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Observation of $B^0 \to K^{*0}\overline{K}^{*0}$ and search for $B^0 \to K^{*0}K^{*0}$

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We report the observation of the $b \to d$ penguin-dominated decay $B^0 \to K^{*0}\overline{K}^{*0}$ with a sample of 383.2 ± 4.2 million $B\overline{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at the Stanford Linear Accelerator Center. The measured branching fraction is $\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) = [0.49^{+0.16}_{-0.13} \pm 0.05] \times 10^{-6}$ and the fraction of longitudinal polarization $f_L(B^0 \to K^{*0}\overline{K}^{*0}) = 0.81^{+0.10}_{-0.12} \pm 0.06$. The first error quoted is statistical and the second systematic. We also obtain an upper limit at the 90% confidence level on the branching fraction for $\mathcal{B}(B^0 \to K^{*0}K^{*0}) < 0.18 \times 10^{-6}$.

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The study of the branching fractions and angular distributions of B meson decays to hadronic final states without a charm quark probes the dynamics of both weak- and strong-interactions, and plays an important role in understanding CP violation. The charmless decay $B^0 \to K^{*0}\overline{K}^{*0}$ proceeds through both $b \to d$ electroweak and gluonic penguin loops to two vector particles (VV). The Standard Model (SM) suppressed decay $B^0 \to K^{*0}K^{*0}$ could appear via an intermediate heavy boson.

Theoretical models in the framework of QCD factorization predict the angular distribution of the VV decays of the B meson, as measured by the longitudinal polarization fraction f_L, to be ~ 0.9 for both tree- and penguin-dominated decays [1]. However, recent measurements of the pure penguin VV decay $B \to \phi K^*$ indicate $f_L \sim 0.5$ [2]. Several attempts to understand this small value of f_L within or beyond the Standard Model have been made [3]. Further information about decays related by $SU(3)$ symmetry may provide some insight into this polarization puzzle and test factorization models. A time-dependent angular analysis of $B^0 \to K^{*0}\overline{K}^{*0}$ can distinguish between penguin annihilation and rescattering as mechanisms for the value of f_L observed in $B \to \phi K^*$ [4]. The $B^0 \to K^{*0}\overline{K}^{*0}$ mode can also be used within the SM framework to help constrain the angles α and γ of the Unitarity Triangle [5].

Theoretical calculations for $B^0 \to K^{*0}\overline{K}^{*0}$ branching fractions have existed for some time and cover the range (0.16-0.96) $\times 10^{-6}$ [6–9]. Recently, Beneke, Rohrer, and Yang [10] predicted $(0.6^{+0.1+0.3}_{-0.1-0.2}) \times 10^{-6}$ and $f_L = 0.69 \pm 0.01^{+0.16}_{-0.20}$. Experimentally, upper limits on the branching fractions at the 90% confidence level of 22×10^{-6} and 37×10^{-6} exist for $B^0 \to K^{*0}\overline{K}^{*0}$ and $B^0 \to K^{*0}K^{*0}$, respectively [11].

We report measurements of the branching fraction and the fraction of longitudinal polarization for the decay mode $B^0 \to K^{*0}\overline{K}^{*0}$, with explicit consideration of non-resonant backgrounds and interference from K^{*0} $\overline{K}^{*0}(1430)$. We also place an upper limit on the branching fraction of $B^0 \to K^{*0}K^{*0}$. Charge-conjugate modes are implied throughout this letter.

This analysis is based on a data sample of 383.2 ± 4.2 million $B\overline{B}$ pairs, corresponding to an integrated luminosity of 348 fb^{-1}, collected with the *BABAR* detector [12] at the PEP-II asymmetric-energy e^+e^- collider operated at the Stanford Linear Accelerator Center. The e^+e^- center-of-mass (c.m.) energy is $\sqrt{s} = 10.58$ GeV, corresponding to the $\Upsilon(4S)$ resonance mass (on-resonance data). In addition, 36.6 fb^{-1} of data collected 40 MeV below the $\Upsilon(4S)$ resonance (off-resonance data) are used for background studies.

The *BABAR* detector is described in detail in Ref. [12]. Charged particles are reconstructed as tracks with a 5-layer silicon vertex detector and a 40-layer drift chamber inside a 1.5 T solenoidal magnet. An electromagnetic calorimeter is used to identify electrons and photons. A ring-imaging Cherenkov detector is used to identify charged hadrons and provides additional electron identification information. Muons are identified by an instrumented magnetic-flux return.

The $B^0 \to K^{*0}\overline{K}^{*0}$ and $B^0 \to K^{*0}K^{*0}$ candidates are reconstructed through the decays $K^{*0} \to K^+\pi^-$ and $\overline{K}^{*0} \to K^-\pi^+$. The angular distribution of the two vector decay products, after integrating over the angle between the decay planes of the vector mesons, for which the acceptance is uniform, is proportional to

$$\frac{1}{4}(1 - f_L)\sin^2\theta_1\sin^2\theta_2 + f_L\cos^2\theta_1\cos^2\theta_2, \quad (1)$$

where θ_1 and θ_2 are the helicity angles of the K^{*0} or $\overline{K}^{*0}$. The helicity angle of the K^{*0} ($\overline{K}^{*0}$) is defined as the angle between the $K^+(K^-)$ momentum and the direction opposite to the B meson in the K^{*0} ($\overline{K}^{*0}$) rest frame [13].

The charged tracks from the K^{*0} decays are required to have at least 12 hits in the drift chamber and a transverse momentum greater than 0.1 GeV/c. The tracks are identified as either pion or kaon candidates by measurement of the energy loss in the tracking devices, the number of photons measured by the Cherenkov detector and the corresponding Cherenkov angles. These measurements are combined with calorimeter information to reject electrons, muons, and protons. We require the invariant mass of the K^{*0} candidates to be $0.792 < m_{K\pi} < 1.025\,\mathrm{GeV}/c^2$. A B meson candidate is formed from two K^{*0} candidates, with the constraint that the two K^{*0} candidates originate from the interaction region.

B meson candidates are characterized kinematically by the energy difference $\Delta E = E^*_B - \sqrt{s}/2$ and the energy-substituted mass $m_{\mathrm{ES}} = \left[(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2\right]^{1/2}$, where $(E_i, \mathbf{p}_i)$ and $(E_B, \mathbf{p}_B)$ are the four-momenta of the $\Upsilon(4S)$ and B meson candidate respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. We select events with $-0.08 \le \Delta E \le 0.2\,\mathrm{GeV}$ and $5.25 \le m_{\mathrm{ES}} \le 5.29\,\mathrm{GeV}/c^2$. The signal events are found in the region $|\Delta E| \le 0.07\,\mathrm{GeV}$ and $5.27 \le m_{\mathrm{ES}} \le 5.29\,\mathrm{GeV}/c^2$; events outside this region are used to characterize the background. The average number of signal B meson candidates per selected data event is 1.03. A single B meson candidate per event is chosen as the one whose fitted decay vertex has the smallest χ^2. MC simulation shows that up to 4% (1.6%) of longitudinally (transversely) polarized signal events are misreconstructed, with one or more tracks originating from the other B meson in the event.

To reject the dominant light-quark $q\overline{q}$ ($q = u, d, s, c$) continuum background, we require $|\cos\theta_T| < 0.8$, where θ_T is the angle, in the c.m. frame, between the thrust axes [14] of the B meson and that formed from the other tracks and neutral clusters in the event. We create a Fisher discriminant $\mathcal{F}$ to be used in the maximum-likelihood fit, constructed from a linear combination of five variables: the polar angles of the B meson momentum vector and the B meson thrust axis with respect to the beam axis, the ratio of the two Legendre moments L_2 and L_0 of the energy flow around the B meson thrust axis in the c.m. frame [15], the output of the flavor-tagging algorithm [16], and the boost-corrected proper time difference between the decays of the two B mesons divided by its variance.

We suppress background from B meson decays to charmed states by removing signal candidates that have decay products consistent with $D^- \rightarrow K^+\pi^-\pi^-$ and an invariant mass in the range $1.845 < m_{K^+\pi^-\pi^-} < 1.895\,\mathrm{GeV}/c^2$. We reduce backgrounds from $B^0 \rightarrow \phi K^{*0}$ by assigning the kaon mass to the pion candidate and rejecting the event if the combined invariant mass of the two charged tracks is between 1.0 and $1.04\,\mathrm{GeV}/c^2$. Finally, we require the cosine of the helicity angle of both K^{*0} candidates to be less than 0.98 to reduce continuum background and avoid the region where the reconstruction efficiency falls off rapidly.

We use an extended unbinned maximum-likelihood (ML) fit to extract the signal yield and polarization simultaneously for each mode. The extended likelihood function is

$$\mathcal{L} = \frac{1}{N!} \exp\left(-\sum_j n_j\right) \prod_{i=1}^{N} \left[\sum_j n_j \mathcal{P}_j(\vec{x}_i; \vec{\alpha}_j)\right]. \quad (2)$$

We define the likelihood $\mathcal{L}_i$ for each event candidate i as the sum of $n_j\mathcal{P}_j(\vec{x}_i; \vec{\alpha}_j)$ over four hypotheses j (signal, $q\overline{q}$ background, $K^{*0}(1430)$ and $B\overline{B}$ backgrounds as discussed below), where $\mathcal{P}_j(\vec{x}_i; \vec{\alpha}_j)$ is the product of the probability density functions (PDFs) for hypothesis j evaluated for the i-th event's measured variables $\vec{x}_i$, n_j is the yield for hypothesis j, and N is the total number of events in the sample. The quantities $\vec{\alpha}_j$ represent parameters in the expected distributions of the measured variables for each hypothesis j. Each discriminating variable $\vec{x}_i$ in the likelihood function is modeled with a PDF and the parameters $\vec{\alpha}_j$ extracted from MC simulation, off-resonance data, or ($m_{\rm ES}$, ΔE) sideband data.

The seven variables $\vec{x}_i$ used in the fit are $m_{\rm ES}$, ΔE, $\mathcal{F}$, and the invariant masses and cosines of the helicity angle of the two K^{*0} candidates. Since the correlations among the fitted input variables are found to be small, we take each $\mathcal{P}_j$ to be the product of the PDFs for the separate variables. The effect of neglecting correlations is evaluated by fitting ensembles of simulated experiments in which we embed signal and background events, randomly extracted from fully-simulated MC samples.

The two invariant mass and helicity angle distributions for each K^{*0} meson are indistinguishable and so we use the same PDF parameters for both K^{*0} candidates. We use an asymmetric Gaussian for $\mathcal{F}$ for all hypotheses. To describe the signal, we use the sum of two Gaussians for $m_{\rm ES}$, ΔE and the K^{*0} masses. The transverse (longitudinal) helicity angle distributions are described with a $\cos^2\theta$ ($\sin^2\theta$) function corrected for changes in efficiency as a function of helicity angle. The $B\overline{B}$ backgrounds use the sum of two Gaussians for $m_{\rm ES}$ and an empirical non-parametric function for ΔE, the masses and helicity angles. The continuum background $m_{\rm ES}$ shape is described by the function $x\sqrt{1-x^2}\exp[-\xi(1-x^2)]$ (with $x = m_{\rm ES}/E_B^*$) [17] and a first- or third-order polynomial is used for ΔE and the helicity angles, respectively. The continuum invariant mass distributions contain real K^{*0} candidates; we model the peaking mass component using the parameters extracted from the fit to the signal invariant mass distributions together with a second-order polynomial to represent the non-peaking component.

We use the decay $B^0 \rightarrow D^-\pi^+(D^- \rightarrow K^{*0}\pi^-)$ as a calibration channel. This decay has a similar topology to the modes under study and is selected using the same criteria as for $K^{*0}\overline{K}^{*0}$ but requiring the reconstructed K^{*0} $\pi^\pm$ invariant mass to be in the range $1.845 < m_{K^{*0}\pi^\pm} < 1.895\,\mathrm{GeV}/c^2$. With more than 7500 signal events and a signal to background ratio of approximately 2.5 in the total number of $B^0 \rightarrow D^-\pi^+(D^- \rightarrow K^{*0}\pi^-)$ candidates, it is possible to adjust the PDFs to account for small differences between MC simulation and reconstructed data.

We use MC-simulated events to study backgrounds from other B meson decays. The major charmless $B\overline{B}$ background to $B^0 \rightarrow K^{*0}\overline{K}^{*0}$ is $B^0 \rightarrow \phi K^{*0}$, while charm $B\overline{B}$ backgrounds are effectively suppressed by the requirement that the two pions (and kaons) have opposite charge. For $B^0 \rightarrow K^{*0}K^{*0}$, $B^0 \rightarrow \phi K^{*0}$ remains the major charmless $B\overline{B}$ backgrounds but a number of charm decays contaminate the signal, dominated by decays of the type $B^0 \rightarrow D^-K^+$ and $B^- \rightarrow D^0K^-$. Given the uncertainty in the polarization and branching fractions of these backgrounds, we allow the $B\overline{B}$ background yield to float in the fit.

A possible background is the decay $B^0 \rightarrow K^{*0}\overline{K}^{*0}(1430)$. We use the LASS parameterization for the $\overline{K}^{*0}(1430)$ lineshape, which consists of the $\overline{K}^{*0}(1430)$ resonance together with an effective-range non-resonant component [18]. We apply the same selection criteria used for $K^{*0}\overline{K}^{*0}$ but require one of the K^{*0} to have an invariant mass in the range $1.025 < m_{K\pi} < 1.53\,\mathrm{GeV}/c^2$ and perform an extended unbinned ML fit with the four variables $m_{\rm ES}$, ΔE, $\mathcal{F}$, and the K^{*0} mass. We fit the LASS parameterization to the selected signal events in the $\overline{K}^{*0}(1430)$ mass range and extrapolate to the K^{*0} mass range. Assuming zero interference, we expect 6 ± 5

$B^0 \to K^{*0}\overline{K}^{*0}(1430)$ events in the fitted $B^0 \to K^{*0}\overline{K}^{*0}$ signal region. The uncertainty on the contribution is calculated from the statistical error and the large uncertainty in the fitted LASS parameters used to describe the $\overline{K}^{*0}(1430)$ lineshape. We fix the yield in the final fit and vary the yield by its error to assess the systematic uncertainty.

The peak position of the signal $\mathcal{F}$ PDF distribution is allowed to vary in the fit. The continuum background PDF parameters that are allowed to vary are the $\mathcal{F}$ peak position, ξ for $m_{\rm ES}$, the slope of ΔE and the polynomial coefficients describing the mass and helicity angle distributions. We extract the branching fractions from a direct fit with the free parameters $\mathcal{B}$ and f_L. This choice exploits the feature that $\mathcal{B}$ is less correlated with f_L than is either the yield or efficiency taken separately.

The total event sample consists of 7363 and 1390 events for $B^0 \to K^{*0}\overline{K}^{*0}$ and $B^0 \to K^{*0}K^{*0}$, respectively. The results of the ML fits are summarized in Table I. For the branching fractions, we assume equal production rates of B^+B^- and $B^0\overline{B}^0$. The significance S of a signal is defined as $S = \sqrt{2\Delta \ln \mathcal{L}}$, where $\Delta \ln \mathcal{L}$ represents the change in likelihood from the maximal value when the number of signal events is set to zero, corrected for the systematic error defined below. The significance of the $B^0 \to K^{*0}\overline{K}^{*0}$ branching fraction is 6.3σ, including statistical and systematic uncertainties. For $B^0 \to K^{*0}K^{*0}$, we compute the 90% confidence level (C.L.) upper limit as the branching fraction below which lies 90% of the total likelihood integral, taking into account the systematic uncertainty. Fig. 1 shows the projections of the fits onto $m_{\rm ES}$, ΔE, K^{*0} mass and cosine of the K^{*0} helicity angle for $B^0 \to K^{*0}\overline{K}^{*0}$.

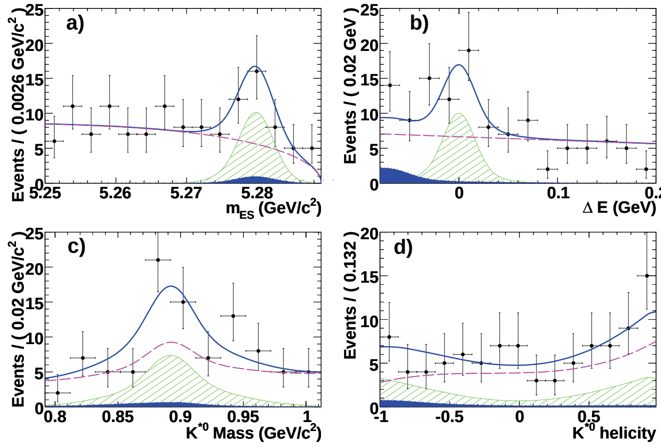

FIG. 1: (color online) Projections of the multidimensional fit onto (a) $m_{\rm ES}$; (b) ΔE; (c) K^{*0} mass; and (d) cosine of K^{*0} helicity angle for $B^0 \to K^{*0}\overline{K}^{*0}$ events passing a signal-to-total likelihood probability ratio cut, with the plotted variable excluded. The points with error bars show the data; the solid line shows the projections for signal-plus-background; the dashed line is the continuum background; the hatched region is the signal; and the shaded region is the $B\overline{B}$ background.

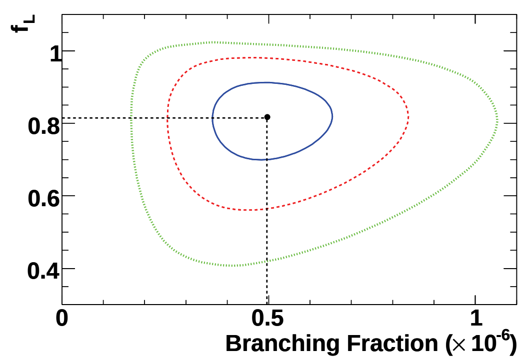

FIG. 2: Distribution of $-2\ln\mathcal{L}(\mathcal{B}, f_L)$ for $B^0 \to K^{*0}\overline{K}^{*0}$ decays. The solid dot gives central value and the curves give contours in steps of one sigma ($\Delta\sqrt{-2\ln\mathcal{L}(\mathcal{B}, f_L)} = 1$).

Systematic uncertainties in the branching fractions are dominated by our knowledge of the signal and background PDF modeling. Varying the PDF parameters by their errors results in changes in the yields of 7.1% and 19.0% for $B^0 \to K^{*0}\overline{K}^{*0}$ and $B^0 \to K^{*0}K^{*0}$, respectively.

The reconstruction efficiency depends on the decay polarization. For the $B^0 \to K^{*0}\overline{K}^{*0}$ mode, we calculate the efficiency using the measured polarization and assign a systematic error from the uncertainty of the polarization measurement of 3.4% and 27.0% for $B^0 \to K^{*0}\overline{K}^{*0}$ and $B^0 \to K^{*0}K^{*0}$, respectively. Figure 2 shows the behavior of $-2\ln\mathcal{L}(\mathcal{B}, f_L)$ for the $B^0 \to K^{*0}\overline{K}^{*0}$ mode.

Additional systematic errors on the branching fraction include reconstruction efficiency uncertainties from tracking (3.2%) and particle identification (4.4%), track multiplicity (1%), MC signal efficiency statistics (0.6%), and the number of $B\overline{B}$ pairs (1.1%). Variation of the expected yield from $B^0 \to K^{*0}\overline{K}^{*0}(1430)$ events has a negligible effect on the signal.

The systematic uncertainty in f_L is dominated by the PDF shape variations, which contribute 7.0% for $B^0 \to K^{*0}\overline{K}^{*0}$ and 20.0% for $B^0 \to K^{*0}K^{*0}$. Other systematic errors identified above for the branching fraction have a very small effect on f_L and contribute in total 0.7% to the systematic error. The total systematic error is summarised in Table I.

In summary, we have measured the branching fraction $\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) = [0.49^{+0.16}_{-0.13}\,(\text{stat}) \pm 0.05\,(\text{syst})] \times 10^{-6}$ with a significance of 6.3σ. We find the fraction of longitudinal polarization $f_L = 0.81^{+0.10}_{-0.12}\,(\text{stat}) \pm 0.06\,(\text{syst})$. Both results are in good agreement with recent theoretical predictions. The 90% C.L. upper limit on the branching fraction $\mathcal{B}(B^0 \to K^{*0}K^{*0}) < 0.18 \times 10^{-6}$ is two orders of magnitude more stringent than previous measurements.

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TABLE I: Summary of results for the measured B meson decay modes: signal yield $n_{\rm sig}$, the $B\overline{B}$ background yield $n_{B\overline{B}}$, signal reconstruction efficiency ε, significance S (systematic uncertainties included), branching fraction $\mathcal{B}$, 90% C.L. upper limit for $B^0 \to K^{*0}K^{*0}$ branching fraction, and the longitudinal polarization f_L. The first error given is statistical and the second is systematic.

Channel	$K^{*0}\overline{K}^{*0}$	$K^{*0}K^{*0}$
$n_{\rm sig}$	$28.8^{+9.1}_{-7.8}$	2.7 ± 3.3
$n_{B\overline{B}}$	19 ± 12	68 ± 29
ε (%)	15.3	14.3
S (σ)	6.3	0.94
$\mathcal{B}(10^{-6})$	$0.49^{+0.16}_{-0.13} \pm 0.05$	$0.05^{+0.07}_{-0.10} \pm 0.018$
UL $\mathcal{B}(10^{-6})$	-	0.18
f_L	$0.81^{+0.10}_{-0.12} \pm 0.06$	$1.0 \pm 0.95 \pm 0.20$

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