Observation of $B^0 \rightarrow p\bar{p}K^{*0}$ with a large $K^{*0}$ polarization

J.-H. Chen, M.-Z. Wang, I. Adachi, H. Aihara, K. Arinstein, V. Aulchenko, T. Aushev, A. M. Bakich, V. Balagura, E. Barberio, A. Bay, I. Bedny, K. Belous, U. Bitenc, A. Bondar, A. Bozek, M. Bračko, T. E. Browder, M.-C. Chang, Y. Chao, A. Chen, W. T. Chen, B. G. Cheon, R. Chistov, I.-S. Cho, S.-K. Choi, Y. Choi, J. Dalseno, M. Dash, A. Drutskoy, S. Eidelman, B. Golob, H. Ha, J. Haba, J. Hara, K. Hayasaka, H. Hayashii, M. Hazumi, Y. Hoshi, W.-S. Hou, Y. B. Hsiung, H. J. Hyun, K. Inami, A. Ishikawa, H. Ishino, R. Itoh, M. Iwasaki, N. J. Joshi, D. H. Kah, H. Kaji, P. Kapusta, N. Katayama, T. Kawasaki, H. Kichimi, H. J. Kim, S. K. Kim, Y. J. Kim, K. Kinoshita, P. Krokovny, R. Kumar, C. C. Kuo, Y.-J. Kwon, J. S. Lee, M. J. Lee, S. E. Lee, T. Lesiak, J. Li, A. Limosani, C. Liu, D. Liventsev, F. Mandl, A. Matyja, S. McOnie, T. Medvedeva, W. Mitaroff, H. Miyake, H. Miyata, Y. Miyazaki, R. Mizuk, E. Nakano, M. Nakao, H. Nakazawa, Z. Ntikaniec, O. Nitoh, S. Ogawa, T. Ohshima, S. L. Olsen, H. Ozaki, P. Pakhlov, G. Pakhlova, H. Palka, C. W. Park, H. Park, L. S. Peak, R. Pestotnik, L. E. Piilonen, M. Rozanska, H. Sahoo, Y. Sakai, O. Schneider, K. Senyo, M. E. Sevior, M. Shapkin, C. P. Shen, H. Shibuya, J.-G. Shiu, J. B. Singh, A. Somov, S. Stanič, T. Sumiyoshi, F. Takasaki, M. Tanaka, G. N. Taylor, Y. Teramoto, I. Tikhomirov, K. Trabelsi, S. Uehara, K. Ueno, T. Uglov, Y. Unno, P. Urquijo, Y. Usov, G. Varner, K. Vervink, S. Villa, A. Vinokurova, C. P. Shen, H. Yamamoto, Y. Yamashita, C. C. Zhang, Z. P. Zhang, V. Zhulanov, and A. Zupanc (The Belle Collaboration)

1Budker Institute of Nuclear Physics, Novosibirsk
2University of Cincinnati, Cincinnati, Ohio 45221
3Department of Physics, Fu Jen Catholic University, Taipei
4The Graduate University for Advanced Studies, Hayama
5Gyeongsang National University, Chinju
6Hanyang University, Seoul
7University of Hawaii, Honolulu, Hawaii 96822
8High Energy Accelerator Research Organization (KEK), Tsukuba
9Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
10Institute of High Energy Physics, Vienna
11Institute of High Energy Physics, Protvino
12Institute for Theoretical and Experimental Physics, Moscow

Typeset by REVTeX
J. Stefan Institute, Ljubljana
Kanagawa University, Yokohama
Korea University, Seoul
Kyungpook National University, Taegu
École Polytechnique Fédérale de Lausanne (EPFL), Lausanne
Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana
University of Maribor, Maribor
University of Melbourne, School of Physics, Victoria 3010
Nagoya University, Nagoya
Nara Women’s University, Nara
National Central University, Chung-li
National United University, Miao Li
Department of Physics, National Taiwan University, Taipei
H. Niewodniczanski Institute of Nuclear Physics, Krakow
Nippon Dental University, Niigata
Niigata University, Niigata
University of Nova Gorica, Nova Gorica
Osaka City University, Osaka
Osaka University, Osaka
Panjab University, Chandigarh
Saga University, Saga
University of Science and Technology of China, Hefei
Seoul National University, Seoul
Sungkyunkwan University, Suwon
University of Sydney, Sydney, New South Wales
Tata Institute of Fundamental Research, Mumbai
Toho University, Funabashi
Tohoku Gakuin University, Tagajo
Tohoku University, Sendai
Department of Physics, University of Tokyo, Tokyo
Tokyo Institute of Technology, Tokyo
Tokyo Metropolitan University, Tokyo
Tokyo University of Agriculture and Technology, Tokyo
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
Yonsei University, Seoul
Abstract

Using a 492 fb$^{-1}$ data sample collected near the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider, we observe the decay $B^0 \rightarrow p\bar{p}K^{*0}$ with a branching fraction of $(1.18^{+0.20}_{-0.25}(\text{stat.}) \pm 0.11(\text{syst.})) \times 10^{-6}$. The statistical significance is $7.2\sigma$ for the signal in the low $p\bar{p}$ mass region. We study the decay dynamics of $B^0 \rightarrow p\bar{p}K^{*0}$ and compare with $B^+ \rightarrow p\bar{p}K^{*+}$. The $K^{*0}$ meson is found to be almost 100% polarized (with a fraction of $(101 \pm 13 \pm 3)\%$ in the helicity zero state), while the $K^{*+}$ meson has a $(32 \pm 17 \pm 9)\%$ fraction in the helicity zero state. The direct $CP$ asymmetries for $B^0 \rightarrow p\bar{p}K^{*0}$ and $B^+ \rightarrow p\bar{p}K^{*+}$ are measured to be $-0.08 \pm 0.20 \pm 0.02$ and $-0.01 \pm 0.19 \pm 0.02$, respectively. We also study the characteristics of the low mass $p\bar{p}$ enhancements near threshold and the associated angular distributions. In addition, we report improved measurements of the branching fractions $B(B^+ \rightarrow p\bar{p}K^{*+}) = (3.38^{+0.73}_{-0.60} \pm 0.39) \times 10^{-6}$ and $B(B^0 \rightarrow p\bar{p}K^{*0}) = (2.51^{+0.35}_{-0.29} \pm 0.21) \times 10^{-6}$, which supersede our previous measurements.

PACS: 13.25.Hw

PACS numbers:
After the first observation of the charmless baryonic $B$ meson decay, $B^+ \rightarrow p\bar{p}K^+$ [1,2], many three-body charmless baryonic decays were found [3,4,5,6]. One important and intriguing feature of these decays is that the baryon-antibaryon mass distributions all peak near threshold. However, the BaBar collaboration recently reported evidence of the decay $B^0 \rightarrow p\bar{p}K^{*0}$ but could not establish either the presence or absence of such a threshold enhancement [7]. On the theoretical side, it is generally believed that the $B \rightarrow p\bar{p}K^*$ decays proceed predominantly through a $b \rightarrow s$ penguin loop diagram, which could be sensitive to new physics from heavy virtual particles in the loop. Large direct $CP$ violation, $\sim 20\%$, is predicted using an effective-amplitude approach in the standard model [8]. From a pole model [9], it is expected that $B(B^+ \rightarrow p\bar{p}K^{++}) < B(B^+ \rightarrow p\bar{p}K^*)$ due to the absence of some QCD penguin and electroweak penguin contributions in the $p\bar{p}K^{++}$ mode, and that $B(B^0 \rightarrow p\bar{p}K^{*0}) < B(B^+ \rightarrow p\bar{p}K^{*+})$ due to the absence of a specific pole contribution and the external $W$ emission diagram in the $p\bar{p}K^{*0}$ mode.

In this paper, we study the three-body charmless baryonic decays $B^0 \rightarrow p\bar{p}K^{*0}(K^{*0} \rightarrow K^+\pi^-)$ and $B^+ \rightarrow p\bar{p}K^{*+}(K^{*+} \rightarrow K^0\pi^+)$. The polarization of the $K^*$ meson is determined, which provides information about the relative importance of penguin and external $W$-emission contributions [10]. The differential branching fractions as a function of the baryon-antibaryon mass and the polar angle distributions of the proton in the baryon-antibaryon system are also presented. The direct $CP$ violation parameters of these two decays are also measured. We use a 492 fb$^{-1}$ data sample, consisting of 535 $\times 10^6 B\bar{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ (3.5 on 8 GeV) collider [11]. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter composed of CsI(Tl) crystals located inside a super-conducting 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 [12].

The event selection criteria for the primary charged tracks can be found in Ref. [13]. $K^0_S$ candidates are reconstructed as $\pi^+\pi^-$ pairs with an invariant mass in the range 490 MeV/$c^2 < M_{\pi^+\pi^-} < 510$ MeV/$c^2$. The candidate must have a displaced vertex and flight direction consistent with a $K^0_S$ originating from the interaction point. We use the selected kaons and pions to form $K^{*+} (\rightarrow K^0_S\pi^+)$ and $K^{*0} (\rightarrow K^+\pi^-)$ candidates. Events with a $K^*$ candidate mass between 0.6 GeV/$c^2$ and 1.2 GeV/$c^2$ are used for further analysis. Candidate $B$ mesons are reconstructed in the $B^0 \rightarrow p\bar{p}K^{*0}$ and $B^+ \rightarrow p\bar{p}K^{*+}$ modes. We use two kinematic variables in the center-of-mass (CM) frame to identify the reconstructed $B$ meson candidates: the beam energy constrained mass $M_{bc} = \sqrt{E_B^2 - p_B^2}$, and the energy difference $\Delta E = E_B - E_{\text{beam}}$, where $E_{\text{beam}}$ is the beam energy, and $p_B$ and $E_B$ are the momentum and energy, respectively, of the reconstructed $B$ meson. The candidate region is defined as $5.2$ GeV/$c^2 < M_{bc} < 5.3$ GeV/$c^2$ and $-0.1$ GeV $< \Delta E < 0.3$ GeV. The lower bound in $\Delta E$ is chosen to exclude possible background from baryonic $B$ decays with higher multiplicities. From a GEANT [14] based Monte Carlo (MC) simulation, the signal peaks in a signal box defined by the requirements $5.27$ GeV/$c^2 < M_{bc} < 5.29$ GeV/$c^2$ and $|\Delta E| < 0.05$ GeV. To ensure the decay process is genuinely charmless, we apply charm vetoes. The regions $2.850$ GeV/$c^2 < M_{p\bar{p}} < 3.128$ GeV/$c^2$ and $3.315$ GeV/$c^2 < M_{p\bar{p}} < 3.735$ GeV/$c^2$ are excluded to remove background from modes with $\eta_c, J/\psi$ and $\psi', \chi_{c0}, \chi_{c1}, h_c$ mesons, respectively. The region $2.262$ GeV/$c^2 < M_{pK^0_S}, M_{pK^-\pi^+} < 2.310$ GeV/$c^2$ is also
excluded to remove a possible $\Lambda^+_c$ background. From a study of a charmless $B$ decay MC sample, there are non-negligible backgrounds in the candidate region due to $B^+ \rightarrow p\bar{p}K^+$ and $B^0 \rightarrow p\bar{p}K^0_S$. We remove the $B$ candidates when their $M_{bc}$ and $\Delta E$ values reconstructed for the $p\bar{p}K$ hypothesis are in the signal box.

After the above selection cuts, the background in the fit region arises dominantly from continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) processes. We suppress the jet-like continuum background relative to the more spherical $B\bar{B}$ signal using a Fisher discriminant [15] that combines seven event shape variables, as described in Ref. [16]. 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 using signal MC simulation; the background PDFs are obtained from the sideband data: $5.23 \text{ GeV}/c^2 < M_{bc} < 5.26 \text{ GeV}/c^2$ and $|\Delta E| < 0.06 \text{ GeV}$ for the $p\bar{p}K^{*0}$ mode; $5.25 \text{ GeV}/c^2 < M_{bc} < 5.26 \text{ GeV}/c^2$ and $|\Delta E| < 0.2 \text{ GeV}$ for the $p\bar{p}K^{*+}$ mode. The different selections for sideband regions of the two $K^*$ modes ensure similar statistics to determine the background PDFs. We require the likelihood ratio $R = L_s/(L_s + L_b)$ to be greater than 0.7 for both decay modes. These selection criteria are determined by optimization of $n_s/\sqrt{n_s + n_b}$, where $n_s$ and $n_b$ denote the expected numbers of signal and background events in the signal box, respectively. We use the branching fractions from our previous measurements [4] in the calculation of $n_s$ and use the number of sideband events to estimate $n_b$. If there are multiple $B$ candidates in a single event, we select the one with the best $\chi^2$ value from the vertex fit. The fractions of events that have multiple $B$ candidates are 21% and 32% for the $p\bar{p}K^{*0}$ and $p\bar{p}K^{*+}$ modes, respectively.

We perform an unbinned extended likelihood fit that maximizes the likelihood function

$$L = \frac{e^{-(n_{K^*} + n_{K^*} + n_{q\bar{q}})}}{N!} \prod_{i=1}^{N} (n_{K^*}P_{K^*} + n_{K^*}P_{K^*} + n_{q\bar{q}}P_{q\bar{q}})$$

to estimate the signal yield of $p\bar{p}K^*$ in the region $-0.1 \text{ GeV} < \Delta E < 0.3 \text{ GeV}$, $5.2 \text{ GeV}/c^2 < M_{bc} < 5.3 \text{ GeV}/c^2$ and $0.6 \text{ GeV}/c^2 < M_{K^*} < 1.2 \text{ GeV}/c^2$; here $N$ is the number of events in the fit, and $n_{K^*}, n_{K^*}$ and $n_{q\bar{q}}$ are fit parameters representing the yields of $B \rightarrow p\bar{p}K^*$, $B \rightarrow p\bar{p}K\pi$ and continuum background, respectively. Each PDF is the product of shapes in $M_{bc}, \Delta E$ and $M_{K^*}$, which are assumed to be uncorrelated, e.g., for the $i$th event, $P_{q\bar{q}K^*} = P_{M_{bc}}(M_{bc_i}) \times P_{\Delta E}(\Delta E_i) \times P_{K^*}(M_{K^*_i})$.

For the PDFs of $p\bar{p}K^{*0}$, $p\bar{p}K^{*+}$ and $p\bar{p}K\pi$ decay modes, we use a Gaussian function to represent $P_{M_{bc}}$ and a double Gaussian for $P_{\Delta E}$ with parameters determined by MC signal events. Moreover, we use a p-wave Breit-Wigner function [17] to parameterize the $P_{M_{K^*}}$ distribution for $p\bar{p}K^{*0}$ and $p\bar{p}K^{*+}$ and use a function obtained by the LASS collaboration [18] for $p\bar{p}K\pi$. The parameters of these PDFs have been modified to account for the differences between data and MC using control samples of $J/\psi K^{*0}$ and $J/\psi K^{*+}$ with $J/\psi \rightarrow p\bar{p}$. The modifications related to the mass peaks are all less than 1 MeV$/c^2$. The $\Delta E$ distribution has a $\sim -3$ MeV shift while the modification for its width is $\sim 1$ MeV. For the continuum background PDFs, we use a parameterization that was first employed by the ARGUS collaboration [19], $f(M_{bc}) \propto M_{bc} \sqrt{1 - x^2} e^{-\xi(1 - x^2)}$, to model the $P_{M_{bc}}$ with $x$ given by $M_{bc}/E_{beam}$ and where $\xi$ is a fit parameter. The $P_{\Delta E}$ distribution is modeled by a normalized second-order polynomial whose coefficients are fit parameters. The PDF $P_{M_{K^*}}$ is modeled by a p-wave function and a threshold function, $P_{M_{K^*}} = r \times P_{p-wave} + (1 - r) \times P_{\text{threshold}}$ and $P_{\text{threshold}} \propto (M_{K^*} - M_K - M_\pi)^s \times e^{[c_1 \times (M_{K^*} - M_K - M_\pi) + c_2 \times (M_{K^*} - M_K - M_\pi)^2]}$ where $r, s, c_1$ and
FIG. 1: Distributions of $\Delta E$ (with $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$ and $0.812 \text{ GeV}/c^2 < M_{K\pi} < 0.972 \text{ GeV}/c^2$), $M_{bc}$ (with $|\Delta E| < 0.05 \text{ GeV}$ and $0.812 \text{ GeV}/c^2 < M_{K\pi} < 0.972 \text{ GeV}/c^2$) and $M_{K\pi}$ (with $|\Delta E| < 0.05 \text{ GeV}$ and $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$), respectively, with proton-antiproton pair mass less than 2.85 GeV/$c^2$ for (a) $p\bar{p}K^*_{0}$ and (b) $p\bar{p}K^*_{+}$ modes. The solid curves, solid peaks, dotted curves and dashed curves represent the combined fit result, fitted $B \rightarrow p\bar{p}K^*$ signal, $B \rightarrow p\bar{p}K\pi$ signal and fitted background, respectively. The areas of dotted curves are about 15% of those of the solid peaks.

$c_2$ are fit parameters. Figure 1 shows the fits used to obtain the $B \rightarrow p\bar{p}K^*$ yields in the proton-antiproton mass region below 2.85 GeV/$c^2$, which we refer to as the threshold-mass-enhanced region. The signal yields are $70.1^{+14.8}_{-13.9}$ and $54.2^{+10.9}_{-10.1}$ with statistical significances of 7.2 and 8.8 standard deviations for the $p\bar{p}K^{*0}$ and $p\bar{p}K^{*+}$ modes, respectively. 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.

We determine the angular distribution of the $K^*$ meson in the region $M_{p\bar{p}} < 2.85 \text{ GeV}/c^2$ using likelihood fits to obtain signal yields in bins of $\cos \theta_K$, where $\theta_K$ is the polar angle of the $K$ meson in the $K^*$ helicity frame. The theoretical PDF for the $K^*$ meson has the form $3/2 \cos^2 \theta_K$ for a pure helicity zero state and $3/4 \sin^2 \theta_K$ for a pure helicity one ($\pm 1$) state. We use MC simulation to obtain the efficiency function and convolve it with the theoretical forms in order to obtain the final PDFs for different helicity states. The signal yields in bins of $\cos \theta_K$ are then fitted with the above two different PDFs where the fraction of the helicity zero state is floated in the fit and the total yield is fixed to the experimental result. The $B$ yield distributions in bins of $\cos \theta_K$ with the corresponding fit curves are shown in Fig. 2. We find that the $K^{*0}$ meson has a fraction of $(101 \pm 13 \pm 3)\%$ in the helicity zero state and the $K^{*+}$ meson has a $(32 \pm 17 \pm 9)\%$ fraction in the helicity zero state. It is interesting to note that the helicity zero amplitude is expected to be dominant in the $b \rightarrow s$ penguin transition due to the $(V-A)$ nature of the weak interaction and helicity conservation in the strong
to Ref. [7], we find that a threshold enhancement is present for the mass-dependent efficiencies. The differential branching fractions as a function of \(M_{\vec{p}p}\) results, (5.36^{+0.23}_{-0.22}) \times 10^{-6}, which agrees well with our latest results, (5.54^{+0.27}_{-0.25} \pm 0.36) \times 10^{-6} [13]. The measured value of \(B(\bar{B}^{0} \rightarrow \vec{p}\bar{p}K^{0})\) is (2.51^{+0.35}_{-0.29} \pm 0.21) \times 10^{-6}. This result also supersedes our previous measurement [4]. With improved experimental accuracy, the following relationships \(B(\bar{B}^{+} \rightarrow \vec{p}\bar{p}K^{+}) > B(\bar{B}^{+} \rightarrow \vec{p}\bar{p}K^{*+})\) and \(B(\bar{B}^{+} \rightarrow \vec{p}\bar{p}K^{*+}) > B(\bar{B}^{0} \rightarrow \vec{p}\bar{p}K^{0})\) are established. These inequalities agree with the pole model predictions [3], but the measured \(B(\bar{B}^{0} \rightarrow \vec{p}\bar{p}K^{0})\) is about a factor of 20 larger than predicted. This may indicate that the relative weights of different pole contributions

interaction [10]. The systematic uncertainty is obtained from the \(B \rightarrow J/\psi K^{*}, J/\psi \rightarrow \mu^{+}\mu^{-}\) control sample. We compare our measured \(K^{*}\) polarization in the helicity zero state with the PDG value [20]. The difference is added in quadrature with the PDG error and the fit error to extract the final systematic uncertainty. These uncertainties are 0.03 and 0.09 for the \(p\bar{p}K^{*0}\) and \(p\bar{p}K^{*+}\) modes, respectively.

Since the detection efficiency depends on \(M_{p\bar{p}}\), we determine the \(B \rightarrow p\bar{p}K^{*}\) yields in bins of \(M_{p\bar{p}}\). We generate a large phase-space MC sample in order to estimate the efficiencies properly where the sub-decay branching fractions of \(K^{*}\) to corresponding final states are included. The \(K\pi\) angular distribution is fixed by the measured \(K^{*}\) polarization for all \(M_{p\bar{p}}\) bins. The partial branching fractions are obtained by correcting the fitted \(B\) yields for the mass-dependent efficiencies. The differential branching fractions as a function of the proton-antiproton mass for both \(p\bar{p}K^{*0}\) and \(p\bar{p}K^{*+}\) modes are shown in Fig. 3 and the measured branching fractions for different \(M_{p\bar{p}}\) bins are listed in Table I. Applying 3.075 GeV/c^2 < \(M_{p\bar{p}}\) < 3.117 GeV/c^2 for \(J/\psi\) selection, we find good agreement, within 1\(\sigma\), between our branching fraction measurements and the PDG values [20]. In contrast to Ref. [7], we find that a threshold enhancement is present for the \(B^{0} \rightarrow p\bar{p}K^{*0}\) decay.
FIG. 3: Differential branching fractions for (a) the $p\bar{p}K^*$ and (b) the $p\bar{p}K^{*+}$ modes as a function of proton-antiproton invariant mass. Note that the two shaded mass bins contain charmonium events and are excluded from the charmless signal yields. The data points for the $2.85 \text{ GeV}/c^2 < M_{p\bar{p}} < 3.128 \text{ GeV}/c^2$ mass region are off-scale.

in Ref. [9] are incorrect.

Systematic uncertainties are determined using high-statistics control data 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. Note that the average efficiency difference for PID between data and MC has been corrected to obtain the final branching fraction measurements. The corrections are about 11.5% and 11.7% for the $p\bar{p}K^*$ and $p\bar{p}K^{*+}$ modes, respectively. The uncertainties associated with the PID corrections are estimated to be 4% for two protons and 1% for one kaon/pion. The tracking uncertainty is determined with fully and partially reconstructed $D^*$ samples. It is about 1% per charged track. The uncertainty in $K^0_S$ reconstruction is determined to be 4% from a sample of $D^- \rightarrow K^0_S\pi^-$ events. The $R$ continuum suppression uncertainty of 2.3% is estimated from control samples with similar final states, $B \rightarrow J/\psi K^*$ with $J/\psi \rightarrow \mu^+\mu^-$. The uncertainties in the best $B$ candidate selection are estimated to be 2.0% and 3.5% for the $p\bar{p}K^*$ and $p\bar{p}K^{*+}$ modes, respectively, by taking a difference in the branching fractions with and without the best candidate selection. A systematic uncertainty of 5.2% in the fit yield is determined by varying the parameters (or changing the functional forms) of the signal and background PDFs. The MC statistical uncertainty is less than 3%. The efficiency error caused by the $K^*$ polarization modeling is estimated to be 2.4% and 4.0% for the $p\bar{p}K^*$ and $p\bar{p}K^{*+}$ modes, respectively, by changing the polarization value by $\pm 1\sigma$. The error on the number of $B\bar{B}$ pairs is 1.3%, where we assume that the branching fractions of $\Upsilon(4S)$ to neutral and charged $B\bar{B}$ pairs are equal. We first sum the correlated errors linearly and then combine them with the uncorrelated ones in quadrature. The total systematic uncertainties are 9.7% and 11.6% for the $p\bar{p}K^*$ and $p\bar{p}K^{*+}$ modes, respectively.
TABLE I: Signal yields and branching fractions $B \left( 10^{-6} \right)$ in different $M_{p\bar{p}}$ regions for $B^0 \to p\bar{p}K^{*0}(\text{left})$ and $B^+ \to p\bar{p}K^{*+}(\text{right})$.

| $M_{p\bar{p}}$ (GeV) | yield | $B \left( 10^{-6} \right)$ | yield | $B \left( 10^{-6} \right)$ |
|----------------------|-------|-----------------|-------|-----------------|
| $< 2.0$              | 21.4$^{+8.0}_{-7.1}$ 0.36$^{+0.11}_{-0.10}$ | 9.0$^{+4.4}_{-3.7}$ 0.43$^{+0.21}_{-0.18}$ |
| $2.0 - 2.2$          | 21.5$^{+8.4}_{-7.5}$ 0.31$^{+0.12}_{-0.11}$ | 25.1$^{+7.1}_{-6.3}$ 1.28$^{+0.36}_{-0.32}$ |
| $2.2 - 2.4$          | 15.7$^{+6.4}_{-5.6}$ 0.26$^{+0.10}_{-0.09}$ | 6.4$^{+5.4}_{-4.5}$ 0.37$^{+0.31}_{-0.26}$ |
| $2.4 - 2.6$          | 12.3$^{+6.2}_{-5.4}$ 0.22$^{+0.11}_{-0.10}$ | 4.5$^{+3.3}_{-2.5}$ 0.30$^{+0.22}_{-0.17}$ |
| $2.6 - 2.85$         | 1.2$^{+4.9}_{-3.9}$ 0.02$^{+0.09}_{-0.07}$ | 9.6$^{+4.8}_{-3.9}$ 0.62$^{+0.31}_{-0.25}$ |
| $2.85 - 3.128(\text{veto})$ | 224.2$^{+18.2}_{-17.6}$ 4.12$^{+0.34}_{-0.32}$ | 55.7$^{+9.8}_{-9.0}$ 3.66$^{+0.65}_{-0.59}$ |
| $3.128 - 3.315$      | 2.6$^{+4.7}_{-3.5}$ 0.05$^{+0.09}_{-0.06}$ | 1.5$^{+2.1}_{-1.5}$ 0.11$^{+0.15}_{-0.11}$ |
| $3.315 - 3.735(\text{veto})$ | 11.9$^{+6.6}_{-5.6}$ 0.24$^{+0.13}_{-0.11}$ | 7.1$^{+4.8}_{-4.1}$ 0.58$^{+0.40}_{-0.34}$ |
| $> 3.735$            | 0.7$^{+5.5}_{-4.4}$ 0.02$^{+0.14}_{-0.11}$ | 2.5$^{+2.9}_{-2.0}$ 0.27$^{+0.31}_{-0.22}$ |
| Charmless             | 75.4$^{+17.1}_{-14.7}$ 1.18$^{+0.29}_{-0.25}$ | 58.7$^{+12.1}_{-10.1}$ 3.38$^{+0.73}_{-0.60}$ |

We study the proton angular distribution in the proton-antiproton helicity frame with $M_{p\bar{p}} < 2.85$ GeV/$c^2$. The angle $\theta_p$ is defined as the angle between the proton direction and the positive strangeness $K^*$ (i.e. $K^{*-}$ or $\bar{K}^{*0}$) direction in the proton-antiproton pair rest frame. The $\cos\theta_p$ distributions, shown in Fig. 3A do not have a prominent peaking feature toward $\cos\theta_p \sim 1$, which was first observed in the decay $B^+ \to p\bar{p}K^+$ [21]. However, current statistics are inadequate to draw any definitive conclusions about $B \to p\bar{p}K^*$.

To examine the prediction [8] that direct $CP$ violation in $B^+ \to p\bar{p}K^{*+}$ can be as large as $\sim 20\%$, we define the charge asymmetry $A_{ch}$ as $(N_b - N_h)/(N_b + N_h)$ for the $p\bar{p}K^{*0}$ and $p\bar{p}K^{*+}$ modes, where $N$ and $b$ stand for the efficiency corrected $B$ yield and quark flavor, respectively. The results are $-0.08 \pm 0.20 \pm 0.02$ and $-0.01 \pm 0.19 \pm 0.02$ for the $p\bar{p}K^{*0}$ and $p\bar{p}K^{*+}$ modes, respectively. The systematic uncertainty is estimated from the measured charge asymmetry for the sideband data.

In summary, using $535 \times 10^6 BB$ events and applying charmonium vetoes, we observe the $B^0 \to p\bar{p}K^{*0}$ decay with a branching fraction of $(1.18^{+0.29}_{-0.25}(\text{stat.}) \pm 0.11(\text{syst.})) \times 10^{-6}$. The signal yield is $70.1^{+14.8}_{-13.9}$ with a significance of 7.2 standard deviations in the $M_{p\bar{p}} < 2.85$ GeV/$c^2$ mass region. The $K^{*0}$ meson is found to be $(101 \pm 13 \pm 3)\%$ in the helicity zero state, compared to $(32 \pm 17 \pm 9)\%$ for the $K^{*+}$ meson. The smaller $K^{*+}$ polarization in the $p\bar{p}K^{*+}$ decay may be attributed to an additional contribution from external $W$ emission. We also observe a low mass $p\bar{p}$ enhancement near threshold for the $p\bar{p}K^{*0}$ mode. The direct $CP$ asymmetries for $p\bar{p}K^{*0}$ and $p\bar{p}K^{*+}$ are measured to be $-0.08 \pm 0.20 \pm 0.02$ and $-0.01 \pm 0.19 \pm 0.02$, respectively. With improved experimental accuracy, the relationships $B(B^+ \to p\bar{p}K^+) > B(B^+ \to p\bar{p}K^{*+})$ and $B(B^+ \to p\bar{p}K^{*+}) > B(B^0 \to p\bar{p}K^{*0})$ are established.

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NII for valuable computing and Super-SINET network support. We acknowledge support from MEXT and JSPS (Japan); ARC and DEST (Australia); NSFC (China); DST (India); MOEHRD,
FIG. 4: Distributions of efficiency corrected signal yields vs. $\cos \theta_p$ in the proton-antiproton system with $M_{p\bar{p}} < 2.85$ GeV/$c^2$ for (a) $B^0 \rightarrow p\bar{p}K^{*0}$ and (b) $B^+ \rightarrow p\bar{p}K^{*+}$.

KOSEF and KRF (Korea); KBN (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA).

[1] K. Abe et al. (Belle Collaboration), Phys. Rev. Lett. 88, 181803 (2002).
[2] Throughout this report, inclusion of charge-conjugate mode is always implied unless otherwise stated.
[3] M.Z. Wang et al. (Belle Collaboration), Phys. Rev. Lett. 90, 201802 (2003).
[4] M.Z. Wang et al. (Belle Collaboration), Phys. Rev. Lett. 92, 131801 (2004).
[5] Y.J. Lee et al. (Belle Collaboration), Phys. Rev. Lett. 93, 211801 (2004).
[6] Y.J. Lee et al. (Belle Collaboration), Phys. Rev. Lett. 95, 061802 (2005).
[7] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 76, 092004 (2007).
[8] C.Q. Geng, Y.K. Hsiao, and J.N. Ng, Phys. Rev. Lett. 98, 011801 (2007); C.Q. Geng, Y.K. Hsiao, and J.N. Ng, Phys. Rev. D 75, 094013 (2007).
[9] H.Y. Cheng and K.C. Yang, Phys. Rev. D 66, 014020 (2002).
[10] For a review article and references therein, see [20], p833.
[11] S. Kurokawa and E. Kikutani, Nucl. Instr. and Meth. A 499, 1 (2003) and other papers included in this Volume.
[12] A. Abashian et al. (Belle Collaboration), Nucl. Instr. and Meth. A 479, 117 (2002).
[13] J.-T. Wei et al. (Belle Collaboration), Phys. Lett. B 659, 80 (2008).
[14] R. Brun et al., GEANT 3.21, CERN Report No. DD/EE/84-1, 1987.
[15] R.A. Fisher, Annals of Eugenics 7, 179 (1936).
[16] K. Abe et al. (Belle Collaboration), Phys. Lett. B 517, 309 (2001).
[17] J. Zhang et al. (Belle Collaboration), Phys. Rev. Lett. 95, 141801 (2005).
[18] D. Aston et al. (LASS Collaboration), Nucl. Phys. B 296, 493 (1988).
[19] H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 241, 278 (1990); ibid. B 254, 288 (1991).
[20] W.-M. Yao et al. (Particle Data Group), J. Phys. G 33, 1 (2006).
[21] M.Z. Wang et al. (Belle Collaboration), Phys. Lett. B 617, 141 (2005).