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Abstract

We report on a search for the exclusive two-body charmless hadronic $B$ meson decays $B \to \eta' \rho$, $B \to \eta' K^*$, $B^0 \to \eta' \phi$, $B^0 \to \eta' \omega$ and $B^0 \to \eta' \eta^{(')}$. The results are obtained from a data sample containing $535 \times 10^6$ $B \bar{B}$ pairs that were collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. We find no significant signals and report upper limits in the range $(0.5–6.5) \times 10^{-6}$ for all of the above decays.

PACS numbers: 13.25.Hw, 11.30.Er
INTRODUCTION

Information on the two-body charmless hadronic $B$ meson decays with an $\eta'$ meson in the final state ($B \to \eta' h^{(*)}$) is incomplete at present. While the decay $B \to \eta' K$ is observed with a large branching fraction, so far no other $B \to \eta' h^{(*)}$ decay mode has been observed with greater than $5\sigma$ significance. The first evidence of $B \to \eta' \pi$ has recently been reported [1, 2] and BABAR found evidence for $B \to \eta' K^*$ with larger than $4\sigma$ significance [3], and thus additional observations are expected in the near future. The study of these decay modes can improve the understanding of the flavor-singlet penguin amplitude with intermediate $t$, $c$ and $u$ quarks [4]. Furthermore, these studies increase our confidence in the reliability of a variety of other predictions, e.g., for the $CP$ violating parameter $\phi_3 (\gamma)$, and are necessary to extract theory parameters such as the scalar penguin operator [4, 5]. Presently, theoretical predictions for the branching fractions of these decay modes cover the range $(0.0001–7.6) \times 10^{-6}$ [4, 5, 6]. The most stringent upper limits for presently unobserved decays were reported by BABAR [1, 3, 7].

DATA SET AND APPARATUS

The study performed here includes the decays $B^{0, +} \to \eta' \rho^{0, +}$, $B^{0, +} \to \eta' K^{*0, (+)}$, $B^0 \to \eta' \phi$, $B^0 \to \eta' \omega$ and $B^0 \to \eta' \eta^{(*)}$ and is based on a data sample that contains $535 \times 10^6$ $B \bar{B}$ pairs, collected with the Belle detector at the KEKB asymmetric energy $e^+ e^-$ (3.5 GeV on 8 GeV) collider [8]. Throughout this paper, the inclusion of the charge conjugate decay is implied unless stated otherwise.

KEKB operates at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) with a peak luminosity that exceeds $1.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$. 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 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 [9]. Two inner detector configurations were used. A 2.0 cm beampipe and a 3-layer SVD were used for the first data sample of $152 \times 10^6$ $B \bar{B}$ pairs (Set I), while a 1.5 cm beampipe, a 4-layer SVD and a small-cell inner drift chamber were used to record the remaining $383 \times 10^6$ $B \bar{B}$ pairs (Set II) [10].

EVENT SELECTION AND RECONSTRUCTION

For what follows, unless stated otherwise, all variables are defined in the center-of-mass frame with the $z$ axis anti-parallel to the positron direction.

Charged hadrons are identified by combining information from the CDC ($dE/dx$), ACC and TOF systems. Both kaons and pions are selected with an average efficiency of 86% and are misidentified as pions or kaons, respectively, in 4% of the cases.

The $\eta'$ mesons are reconstructed in the decays $\eta' \to \eta \pi^+ \pi^-$ (with $\eta \to \gamma \gamma$) and $\eta' \to \rho^0 \gamma$, except for the decays $B^0 \to \eta' \eta$, $B^0 \to \eta' \eta'$ and $B^0 \to \eta' \omega$, which use only the $\eta' \to \eta \pi^+ \pi^-$ channel. We define the $\eta' (h^{(*)})$ side as all particles involved in the decay of the $\eta' (h^{(*)})$
from the decay $B \to \eta' h^{(*)}$. The $\eta, \rho^0$ and $\eta'$ candidates on the $\eta'$ side are reconstructed using the mass windows given in Table I. Mass windows used to reconstruct the $h^{(*)}$ are given in Table II. In addition, we require the following: photons originating from $\pi^0$ and $\eta$ decays are required to have energies of at least 100 MeV, photons from the $\eta'$ in $\eta' \to \rho^0 \gamma$ have to be above 200 MeV in the laboratory frame. The transverse momenta of the $\pi^\pm$ for $\eta' \to \eta \pi^+ \pi^- (\eta' \to \rho^0 \pi^+ \pi^- \gamma)$ candidates have to be greater than 100 MeV/c (200 MeV/c). An additional requirement on the cosine of the $\rho^0$ helicity angle in $\eta' \to \rho^0 \gamma$ of $|\cos \theta_h| < 0.85$ is applied, where $\theta_h$ is the angle between the momenta of one of the daughter pions of the $\rho^0$ and the $\eta'$ in the $\rho^0$ rest frame. The vertex of the $K_0^S \to \pi^+ \pi^-$ has to be displaced from the interaction point (IP) and the $K_0^S$ momentum direction must be consistent with its flight direction as indicated in Table III [11].

### TABLE I: Invariant mass windows used to select intermediate states on the $\eta'$ side. $\sigma$ denotes a standard deviation of the reconstructed mass distribution.

| Mode               | Mass window (MeV/c$^2$) | in units of $\sigma$ |
|--------------------|--------------------------|-----------------------|
| $\rho^0 \to \pi^+ \pi^-$ | [550,870]                | —                     |
| $\eta \to \gamma \gamma$ | [500,570]                | $+2.5/-3.3$           |
| $\eta' \to \eta \pi^+ \pi^-$ | [950,965]                | $\pm 2.5$             |
| $\eta' \to \rho^0 \gamma$ | [941,970]                | $\pm 2.5$             |

### TABLE II: Invariant mass windows used to select intermediate states on the $h^{(*)}$ side. $\sigma$ denotes a standard deviation of the reconstructed mass distribution.

| Mode               | Mass window (MeV/c$^2$) | in units of $\sigma$ |
|--------------------|--------------------------|-----------------------|
| $\pi^0 \to \gamma \gamma$ | [118,150]                | $\pm 2.5$             |
| $K_0^S \to \pi^+ \pi^-$ | [485,510]                | $\pm 3$               |
| $\rho^+ \to \pi^+ \pi^0$ | [620,920]                | —                     |
| $\rho^0 \to \pi^+ \pi^-$ | [620,920]                | —                     |
| $K^{*0} \to K^+ \pi^-$ | [820,965]                | —                     |
| $K^{*+} \to K_0^S \pi^+$ | [820,965]                | —                     |
| $K^{*+} \to K^+ \pi^0$ | [820,965]                | —                     |
| $\phi \to K^+ K^-$ | [1010,1030]              | $\pm 3$               |
| $\eta \to \gamma \gamma$ | [510,575]                | $\pm 2.5$             |
| $\eta' \to \eta \pi^+ \pi^-$ | [950,965]                | $\pm 2.5$             |
| $\omega \to \pi^+ \pi^- \pi^0$ | [750,810]                | $\pm 2.5$             |

$B$ meson candidates are formed by combining an $\eta'$ meson with one of the hadrons listed in Table III excluding $\pi^0$’s and $K_0^S$’s. $B$ candidates are identified using two kinematic variables: the energy difference, $\Delta E = E_B - E_{\text{beam}}$, and the beam-energy constrained mass, $M_{bc} = \sqrt{E_{\text{beam}}^2/c^4 - (P_B/c)^2}$, where $E_{\text{beam}}$ is the beam energy and $E_B$ ($P_B$) is the reconstructed energy (momentum) of the $B$ candidate. Signal events peak at $\Delta E = 0$ GeV.
and $M_{bc} = M_B$, where $M_B$ is the $B$ meson mass, with resolutions around 15 MeV and 3 MeV for $\Delta E$ and $M_{bc}$ respectively. An $\eta$ mass constraint fit is applied in the $\eta' \rightarrow \eta \pi^+ \pi^-$ subdecay in order to improve the $\Delta E$ resolution. Here the two photons from $\eta \rightarrow \gamma \gamma$ are constrained to have the nominal $\eta$ mass given by the Particle Data Group (PDG) \[20\]. Events satisfying the requirements $M_{bc} > 5.22$ GeV/$c^2$ and $|\Delta E| < 0.25$ GeV are selected for further analysis. After all selections are applied, depending on the decay mode between 3% and 20% of the events have multiple $B$ candidates in one event. A $\chi^2$ variable is calculated to select the best candidate of such events. We select the $B$ with the smallest $\chi^2 = \chi^2_{\text{vx}} + \chi^2(M_{\eta'}) + \chi^2(M_{h^{(*)}})$, where $\chi^2_{\text{vx}}$ is an estimator of the vertex quality for all charged particles not from the $K_S^0$ and $\chi^2(M_{X}) = [(M_{X} - m_{X})/\sigma_{X}]^2$, where $M_{X}$ ($m_{X}$) is the reconstructed (nominal) mass of the particle candidate $X$ ($= \eta'$ or $h^{(*)}$) and $\sigma_{X}$ is the standard deviation of the reconstructed $X$ mass distribution as obtained from fits to MC distributions.

**BACKGROUND SUPPRESSION**

The dominant background for this analysis is continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$). Other background sources are charmless $B$ decays such as $B \rightarrow \eta' K$ and $b \rightarrow c$ decays. The background is 90% continuum with the remaining 10% nearly evenly split between the other two contributions.

Several event shape variables are used to distinguish the spherical $B\bar{B}$ topology from the jet-like $e^+e^- \rightarrow q\bar{q}$ continuum background. The thrust angle $\theta_T$ is defined as the angle between the $\eta'$ momentum direction and the thrust axis formed by all particles not belonging to the reconstructed $B$ meson. Continuum events tend to peak near $|\cos \theta_T| = 1$, while $B\bar{B}$ events have a uniform distribution. The requirement $|\cos \theta_T| < 0.9$ is applied prior to all other event topology selections resulting in a signal efficiency (background reduction) of 90% (56%).

Additional continuum background suppression is obtained by using modified Fox-Wolfram moments \[12\] and $|\cos \theta_B|$, where $\theta_B$ is the angle between the flight direction of the reconstructed $B$ candidate and the beam axis. A Fisher discriminant ($F$) \[13\] is formed from a linear combination of $|\cos \theta_T|$, $S_\perp$ \[14\] and five modified Fox-Wolfram moments. $S_\perp$ is the ratio of the scalar sum of the transverse momenta of all tracks outside a $45^\circ$ cone around the $\eta'$ direction to the scalar sum of their total momenta. The Fisher discriminant is then combined with the $B$ flight direction information to form an event topology likelihood function $\mathcal{L}_S (\mathcal{L}_{q\bar{q}})$, where the subscript $S$ ($q\bar{q}$) represents signal (continuum background). The signal
over continuum background ratio varies over the range of the quality parameter \( r \) of the \( B \) flavor tagging of the accompanying \( B \) meson. We use the standard Belle \( B \) tagging algorithm \cite{15}, which gives the \( B \) flavor and the tagging quality \( r \) ranging from zero for no flavor to unity for unambiguous flavor assignment. The data is divided into three \( r \) regions and the likelihood ratio \( R_L = L_S/(L_S + L_B) \) requirements are determined to maximize \( N_S/\sqrt{N_B} \), with \( N_S \) (\( N_B \)) the expected number of signal (background), on Monte Carlo (MC) events in each \( r \) region separately. More stringent selections are imposed for the first \( r \) region at zero while looser criteria are used for \( r \) close to one. More stringent selections are applied for decays with large continuum contribution such as \( B \to \eta' \rho \), while relatively clean decays such as \( B^0 \to \eta' \phi \) have very loose requirements. The signal efficiencies (continuum background reduction) lie in the range of 42%-88% (98%-45%).

Contributions from other charmless \( B \) decays can contaminate the signal when a pion is misidentified as a kaon or when a random pion is added or missed. The dominant contribution for such misidentified events originates from \( B \to \eta' K \) decays. For the decays \( B \to \eta' \rho \), \( B \to \eta' K \) and \( B^0 \to \eta' \omega \) the \( B \to \eta' K \) contamination is significant. For these decays we construct an alternative \( B \) meson hypothesis assuming that it originates from a \( B \to \eta' K \) decay. We then veto an event if the alternative \( \Delta E \) variable is within a decay-dependent window around \( \Delta E = 0 \) GeV and \( M_{bc} > 5.27 \) GeV/c. The selection is optimized for each decay and results in negligible signal suppression (< 0.5%) while removing around 80% of the \( B \to \eta' K \) background.

**MEASUREMENT OF BRANCHING FRACTIONS**

The branching fractions are obtained using an extended unbinned maximum-likelihood fit to the \( \Delta E \) and \( M_{bc} \) distributions of selected events. This fit is performed simultaneously in the \( \eta' \to \eta \pi^+ \pi^- \) and \( \eta' \to \rho^0 \gamma \) subdecay channels for all \( B \) decay modes, where applicable. In the case of \( B^+ \to \eta' K^{**} \) the two \( K^{**} \) subdecay modes (thus four subdecay channels in total) are fitted simultaneously. The extended likelihood function used is:

\[
L(N_S, N_{B_j}) = \frac{e^{-(N_S+\sum_j N_{B_j})}}{N!} \left[ \frac{N_S}{N} \right] \prod_{i=1}^{N_S} P_S(\Delta E_i, M_{bc_i}) \times \frac{N_{B_j}}{N} \prod_{i=1}^{N_{B_j}} P_{B_j}(\Delta E_i, M_{bc_i}) + \sum_j N_{B_j} P_{B_j}(\Delta E_i, M_{bc_i})
\]

where \( N_S \) (\( N_{B_j} \)) is the number of signal events (background events of source \( j \)) with probability density functions (PDFs) \( P_S \) (\( P_{B_j} \)). The index \( i \) runs from 1 to the total number of events \( N \) in the selected sample.

The branching fraction \( \mathcal{B} \) is determined by maximizing the combined likelihood for both data sets and all subdecays with \( \mathcal{B} \) constrained to be the same for the subdecays. The number of signal events \( (N_S) \) for each decay mode is calculated by

\[
N_S = \mathcal{B} [N_{BB}(I) \epsilon_I(I) + N_{BB}(II) \epsilon_I(II)],
\]

where \( N_{BB}(k) \) is the number of \( B\bar{B} \) produced for set \( k = I \) or \( II \) and \( \epsilon_I(k) \) is the total reconstruction efficiency including subdecay branching fractions for set \( k \).

The reconstruction efficiencies are determined from signal MC samples using the EvtGen package \cite{16} with final state radiation simulated by the PHOTOS package \cite{17} (thus measuring \( B \to \eta'h^{(*)}(\gamma) \)). The efficiencies are calculated separately for Set \( I \) and Set \( II \). The absolute efficiency for Set \( II \) is typically about 0.5% larger than for Set \( I \) (for efficiencies averaged over the two sets see Tables [V] and [V]). Corrections due to differences between
TABLE IV: Average efficiencies (\(\epsilon\)) for the two data sets for \(\eta'\rightarrow\eta\pi^+\pi^-\) and \(\eta'\rightarrow\rho^0\gamma\), total efficiencies (\(\epsilon_t\)) with systematic errors of secondary branching fractions included, signal yield (\(N_S\)) with statistical errors only and the 90\% confidence level upper limit on the branching fraction in units of \(10^{-6}\) including systematic errors for each decay of this analysis (UL) and latest results from BABAR in units of \(10^{-6}\).

|                | \(B^0 \rightarrow \eta'\rho^0\) | \(B^+ \rightarrow \eta'\rho^+\) | \(B^0 \rightarrow \eta'K^{*0}\) | \(B^+ \rightarrow \eta'K^{*+}\) | \(B^0 \rightarrow \eta'\phi\) |
|----------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| \(\epsilon(\eta\pi\pi)\) [\%] | 7.0 ± 0.1                         | 5.9 ± 0.1                         | 8.5 ± 0.1                         | 4.5 ± 0.1                         | 12.9 ± 0.1                         |
| \(\epsilon(\rho\gamma)\) [\%] | 5.4 ± 0.1                         | 3.9 ± 0.1                         | 5.9 ± 0.1                         | 2.2 ± 0.1                         | 7.4 ± 0.1                         |
| \(\epsilon_t(\eta\pi\pi)\) [%] | 1.13 ± 0.02                       | 0.93 ± 0.02                       | 0.92 ± 0.01                       | 0.35 ± 0.01                       | 1.08 ± 0.01                       |
| \(\epsilon_t(\rho\gamma)\) [%] | 1.51 ± 0.03                       | 1.07 ± 0.02                       | 1.09 ± 0.02                       | 0.30 ± 0.01                       | 1.08 ± 0.02                       |
| \(N_S\) | 0.1^{+8.2}_{-7.0}                 | 18.5^{+23.3}_{-21.7}             | 14.2^{+9.1}_{-8.0}               | -6.4^{+10.9}_{-7.9}              | -2.4^{+2.5}_{-3.5}               |
| UL \([10^{-6}]\) | < 1.3                             | < 5.8                             | < 2.6                             | < 2.9                             | < 0.5                             |
| BABAR\([10^{-6}]\) | < 3.7                             | < 14                              | 3.8 ± 1.1 ± 0.5                   | 4.9^{+1.9}_{-1.7} ± 0.8           | < 4.5                             |

**SYSTEMATICS**

Systematic errors on the branching fractions are estimated with various high statistics data samples. The dominant sources are the uncertainties in the reconstruction efficiency of charged tracks (3–4\%), the uncertainties in the reconstruction efficiencies of \(\eta\) mesons, \(\pi^0\)’s and photons (3–6\%) and the \(K_S^0\) reconstruction efficiency uncertainty (4\%). Other systematic uncertainties arise from signal MC statistics (2\%), likelihood ratio selections...
TABLE V: Average efficiencies ($\epsilon$) for the two data sets for $\eta' \rightarrow \eta \pi^+ \pi^-$, total efficiencies ($\epsilon_t$) with systematic errors of secondary branching fractions included, signal yield ($N_S$) with statistical errors only and the 90% confidence level upper limit on the branching fraction in units of $10^{-6}$ including systematic errors for each decay of this analysis (UL) and latest results from BaBar in units of $10^{-6}$.

|          | $B^0 \rightarrow \eta'$ $\eta$ | $B^0 \rightarrow \eta'$ $\eta'$ | $B^0 \rightarrow \eta'$ $\omega$ |
|----------|---------------------------------|---------------------------------|---------------------------------|
| $\epsilon(\eta \pi \pi)$ [%] | 5.7 ± 0.1                       | 4.8 ± 0.1                       | 7.5 ± 0.1                       |
| $\epsilon_t(\eta \pi \pi)$ [%] | 0.37 ± 0.007                    | 0.16 ± 0.003                    | 1.09 ± 0.02                     |
| $N_S$    | 1.0 $^{+4.6}_{-3.6}$           | $^-6.3^+2.2$                    | 0.9 $^{+6.3}_{-5.2}$           |
| UL $[10^{-6}]$ | < 4.5                           | < 6.5                           | < 2.2                           |
| BaBar $[10^{-6}]$ | < 1.7                           | < 10                            | < 2.8                           |

FIG. 1: $\Delta E$ (upper) and $M_{bc}$ (lower) distributions for (from left to right) $B^0 \rightarrow \eta' \rho^0$, $B^+ \rightarrow \eta' \rho^+$, $B^0 \rightarrow \eta' K^{*0}$ and $B^+ \rightarrow \eta' K^{*+}$.

(2%), uncertainties of the subdecay branching fractions as given by the PDG (1.7–3.0%), the number of $BB$ mesons produced (1.4%) and the uncertainty from particle identification (0.5–1.3%). In addition, we calculate systematic uncertainties for the fitting procedure by varying all PDF shape parameters by $\pm 1\sigma$. Background normalization systematic uncertainties are estimated by varying the background normalizations by 20%–50% while those for $\Delta E/M_{bc}$ corrections are obtained by varying the corrections by one standard deviation. Since for most decays the fits yield branching fractions close to zero, we use absolute errors in these cases. Fractional errors are translated into absolute values by multiplying the obtained upper limit value by the fractional error. The combined absolute errors are decay dependent and lie in the range $(0.01 – 4.93 ) \times 10^{-6}$. The total systematic uncertainties are listed in Table VI.
TABLE VI: Total systematic uncertainties for each decay. Listed are combined errors for fitting, efficiency related errors and the error in the number of $\bar{B}B$ events. Conservatively, we take the total systematic error to be the linear sum of these. All errors are in absolute values in units of $10^{-7}$.

| Decay | Fitting | Efficiency | $\#BB$ | Total |
|-------|---------|------------|--------|-------|
| $B^0 \to \eta'\rho^0$ | $+0.33$ | 0.07 | 0.02 | $+0.42$ |
| $B^+ \to \eta'\rho^+$ | $+2.90$ | 0.32 | 0.06 | $+3.28$ |
| $B^0 \to \eta'K^{*0}$ | $-0.03$ | 0.16 | 0.04 | $-0.23$ |
| $B^+ \to \eta'K^{*+}$ | $+0.84$ | 0.21 | 0.04 | $+1.09$ |
| $B^0 \to \eta'\phi$ | $\pm 0.10$ | 0.03 | 0.01 | $\pm 0.14$ |
| $B^0 \to \eta'\eta$ | $+2.43$ | 0.26 | 0.05 | $+2.74$ |
| $B^0 \to \eta'\eta'$ | $-0.36$ | 0.29 | 0.05 | $-0.67$ |
| $B^0 \to \eta'\omega$ | $+24.85$ | 0.16 | 0.03 | $+25.19$ |
| $B^0 \to \eta'\omega$ | $-48.94$ | 0.29 | 0.05 | $-49.28$ |
| $B^0 \to \eta'\omega$ | $+0.58$ | 0.16 | 0.03 | $+0.77$ |
| $B^0 \to \eta'\omega$ | $-5.19$ | 0.29 | 0.05 | $-5.38$ |

UPPER LIMIT CALCULATION

Since no decay has more than $2\sigma$ significance [21], we calculate upper limits on the branching fractions by integrating the likelihood function starting at $B = 0$ using a Bayesian approach assuming a uniform distribution for $B > 0$. We set the upper limit when the integral reaches 90% of the total area under the likelihood function. The systematic error is accounted for by folding the systematic error into the width of the likelihood distribution (Eq. 1) when integrating the likelihood. Thus the upper limit (UL) is calculated with the
FIG. 3: Distributions of likelihood vs. branching fraction for each decay. The systematic error is included as described in the text. Two dashed lines indicate $B = 0$ and the 90% confidence level upper limit.

formula:

$$\frac{\int_{B=0}^{UL} L_{\text{sys}}(N_S, N_{Bj})dB}{\int_{B=0}^{1} L_{\text{sys}}(N_S, N_{Bj})dB} = 0.9,$$

(2)

where $L_{\text{sys}}(N_S, N_{Bj})$ is the likelihood function with its width increased by the systematic error. The likelihood distribution is shown in Fig. 3 for each decay mode.

The thus calculated upper limits are $0.5 \times 10^{-6}$ for $B^0 \to \eta'\rho$, $1.3 \times 10^{-6}$ for $B^0 \to \eta'\rho^0$, and in the range $2.2-6.5 \times 10^{-6}$ for other modes, as given in Tables IV and V. We note that our upper limits for $B^0 \to \eta'K^*$ and $B^+ \to \eta'K^{*+}$ are below the central values of the BaBar measurement.

SUMMARY

In summary, no signal was observed with more than $2\sigma$ significance and stringent upper limits in the range $(0.5 - 6.5) \times 10^{-6}$ for the decays $B \to \eta'\rho$, $B \to \eta'K^*$, $B^0 \to \eta'\phi$, $B^0 \to \eta'\eta^{(0)}$ and $B^0 \to \eta'\omega$ have been given. All limits except $B^0 \to \eta'\eta$ are the most stringent upper limits presently available. Our upper limits for $B \to \eta'K^*$ are below BaBar’s central value.

ACKNOWLEDGMENTS

We thank the KEKB group for the excellent operation of the accelerator, the KEK cryogenics group for the efficient operation of the solenoid, and the KEK computer group and
the National Institute of Informatics for valuable computing and Super-SINET network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Education, Science and Training; the National Science Foundation of China and the Knowledge Innovation Program of the Chinese Academy of Sciences under contract No. 10575109 and IHEP-U-503; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea, the CHEP SRC program and Basic Research program (grant No. R01-2005-000-10089-0) of the Korea Science and Engineering Foundation, and the Pure Basic Research Group program of the Korea Research Foundation; the Polish State Committee for Scientific Research; the Ministry of Science and Technology of the Russian Federation; the Slovenian Research Agency; the Swiss National Science Foundation; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

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