Study of $J/\psi \rightarrow p\bar{p}$, $\Lambda\bar{\Lambda}$ and Observation of $\eta_c \rightarrow \Lambda\bar{\Lambda}$ at Belle

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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 the $\eta_c$ and $J/\psi$ subsequently decay into a $p\bar{p}$ or $\Lambda\bar{\Lambda}$ pair. We measure the $J/\psi \rightarrow p\bar{p}$ and $\Lambda\bar{\Lambda}$ anisotropy parameters $\alpha_B = -0.60 \pm 0.13 \pm 0.14 (p\bar{p})$, $-0.44 \pm 0.51 \pm 0.31 (\Lambda\bar{\Lambda})$ and compare to 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 $\mathcal{B}(\eta_c \rightarrow \Lambda\bar{\Lambda}) = (0.87^{+0.22}_{-0.12}(\text{stat})^{+0.09}_{-0.12}(\text{syst}) \pm 0.27(\text{PDG})) \times 10^{-3}$. This study is based on a 357 fb$^{-1}$ data sample recorded on the Y(4S) resonance with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider.

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$-0.1 \text{ GeV} < \Delta E < 0.2 \text{ GeV}$. The signal peaks at $M_{bc} = 5.279 \text{ GeV}/c^2$ and $\Delta E = 0$.

The dominant background arises from continuum $e^+ e^- \rightarrow q\bar{q}$ processes. The background from $b \rightarrow c$ and from $B$ decays into charmless final states is negligible. In the $Y(4S)$ rest frame, continuum events are jetlike while $BB$ events are more spherical. The reconstructed momenta of final state particles are used to form several event shape variables (e.g., thrust angle, Fox-Wolfram moments, etc.) in order to categorize each event. We follow the scheme described in Ref. [20] 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 $Y(4S)$ rest frame are combined to form the signal likelihood $L_s$ and the background likelihood $L_b$. The signal PDFs are determined from GEANT-based Monte Carlo (MC) simulation, and the background PDFs are obtained from sideband data with $M_{bc} < 5.26 \text{ GeV}/c^2$. We require the likelihood ratio $\mathcal{R} = L_s/(L_s + L_b)$ to be greater than 0.4 for both $p\bar{p}K^+$ and $\Lambda \Lambda K^+$ modes. These selection criteria suppress approximately 69% (66%) of the background while retaining 92% (91%) of the signal for the $p\bar{p}K^+$ ($\Lambda \Lambda K^+$) mode. If there are multiple $B$ candidates in an event, we select the one with the best $\chi^2$ value from the $B$ decay vertex fit. Multiple $B$ candidates are found in less than 2% (5%) of events for the $p\bar{p}K^+$ ($\Lambda \Lambda K^+$) mode.

We use an unbinned extended maximum likelihood fit to estimate the $B$ signal yield. 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 the values determined from MC simulation [21]. Background shapes are fixed from fitting to the sideband events in the region $3.14 \text{ GeV}/c^2 < M_{p\bar{p}} < 3.34 \text{ GeV}/c^2$. The $M_{bc}$ background is modeled using a parametrization used by the ARGUS Collaboration [22]. The $\Delta E$ background shape is modeled by a first order polynomial.

We determine $B$ signal yields in 10 MeV/$c^2$-wide $M_{p\bar{p}}$ ($M_{\Lambda\Lambda}$) mass bins from the kinematic threshold to 4.5 GeV/$c^2$; the result is shown in Fig. 1(a) [Fig. 1(b)]. There are clear $\eta_c$ and $J/\psi$ peaks [and a possible $\psi(2S)$ signal] in the mass spectrum. We use a relativistic Breit-Wigner function for the $\eta_c$ peak, a Gaussian for the $J/\psi$ peak, and a linear function for the nonresonant background. The Breit-Wigner function is convolved with the detector response function, which is taken from Ref. [20] and previous Belle [25] measurements.

![Graphs showing $B$ signal yield versus $M_{p\bar{p}}$ and $B$ signal yield versus $M_{\Lambda\Lambda}$](image)

**Fig. 1.** (a) $B$ signal yield versus $M_{p\bar{p}}$ and (b) $B$ signal yield versus $M_{\Lambda\Lambda}$. The inset shows the $\eta_{c}-J/\psi$ mass region. The curves represent the unbinned likelihood fits to the data.

For analysis of the angular distribution, we define a likelihood $L_e$,
FIG. 2. (a) Likelihood fit and (b) $\chi^2$ fit results of the $J/\psi \to p \bar{p}$ helicity angle distribution. In the maximum likelihood fit plot, the solid, dotted solid, and dashed lines represent the combined fit result, fitted signal, and fitted background, respectively. In the $\chi^2$ fit plot, the inset shows the fit result for $B^+ \to J/\psi K^+$, $J/\psi \to \mu^+ \mu^-$. 

where $\alpha_B$ is a fit parameter in addition to $N_s$ and $N_b$, $\epsilon(\cos \theta_X)$ is the efficiency function, and $\epsilon P$ is normalized to 1. The efficiency $\epsilon(\cos \theta_X)$ obtained from the signal MC simulation is flat as a function of $\cos \theta_X$. From a study of a signal MC simulation, we find that there is no correlation between $M_{bc}$, $\Delta E$, and $\theta_X$. The background PDF as a function of $M_{bc}$, $\Delta E$, and $\cos \theta_X$ is determined from $M_{\bar{p}p}$ sideband data. Figure 2(a) shows the result of the fit to the $J/\psi \to p \bar{p}$ candidates in the entire $M_{bc}$, $\Delta E$ region. We determine $\alpha_B$ to be $-0.60 \pm 0.13$. As a cross-check, we use a $\chi^2$ method and fit the efficiency corrected $B$ signal yields in bins of $\cos \theta_X$ to a $1 + \alpha_B \cos^2 \theta_X$ parametrization. The results of the fit are shown in Fig. 2(b). We obtain $\alpha_B = -0.53 \pm 0.15$, with $\chi^2$/d.o.f. = 0.9, consistent with the result of the unbinned fit. We measure the angular distribution of $J/\psi \to \mu^+ \mu^-$ decays from $B^+ \to J/\psi K^+$ to verify the fitting procedure. The result is shown in the inset in Fig. 2(b). The fitted value agrees with the expectation for massless fermions.

We determine the systematic error in $\alpha_B$ by varying the value of various selection cuts and parameters of PDFs to check for trends in the value of $\alpha_B$. These trends are parametrized by a linear function. 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 estimate, since statistical fluctuations also contribute to changes in $\alpha_B$. We assign a systematic error of 0.08 for the $T$ selection, 0.06 for proton or kaon selection, and 0.02 for fitting PDFs. Other systematic errors are negligible. The observed difference between the maximum likelihood method and the $\chi^2$ method is also included in the systematic error. The total systematic uncertainty in $\alpha_B$ is 0.13.

There are several complicating factors in the analysis of $B^+ \to \Lambda \bar{K} K^+$ decays relative to $B^+ \to p \bar{p} K^+$ decays. The efficiency for detecting slow pion from $\Lambda$ decays is small. As a result, the $\Lambda$ reconstruction efficiency is nonuniform as a function of the polar angle ($\cos \theta_p$) of the secondary proton in the $\Lambda$ helicity frame and is correlated with $\cos \theta_X$, where $\theta_X$ refers to the $\Lambda$ polar angle in the $J/\psi$ helicity frame. The likelihood function is similar to the previous one except that the angular part contains two more vari-

**TABLE I.** Measured branching fractions for $J/\psi, \eta_c \to p \bar{p}, \Lambda \bar{\Lambda}$.

| Modes | Yield | Efficiency (%) | Branching fraction product $(10^{-6})$ | $\mathcal{B}(J/\psi, \eta_c \to p \bar{p}, \Lambda \bar{\Lambda})(10^{-3})$ |
|-------|-------|----------------|--------------------------------------|--------------------------------------------------|
| $B^+ \to \eta_c K^+$, $\eta_c \to p \bar{p}$ | $195^{+16}_{-15}$ | $35.8^{+0.3}_{-0.3}$ | $1.42^{+0.11+0.16}_{-0.11-0.20}$ | $1.58 \pm 0.12^{+0.18+0.2}_{-0.22-0.2} \pm 0.47^a$ |
| $B^+ \to \eta_c K^+$, $\eta_c \to \Lambda \bar{\Lambda}$ | $19.5^{+5.2}_{-4.5}$ | $5.3^{+0.1}_{-0.1}$ | $0.95^{+0.25+0.08}_{-0.22-0.11}$ | $0.87^{+0.24+0.09}_{-0.21-0.14} \pm 0.27^b$ |
| $B^+ \to J/\psi K^+$, $J/\psi \to p \bar{p}$ | $317^{+19}_{-18}$ | $37.3^{+0.4}_{-0.4}$ | $2.21^{+0.13+0.10}_{-0.13-0.10}$ | $2.21 \pm 0.13 \pm 0.31 \pm 0.10^c$ |
| $B^+ \to J/\psi K^+$, $J/\psi \to \Lambda \bar{\Lambda}$ | $45.9^{+7.7}_{-6.7}$ | $5.9^{+0.3}_{-0.3}$ | $2.00^{+0.34}_{-0.29} \pm 0.34$ | $2.00^{+0.34}_{-0.29} \pm 0.34 \pm 0.08^c$ |

$^a\mathcal{B}(B^+ \to \eta_c K^+) = 0.9 \pm 0.27 \times 10^{-3}$ [23].

$^b$We use $\mathcal{B}(B^+ \to \eta_c K^+, \eta_c \to \Lambda \bar{\Lambda})/\mathcal{B}(B^+ \to \eta_c K^+, \eta_c \to p \bar{p}) = 0.67^{+0.19}_{-0.16} \pm 0.12$ measured in this Letter and $\mathcal{B}(\eta_c \to p \bar{p}) = 1.3 \pm 0.4 \times 10^{-3}$ [23].

$^c\mathcal{B}(B^+ \to J/\psi K^+) = 1.00 \pm 0.04 \times 10^{-3}$ [23].
bles, $\cos \theta_p$ and $\cos \theta_{\bar{p}}$. The efficiency function $e(\cos \theta_K, \cos \theta_{\bar{p}}, \cos \theta_p)$ is obtained from a 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 maximum likelihood fit is $-0.44 \pm 0.51 \pm 0.31$, where the systematic error is determined from the same procedure as that used for $J/\psi \rightarrow p\bar{p}$ decays.

We define an $\eta_c$ signal region as $2.94 \text{ GeV}/c^2 < M_{\Lambda \bar{\Lambda}} < 3.02 \text{ GeV}/c^2$. Signal peaks are visible in the $M_{B_c}$ and $\Delta E$ distributions. The fitted $B$ signal yield, efficiency, and obtained branching fraction are shown in Table I. The maximum likelihood fit for $B^+ \rightarrow \eta_c K^+$, $\eta_c \rightarrow \Lambda \bar{\Lambda}$ gives a yield of $19.5^{+3.1}_{-4.4}$ with a statistical significance of 7.9 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 the signal yield fixed to zero and at its best fit value, respectively. The fit yield is consistent with the yield ($18.2 \pm 4.8$) obtained from the first fit shown in Fig. 1(b). As a cross-check, the obtained $B(J/\psi \rightarrow p\bar{p}, \Lambda \bar{\Lambda})$ are in good agreement with the world average and with the latest BES result [13]. We also determine the branching fraction ratios: $B(\eta_c \rightarrow \Lambda \bar{\Lambda})/B(\eta_c \rightarrow p\bar{p}) = 0.67^{+0.19}_{-0.16} \pm 0.12$ and $B(J/\psi \rightarrow \Lambda \bar{\Lambda})/B(J/\psi \rightarrow p\bar{p}) = 0.90^{+0.15}_{-0.14} \pm 0.10$, where common systematic errors in the numerator and denominator cancel.

Systematic uncertainties are studied using high statistics control samples. For proton identification, we use a $\Lambda \rightarrow p\pi^-$ sample, while for $K/\pi$ identification, we use a $D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+$ sample. The tracking efficiency is studied with fully and partially reconstructed $D^+$ samples. The modeling of the requirement on the likelihood ratio $R$ for background suppression is studied with a topologically similar control sample $B^+ \rightarrow J/\psi K^+$, $J/\psi \rightarrow \mu^+\mu^-$. 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 $\Lambda$ decay-time distributions in data and MC simulation. Based on these studies, we assign a 1% error for each track, 2% for each proton identification, 1% for each kaon or pion identification, an additional 3% for $\Lambda$ 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 $Y(4S)$ to neutral and charged $B\bar{B}$ pairs are assumed to be equal. The noncharmonium feeddown background below the $\eta_c$ mass region is estimated to be 8% and 12% for the $p\bar{p}$ and $\Lambda \bar{\Lambda}$ modes, respectively.

The correlated errors are added linearly and combined quadratically with the uncorrelated errors in the systematic error calculation. 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 measure the parameter $\alpha_B$ for baryonic $J/\psi$ decays. The parameters $\alpha_B$ are $-0.60 \pm 0.13 \pm 0.14$ and $-0.44 \pm 0.51 \pm 0.31$ for $J/\psi \rightarrow p\bar{p}$ and $J/\psi \rightarrow \Lambda \bar{\Lambda}$, respectively. This gives an $\alpha$ value for $J/\psi \rightarrow p\bar{p}$ of $0.43 \pm 0.13 \pm 0.14$, which is smaller than, but still consistent with, the current world average $0.66 \pm 0.05$. We also report the first observation of $\eta_c \rightarrow \Lambda \bar{\Lambda}$ decays with $B(\eta_c \rightarrow \Lambda \bar{\Lambda}) = (3.72^{+0.24}_{-0.21} \pm 0.27) \times 10^{-3}$. The observed ratio $B(\eta_c \rightarrow \Lambda \bar{\Lambda})/B(\eta_c \rightarrow p\bar{p})$ is $0.67^{+0.19}_{-0.16} \pm 0.12$, which is consistent with theoretical expectation [16].

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[1] K. Abe et al. (Belle Collaboration), Phys. Rev. Lett. 88, 181803 (2002).
[2] M.Z. Wang et al. (Belle Collaboration), Phys. Rev. Lett. 90, 201802 (2003).
[3] M.Z. Wang et al. (Belle Collaboration), Phys. Rev. Lett. 92, 131801 (2004).
[4] Y.J. Lee et al. (Belle Collaboration), Phys. Rev. Lett. 93, 211801 (2004).
[5] B. Aubert et al. (BABAR Collaboration), Phys. Rev. D 72, 051101 (2005).
[6] M.Z. Wang et al. (Belle Collaboration), Phys. Lett. B 617, 141 (2005).
[7] R. Brandelik et al., Z. Phys. C 1, 233 (1979).
[8] D. Pallin et al., Nucl. Phys. B292, 653 (1987).
[9] I. Peruzzi et al., Phys. Rev. D 17, 2901 (1978).
[10] M.W. Eaton et al., Phys. Rev. D 29, 804 (1984).
[11] J.Z. Bai et al. (BES Collaboration), Phys. Lett. B 591, 42 (2004).
[12] J.Z. Bai et al. (BES Collaboration), Phys. Lett. B 424, 213 (1998).
[13] M. Ablikim et al. (BES Collaboration), Phys. Lett. B 632, 181 (2006).
[14] S.J. Brodsky and G.P. Lepage, Phys. Rev. D 24, 2848 (1981); M. Claudson, S.L. Glashow, and M.B. Wise,
Throughout this Letter, inclusion of the charge conjugate mode is always implied unless otherwise stated.

M. Anselmino, F. Caruso, S. Forte, and B. Pire, Phys. Rev. D 38, 3516 (1988).

S. Kurokawa et al., Nucl. Instrum. Methods Phys. Res., Sect. A 499, 1 (2003).

A. Abashian et al. (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 479, 117 (2002).

K. Abe et al. (Belle Collaboration), Phys. Rev. D 65, 091103 (2002).

K. Abe et al. (Belle Collaboration), Phys. Lett. B 517, 309 (2001).

There are corrections (~2.3 and 0.5 MeV in the mean shift on $\Delta E$ and $M_{bc}$ and 0.98 and 1.14 in the width scale on $\Delta E$ and $M_{bc}$, respectively) applied to these parameters based on the measured difference between data and MC simulation for $B \to D\pi$ decays.

H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 229, 304 (1989).

S. Eidelman et al. (Particle Data Group), Phys. Lett. B 592, 1 (2004).

B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 92, 142002 (2004).

F. Fang et al. (Belle Collaboration), Phys. Rev. Lett. 90, 071801 (2003).

F. Murgia and M. Melis, Phys. Rev. D 51, 3487 (1995).