Study of Charmonium Decays into Baryon-Antibaryon Pairs

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We study the baryonic charmonium decays of $B$ mesons, $B^+ \rightarrow \eta_c K^+$ and $B^+ \rightarrow J/\psi K^+$, where $\eta_c$ and $J/\psi$ subsequently decay into a $p\bar{p}$ or $\Lambda\bar{\Lambda}$ pair. The charmonium produced in the above $B$ meson decays is fully polarized. The polar angular distributions of the baryon-antibaryon pairs are presented, along with fit results to a $1 + \alpha_B \cos^2 \theta$ parametrization. Comparisons are made with the results from $e^+e^- \rightarrow J/\psi$ formation experiments. We also report the first observation of $\eta_c \rightarrow \Lambda\bar{\Lambda}$. The measured branching fraction is $B(\eta_c \rightarrow \Lambda\bar{\Lambda}) = (0.87^{+0.24}_{-0.21} \pm 0.14 \pm 0.27) \times 10^{-3}$. This study is based on a 357 $fb^{-1}$ data sample recorded on the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider.

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There have been many reported observations of baryonic three-body $B$ decays in recent years [1, 2, 3, 4]. An interesting feature of these observations is the presence of a peak near threshold in the mass spectra of the baryon-antibaryon pair. Studies show that these enhancements are not likely to be resonance states, as the baryon angular distributions are not symmetric in their respective helicity frames [3]. Other visible structures in the mass spectra arise from charmonium decays. It is natural to compare the baryon angular distributions from charmonium decays with those in the region of the threshold enhancement.

There is a particular interest in $J/\psi \to p\pi$, $pK\bar{\Lambda}$, $p\Lambda\bar{\Lambda}$, $K\bar{K}$, $\pi\pi\pi$, and $\Lambda\bar{\Lambda}$ angular distributions from charmonium decays with those in the region of the threshold enhancement. To reduce the background, where $\Lambda$ mesons produced in $e^+e^- \to J/\psi$ are transversely polarized. Accordingly, the baryon angular distribution can be parameterized as $\sim 1 + \alpha \cos^2 \theta$, where $\theta$ is the baryon polar angle in the $J/\psi$ helicity frame. Many theoretical predictions [12] exist for the value of $\alpha$. The current world average value of $\alpha$, obtained with above measurements from $J/\psi \to p\bar{p}$ decays, is $0.66 \pm 0.05$.

The study of two-body baryonic decays of charmonia at a $B$-factory has several different features comparing with an $e^+e^-$ machine running at the $J/\psi$ mass. $J/\psi$ mesons from the decay of spinless $B$ mesons are fully longitudinally polarized. This provides a useful cross check for previous measurements with transversely polarized $J/\psi$ mesons. The charmonia from $B$ decays do not suffer from the beam hole effect, such that events with $|\cos \theta|$ near 1 can be detected. These events are effective to determine $\alpha$. A $B$-factory is also immune from $e^+e^- \to q\bar{q} \to p\bar{p}$ background, where $q$ stands for a $u$ or $d$ quark. For previous studies this background is intrinsically embedded and hard to separate on an event-by-event basis.

We use a 357 fb$^{-1}$ data sample, consisting of $386 \times 10^6 B\bar{B}$ pairs, collected by the Belle detector at the KEKB asymmetric energy $e^+e^-$ (3.5 on 8 GeV) collider [3]. The Belle detector is a large solid angle magnetic spectrometer that consists of a three layer silicon vertex detector (SVD), a 50 layer 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 located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside of the coil is instrumented to detect $K^0_L$ mesons and to identify muons. The detector is described in detail elsewhere [14].

In this study of two-body baryonic decays of charmonia we focus on the decay processes, $B^+ \to p\bar{p}K^+$ and $B^+ \to \Lambda\bar{\Lambda}K^+$ [15]. The event selection criteria are based on information obtained from the tracking system (SVD+CDC) and the hadron identification system (CDC+ACC+TOF). All primary charged tracks are required to satisfy track quality criteria based on the track impact parameters relative to the interaction point (IP). The deviations from the IP position are required to be within $\pm 1$ cm in the transverse ($x$–$y$) plane, and within $\pm 3$ cm in the $z$ direction, where the $z$ axis is defined by the positron beam line. Proton, kaon and pion candidates are selected using $p/K/\pi$ likelihood functions obtained from the hadron identification system. For the primary protons from $B$ decays we require $L_p/(L_p + L_K) > 0.6$ and $L_p/(L_p + L_\pi) > 0.6$, where $L_{p/K/\pi}$ stands for the proton/kaon/pion likelihood. We require $L_K/(L_K + L_\pi) > 0.3$ to identify kaons. $\Lambda$ candidates are reconstructed from decays into the $p\pi^-$ channel. Each candidate must have a displaced vertex and flight direction consistent with a $\Lambda$ originating from the interaction point [16]. To reduce background, a $L_p/(L_p + L_\pi) > 0.6$ requirement is applied to the secondary proton from the $\Lambda$ decay.

To identify the reconstructed $B$ meson candidates we use the beam energy constrained mass, $M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$, and the energy difference, $\Delta E = E_B - E_{beam}$, where $E_{beam}$ is
the beam energy, and $p_B$ and $E_B$ are the momentum and energy of the reconstructed $B$ meson in the rest frame of the $\Upsilon(4S)$. The candidate region is defined as $5.2 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$ and $-0.1 \text{ GeV} < \Delta E < 0.2 \text{ GeV}$. From a GEANT based Monte Carlo (MC) simulation, the signal is peaked in the region $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$ and $|\Delta E| < 0.05 \text{ GeV}$.

The dominant background arises from the continuum $e^+e^- \rightarrow q\bar{q}$ process. The background from $b \rightarrow c$ and charmless mesonic decays is negligible. In the $\Upsilon(4S)$ rest frame, continuum events are jet-like while $B\bar{B}$ events are more spherical. The reconstructed momenta of final state particles is used to form various shape variables (e.g. thrust angle, Fox-Wolfram moments, etc.) in order to categorize each event. We follow the scheme defined in Ref. [17] that combines seven event shape variables into a Fisher discriminant to suppress continuum background.

Probability density functions (PDFs) for the Fisher discriminant and the cosine of the angle between the $B$ flight direction and the beam direction in the $\Upsilon(4S)$ rest frame are combined to form the signal (background) likelihood $L_s(L_b)$. The signal PDFs are determined from signal MC simulation; the background PDFs are obtained from the side-band data with $M_{bc} < 5.26 \text{ GeV}/c^2$. We require the likelihood ratio $R = L_s/(L_s + L_b)$ to be greater than 0.4 for both $p\bar{p}K^+$ and $\Lambda\bar{\Lambda}K^+$ modes. These selection criteria suppress approximately 69% (66%) of the background while retaining 92% (91%) of the signal for the $p\bar{p}K^+$ ($\Lambda\bar{\Lambda}K^+$) mode. In this study only one $B$ candidate is allowed per event. If there are multiple $B$ candidates in one event, we select the one with the best $\chi^2$ value from the vertex fit. Multiple $B$ candidates are found in less than 2% (5%) of events for the $p\bar{p}K^+$ ($\Lambda\bar{\Lambda}K^+$) mode.

![FIG. 1: $B$ yield versus $M_{p\bar{p}}$. The inset shows the $J/\psi$ mass region. (green dots, red dots, and solid line represent fitting background shape, signal shape, and combined result, respectively)](image-url)
We use an unbinned likelihood fit to estimate the $B$ yield:

$$L = \frac{e^{-(N_s+N_b)}}{N!} \prod_{i=1}^{N} [N_s P_s(M_{bc_i}, \Delta E_i) + N_b P_b(M_{bc_i}, \Delta E_i)];$$

where $P_s(P_b)$ denotes the signal (background) PDF, $N$ is the number of events in the fit, and $N_s$ and $N_b$ are fit parameters. For the signal PDF, we use a Gaussian in $M_{bc}$ and a double Gaussian in $\Delta E$. We fix the parameters of these functions to values determined by MC simulation [18]. Background shapes are fixed from fitting to sideband events in the region: $3.14 \text{ GeV/}c^2 < M_{pp} < 3.34 \text{ GeV/}c^2$. The $M_{bc}$ background is modelled using a parametrization first used by the ARGUS collaboration, $f(M_{bc}) \propto M_{bc} \sqrt{1-x^2} \exp[-\xi(1-x^2)]$, where $x$ is defined as $M_{bc}/E_{beam}$ and $\xi$ is a fixed value. The $\Delta E$ background shape is modeled by a first order polynomial.

As the mass resolution of $M_{pp}$ ($M_{\Lambda \bar{\Lambda}}$) is about 10 MeV/$c^2$, we determine the $B$ yield as a function of $M_{pp}$ ($M_{\Lambda \bar{\Lambda}}$) from 1.85 GeV/$c^2$ to 4.5 GeV/$c^2$ in 10 MeV/$c^2$ bins. The result is shown in Fig. 1 (Fig. 4). There are clear $\eta_c$ and $J/\psi$ peaks in the mass spectrum. A fit to the data is shown in the inset. We use a Breit-Wigner function for the $\eta_c$ peak, a Gaussian for the $J/\psi$ peak and a line for the non-charmonium background. The background is negligible. We define the $\eta_c$ signal region as $2.94 \text{ GeV/}c^2 < M_{pp} < 3.02 \text{ GeV/}c^2$ and the $J/\psi$ signal region as $3.06 \text{ GeV/}c^2 < M_{pp} < 3.14 \text{ GeV/}c^2$. The measured $B$ yield is $329 \pm 19 (195 \pm 15)$ for $B^+ \rightarrow J/\psi K^+, J/\psi \rightarrow pp$ ($B^+ \rightarrow \eta_c K^+, \eta_c \rightarrow pp$). We use a phase space MC sample to determine the efficiency in this $M_{pp}$ range. The obtained efficiency is $38\%$ ($36\%$) for $B^+ \rightarrow J/\psi K^+, J/\psi \rightarrow pp$ ($B^+ \rightarrow \eta_c K^+, \eta_c \rightarrow pp$). The measured branching fractions for charmonia decaying into $pp$ are $B(\eta_c \rightarrow pp) = (1.58 \pm 0.12(stat) \pm 0.22(syst) \pm 0.47(PDG)) \times 10^{-3}$ and $B(J/\psi \rightarrow pp) = (2.24 \pm 0.13(stat) \pm 0.31(syst) \pm 0.01(PDG)) \times 10^{-3}$, where the last errors are related to the uncertainty in the current world average values of the branching ratios $B(B^+ \rightarrow \eta_c K^+)$ and $B(B^+ \rightarrow J/\psi K^+)$. We study the proton angular distribution in the helicity frame of the $J/\psi$. $\theta_X$ is defined as the angle between the proton flight direction and the direction opposite to the flight of the kaon in the $J/\psi$ rest frame. The angular distribution is parameterized as $P(\cos \theta_X) = (1 + \alpha_B \cos^2 \theta_X)/(2 + 2/3\alpha_B)$. Note that $\alpha_B$ determined from longitudinally polarized $J/\psi$ is related to the $\alpha$ determined from transversely polarized $J/\psi$ by $\alpha_B = \frac{2\alpha}{(2\alpha+1)}$ [19]. From previous measurements of $\alpha$, the expectation of $\alpha_B$ is $-0.80 \pm 0.04$. We modify the likelihood function to

$$L = \frac{e^{-(N_s+N_b)}}{N!} \prod_{i=1}^{N} [N_s P_s(M_{bc_i}, \Delta E_i)\epsilon(\cos \theta_X)P(\cos \theta_X) + N_b P_b(M_{bc_i}, \Delta E_i, \cos \theta_X)] ,$$

where $\epsilon(\cos \theta_X)$ is the normalized efficiency function. The observed distribution of $\epsilon(\cos \theta_X)$ is flat. We assume there is no correlation between $M_{bc}$, $\Delta E$ and $\theta_X$ based on a study with MC data. The background PDF, including $\cos \theta_X$, is determined from $M_{pp}$ sideband data. The distribution of $\cos \theta_X$ for $J/\psi$ candidates and fit result in whole $M_{bc}, \Delta E$ region is shown in Fig. 2. $\alpha_B$ is determined to be $-0.54 \pm 0.14$.

As a cross check, we fit the $1 + \alpha_B \cos^2 \theta_X$ parametrization to the efficiency corrected $B$ yield as a function of $\cos \theta_X$. The results of the fit are shown in Fig. 3. The value of $\alpha_B$ obtained from the fit is $-0.46 \pm 0.16$ with $\chi^2/d.o.f. = 1.1$. This is consistent with the likelihood result from a toy MC study, where samples with the same number of events as our data are generated to check the $\alpha_B$ difference between the likelihood and $\chi^2$ methods.
The $\alpha_B$ difference follows a Gaussian distribution with a width of approximately 0.05. We also apply both the likelihood and $\chi^2$ methods to a $J/\psi \rightarrow \mu^+ \mu^-$ event sample. The result is shown as an inset in Fig. 3. It is in excellent agreement with theoretical prediction which has a $\sin^2 \theta_X$ shape ($\alpha_B = -0.999 \pm 0.003$).

We study the systematic error of $\alpha_B$ by varying the value of various selection cuts and parameters of PDFs to check for trends in the value of $\alpha_B$. This relation is smooth and can be fitted to a line. We then quote the change in $\alpha_B$ along the line between the selected point and the far end of the tested region as a systematic error. Note that this is a conservative estimation, since the statistical fluctuation of this data set also contributes to changes in $\alpha_B$. We assign a systematic error of 0.08 for the $R$ selection, 0.06 for PID selection, and 0.02 for fitting PDFs. Other systematic errors are negligible. To be conservative, we also quote the observed difference between the likelihood method and the $\chi^2$ method as a systematic error. The total systematic uncertainty in $\alpha_B$ is 0.13.

The baryon-antibaryon mass spectrum from $B^+ \rightarrow \Lambda \bar{\Lambda} K^+$ decays is shown in Fig. 4. Similar structures are seen in the mass spectrum of $B^+ \rightarrow \Lambda \bar{\Lambda} K^+$ decays as were seen in the $B^+ \rightarrow p \bar{p} K^+$ mass spectrum. There are several complicating factors in the analysis of $B^+ \rightarrow \Lambda \Lambda K^+$ decays, relative to $B^+ \rightarrow p \bar{p} K^+$ decays. The slow pion from $\Lambda$ decays has a low detection efficiency. This causes the $\Lambda$ reconstruction efficiency to be non-uniform in the polar angle ($\theta_p$) of the secondary decay proton in the $\Lambda$ helicity frame, and is correlated with $\cos \theta_X$, where $X$ refers to the $\Lambda$. The likelihood function becomes

$$L = \frac{e^{-(N_s+N_b)}}{N!} \prod_{i=1}^{N} [N_s P_s(M_{bc_i}, \Delta E_i) \epsilon(\cos \theta_X, \cos \theta_p, \cos \theta_{\bar{p}}) P(\cos \theta_X, \cos \theta_p, \cos \theta_{\bar{p}})$$

$$+ N_b P_b(M_{bc_i}, \Delta E_i, \cos \theta_X, \cos \theta_p, \cos \theta_{\bar{p}})].$$

FIG. 2: Likelihood fit of the $J/\psi \rightarrow p \bar{p}$ helicity angle distribution. The blue solid, red solid, and dashed line represent the fit results, the signal shape, and the background shape, respectively.
where $\epsilon(\cos \theta_X, \cos \theta_p, \cos \theta_{\bar{p}})$ is determined by a huge signal MC sample with $4 \times 10^6$ events. The background PDF is determined from $M_{\Lambda \bar{\Lambda}}$ sideband data in the region $3.14 \text{ GeV}/c^2 < M_{\Lambda \bar{\Lambda}} < 3.54 \text{ GeV}/c^2$. The value of $\alpha_B$ obtained from the fit is $-0.63 \pm 0.46 \pm 0.27$, where the systematic error is determined from the same procedure used for $J/\psi \to p\bar{p}$ decays.

The $M_{bc}$ distribution (with $|\Delta E| < 0.05$ GeV) and the $\Delta E$ distribution (with $M_{bc} > 5.27$ GeV/$c^2$) for $B^+ \to \eta_c K^+, \eta_c \to \Lambda \bar{\Lambda}$ decays are shown in Fig. 5. $\eta_c$ signal peaks are visible in the $M_{bc}$ and $\Delta E$ distributions. The yield from the fit is $19.5^{+0.6}_{-0.4} \pm 4.4$ with a statistical significance of 8.1 standard deviations. The significance is defined as $\sqrt{-2\ln(L_0/L_{\text{max}})}$, where $L_0$ and $L_{\text{max}}$ are the likelihood values returned by the fit with signal yield fixed at zero and its best fit value, respectively. The fit yield is consistent with that obtained in Fig. 4. We estimate the branching fraction from the ratio of the efficiency corrected yield of $\eta_c \to \Lambda \bar{\Lambda}$ and $\eta_c \to p\bar{p}$. The result is $\mathcal{B}(\eta_c \to \Lambda \bar{\Lambda}) = (0.87^{+0.24}_{-0.21}(\text{stat}) \pm 0.14(\text{syst}) \pm 0.27(\text{PDG})) \times 10^{-3}$, where the last error is associated with the world average value for $\mathcal{B}(\eta_c \to p\bar{p})$. We apply the same procedure to obtain $\mathcal{B}(J/\psi \to \Lambda \bar{\Lambda}) = (2.00^{+0.33}_{-0.29}(\text{stat}) \pm 0.34(\text{syst}) \pm 0.08(\text{PDG})) \times 10^{-3}$.

Systematic uncertainties are studied using high statistics control samples. For proton identification, we use a $\Lambda \to p\pi^-$ sample, while for $K/\pi$ identification we use a $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ sample. Tracking efficiency is studied with fully and partially reconstructed $D^*$ samples. The $\mathcal{R}$ continuum suppression uncertainty is studied with $b \to c$ control samples with similar final states. For $\Lambda$ reconstruction, we have an additional uncertainty on the efficiency for detecting tracks away from the IP. The size of this uncertainty is determined from the difference between $\Lambda$ proper time distributions in data and MC simulation. Based

![FIG. 3: $J/\psi \to p\bar{p}$ helicity angle distribution. The dashed line shows the $\chi^2$ fit result for $B$ events of $B^+ \to J/\psi K^+, J/\psi \to p\bar{p}$. The inset shows the $\chi^2$ fit result for $B$ yield of $B^+ \to J/\psi K^+, J/\psi \to \mu^+\mu^-$.](image)
on these studies, we assign a 1% error for each track, 2% for each proton identification, 1% for each kaon/pion identification, an additional 3% for Λ reconstruction and 3% for the \( R \) selection.

The systematic uncertainty in the fit yield is studied by varying the parameters of the signal and background PDFs and is approximately 5%. The MC statistical uncertainty and modeling contributes a 5% error. The error on the number of \( B\bar{B} \) pairs is determined to be 1%, where the branching fractions of \( \Upsilon(4S) \) to neutral and charged \( B\bar{B} \) pairs are assumed to be equal. Although the background in the \( M_{pp} \) and \( M_{\Lambda\bar{\Lambda}} \) spectra appear negligible, we forced
the $B$ yield to be positive and re-fit the spectra. The feed-down background is estimated to be 8% and 12% for the $p\bar{p}$ and $\Lambda\bar{\Lambda}$ modes, respectively.

To produce a combined systematic error, the correlated errors are added linearly and then combined with the uncorrelated errors in quadrature. The total systematic uncertainties are 14% and 17% for the $p\bar{p}K^+$ and $\Lambda\bar{\Lambda}K^+$ modes, respectively.

In summary, using $386 \times 10^6$ $B\bar{B}$ events, we measure the branching fractions of $J/\psi \rightarrow p\bar{p}$, $\eta_c \rightarrow p\bar{p}$, $J/\psi \rightarrow \Lambda\bar{\Lambda}$ and $\eta_c \rightarrow \Lambda\bar{\Lambda}$ from $B^+ \rightarrow p\bar{p}K^+$ and $B^+ \rightarrow \Lambda\bar{\Lambda}K^+$ decays. We report the first observation of $\eta_c \rightarrow \Lambda\bar{\Lambda}$ decays, with $B(\eta_c \rightarrow \Lambda\bar{\Lambda}) = (0.87_{-0.21}^{+0.27} \pm 0.14 \pm 0.27) \times 10^{-3}$. We also measure the parameter $\alpha_B$ for baryonic $J/\psi$ decays. The measured values are $-0.54 \pm 0.14 \pm 0.13$ and $-0.63 \pm 0.46 \pm 0.27$ for $J/\psi \rightarrow p\bar{p}$ and $J/\psi \rightarrow \Lambda\bar{\Lambda}$, respectively. The above measurements are in agreement with the current world average values as shown in TABLE I. The $B$-factories will rapidly accumulate charmonia decays in the coming years, enabling more accurate cross checks.

**TABLE I: List of $\alpha$ in previous experiments**

| Coll./Mode | $J/\psi \rightarrow p\bar{p}$ | $J/\psi \rightarrow \Lambda\bar{\Lambda}$ |
|------------|----------------|----------------|
| Mark1      | $1.45 \pm 0.56$ | $0.72 \pm 0.36$ |
| Mark2      | $0.61 \pm 0.23$ | $0.58 \pm 0.14$ |
| Mark3      | $0.62 \pm 0.11$ | $0.62 \pm 0.22$ |
| DASP       | $0.68 \pm 0.06$ | $0.52 \pm 0.35$ |
| world average | $0.66 \pm 0.05(\alpha_B = -0.80 \pm 0.04)$ | $0.62 \pm 0.17(\alpha_B = -0.77 \pm 0.13)$ |

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