsilon(5S)$. Several models attempt to describe the hadronic cross-section in the 10-11 GeV region. The simplest model, the quark-pair creation model (QPC) [5], allows for quark pairs to be ‘popped’ out of the vacuum. This model by itself is insufficient to describe the hadronic cross-section. Ono et al. [7] are able to reproduce the spectrum by introducing a $b\bar{b}g$ hybrid at 10683 MeV (the QHM model). A third model, the unitarized quark model (UQM) [6] includes coupled channel effects between $b\bar{b}$ states via real (two-meson) intermediate states. The QHM predicts $B^*\bar{B}$ is dominant at 10865 MeV, with relative rates of $B^*\bar{B}^*:B^*\bar{B}:BB \sim 1:3:6$. On the other hand, the UQM also reproduces the hadronic cross-section, but predicts that $B^*\bar{B}^*$ is dominant, e.g., $B^*\bar{B}^*:B^*\bar{B}:BB \sim 2:1:0.3$.

A more thorough experimental study of the $\Upsilon(5S)$ has been undertaken by CLEO, followed by Belle, to better understand the hadronic cross-section in this region as well as assess the potential for a future high luminosity $e^+e^-$ machine operating at the $\Upsilon(5S)$.

In 2003, CLEO collected 0.42 fb$^{-1}$ of data at the $\Upsilon(5S)$ (10871 MeV) In 2005, Belle collected about 1.9 fb$^{-1}$ on the $\Upsilon(5S)$ resonance, followed by a larger sample of 22 fb$^{-1}$ a year later. Here we report on results from CLEO and the first Belle data set.

2. HADRONIC RESONANCE CROSS SECTION

The hadronic resonance cross section is measured by counting hadronic events recorded at the $\Upsilon(5S)$ using various selection criteria employed to reduce the continuum background.
The continuum background is estimated using data taken below the Υ(4S), and is scaled by: 
\( \langle \mathbb{L}_{\Upsilon(5S)}/\mathbb{L}_{\Upsilon(4S)} \rangle \times (s_{\Upsilon(5S)}/s_{\Upsilon(4S)}) \), where \( \mathbb{L} \) and \( s_i \) are the integrated luminosities and center-of-mass energies squared at the Υ(4S) and Υ(5S). The Υ(5S) cross-sections are measured to be (0.301 ± 0.002 ± 0.039) nb \( \text{[8]} \) and (0.302 ± 0.002 ± 0.015) nb \( \text{[12]} \), by CLEO and Belle, respectively.

3. \( B \) AND \( B^0_s \) OVERVIEW

Many of the same techniques of exclusive reconstruction that are employed at the Υ(4S) are used to reconstruct \( B \) and \( B^0_s \) mesons at the Υ(5S). The kinematic variables \( \Delta E = E_{\text{beam}} - E_B \) and the beam-energy constrained mass, \( m_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2} \), are used. Here, \( E_{\text{beam}} \) is the beam energy and \( E_B \) (\( p_B \)) is the energy (momentum) of the \( B \) candidate. Because of the proximity of the \( B^0_s \) mass to the beam energy, \( B^0_sB^0_s, B^0_sB^* \), and \( B^0_sB^* \) are kinematically well-separated. For \( B \) mesons, \( B\bar{B}, B^*\bar{B}, B^* B^* \) and \( B\bar{B}pi \) are also kinematically separated. \( B\bar{B}, B^*\bar{B}, \) and \( B^* B^* \) occupy a broad, but distinct region in \( \Delta E - m_{bc} \) and overlap with one another, and partially with \( B\bar{B}pi \). Because \( B_s \) candidates are reconstructed (not \( B^*_s \)), only for \( B\bar{B} \) and \( B^0_sB^0_s \) does \( \Delta E \) peak at zero and \( m_{bc} \) peak at the physical \( B \) and \( B^0_s \) masses. For the other processes, \( \Delta E \) and \( m_{bc} \) are offset by a predictable amount. By measuring the yields in each of these kinematically defined regions, one can determine the \( B \) and \( B^0_s \) fractions at the Υ(5S) as well as the contributing subprocesses.

A second approach for obtaining the \( B \) and \( B^0_s \) yields at the Υ(5S) is to use inclusive particle yields. This technique exploits the large difference in inclusive rates for \( B \) and \( B^0_s \) to various particles, such as \( D_s, D^0 \), and \( \phi \).

4. EXCLUSIVE \( B \) MESON FINAL STATES AT THE Υ(5S)

CLEO reconstructs \( B \) mesons via their decays \( B \to J/\psi(K^+, K^0_s, K^{*0}) \) and \( B \to D^{(*)}(\pi, \rho) \) (25 channels in total) \( \text{[10]} \). First, the inclusive \( B \) yield is determined by computing the invariant mass of all \( B \) meson candidates with \(-200 < \Delta E < 450 \text{ MeV} \) and \( 5272 < m_{bc} < 5448 \text{ MeV} \). Unlike \( m_{bc} \), invariant mass does not depend on the particular \( \Upsilon(5S) \) decay mode. A fit to the invariant mass spectrum yields a signal of (53.2 ± 9.0) events. Using efficiencies (\( \epsilon \)) from Monte Carlo (MC) simulation and branching fractions (\( B \)) from the PDG \( \text{[11]} \), it is found \( \sum \epsilon_i B_i = 7.2 \times 10^{-4} \), where the sum is over the 25 decay modes. From this it is concluded that \( \sigma(e^+e^- \to B\bar{B}(X)) = (0.177 \pm 0.030 \pm 0.016) \text{ nb} \). Using this cross-section and the measured total hadronic cross-section, the \( B^0_s \) fraction in \( \Upsilon(5S) \) decays, \( f_s \), is computed to be \( f_s = 1 - (\sigma_{B\bar{B}X}/\sigma_{\text{had}}) = (0.41 \pm 0.10 \pm 0.09) \). To determine the contributing subprocesses, events are selected in the expected signal band in the \( \Delta E - m_{bc} \) plane and projected onto the \( m_{bc} \) axis. The resulting distribution of events is shown in Fig. \( \text{[1]} \) A dominant \( B^*\bar{B} \) peak is observed, along with a smaller contribution from \( B^* B^* \), and an insignificant yield from \( \bar{B} \). The distributions are fit to the sum of 3 Gaussians, with resolutions determined from MC and the mass difference between the \( B^*\bar{B} \) and \( B\bar{B} \) peaks constrained to the expected value of 47.5 MeV. The fitted yields are \( 3.7^{+3.1}_{-2.4} \) \( B\bar{B} \), 10.3 ± 3.9 \( B^*\bar{B} \), and 31.4 ± 6.1 \( B^* B^* \) events. Insignificant yields in \( B^{(*)}\bar{B}^{(*)}(\pi, \rho) \) and \( B\bar{B}\pi \) lead to 90% confidence level upper limits of 13.1 and 6.4 events, respectively. Thus, it is found that \( (74\pm15\pm8)\% \) of the \( B \) production is through \( B^*\bar{B} \) and \( (24\pm9\pm3) \) is from \( B^* B^* \). For \( B\bar{B} \), \( B^{(*)}\bar{B}^{(*)}(\pi, \rho) \), and \( B\bar{B}\pi \) 90% upper limits of 22%, 32%, and 14%, respectively, are obtained. These results strongly disfavor the QHM and are consistent with the UQM.

The \( m_{bc} \) peak position for \( B^*\bar{B} \) and the corresponding peak position from \( B^{(*)}_s\bar{B}^{(*)}_s \) \( \text{[12]} \) can be used to make a precise measurement of the \( B^*_s \) mass. Noting that \( M(B^*_s) - M(B^*) = m_{bc}(B^{(*)}_s\bar{B}^{(*)}_s) - m_{bc}(B^* B^*) + 1.6 \text{ MeV} \), and using the well-measured \( B^* \) mass \( \text{[11]} \), gives \( M(B^*_s) = (5411.7 \pm 1.6 \pm 0.6) \text{ MeV} \), which provides a significant improvement over the previous measurement. The M1 mass splitting for \( B^0_s \) is thus found to be \((45.7 \pm 1.7 \pm 0.7) \text{ MeV} \), which is consistent with the value in the \( B \) system of \((45.78 \pm 0.35) \text{ MeV} \) \( \text{[11]} \), as expected from heavy
quark symmetry.

Figure 1. $m_{bc}$ for $B$ signal candidates in CLEO. The histogram is the data and the line is a fit as described in the text. The shaded regions indicate the shapes expected from $B^{(*)}B^{(*)}\pi$ and $B\bar{B}\pi\pi$. The inset shows the invariant mass for these particular final states, as described in the text.

5. EXCLUSIVE $B^0_s$ MESON FINAL STATES AT THE $\Upsilon(5S)$

Both CLEO and Belle reconstruct $B^0_s \rightarrow J/\psi(\phi, \eta, \eta')$ [14] and $B^0_s \rightarrow D^{(*)+}(\pi, \rho)$ candidates. In Fig. 2 we show the $\Delta E$ versus $m_{bc}$ and $m_{bc}$ distribution for $B^0_s \rightarrow D^{(*)}(\pi, \rho)$ candidates from the CLEO $\Upsilon(5S)$ data sample. The three boxes, from left to right, indicate signal regions for $B_s^0 \bar{B}_s^0$, $B_s^0 \bar{B}_s^0$, and $B_s^0 \bar{B}_s^0$. All 10 signal candidates are $B_s^0 \bar{B}_s^0$. An additional 4 events are observed in the $J/\psi$ modes, all of which are also $B_s^0 \bar{B}_s^0$. Using efficiencies from simulation and branching fractions from the PDG [11], yields $f_s^* = \sigma(\Upsilon(5S) \rightarrow B_s^0 \bar{B}_s^0) / \sigma(\Upsilon(5S)) = (37^{+14}_{-9} \pm 9)\%$, where $f_s^*$ neglects the evidently small $B_s^0 \bar{B}_s^0$ contributions. Belle observes a total of 23 events ($21 B_s^0 \bar{B}_s^0$, 2 $B_s^0 \bar{B}_s^0$, 0 $B_s^0 \bar{B}_s^0$) and determines $94^{+6}_{-9}\%$ of $B_s^0$ are from $B_s^0 \bar{B}_s^0$ [9].

6. INCLUSIVE ANALYSES

Inclusive analyses are sensitive to $f_s$, provided the probe particle chosen has sufficiently different production rate for $B$ and $B^0$ decays. CLEO has used both $D_s$ and $\phi$ mesons, both of which are expected to have substantially higher rates from $B^0$ than $B$ mesons [8]. Belle followed up with a similar pair of analyses that use $D_s$ and $D^0$ mesons [9]. Measurement of the $B_s^0$ fraction, $f_s$, is obtained using an expression of the form:

$$B(\Upsilon(5S) \rightarrow D_s X) = N_{\Upsilon(5S)}(2f_s B(B_s^0 \rightarrow D_s X) + (1 - f_s) B(\Upsilon(4S) \rightarrow D_s X)), \quad (1)$$

where $N_{\Upsilon(5S)}$ is the number of $\Upsilon(5S)$ decays, and we have inserted $D_s$ as the probe particle as an example. Here one measures $B(\Upsilon(5S) \rightarrow D_s X)$ and $B(\Upsilon(4S) \rightarrow D_s X)$, and makes a model-dependent estimate of $B(B_s^0 \rightarrow D_s X) = (92 \pm 11)\%$ [8], leaving only $f_s$ unknown. Using similar arguments, it is estimated that $B(B_s^0 \rightarrow D^0 X) = (8 \pm 7)\%$ [9]. The first measurement of $f_s$ using this technique was reported by CLEO, where they measure: $f_s = (16.8 \pm 2.6^{+0.7}_{-3.4})\%$ [8] using $D_s \rightarrow \phi \pi^+$ mesons. The $D^0$ and $D_s$ scaled momentum spectra from Belle using $\Upsilon(5S)$ data (points) and the below-$\Upsilon(4S)$ continuum (histogram) are shown in Fig. 3. The excess above continuum corresponds to the left-hand side of

Figure 2. $\Delta E$ versus $m_{bc}$ (left) and $m_{bc}$ (right) for $B_s^0 \rightarrow D^{(*)+}(\pi, \rho)$ candidates in the CLEO $\Upsilon(5S)$ data sample. The superimposed boxes are discussed in the text.
Eqn. 1. Using $B(B \rightarrow D_sX) = (8.7 \pm 1.2)\%$ and $B(B \rightarrow D^0X) = (64.0 \pm 3.0)\%$, Belle obtains: $f_s = (17.9 \pm 1.4 \pm 4.1)\%$ from $D_s$ and $f_s = (18.1 \pm 3.6 \pm 7.5)\%$ from $D^0$, which are consistent with each other and with the previous CLEO result.

CLEO has also performed an analysis using inclusive $\phi$ production $[8]$, where $\phi \rightarrow K^+K^-$. The measured yields as a function of scaled momentum are shown in Fig. 3. The first bin $0 < x < 0.05$ is obtained from MC simulation, because in this bin the kaons generally have too low momentum to be reconstructed. The uncertainty is taken to be 100\% of its value. From the measured $D^0 \rightarrow \phi X$, $D^+ \rightarrow \phi X$ and $D_s \rightarrow \phi X$ branching fractions $[13]$, it is deduced that most $\phi$ mesons in $B_s$ decay come from the cascade $B_s \rightarrow D \rightarrow \phi$ or $B_s \rightarrow D_s \rightarrow \phi$, which allows one to make a model-dependent estimate $B(B_s^0 \rightarrow \phi X) = (16.1 \pm 2.4)\%$. One then uses Eqn. 1 to obtain $f_s = (24.6 \pm 2.9 \pm 11.0)\%$.

The combined CLEO average, using exclusive $B$ mesons, and inclusive $D_s$ and $\phi$ mesons, is $f_s = 21^{+6}_{-3}\%$.

These studies firmly establish the $B_s^0$ production rate to be about 25\%, with roughly 90\% of it produced as $B_s^0 \rightarrow B_s^{\ast}\bar{B}_s^\ast$. It is also found that $B_s^\ast \bar{B}_s^\ast$ is dominant, with $B_s^\ast$ about $(1/3)B_s^\ast\bar{B}_s^\ast$.

Figure 3. Scaled momentum distributions, $x = p_D/E_{\text{beam}}$, for (a) $D_s^+ \rightarrow \phi\pi^+$ and (b) $D^0 \rightarrow K^-\pi^+$ from Belle. The points are data taken at the $\Upsilon(5S)$ resonance and the histogram is the continuum obtained from $\Upsilon(4S)$ data, normalized by the ratio of luminosities and $s = E_{\text{cm}}^2$. Other processes are less than about 25\% of $B_s^\ast \bar{B}_s^\ast$. These results are consistent with the UQM, and inconsistent with the QHM.

7. $\Delta \Gamma_s$ AND RARE DECAYS

With a large sample of data collected on the $\Upsilon(5S)$, one can begin to search for rare $B_s^0$ decays. While many of the decays can be searched for in $p\bar{p}$ (CDF, D0) and $pp$ (LHCb at CERN, starting 2008), the $e^+e^-$ environment enjoys low particle multiplicity and good signal-to-background for low energy photons. Final states with soft photons are particularly difficult for detectors at hadron machines, and so this is an area where machines operating at the $\Upsilon(5S)$ can make significant contributions. Taking $\sigma(e^+e^- \rightarrow B_s^0\bar{B}_s^0) = 0.075$ nb (25\% of the resonance cross-section), a 50 fb$^{-1}$ dataset, which could be collected by Belle in a couple of months, yields about 7.5 million $B_s^0$ decays.

In the Standard Model, the width difference, $\Delta \Gamma_s^{CP}$ between the CP eigenstates, $B_s^{\text{odd}}$ and $B_s^{\text{even}}$ is given by $\Delta \Gamma_s^{CP} = 2|\Gamma_{12}|$, where $\Gamma_{12}$ is the off-diagonal matrix element in the $B_s$ decay matrix, which connects $B_s^0$ and $\bar{B}_s^0$ via on-shell intermediate states. These matrix elements are saturated by tree-diagrams, such as $B_s^0 \rightarrow$...
$D_s^{+(-)}D_s^{-(+)}$, and therefore $\Gamma_s^{CP}$ is expected to be insensitive to new physics. Because there are more CP even than CP odd final states in $B_s^0$ decays, one expects $\Delta \Gamma_s^{CP} \simeq (0.12 \pm 0.06)$ \cite{3}. In the presence of CP violation, one finds a width difference between the mass eigenstates of $\Delta \Gamma_s = \Delta \Gamma_s^{CP} \cos \phi$, where $\phi = \arg (-M_{12}/\Gamma_{12})$, is the difference between the $B_s^0$ mixing phase and the phase of $-\Gamma_{12}$. In the Standard Model, $\phi$ is expected to be small, of order 0.01. Therefore, one expects $\Delta \Gamma_s^{CP} \simeq \Delta \Gamma_s$. Since new physics could affect $B_s^0$ mixing, i.e., the phase of $M_{12}$, new physics could drive $\Delta \Gamma_s$ away from $\Delta \Gamma_s^{CP}$. Precise measurements of $\Delta \Gamma_s^{CP}$ can be obtained by measuring the branching fractions and CP content of final states accessible to $B_s^0$ and $\bar{B}_s^0$. Such final states are dominated by $D_s^{+(-)}D_s^{-(+)}$, but also include $J/\psi \phi$, $J/\psi \eta$, $J/\psi \eta'$, etc. Under certain assumptions \cite{3}, it can be shown that $B_s^0 \rightarrow D_s^{+(-)}D_s^{-(+)}$ is pure CP even, and neglecting the charmonium states, one finds $\Delta \Gamma_s^{CP} / \Gamma_s \simeq 2B(B_s^0 \rightarrow D_s^{+(-)}D_s^{-(+)}).$ With a 50 fb$^{-1}$ $\Upsilon(5S)$ data sample, one would expect $\sim 10$ events in each decay mode \cite{10}, yielding $\sim 25\%$ accuracy on $B(B_s^0 \rightarrow D_s^{+(-)}D_s^{-(+)}).$ If these assumptions are relaxed, one must measure the CP fraction of the various vector-vector final states, which would require substantially larger statistics.

Various rare loop-induced decay modes have been searched for in the Belle data sample, including $B_s^0 \rightarrow J/\psi \phi$, $B_s^0 \rightarrow \phi \phi$, and $B_s^0 \rightarrow K^+K^-$. The limit $B(B_s^0 \rightarrow \gamma \gamma) < 0.53 \times 10^{-4}$, is already more stringent than the current world average.

8. CONCLUSIONS

In summary, we report on measurements of the $B_s^0$ fraction, $f_s$ at CLEO and Belle, and find about 25% of the $\Upsilon(5S)$ decays produce $B_s^0$, predominantly in the form of $B_s^{0\ast} \bar{B}_s^{+\ast}$. We also find a dominance of $B^+\bar{B}^-$ among ordinary $B$ decays. Both of these observations are consistent with the UQM and inconsistent with the QHM. An $e^+e^-$ machine operating at the $\Upsilon(5S)$ produces about 15 million $B_s^0$ per 100 fb$^{-1}$. Studies of decay channels that produce soft photons could provide complementary information to $B_s^0$ studies at hadron machines.

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