Measurements of exclusive $B_s^0$ decays at the $\Upsilon(5S)$ resonance

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INTRODUCTION

A considerable $B^0$ production rate has been recently measured in $e^+e^-$ collisions at the energy of the $\Upsilon(5S)$ resonance [1, 2]. Thus, high luminosity $e^+e^-$ $B$-factories have great potential for studies of exclusive $B^0_s$ decays. Although several $B^0_s$ decay channels have been recently observed by the Tevatron experiments [3, 4], a number of $B^0_s$ decay modes can be better measured at $e^+e^-$ colliders running at the $\Upsilon(5S)$ energy. The detectors taking data at the $\Upsilon(5S)$ have many advantages in studies of $B^0_s$ decays, such as high photon and $\pi^0$ reconstruction efficiency, trigger efficiency of almost 100% for hadronic modes and excellent charged kaon and pion identification. The possibility of partial reconstruction of specific $B^0_s$ decays and a model-independent determination of the number of initial $B^0_s$ mesons, which opens the possibility of precise absolute $B^0_s$ branching fraction measurements, are additional advantages of $B^0_s$ studies at $e^+e^-$ colliders running at the $\Upsilon(5S)$.

In this paper we report measurements of exclusive $B^0_s$ decays based on an $\Upsilon(5S)$ data sample of 1.86 fb$^{-1}$, collected with the Belle detector at the KEKB asymmetric energy $e^+e^-$ collider [4]. This data sample is more than four times larger than the 0.42 fb$^{-1}$ dataset collected at the $\Upsilon(5S)$ by the CLEO experiment in 2003 [5], where first evidence of exclusive $B^0_s$ decays at the $\Upsilon(5S)$ was found.

We fully reconstruct six modes $B^0_s \to D^*_s \pi^+$, $B^0_s \to D^*_s \pi^-$, $B^0_s \to D^*_s \rho^+$, $B^0_s \to D^*_s \rho^-$, $B^0_s \to J/\psi \phi$ and $B^0_s \to J/\psi\eta$, which have large reconstruction efficiencies and are mediated by unsuppressed $b \to c$ tree diagrams. Charge-conjugate modes are implicitly included everywhere in this paper. To improve the statistical significance of the $B^0_s$ signal, these six modes are combined; the masses of the $B^0_s$ and $B^*_{s}$ mesons are determined from a common signal fit.

In addition, we search for several rare $B^0_s$ decays: the penguin annihilation decay $B^0_s \to \gamma\gamma$, the electromagnetic $b \to s$ penguin decay $B^0_s \to \gamma\gamma$, and the hadronic $b \to s$ penguin decay $B^0_s \to K^+K^-$. Although the branching fractions for these decays are expected to be too small to be observed with this dataset, we can obtain useful upper limits. To date, only upper limits for the decays $B^0_s \to \gamma\gamma$ [6] and $B^0_s \to \phi\gamma$ [7] have been published. Within the Standard Model the $B^0_s \to \gamma\gamma$ decay is expected to proceed via a penguin annihilation diagram and to have a branching fraction in the range $(0.5 \pm 1.0) \times 10^{-6}$ [10, 11]. However, this decay is sensitive to some beyond-the-Standard Model (BSM) contributions and can be enhanced by one to two orders of magnitude in some BSM models [12, 13]. Although current measurements of the process $B \to X_s\gamma$ provide a more restrictive constraint for many BSM models, in these models the $B^0_s \to \gamma\gamma$ process is more sensitive.

The decay modes $B^0_s \to \phi\gamma$ and $B^0_s \to K^+K^-$ are also mediated by penguin diagrams; these decays are natural processes in which to search for BSM physics [14, 15, 16, 17, 18]. The decay $B^0_s \to K^+K^-$ has been observed by CDF using a simultaneous multi-channel analysis [19], where overlapping signal peaks from the $B^0_s \to K^+K^-$, $B^0_s \to K^+\pi^-$, $B^0_s \to \pi^+\pi^-$ and $B^0_s \to K^+\pi^+$ decay modes were separated statistically in the fit. In this analysis the ratio $\left(f^+ f^-/f^2\right) \times \mathcal{B}(B^0_s \to K^+K^-)/\mathcal{B}(B^0 \to$
work the relative decay-width difference $\Delta \Gamma_{B^\pm}$ is the ratio of production fractions of $B^0_s$ and $B^0$ at Tevatron center-of-mass energy $\sqrt{s} = 1.96$ TeV.

We have also searched for the $B^0_s \to D^{(*)+}_s D^{(*)-}_s$ decay modes. These decay branching fractions are of special interest \cite{21,22}. These modes are expected to be predominantly $CP$ eigenstates and, because their branch-

ing fractions are expected to be large, they should lead to a sizable lifetime difference between the $CP$-odd and $CP$-even $B^0_s$ mesons. Therefore within the SM framework the relative decay-width difference $\Delta \Gamma_{B^0_s}/\Gamma_{B^0}$ can be obtained from measurement of the $B^0_s \to D^{(*)+}_s D^{(*)-}_s$ branching fractions. The first observation of the $B^0_s \to D^{(*)+}_s D^{(*)-}_s$ decay has recently been published by the CDF collaboration \cite{22}.

**BELLE DETECTOR AND EVENT SELECTION**

The Belle detector operates at KEKB \cite{6}, an asymmetric energy double storage ring designed to collide 8 GeV electrons and 3.5 GeV positrons to produce $\Upsilon(4S)$ mesons with a boost of $\beta\gamma = 0.425$. In this analysis we use a data sample of 1.86 fb$^{-1}$ taken at the $\Upsilon(5S)$ energy of $\sim$10869 MeV with the same boost. The experimental conditions for data taking at the $\Upsilon(5S)$ were identical to those for $\Upsilon(4S)$ or continuum running.

The Belle detector is a general-purpose large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoidal coil with a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect $K^0_L$ mesons and to identify muons (KLM). The detector is described in detail elsewhere \cite{3}. A GEANT-based detailed simulation of the Belle detector is used to produce Monte Carlo event samples (MC) and determine efficiencies.

Charged tracks are required to have momenta greater than 100 MeV/c. Kaon and pion mass hypotheses are assigned based on a likelihood ratio $L_{K^0/\pi} = L_{K}/(L_{K} + L_{\pi})$, obtained by combining information from the CDC ($dE/dx$, ACC, and TOF systems. We require $L_{K^0/\pi} > 0.6$ ($L_{K^0/\pi} < 0.6$) for kaon (pion) candidates \cite{23}. With these requirements, the identification efficiency for particles used in this analysis varies from 86% to 91% (94% to 98%) for kaons (pions). A tighter kaon identification requirement $L_{K^0/\pi} > 0.8$ is applied for the $B^0_s \to K^+ K^-$ decay, where the pion misidentification background is large.

Electrons are identified combining information from the CDC (specific ionization $dE/dx$), the ACC, and the ECL (electromagnetic shower position, shape and energy) \cite{24}. Muons are identified by matching tracks to KLM hits and by using penetration depth information \cite{25}.

ECL clusters with a photon-like shape that are not associated with charged tracks are accepted as photon candidates. Primary candidate photons ($\gamma$) that are used to reconstruct the $B^0_s \to \phi \gamma$ and $B^0_s \to \gamma \gamma$ decays are required to have proper bunch-crossing timing and to lie within the acceptance of the ECL barrel ($33^\circ < \theta_{\gamma} < 128^\circ$). To reduce the background from high-energy $\pi^0$ decays where the two daughter photons have merged into a single cluster in the calorimeter, the ECL energy deposition in a group of 3×3 cells is required to exceed 95% of that in the group of 5×5 cells around the maximum energy cell. The main background sources of high energy photons are $\pi^0 \to \gamma \gamma$ and $\eta \to \gamma \gamma$ decays. To reduce these backgrounds, restrictions are imposed on the invariant mass of the candidate primary photon and any other photon ($\gamma'$) in the event. The primary photon is rejected if 120 MeV/$c^2 < M(\gamma \gamma') < 145$ MeV/$c^2$ and $E_{\gamma'} > 30$ MeV, or if 510 MeV/$c^2 < M(\gamma \gamma') < 570$ MeV/$c^2$ and $E_{\gamma'} > 200$ MeV.

Neutral pion candidates are formed from pairs of photons, each with energy greater than 150 MeV; the photons must have an invariant mass within ±15 MeV/$c^2$ of the nominal $\pi^0$ mass (i.e. $\sim 3\sigma$, where $\sigma \sim 5$ MeV/$c^2$ is the $\pi^0$ mass resolution). A mass-constrained kinematic fit is performed on the $\pi^0$ candidates to improve their energy resolution. We reconstruct $\eta$ mesons only in the clean $\eta \to \gamma \gamma$ mode, requiring an invariant mass within ±20 MeV/$c^2$ ($\sim 2\sigma$) of the nominal $\eta$ mass and photon energies larger than 50 MeV. $K^0_S$ candidates are formed from $\pi^+ \pi^-$ pairs with an invariant mass within ±10 MeV/$c^2$ ($\sim 3\sigma$) of the nominal $K^0_S$ mass and having a common vertex displaced from the interaction point by more than 0.1 cm in the plane perpendicular to the beam direction.

The invariant mass for $K^{*0} \to K^+ \pi^-$ candidates is required to be within ±50 MeV/$c^2$ of the nominal $K^{*0}$ mass; those of $\phi \to K^+ K^-$ candidates, within ±12 MeV/$c^2$ of the $\phi$ mass. A ±100 MeV/$c^2$ mass window is used to select $\rho^+ \to \pi^+ \pi^0$ candidates. $D_s^-$ mesons are reconstructed in the $\phi \pi^-$, $K^{*0} K^- \text{ and } K^0_S K^- \text{ decay channels}$; all candidates must have a mass within ±10 MeV/$c^2$ ($\sim 2.5\sigma$) of the nominal $D_s^-$ mass. The $D_s^-$ helicity angle distributions are expected to be proportional to $\cos^2 \theta_{D_s^0}^{\text{hel}}$ for pseudoscalar-vector final states; thus a $|\cos \theta_{D_s^0}^{\text{hel}}| > 0.25$ requirement is applied for the $D_s^- \to \phi \pi^-$ and $D_s^- \to K^{*0} K^-$ decays. The helicity angle $\theta_{D_s^0}^{\text{hel}}$ is defined as the angle between the directions of the $K^-$ and $D_s^-$ momenta in the $\phi$ rest frame (or the directions of the $\pi^-$ and $D_s^-$ momenta in the $K^{*0}$ rest frame in the case of $K^{*0} K^-$ decay).

$D_s^-$ candidates are reconstructed in the $D_s^- \to D_s^- \gamma$ mode; the measured $D_s^-$ and $D_s^-$ mass difference is re-
The ratio of the second to the zeroth Fox-Wolfram moments is required to be within \( \pm 10 \text{MeV}/c^2 \) of its nominal value. The invariant mass of candidate \( J/\psi \) mesons is required to satisfy \( |M(\mu^+\mu^-) - m_{J/\psi}| < 30 \text{MeV}/c^2 \) for the muon decay mode and satisfy \( -100 \text{MeV}/c^2 < M(e^+e^-) - m_{J/\psi} < 30 \text{MeV}/c^2 \) for the electron decay mode, where \( m_{J/\psi} \) is the nominal \( J/\psi \) mass.

\( B_s^0 \) decays are reconstructed in the following final states: \( D_s^-\pi^+, D_s^-\rho^+, D_s^-\pi^-, D_s^-\rho^+, J/\psi\phi, J/\psi\eta, D_s^{(*)+}\bar{D}_s^{(*)-}, K^+K^-\phi, \gamma\gamma, \) and \( \gamma\gamma \). The signals can be observed using two variables: the energy difference \( \Delta E = E_{BC}^M - E_{BC}^{CM} \) and the beam-energy-constrained mass \( M_{bc} = \sqrt{(E_{BC}^{CM})^2 - (p_{BC}^{CM})^2} \), where \( E_{BC}^{CM} \) and \( p_{BC}^{CM} \) are the energy and momentum of the \( B_s^0 \) candidate in the \( e^+e^- \) center-of-mass (CM) system, and \( E_{beam} \) is the CM beam energy. The \( B_s^0 \) mesons can be produced in \( e^+e^- \) collisions at the \( \Upsilon(5S) \) energy via intermediate \( B_s^0\bar{B}_s^0 \), \( B_s^0\bar{B}_s^0 \), \( B_s^0\bar{B}_s^0 \), and \( B_s^0\bar{B}_s^0 \) channels, with \( B_s^0 \to B_s^0 \gamma \). These intermediate channels can be distinguished kinematically in the \( M_{bc} \) and \( \Delta E \) plane, where three well-separated \( B_s^0 \) signal regions can be defined corresponding to the cases where both, only one, or neither of the \( B_s^0 \) mesons originate from a \( B_s^0 \) decay. The events obtained from MC simulation of the \( B_s^0 \to D_s^-\pi^+ \) decay are shown in Fig. 1 for the intermediate \( \Upsilon(5S) \) decay channels \( B_s^0\bar{B}_s^0 \), \( B_s^0\bar{B}_s^0 \), and \( B_s^0\bar{B}_s^0 \). The signal regions are defined as ellipses corresponding to \( \pm(2.0-2.5)\sigma \) (i.e. \((95-98)\%\) acceptance) resolution intervals in \( M_{bc} \) and \( \Delta E \). The signal events from the different intermediate channels are well separated in the \( M_{bc} \) and \( \Delta E \) plane. MC simulation shows that the separation between the channels in the \( M_{bc} \) projection is \( \sim 3\sigma \) or better for all studied \( B_s^0 \) decays. Elliptical regions do not describe well the signal shape in the case of \( B_s^0 \) decays to the final states with photons or electrons, because the radiative energy losses result in a long tail on the left side of the signal \( \Delta E \) distribution. In such decay modes the acceptance of the elliptical signal regions decreases to \((70-80)\%\). A MC simulation indicates that the correlation between the \( M_{bc} \) and \( \Delta E \) variables is small and can be neglected in this analysis. The numbers of events inside and outside these elliptical regions can be used to estimate the number of \( B_s^0 \) signal and background events.

After all selections the dominant background is from \( e^+e^- \to q\bar{q} \) continuum events (\( q = u, d, s, \) or \( c \)). Topologically, \( B_s^0 \) events are expected to be spherical, whereas continuum events are expected to be jet-like. To suppress continuum background, we apply topological cuts. These were optimized using MC to model the signal and data outside the \( B_s^0 \) signal regions to estimate background. The ratio of the second to the zeroth Fox-Wolfram moments is required to be less than 0.3 for the high background \( D_s^{(*)-}\pi^+, D_s^{(*)-}\rho^+ \) and \( K^+K^- \) final states, less than 0.5 for the \( \gamma\gamma \) final state (to increase the signal efficiency of such non-spherical \( B_s^0 \) decays) and less than 0.4 for all the other final states. To suppress continuum further, the angle \( \theta_{thr}^{B_s^0} \) in the CM between the thrust axis of the particles forming the \( B_s^0 \) candidate and the thrust axis of all other particles in the event is used. We require \( |\cos\theta_{thr}^{B_s^0}| < 0.9 \) for the low background final states with a \( J/\psi, |\cos\theta_{thr}^{\mu\mu}| < 0.7 \) for the \( D_s^{(*)-}\rho^+ \) final states, \( |\cos\theta_{thr}^{\gamma\gamma}| < 0.6 \) for \( B_s^0 \) events reconstructed using the \( D_s^- \to K^{*0}K^- \) decay mode, \( |\cos\theta_{thr}^{\gamma\gamma}| < 0.5 \) for the very high background \( K^+K^- \) final state, and \( |\cos\theta_{thr}^{\gamma\gamma}| < 0.8 \) for all the other final states.

More than one \( B_s^0 \) candidate per event can be selected. Using MC simulation we find that \( B_s^0 \) decays to channels with \( D_s^- \) or \( D_s^{(*)-} \) mesons can produce incorrect candidates reconstructed in a cross-channel. Because the photon from the \( D_s^- \to D_s^-\gamma \) decay has a low energy, this photon can be removed from the \( B_s^0 \) reconstruction resulting in the replacement of an original \( D_s^- \) by its daughter \( D_s^- \) or, conversely, an original \( D_s^- \) meson can be combined with a random photon to produce a false \( D_s^- \) candidate. For example, every \( B_s^0 \to D_s^-\pi^+ \) decay will produce an incorrect \( B_s^0 \to D_s^+\pi^- \) candidate and \( \sim 37\% \) of \( B_s^0 \to D_s^-\pi^+ \) decays will produce incorrect \( B_s^0 \to D_s^+\pi^- \) candidates. Moreover, multiple candidates can be reconstructed in the \( B_s^0 \to D_s^-\pi^+ \) decay mode if the original photon from the \( D_s^- \) decay is replaced by a random photon that satisfies the \( D_s^- \) mass window requirement. The \( M_{bc} \) distribution of incorrectly reconstructed \( B_s^0 \) candidates has the same central value as the original signal, but the width is slightly larger. However, the \( \Delta E \) distribution of these incorrectly reconstructed \( B_s^0 \) candidates is \((200-300)\text{MeV}\) wide and shifted to negative values if the correct photon is lost and to positive values when a random photon is added.

We checked the effects of incorrectly reconstructed \( B_s^0 \) candidates on the results of the measurements reported in the next section.
in this paper. Because of the large spread in the $\Delta E$ distribution of the incorrectly reconstructed candidates and the low statistics used in this analysis, these effects are found to be small and are neglected; the corresponding uncertainties are included in the systematic error. We also checked other sources of multiple candidates in all studied decay modes and found that these effects can be neglected in the $M_{bc}$ and $\Delta E$ measurements presented below. It should be noted that the MC efficiency calculations also include multiple candidates and, therefore, a corresponding correction for this effect is applied.

**STUDY OF $B^0_s \to D_s^{(*)}\pi^+$, $B^0_s \to D_s^{(*)}\rho^+$, $B^0_s \to J/\psi\phi$ AND $\bar{B}^0_s \to J/\psi\eta$ DECAYS**

The $M_{bc}$ versus $\Delta E$ distribution for the $B^0_s \to D_s^-\pi^+$ candidates is shown in Fig. 2a. Nine events are observed within the elliptical signal region corresponding to the $B^+_s\bar{B}^-_s$ pair production channel. Only one event is observed in the signal region for the $B^+_s\bar{B}^-_s + B^0_s\bar{B}^+_s$ channels, and no events are observed for the $B^0_s\bar{B}^+_s$ channel. Background outside the signal regions is small and corresponds to $\sim 0.1$ events in each of the three signal regions. The total number of $bb$ events in the sample and the fraction of $B_s^{(*)}\bar{B}_s^{(*)}$ events among all $bb$ events at the $\Upsilon(5S)$ have been determined in [2] to be $N_{bb} = (5.61 \pm 0.03_{\text{stat}} \pm 0.29_{\text{syst}}) \times 10^5$ and $f_s = (18.0 \pm 1.3 \pm 3.2\%)$, respectively. We assume that 100% of $B_s^*$ mesons decay to the ground state $B^0_s$. From the 10 observed events, the background estimate of 0.3 events, and the full reconstruction efficiency of $(0.71 \pm 0.10\%)$ (intermediate branching fractions are included), we measure the branching fraction $B(B^0_s \to D_s^-\pi^+) = (0.68 \pm 0.22 \pm 0.16\%)$. The systematic uncertainty includes the $N_{bb}^s$ and $f_s$ uncertainties and the uncertainty of $\sim 14\%$ in the reconstruction efficiency, which is dominated by the uncertainty in the value of $B(D_s^- \to \phi\pi^-)$. This branching fraction is consistent with the value $B(B^0_s \to D_s^-\pi^+) = (0.38 \pm 0.05 \pm 0.14\%)$ derived from a CDF measurement of $B(B^0_s \to D_s^-\pi^+)/B(B^0_s \to D^-\pi^+)\ [27]$ using the 2006 PDG values of the $B^0 \to D^-\pi^+$ and $D_s^- \to \phi\pi^-$ branching fractions [28].

$M_{bc}$ and $\Delta E$ scatterplots are also obtained for the $B^0_s \to D_s^-\pi^+$ (Fig. 2b) and $B^0_s \to D_s^{(*)}\rho^+$ (Fig. 2c) decay modes. We observe four $B^0_s \to D_s^-\pi^+$ candidates and seven $B^0_s \to D_s^{(*)}\rho^+$ candidates in the $B^+_s\bar{B}^-_s$ channel, one $B^0_s \to D_s^{(*)}\rho^+$ candidate in the $B^+_s\bar{B}^-_s + B^0_s\bar{B}^+_s$ channel, and no candidates in the $B^0_s\bar{B}^+_s$ channel. The scatterplot in $M_{bc}$ and $\Delta E$ for the $B^0_s \to J/\psi\phi$ and $\bar{B}^0_s \to J/\psi\eta$ decays is shown in Fig. 2d. Two candidates are reconstructed in the $B^0_s \to J/\psi\phi$ mode and one candidate is reconstructed in the $B^0_s \to J/\psi\eta$ mode. One of the observed $B^0_s \to J/\psi\phi$ candidates is reconstructed in the $J/\psi \to \mu^+\mu^-$ mode and one in the $J/\psi \to e^+e^-$ mode. As a cross-check, the branching fraction $B(B^0_s \to J/\psi\phi) = (0.9 \pm 0.6 \pm 0.2) \times 10^{-3}$ is obtained for these two candidates, which agrees with the CDF measurement [29] within the large errors. The numbers of $B^0_s$ candidates reconstructed in the $D_s^-\pi^+$, $D_s^-\rho^+$, $D_s^{(*)}\rho^+$, $J/\psi\phi$ and $J/\psi\eta$ decay modes and lying in the signal region corresponding to the $B^+_s\bar{B}^-_s$ channel are listed in Table I. In addition, the numbers of events reconstructed in the three $D_s^-$ decay modes are shown separately.

**TABLE I: The number of the $B^0_s$ candidates located within the elliptical signal region corresponding to the $B^+_s\bar{B}^-_s$ channel.**

| Decay mode | $D_s^- \to \phi\pi^-$ | $K^{*0}K^-K^-\bar{K}^0K^-$ | Sum |
|------------|----------------------|-----------------------------|-----|
| $B^0_s$    | $D_s^- \to \phi\pi^-$ | 4              | 2   | 3  | 9  |
| $B^0_s$    | $D_s^- \to D_s^-\pi^+$ | 2              | 1   | 1  | 4  |
| $B^0_s$    | $D_s^- \to D_s^-\rho^+$ | 4              | 1   | 0  | 3  |
| $B^0_s$    | $D_s^- \to D_s^-\rho^+$ | 2              | 2   | 0  | 4  |
| $B^0_s$    | $B^0_s \to J/\psi\phi$ | 0              | 2   | 0  | 2  |
| $B^0_s$    | $B^0_s \to J/\psi\eta$ | 0              | 1   | 0  | 1  |

Although the $M_{bc}$ and $\Delta E$ signal significances of the $B^0_s$ signal. Distributions in $\Delta E$ are obtained separately for events from three $M_{bc}$ intervals, $5.408\text{GeV}/c^2 < M_{bc} < 5.429\text{GeV}/c^2$ (Fig. 3a), $5.384\text{GeV}/c^2 < M_{bc} < 5.405\text{GeV}/c^2$ (Fig. 3b) and $5.360\text{GeV}/c^2 < M_{bc} < 5.380\text{GeV}/c^2$ (Fig. 3c), corresponding to $B_s^0$ production proceeding through the $B^+_s\bar{B}_s^-$, $B^+_s\bar{B}_s^0 + B^0_s\bar{B}_s^+$ or $B^0_s\bar{B}_s^0$ channels, respectively.

Each of these three distributions is fitted with the sum of a Gaussian to describe the signal and a linear function to describe the background. In the $B^+_s\bar{B}_s^-$ channel (Fig. 3a), the width and the peak position are allowed to float, and their values $\sigma_{\Delta E} = (10.2 \pm 1.9)\text{MeV}$ and $\langle \Delta E \rangle = (-47.6 \pm 2.6)\text{MeV}$, respectively, are obtained from the fit. The width agrees with the value of $\sim 12\text{MeV}$ obtained from a MC simulation of the dominant $B^0_s \to D_s^-\pi^+$ decay channel. Due to low statistics in the other two distributions, the peak positions and widths are fixed. The widths are taken from MC simulations. The peak position is fixed to zero for the $B^0_s\bar{B}_s^0$ channel and that for the $B^+_s\bar{B}_s^0 + B^0_s\bar{B}_s^+$ channel is fixed to $-23.8\text{MeV}$, which is half of the value obtained for the $\langle \Delta E \rangle$ peak position in the $B^+_s\bar{B}_s^-$ channel. The
fits yield 20.3 ± 4.8 events and 1.5 ± 2.0 events for the $B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0$ channels, respectively; no events are observed in the $B_s^0; B_s^0; B_s^0$. From these numbers and approximately equal $B_s^0$ reconstruction efficiency in these three channels found in MC simulation, we obtain the ratio $\sigma(e^+e^- \to B_s^0; B_s^0)/\rho(e^+e^- \to B_s^0; B_s^0)$ = (93 ± 5)% at the $\Upsilon(5S)$ energy. The first uncertainty is statistical and the second uncertainty is systematic, dominated by uncertainties in the fit procedure. Potential models predict the fraction of $B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0$ production to be around 70% [34,31,32].

The $B_s^0$ mass can be extracted from fit to the $M_{bc}$ distribution of the observed events in the $B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0$ channel. In this channel the $M_{bc}$ variable, calculated from the formula $M_{bc} = \sqrt{(E_{beam}^{CM})^2 - (p_{B_s^0}^{CM})^2}$, is equal, to a good approximation, to the mass of $B_s^0$ meson. This follows from the fact that the difference between the $B_s^0$ and $B_s^0$ momenta is statistically unbiased from zero and is smaller than the experimental resolution in $B_s^0$ momentum. Figure 4 shows the $M_{bc}$ distribution of the candidates in the range $-80 \text{ MeV} < \Delta E < -20 \text{ MeV}$, where signal events from the $B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0$ production channel are expected. We fit this distribution with the sum of a Gaussian to describe the signal and a so-called ARGUS function [33] to describe the background. The fit yields a mass value of $M(B_s^0) = (5418.7 ± 1.3) \text{ MeV}/c^2$. The large systematic error is dominated by the uncertainty in the collider beam energy calibration resulting in a $e^+e^- \text{ CM}$ beam energy uncertainty of $\sim 3 \text{ MeV}$. The uncertainty of the method used to determine the $M(B_s^0)$ mass is estimated by MC simulation to be around $0.5 \text{ MeV}/c^2$. The uncertainty in the particle momenta measurements translated to the $M(B_s^0)$ mass uncertainty is also around $0.5 \text{ MeV}/c^2$. The observed width of the $B_s^0$ signal is $(3.6 ± 0.6) \text{ MeV}/c^2$ and agrees with the value obtained from the MC simulation, which assumes zero natural width and is dominated by the KEKB energy spread. The obtained $B_s^0$ mass is 1.8σ higher than the value measured recently by CLEO [34], $M(B_s^0) = (5411.7 ± 1.6 ± 0.6) \text{ MeV}/c^2$. 

FIG. 4: The $B_s^0$ mass distribution for events within the $-80 \text{ MeV} < \Delta E < -20 \text{ MeV}$ interval, where the $B_s^0$ signal from the $B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0; B_s^0$ channel is expected. Curve represents the result of the fit described in the text.
calculate the $B_0^0$ mass. The value $\langle \Delta E \rangle$ is the mean energy difference between the $B_0^0$ and $B_s^0$ mesons in the CM system and, in a good approximation, is equal to the mass difference of the $B_0^0$ and $B_s^0$ mesons. The photon energy in the $B_s^0 \rightarrow B_s^\pm \gamma$ decay is a constant in the $B_s^0$ rest frame, and the smearing due to the Lorentz transformation from the $B_s^0$ rest frame to the CM rest frame is small compared with the central value of the photon energy. Finally we obtain a mass value of $M(B_0^0) = (5370 \pm 1 \pm 3) \text{MeV}/c^2$. The second uncertainty in the $B_0^0$ mass value is the systematic uncertainty dominated by the statistical uncertainty on the $\langle \Delta E \rangle$ measurement, which will improve once more statistics become available. The uncertainty due to the collider beam energy calibration almost linearly affects both the $M(B_s^0)$ and $\langle \Delta E \rangle$ values and nearly cancels in the $M(B_s^0)$ mass calculations. Other systematic uncertainties affecting the $B_0^0$ mass are similar to those in the $B_s^0$ mass measurement and are small. The obtained $B_0^0$ mass agrees well with the PDG value, $M(B_0^0) = (5369.6 \pm 2.4) \text{MeV}/c^2$ \cite{38}, and the most recent CDF measurement, $M(B_0^0) = (5366.01 \pm 0.73 \pm 0.33) \text{MeV}/c^2$ \cite{39}.

**SEARCH FOR $B_0^0 \rightarrow \gamma \gamma$, $B_0^0 \rightarrow \phi \gamma$, $B_0^0 \rightarrow K^+ K^-$, AND $B_S^0 \rightarrow D_S^{(*)+} D_S^{(*)-}$ DECAYS**

Distributions in $M_{bc}$ and $\Delta E$ are also obtained for the reconstructed $B_0^0 \rightarrow \gamma \gamma$ (Fig. 5a), $B_0^0 \rightarrow \phi \gamma$ (Fig. 5b), $B_0^0 \rightarrow K^+ K^-$ (Fig. 5c) and $B_0^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$ (Fig. 5d) candidates. Only the $B_0^0$ signal regions corresponding to the dominant $B_0^0 \rightarrow D_+ D_0^-$ channel are considered for the searches reported here. These regions are wider for the $B_0^0 \rightarrow \phi \gamma$ and $B_0^0 \rightarrow \gamma \gamma$ decays, where energy losses due to photon radiation lead to a large tail at lower values of $\Delta E$. The signal region for the $B_0^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$ search is slightly smaller, because of the kinematics of the decay to two heavy particles. The shapes of the signal regions for these decays are optimized from the MC simulation.

To avoid multiple $D_s^+$ and $D_s^-$ cross-channel candidates, only one candidate per event is selected in the $B_0^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$ analysis, where the number of multiple candidates can be rather large. The candidate with the $M_{bc}$ value closest to the nominal $M(B_s^0)$ value measured above is chosen. No significant signals are observed in any of the distributions shown in Fig. 5. However one $B_0^0 \rightarrow \phi \gamma$ event, two $B_0^0 \rightarrow K^+ K^-$ events and one $B_0^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$ event lie within the signal regions, whereas backgrounds outside the signal regions are not large. The numbers of events within the signal regions, the estimated background contributions, the efficiencies, and the upper limits for the corresponding $B_0^0$ branching fractions are listed in Table II. For comparison, the previously published upper limits and branching fractions are also shown. The numbers of events and the upper limits are obtained using only the $B_s$ signal region corresponding to the $B_s^0 \bar{B}_s^0$ channel. The upper limits are obtained using the Feldman-Cousins method \cite{32}, and a small correction due to systematic uncertainties is applied. The efficiencies are determined from the MC simulation. The number of initial $B_s^0 \bar{B}_s^0$ pairs is obtained by multiplying the number of $B_s^{(*)} \bar{B}_s^{(*)}$ pairs measured in the inclusive analysis \cite{2} by the production ratio of $B_s^0 \bar{B}_s^0$ pairs to all $B_s^{(*)} \bar{B}_s^{(*)}$ pairs obtained in this analysis. We calculated the previous $B_s^0 \rightarrow D_s^+ D_s^-$ branching fraction listed in Table II using the measurement $B(B_s^0 \rightarrow D_s^+ D_s^-)/B(B_0^0 \rightarrow D_s^+ D_s^-) = 1.67 \pm 0.41 \pm 0.47$ from CDF \cite{22} and the $B(B_0^0 \rightarrow D_s^+ D^-)$ value from the PDG \cite{28}.

The upper limit obtained for the decay $B_0^0 \rightarrow \gamma \gamma$ is about three times smaller than the most restrictive published limit \cite{33}. However, it is still two orders of magnitude above SM predictions \cite{10,11}. The upper limit obtained for $B_0^0 \rightarrow \phi \gamma$ is about a factor ten larger than the theoretically expected branching fraction \cite{51}. The upper limit obtained for the $B_0^0 \rightarrow K^+ K^-$ decay is an order of magnitude larger than the value measured by CDF \cite{19}. For SM branching fractions, statistically significant signals of $\sim 10$ events can be obtained for the $B_0^0 \rightarrow \phi \gamma$ and $B_0^0 \rightarrow K^+ K^-$ modes in a $\sim 30 fb^{-1}$ dataset on the $\Upsilon(5S)$.

The upper limits obtained for $B_0^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$ decays are of special interest because the $D_s^{(*)+} D_s^{(*)-}$ states are expected to be dominantly $CP$ eigenstates. Assuming that the branching fractions for the $D_s^{(*)+} D_s^{(*)-}$, $D_s^+ D_s^-$, $D_s^- D_s^+$ and $D_s^+ D_s^-$ final states are each in the range (1–3)%, we expect about 5–10 events in each of these four channels with statistics of $\sim 30 fb^{-1}$. Within the SM framework such measurements can provide an important constraint on the value of $\Delta \Gamma_B / \Gamma_B$ \cite{20,21}.

**CONCLUSIONS**

Several exclusive $B_0^0$ decays are reconstructed using 1.86 fb$^{-1}$ of data taken at the $\Upsilon(5S)$ resonance with the Belle detector at the KEKB asymmetric energy $e^+ e^-$ collider.

$B_0^0$ signals are found in six decay modes: $B_0^0 \rightarrow D_s^{(*)-} \pi^+$, $B_0^0 \rightarrow D_s^{(*)-} \rho^+$, $B_0^0 \rightarrow J/\psi \phi$ and $B_0^0 \rightarrow J/\psi \rho$. The branching fraction $B(B_0^0 \rightarrow D^- \pi^+) = (0.68 \pm 0.22 \pm 0.16)\%$ is measured. Combined the studied six channels, we observe a significant $B_s^0$ signal and obtain the masses $M(B_s^0) = (5370 \pm 1 \pm 3) \text{MeV}/c^2$ and $M(B_s^0) = (5418 \pm 1 \pm 3) \text{MeV}/c^2$. $B_s^0$ production through the $B_s^0 \bar{B}_s^0$ channel is found to dominate over other $B_s^{(*)} \bar{B}_s^{(*)}$ channels; the ratio $\sigma(e^+ e^- \rightarrow B_s^0 \bar{B}_s^0)/\sigma(e^+ e^- \rightarrow B_s^{(*)} \bar{B}_s^{(*)}) = (93 \pm 7 \pm 1)\%$ is measured.

These results are in agreement with CLEO measurements \cite{7}.
FIG. 5: The scatter plots in $M_{Bc}$ and $\Delta E$ for the $B^0 \to \gamma\gamma$ (a), $B^0 \to \phi\gamma$ (b), $B^0_s \to K^+K^-$ (c) and $B^0 \to D^{(*)+}D^{(*)-}$ (d) decay modes. In the latter case, the signal event is reconstructed in the $B^0 \to D^{(*)+}D^{(*)-}$ decay mode, while the three background events are reconstructed in the $B^0_s \to D^{(*)+}D^{(*)-}$ decay mode. The ellipses indicate the $B^0_s$ signal regions for the $B^0_s \bar{B}^0_s$ channel.

TABLE II: The number of events in the signal region (Yield), the estimated background contribution (Bkg.), the efficiencies (Eff.), the 90% C.L. upper limits derived in this analysis (Belle upper limit) and previously published upper limits or branching fractions (Previous UL/BF) for the $B^0 \to \gamma\gamma$, $B^0 \to \phi\gamma$, $B^0_s \to K^+K^-$ and $B^0 \to D^{(*)+}D^{(*)-}$ decay modes.

| Decay mode | Yield (events) | Bkg. (events) | Eff. (%) | Belle upper limit | Previous UL/BF |
|------------|----------------|---------------|---------|------------------|-----------------|
| $B^0 \to \gamma\gamma$ | 0 | 0.5 | 20.0 | $<0.53 \times 10^{-4}$ | $<1.48 \times 10^{-4}$ [8] |
| $B^0 \to \phi\gamma$ | 1 | 0.15 | 5.9 | $<3.9 \times 10^{-4}$ | $<1.2 \times 10^{-4}$ [9] |
| $B^0 \to K^+K^-$ | 2 | 0.16 | 9.8 | $<3.1 \times 10^{-4}$ | $(3.30 \pm 0.57 \pm 0.67) \times 10^{-5}$ [10] |
| $B^0 \to D^{(*)+}D^{(*)-}$ | 0 | 0.02 | 0.020 | $<6.7\%$ | $(1.09 \pm 0.27 \pm 0.47)\%$ [22] |
| $B^0_s \to D^{(*)+}\bar{D}^{(*)-}$ | 1 | 0.01 | 0.0099 | $<12.1\%$ | - |
| $B^0_s \to D^{(*)+}\bar{D}^{(*)-}$ | 0 | $<0.01$ | 0.0052 | $<25.7\%$ | - |

We have also searched for $B^0_s \to \gamma\gamma$, $B^0 \to \phi\gamma$, $B^0 \to K^+K^-$ and $B^0 \to D^{(*)+}D^{(*)-}$ decay modes and set upper limits on their branching fractions. The upper limit on $B^0 \to \gamma\gamma$ is three times more restrictive than the best existing limit. The background levels in these decays are low, indicating that the sensitivity of future studies of these decays with larger statistics will not be limited by backgrounds. We expect that significant signals for $B^0 \to K^+K^-$, $B^0 \to \phi\gamma$ and $B^0 \to D^{(*)+}D^{(*)-}$ decays can be observed in $\sim$30 fb$^{-1}$ of data. With such statistics the upper limit for the $B^0 \to \gamma\gamma$ decay should provide an important constraint on some BSM models.

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