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# HEAVY QUARK PRODUCTION AND DECAY IN THE UPSILON REGION: RESULTS FROM BELLE *

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$b$- and $c$-quarks are produced in abundance at the KEKB asymmetric $e^+e^-$ collider, and the events are detected with high efficiency by the Belle detector. Some of the recent results from Belle that pertain to heavy quark spectroscopy and decay phenomena are presented, including the observation of $\eta_c'$, a comparison among exclusive B meson decays to final states that include the various charmonia, charmonium and double charm production on the $e^+e^-$ continuum, and decays of $B$ mesons to $\eta'$.

Electron-positron annihilation in the Upsilon region provides a relatively clean environment for the study of heavy quarks. At the Belle experiment, integrated luminosity is accumulated at or just below the $\Upsilon$(4S) resonance, the first of the $\Upsilon$ states that is above $B\bar{B}$ production threshold. As the $b$-quark couples predominantly to $c$, $\Upsilon$(4S) events may be viewed as a source of $c$-quarks and a laboratory for charm spectroscopy. In addition to $e^+e^- \rightarrow \Upsilon$(4S)$\rightarrow B\bar{B}$, continuum $e^+e^- \rightarrow c\bar{c}$ events are produced with a cross section $\sim 1$ nb. In both cases one has a large and well-known production fraction and a clear final state, prior to fragmentation or decay.

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## Belle and KEKB

At KEKB,[1] 3.5 GeV positrons collide with 8.0 GeV electrons, producing annihilations at the $\Upsilon$(4S) mass with a center-of-mass that is traveling in the lab frame with $\gamma\beta = 0.425$. Unless stated otherwise, all event and particle momenta are transformed to the center-of-mass frame for analysis. As of August 2002, the Belle experiment[2] has accumulated 89.6 fb$^{-1}$ of integrated luminosity at the $\Upsilon$(4S) and 9.0 fb$^{-1}$ at a lower energy, below $B\bar{B}$ threshold. This corresponds to a sample of approximately $9\times10^7$ $B\bar{B}$ events and the same order of continuum charm events. The results presented here have been published in the past year and are based on analyses of various fractions of this dataset.

## Prompt $J/\psi$ production

The process or processes governing the fragmentation of $e^+e^- \to c\bar{c}$ events to charmonium is not well understood. Non-relativistic quantum chromodynamics (NRQCD)[3] is a formalism developed to explain an excess of $\psi$(2S) production at the Tevatron, and our measurement of $e^+e^- \to$ charmonium[4] constitutes the first test of NRQCD applied to $e^+e^-$ production in the Upsilon region. NRQCD predicts that the prompt production of charmonium is dominated by $J/\psi gg$ ("2-gluon radiation") with additional contributions of order 10% from $J/\psi g$ and $J/\psi c\bar{c}$ and a total rate in the range 0.7-1.7 pb. The three processes yield distinct momentum and polarization distributions, so these should be a sensitive indicator of the underlying processes.

Belle has examined $J/\psi$, $\psi$(2S), $\chi_{c1}$, and $\chi_{c2}$ and reported measurements on the first two,[4] based on 29.4 fb$^{-1}$ of data collected at the $\Upsilon(4S)$ and 3.0 fb$^{-1}$ collected at a lower energy. The observed $\psi$(2S) momentum distribution is used to derive the contribution to $J/\psi$ from $\psi$(2S), which is then subtracted from the observed $J/\psi$ signal to extract the direct part. This subtraction can be done meaningfully only for momenta above the kinematic limit for $J/\psi$ production from $B$ decay, 2.0 $GeV < p^*_{J/\psi} < p^*_{max}$, where the entire dataset may be used. The measured distributions are shown in Figure 1. The $J/\psi$ distribution is found to be softer than the NRQCD prediction for the $J/\psi gg$ process and is more consistent with the color-singlet $J/\psi c\bar{c}$. There is no evidence for an increase at the endpoint from quasi-two-body color-octet $J/\psi g$. We also measure the distribution of $J/\psi$ production and decay angles as a function of momentum, with no correction for the $\psi$(2S) contribution. No significant dependence of polarization parameters on momentum is seen.

Figure 1. Momentum distributions of prompt charmonia, corrected for efficiency: (a) $J/\psi$ (filled points) and $J/\psi$ from $\psi$(2S)$\rightarrow J/\psi X$ (open points); (b) $\psi$(2S).

## Double $c\bar{c}$ production

As the prompt $J/\psi$ result cannot differentiate strongly between $J/\psi gg$ and $J/\psi c\bar{c}$, a direct search for $J/\psi c\bar{c}$ provides additional information. We have performed this search, both by looking at the missing mass recoiling against prompt $J/\psi$ candidates and by searching for associated $D^{(*)}$ mesons.[5] The recoiling mass is calculated from the $J/\psi$ candidate's momentum and energy. Its resolution is improved nearly a factor of two by performing a mass-constrained fit on the $J/\psi$ candidate before calculating the missing mass. The resulting spectrum (Figure 2) shows three peaks, which may be interpreted as $\eta_c$, $\chi_{c0}$, and $\eta_c$(2S); $e^+e^- \rightarrow \gamma^* \rightarrow J/\psi J/\psi$ is forbidden by $C$ symmetry. Only the peak corresponding to $\eta_c$ is sufficiently significant that we report a cross section, $\sigma(e^+e^- \rightarrow J/\psi \eta_c(\gamma)) \times \mathcal{B}(\eta_c \rightarrow \geq 4 \text{ charged}) = 0.33^{+0.007}_{-0.006} \pm 0.009$ pb, where the acceptance is limited by our criterion of requiring at least 5 charged tracks, and we report the limited result due to the uncertainties in current knowledge of the $\eta_c$.

We have searched for associated charm in $J/\psi$ candidate events by reconstructing the following channels: $D^{*+} \rightarrow D^0\pi^+$ $\{D^0 \rightarrow K^-\pi^+, K^-K^+, K^-\pi^-\pi^+\pi^+, K_S\pi^+\pi^-, K^-\pi^+\pi^0\}$, $D^0 \rightarrow K^-\pi^+, K^-K^+$. Both $D^*$ and $D$ are seen, with $5.3\sigma$ and $3.7\sigma$ significance, respectively. We report $\sigma(e^+e^- \rightarrow J/\psi D^{*+}X) = 0.53^{+0.19}_{-0.15} \pm 0.14$ pb and $\sigma(e^+e^- \rightarrow J/\psi D^0 X)$

Figure 2. (a) The recoil mass distribution for the $J/\psi$ signal region (points) and scaled sidebands (shaded). The inset shows the reconstruction efficiency for $e^+e^- \to J/\psi q\bar{q}$ ($q = u, d, s$; open circles) and $e^+e^- \to J/\psi c\bar{c}$ events (closed circles). (b) The recoil mass distribution after refitting the $J/\psi$ candidate with a mass constraint for signal (points) and scaled sidebands (hatched histogram), with fitted curve.

$= 0.87^{+0.32}_{-0.28} \pm 0.20$ pb. Using the Lund model expectations for $c\bar{c}$ fragmentation we infer, respectively, $\sigma(e^+e^- \to J/\psi c\bar{c}) = 1.01^{+0.36}_{-0.30} \pm 0.26$ pb and $\sigma(e^+e^- \to J/\psi c\bar{c}) = 0.74^{+0.28}_{-0.24} \pm 0.19$ pb, which are consistent with each other and are averaged to obtain $\sigma(e^+e^- \to J/\psi c\bar{c}) = 0.87^{+0.21}_{-0.19} \pm 0.17$ pb. The fraction of prompt direct $J/\psi$ that proceeds via $J/\psi c\bar{c}$ is $0.59^{+0.15}_{-0.13} \pm 0.12$. We conclude that this is not consistent with published estimates based on NRQCD. Our results are based on 41.8 fb$^{-1}$ of data collected at the $\Upsilon(4S)$ and 4.4 fb$^{-1}$ collected at a lower energy.

## Observation of $\eta_c$(2S)

The observation of the charmonium state $\eta_c$(2S) was first reported in 1982,[6] based on the spectrum of $\psi$(2S)$\to \gamma X$. Subsequent attempts to confirm its existence[7] have been unsuccessful, however, and the reported mass of $3594 \pm 5$ MeV/c$^2$ deviates significantly from predicted values (3625-3645 MeV/c$^2$).[8] Decays of $B$ mesons at $B$ factories can provide a new venue for charmonium spectroscopy because there is a known and finite rate of decay via $c\bar{c}$ to two-body final states such as $J/\psi K$ and, because the $c$ and

$\bar{c}$ are created at distinct vertices, there are no strict constraints on $J$, $P$, or $C$. In addition, the reconstruction of exclusive $B$ modes provide significant additional background rejection over inclusive reconstruction.

Belle has searched, in 41.8 fb$^{-1}$ of data from the $\Upsilon(4S)$ and 4.4 fb$^{-1}$ from a lower energy, for $B \to \eta_c(2\text{S})K_S,\ \eta_c(2\text{S})K^+$ in the same subchannel, $\eta_c(2\text{S})\to\ K_S\pi^+\pi^-$, in which the $\eta_c$ was reconstructed to observe $B \to \eta_c K$ earlier this year.[9] The presence of $\eta_c(2\text{S})$ in the selected decays is demonstrated by dividing the data into bins of $K_S\pi\pi$ mass and fitting for $B$ signal candidates. The distribution of $B$ signal as a function of $K_S\pi\pi$ mass is then in turn fitted for $\eta_c$ and $\eta_c(2\text{S})$ signals (Figure 3), to obtain a net signal of $39 \pm 11$.[10] The fit yields a mass of $3654 \pm 6 \pm 8$ MeV/c$^2$, which is consistent with potential model predictions.

Figure 3. Distribution of $B$ signal from fitting of $M_{bc}$ and $\Delta E$ in bins of $K_sK\pi$ mass, shown with the result of fitting for $\eta_c$ states.

## Charmonia in $B$ decay

A comparison of rates for $B$ decay to the various charmonia can provide useful information about the hadronization process. The dominant source of the charm quark pairs are the couplings $b \to cW^{-*}$, $\{W^{-*} \to \bar{c}s\}$, where the rate to $c\bar{c}$ states is color-suppressed. It is convenient to assume factorization, that is, that the formation of the final state mesons proceeds predominantly without additional exchanges of gluons. This assumption, which is not experimentally established for color-suppressed decays, may be tested by comparing rates of $B$ decay to the different charmonium states that can and cannot be produced under the factorization assumption. Belle has observed two non-factorizable states, $\chi_{c0}$ and $\chi_{c2}$ and reports:[11,12]

$$\frac{\mathcal{B}(B^+ \to \chi_{c0} K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = 0.60^{+0.21}_{-0.18} \pm 0.05 \pm 0.08,$$
$$\mathcal{B}(B \to \chi_{c2} X) = (1.53^{+0.21}_{-0.28} \pm 0.27) \times 10^{-3}.$$

The second quantity may be compared to the color-favored rate, $\mathcal{B}(B \to \chi_{c1} X) = (3.32 \pm 0.22 \pm 0.34) \times 10^{-3}$. We observe, based on $\approx$30 fb$^{-1}$ of data, that non-factorizable and factorizable processes are of comparable magnitude in $B \to$charmonium decays and conclude that factorization is not a good approximation.

## Production of $\eta\prime$ from $B$ decay

CLEO II first reported anomalous rates for $B \to \eta' X$.[13] As Standard Model expectations for the branching fraction are in the range $(21-53) \times 10^{-6}$ and $(20-50) \times 10^{-6}$ for $B \to \eta\prime K^+$ and $B \to \eta\prime K^0$, respectively, CLEO's values of $(80^{+10}_{-9} \pm 7) \times 10^{-6}$ and $(89^{+18}_{-16} \pm 9) \times 10^{-6}$ may indicate the presence of new physics. Belle has measured[14] $(79^{+12}_{-11} \pm 9) \times 10^{-6}$ and $(55^{+19}_{-16} \pm 8) \times 10^{-6}$, compatible with the CLEO II results and also somewhat above theoretical expectations. However, it is not yet possible to reach a strong conclusion regarding compatibility with the Standard Model. This result was obtained with 10.4 fb$^{-1}$ of data collected at the $\Upsilon(4S)$.

## Summary

The Belle experiment has collected in three years of operation nearly $10^8$ $e^+e^- \to \Upsilon$(4S)$\to B\bar{B}$ events and as many charm pair events. These data are yielding new results on heavy quark spectroscopy and hadronization, several of which have been presented here.

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