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Search for B Decays into $K^0\overline{K}^0$

The *BABAR* Collaboration

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Abstract

We present preliminary results of a search for $B^0 \to K^0\overline{K}^0$ decays in the $K^0_S K^0_S$ final state using a sample of approximately 23 million $B\overline{B}$ pairs collected by the *BABAR* detector at the PEP-II asymmetric B Factory at SLAC. We find no evidence for a signal and set an upper limit on the branching fraction of 7.3×10^{-6} at the 90% confidence level.

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1 Introduction

The study of B meson decays into charmless hadronic final states plays an important role in the understanding of *CP* violation in the B system. Measurements of rates and *CP*-violating asymmetries for B decays into charmless two-body final states provide information on the angles α and γ of the Unitarity Triangle. However, in contrast to the theoretically clean determination of the angle β in B decays to charmonium final states [1], the extraction of *CP*-violation parameters in charmless decays is complicated by hadronic uncertainties that are difficult to calculate from first principles. Accurate branching fraction measurements provide critical tests of theoretical models that are needed to obtain reliable information on α and γ.

The *BABAR* collaboration has recently published [2] measurements of the branching fractions for B meson decays to the charmless hadronic final states $\pi^+\pi^-$, $K^+\pi^-$, $K^+\pi^0$, $K^0\pi^+$ and $K^0\pi^0$, upper limits on the decays to $\pi^+\pi^0$ and K^0K^+ and the results of a search for charge asymmetries in the modes $B^0 \to K^+\pi^-$, $B^+ \to K^+\pi^0$ and $B^+ \to K^0\pi^+$.[1] In this paper we report preliminary results of a search for $B^0 \to K^0\overline{K}^0$ decays through detection of the $K^0_S K^0_S$ final state. Although the decay rate for $B^0 \to K^0\overline{K}^0$ is expected to be small (10^{-6}–10^{-7}) in the Standard Model [3], final state rescattering effects can lead to enhancement of the branching fraction and the possibility of large strong phases, with correspondingly large *CP*-violating charge asymmetries [3, 4]. Such rescattering effects may also have consequences for constraints on γ derived from $B \to K\pi$ decays [5]. Observation of the $K^0\overline{K}^0$ decay mode would provide important information about the strength of final state rescattering in charmless B decays.

2 Data Sample

The data used in this analysis were collected with the *BABAR* detector at the PEP-II e^+e^- storage ring. The sample corresponds to an integrated luminosity of $20.6\,\mathrm{fb}^{-1}$ taken near the $\Upsilon(4S)$ resonance ("on-resonance") and $2.6\,\mathrm{fb}^{-1}$ taken at a center-of-mass (CM) energy 40 MeV below the $\Upsilon(4S)$ resonance ("off-resonance"), which are used for continuum background studies. The on-resonance sample corresponds to $(22.57 \pm 0.36) \times 10^6$ $B\overline{B}$ pairs. The collider is operated with asymmetric beam energies, producing a boost ($\beta\gamma = 0.56$) of the $\Upsilon(4S)$ along the collision axis. The boost increases the momentum range of two-body B decay products from a narrow distribution centered near $2.6\,\mathrm{GeV}/c$ to a broad distribution extending from 1.7 to $4.3\,\mathrm{GeV}/c$.

The *BABAR* detector is described in detail in Ref. [6]. The primary detector element used in this analysis is the tracking system, which consists of a 5-layer, double-sided, silicon vertex detector and a 40-layer drift chamber filled with a gas mixture of helium (80%) and isobutane (20%). Both tracking detectors operate within a 1.5 T superconducting solenoidal magnet.

3 Event Selection and K^0_S Reconstruction

Hadronic events are selected based on track multiplicity and event topology. Backgrounds from non-hadronic events are reduced by requiring the ratio of Fox-Wolfram moments H_2/H_0 [7] to be less than 0.95 and the sphericity [8] of the event to be greater than 0.01.

Candidate K^0_S mesons are reconstructed in the $\pi^+\pi^-$ final state from pairs of oppositely charged tracks that form a well-measured vertex and have an invariant mass within $11.2\,\mathrm{MeV}/c^2$ (3.5σ) of

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[1] Charge conjugate modes are assumed throught this paper.

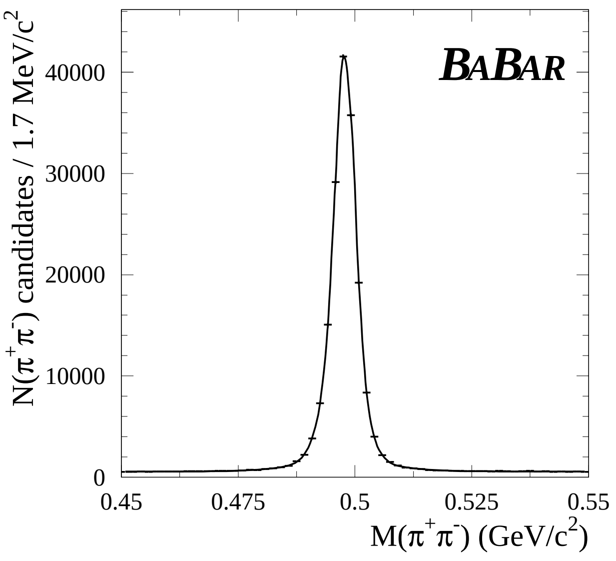

Figure 1: Invariant mass of $\pi^+\pi^-$ pairs in the inclusive K^0_S sample selected with requirements on the angle between the flight direction and momentum of the K^0_S, and on the transverse momenta of the decay products relative to the K^0_S momentum.

the nominal K^0_S mass [9]. The measured proper decay time of the K^0_S candidate is required to exceed 5 times its error. Figure 1 shows the invariant mass distribution of an inclusive sample of high momentum ($> 1\,\mathrm{GeV}/c$) K^0_S candidates.

4 *B* Reconstruction and Background Rejection

B meson candidates are reconstructed by combining pairs of K^0_S candidates. The kinematic constraints provided by the $\Upsilon(4S)$ initial state and relatively precise knowledge of the beam energies are exploited to efficiently identify B candidates. We define a beam-energy substituted mass $m_{\mathrm{ES}} = \sqrt{E_{\mathrm{b}}^2 - \mathbf{p}_B^2}$, where $E_{\mathrm{b}} = (s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)/E_i$, $\sqrt{s}$ and E_i are the total energies of the e^+e^- system in the CM and lab frames, respectively, and $\mathbf{p}_i$ and $\mathbf{p}_B$ are the momentum vectors in the lab frame of the e^+e^- system and the B candidate, respectively. The m_{ES} resolution for B decays into all-charged final states is dominated by the beam energy spread and is determined to be $2.6 \pm 0.1\,\mathrm{MeV}/c^2$ from a Gaussian fit to a large sample of fully reconstructed B decays. Candidates are selected in the range $5.2 < m_{\mathrm{ES}} < 5.3\,\mathrm{GeV}/c^2$. A sideband region is defined as $5.2 < m_{\mathrm{ES}} < 5.26\,\mathrm{GeV}/c^2$.

We define an additional kinematic parameter ΔE as the difference between the energy of the B candidate and half the energy of the e^+e^- system, computed in the CM system. The ΔE distribution for signal events is a Gaussian centered near zero. The resolution on ΔE is estimated to be $21 \pm 5\,\mathrm{MeV}$ based on Monte Carlo simulated $B^0 \to K^0_S K^0_S$ decays and the observed difference in widths between a control sample of fully reconstructed B decays in data and in Monte Carlo simulation. We require $|\Delta E| < 0.1\,\mathrm{GeV}$. A sideband region is defined as $0.1 < |\Delta E| < 0.3\,\mathrm{GeV}$.

Detailed Monte Carlo simulation, off-resonance data, and events in on-resonance sideband re-

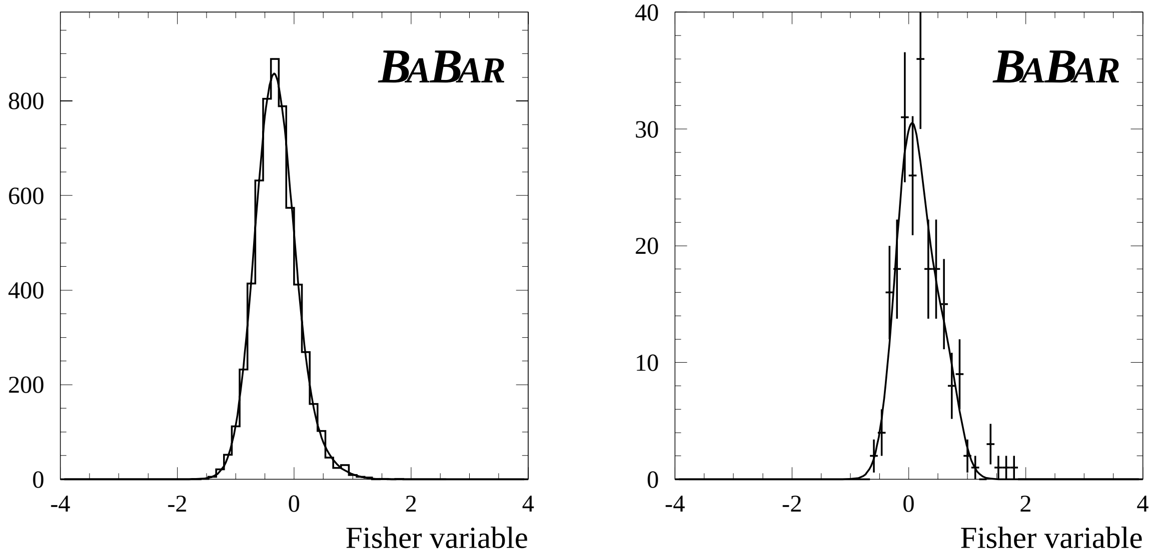

Figure 2: Distributions of Fisher discriminant output for Monte Carlo simulated $B^0 \rightarrow K^0_S K^0_S$ decays (left) and events in the on-resonance $m_{\rm ES}$ sideband data (right).

gions are used to study backgrounds. The contribution due to other B meson decays, both from $b \rightarrow c$ and charmless decays, is found to be negligible from a detailed Monte Carlo study. The dominant source of background is from random combinations of true K^0_S mesons produced in the $e^+e^- \rightarrow q\overline{q}$ continuum events (where $q = u$, d, s, or c). In the CM frame this background typically exhibits a two-jet structure, in contrast to the isotropic decay of $B\overline{B}$ pairs produced in $\Upsilon(4S)$ decays. We exploit the topology difference between signal and background by making use of two event-shape quantities.

The first variable is the angle θ_S between the sphericity axes of the B candidate and of the remaining tracks and photons in the event. The distribution of $|\cos\theta_S|$ in the CM frame is strongly peaked near 1 for continuum events and is approximately uniform for $B\overline{B}$ events. We require $|\cos\theta_S| < 0.9$, which rejects 66% of the background remaining at this stage of the analysis.

The second quantity is a Fisher discriminant $\mathcal{F}$ constructed from the scalar sum of the CM momenta of all tracks and photons (excluding the B candidate decay products) flowing into nine concentric cones centered on the thrust axis of the B candidate. Each cone subtends an angle of 10° and is folded to combine the forward and backward intervals. Monte Carlo samples are used to obtain the values of the Fisher coefficients, which are determined by maximizing the statistical separation between signal and background events. Figure 2 shows distributions of $\mathcal{F}$ for Monte Carlo simulated $B^0 \rightarrow K^0_S K^0_S$ decays and background events in the $m_{\rm ES}$ sideband region. No cut is applyed on $\mathcal{F}$, instead the distributions for signal and background events are included in a maximum likelihood as described in the next section.

A total of 286 candidates in the Run1 on-resonance data satisfy our selection criteria ($|\cos\theta_S| < 0.9$, $5.2 < m_{\rm ES} < 5.3\,{\rm GeV}/c^2$ and $|\Delta E| < 0.1\,{\rm GeV}$) and enter the maximum likelihood fit. The total selection efficiency is $(36.6 \pm 4.6)\%$, where the error is dominated by uncertainty on the K^0_S reconstruction efficiency (6% relative error per K^0_S).

5 Signal Extraction

Signal and background yields are determined from an unbinned maximum likelihood fit using m_{ES}, ΔE and $\mathcal{F}$. The likelihood is defined as

$$\mathcal{L} = e^{-(N_S+N_B)} \prod_i^N \Big(N_S \mathcal{P}_i^S(m_{\mathrm{ES}}, \Delta E, \mathcal{F}) + N_B \mathcal{P}_i^B(m_{\mathrm{ES}}, \Delta E, \mathcal{F}) \Big) \,, \tag{1}$$

where N_S and N_B are the fitted number of signal and background events, respectively; N is the total number of events entering the fit; and $\mathcal{P}_i$ is the product of probability density functions (PDFs) for m_{ES}, ΔE, and $\mathcal{F}$ that are assumed to be uncorrelated. The quantity $-2\ln\mathcal{L}$ is minimized with respect to the fit parameters N_S and N_B.

The parameters for background m_{ES} and ΔE PDFs are determined from events in on-resonance ΔE and m_{ES} sideband regions, respectively. The m_{ES} shape is parameterized by a threshold function [10] $f(m_{\mathrm{ES}}) \propto m_{\mathrm{ES}}\sqrt{1-x^2}\exp[-\xi(1-x^2)]$, where $x = m_{\mathrm{ES}}/m_0$ and m_0 is the average CM beam energy. The background shape in ΔE is parameterized as a second-order polynomial. The signal distributions for m_{ES} and ΔE are described by Gaussians, where the m_{ES} mean and width are determined from a sample of fully reconstructed B decays while the ΔE mean and width are estimated from Monte Carlo simulated $B^0 \to K^0_S K^0_S$ decays and scaled according to the observed difference between a control sample of fully reconstructed B decays in data and in Monte Carlo simulation. Events in on-resonance m_{ES} sideband regions and Monte Carlo simulated signal decays are used to parameterize as the sum of two Gaussians the Fisher discriminant PDFs for background and signal. Alternative parameterizations for $\mathcal{F}$, obtained from off-resonance data (for background) and fully reconstructed B decays (for signal), are used to determine systematic uncertainties.

The fitted number of signal events is $N_S = 3.4^{+3.4}_{-2.4}$, where the error is statistical only. Figure 3 shows the m_{ES} and ΔE distributions for events satisfying the selection criteria and additional requirements on the likelihood ratio $N_S\mathcal{P}_S/(N_S\mathcal{P}_S + N_B\mathcal{P}_B)$, where the probabilities include all variables (m_{ES}, ΔE, $\mathcal{F}$) except the one being plotted. The likelihood ratio cuts are chosen to minimize the upper limit on the branching fration, and the curves represent the fit result scaled by the efficiency of the additional requirements. The statistical significance of the signal yield is 1.5, calculated as the square root of the change in $-2\ln\mathcal{L}$ when the yield is fixed to zero. We conclude there is no evidence for a signal and calculate a 90% confidence level Bayesian upper limit as the value of N_{UL} for which $\int_0^{N_{\mathrm{UL}}} \mathcal{L}_{\max}\, dN_S / \int_0^\infty \mathcal{L}_{\max}\, dN_S = 0.90$, where $\mathcal{L}_{\max}$ is the likelihood as a function of N_S, maximized with respect to the remaining fit parameter (N_B). The resulting upper limit on the yield is $N_{\mathrm{UL}} = 9$. The fitting procedure has been validated with extensive Monte Carlo studies.

6 Branching Fraction Results

The branching fraction is defined as

$$\mathcal{B}(B^0 \to K^0 \overline{K}^0) = \frac{1}{\mathcal{B}(K^0\overline{K}^0 \to K^0_S K^0_S)\cdot \mathcal{B}(K^0_S \to \pi^+\pi^-)^2} \frac{N_S}{\epsilon \cdot N_{B\overline{B}}}, \tag{2}$$

ϵ is the total $K^0_S K^0_S$ selection efficiency, $N_{B\overline{B}} = (22.57 \pm 0.36) \times 10^6$ is the total number of $B\overline{B}$ pairs in the dataset, and $\mathcal{B}(K^0_S \to \pi^+\pi^-) = 0.6861$ [9]. We assume the Standard Model prediction that

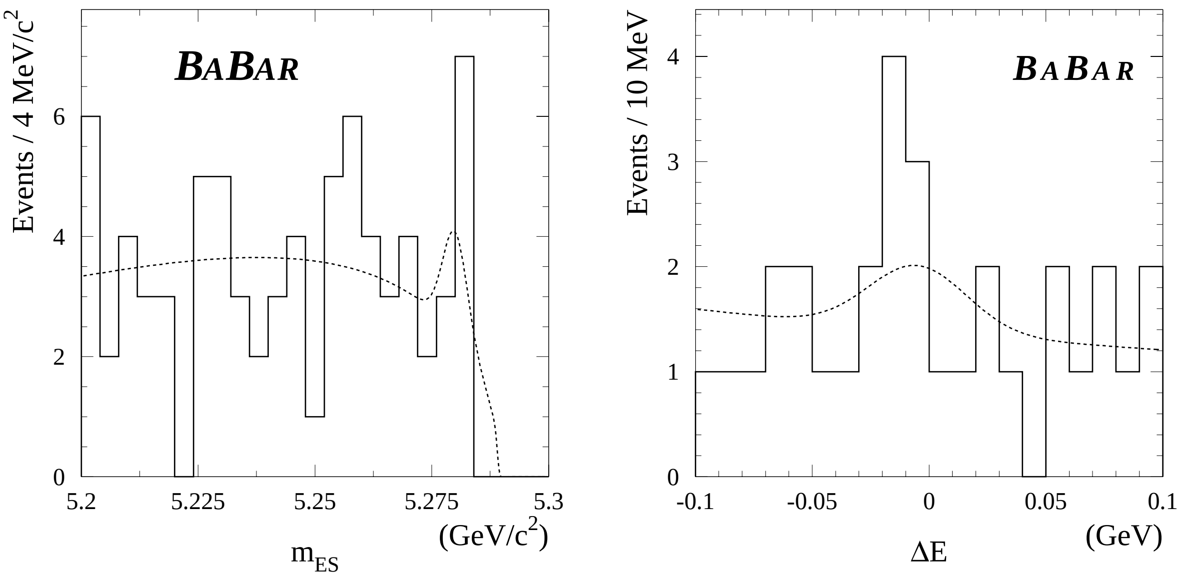

Figure 3: Distributions of $m_{\rm ES}$ (left) and ΔE (right) after additional requirements on likelihood ratios. The curves represent projections of the maximum likelihood fit result.

$B^0 \to K^0_S K^0_S$ proceeds through the $K^0\overline{K}^0$ intermediate state (as opposed to K^0K^0 or $\overline{K}^0\overline{K}^0$) and use $\mathcal{B}(K^0\overline{K}^0 \to K^0_S K^0_S) = 0.5$.[2] Implicit in Eq. 2 is the assumption of equal branching fractions for $\Upsilon(4S) \to B^0\overline{B}^0$ and $\Upsilon(4S) \to B^+B^-$.

Systematic uncertainties on the branching fraction arise primarily from uncertainty on the K^0_S reconstruction efficiency and uncertainty on N_S due to imperfect knowledge of the PDF shapes. The latter is estimated either by varying the PDF parameters within 1σ of their measured uncertainties or by substituting alternative PDFs from independent control samples. Table 1 summarizes the various sources of systematic error on N_S, where the total error is calculated as the sum in quadrature of the individual uncertainties.

We measure a central value branching fraction of $\mathcal{B}(B^0 \to K^0\overline{K}^0) = (1.8^{+1.8}_{-1.2} \pm 1.8) \times 10^{-6}$, where the first error is statistical and the second is systematic. An upper limit is calculated by increasing $N_{\rm UL}$ and decreasing the efficiency by their respective systematic errors. We find $\mathcal{B}(B^0 \to K^0\overline{K}^0) < 7.3 \times 10^{-6}$ at the 90% confidence level. This result is a significant improvement over the existing upper limit from the CLEO Collaboration [11], and is approaching the upper range of current theoretical estimates.

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[2] Assuming conservation of angular momentum and CPT invariance, the decay $B^0 \to K^0\overline{K}^0 \to K^0_S K^0_L$ is forbidden.

Table 1: Summary of absolute systematic errors (σ_{N_S}) on the signal yield due to imperfect knowledge of the PDF shapes. The total error is calculated as the sum in quadrature of the individual uncertainties.

Source	σ_{N_S}
$\boldsymbol{m}_{\mathbf{ES}}$	
signal	$^{+0.3}_{-0.4}$
background	±0.4
$\boldsymbol{\Delta E}$	
signal	$^{+0.1}_{-0.4}$
background	−
$\boldsymbol{\mathcal{F}}$	
signal	±3.2
background	±1.2
total	±3.5

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