

Observation of $B \rightarrow \eta' K^*$ and Evidence for $B^+ \rightarrow \eta' \rho^+$

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We present an observation of $B \rightarrow \eta' K^*$. The data sample corresponds to 232 million $B\bar{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC. We measure the branching fractions (in units of 10^{-6}) $\mathcal{B}(B^0 \rightarrow \eta' K^{*0}) = 3.8 \pm 1.1 \pm 0.5$ and $\mathcal{B}(B^+ \rightarrow \eta' K^{*+}) = 4.9^{+1.9}_{-1.7} \pm 0.8$, where the first error is statistical and the second systematic. A simultaneous fit results in the observation of $B \rightarrow \eta' K^*$ with $\mathcal{B}(B \rightarrow \eta' K^*) = 4.1^{+1.0}_{-0.9} \pm 0.5$. We also search for $B \rightarrow \eta' \rho$ and $\eta' f_0(980)(f_0 \rightarrow \pi^+ \pi^-)$ with results and 90% confidence level upper limits $\mathcal{B}(B^+ \rightarrow \eta' \rho^+) = 8.7^{+3.1+2.3}_{-2.8-1.3} (< 14)$, $\mathcal{B}(B^0 \rightarrow \eta' \rho^0) < 3.7$, and $\mathcal{B}(B^0 \rightarrow \eta' f_0(980)(f_0 \rightarrow \pi^+ \pi^-)) < 1.5$. Charge asymmetries in the channels with significant yields are consistent with zero.

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Decays of B mesons involving the flavor-changing neutral current transition $b \rightarrow s$ are an important place to search for evidence of physics beyond the Standard Model. A comparison of the amplitude $\sin 2\beta$ of time-dependent CP violation in the neutral CP eigenstates $J/\psi K_S^0$ and $\eta' K_S^0$ provides one of the most sensitive tests [1]. In order to unambiguously interpret the time-dependent CP violation measurement in $\eta' K_S^0$ it is important to understand the full set of underlying amplitudes by making measurements of branching fractions in the $\eta' K^*$ decays.

In B decays to final states comprising $\eta^{(\prime)} K^{(*)}$ the final states $\eta' K^*$ and ηK are suppressed, and the final states $\eta' K$ and ηK^* are enhanced. Two explanations of the experimentally observed pattern differ substantially in the details of the suppression for $B \rightarrow \eta' K^*$ [2, 3]. From previous experimental data and flavor $SU(3)$ arguments it is expected that the branching fractions for $B \rightarrow \eta' K^*$ are less than 10^{-5} [4]. The related decays $B \rightarrow \eta' \rho$ occur via CKM suppressed tree diagrams and are expected to be small. Theoretical approaches using QCD factorization [5] and perturbative QCD [6] predict branching fractions for $B^+ \rightarrow \eta' \rho^+$ of $6-9 \times 10^{-6}$ and for $B^0 \rightarrow \eta' \rho^0$ of $0.5-2 \times 10^{-7}$.

In this Letter, we present searches for $B \rightarrow \eta' K^*$, $B \rightarrow \eta' \rho$ and $B^0 \rightarrow \eta' f_0(980)(f_0 \rightarrow \pi^+ \pi^-)$, which shares the same final state as $B^0 \rightarrow \eta' \rho^0$. Throughout this Letter, charge conjugation is implied. Results are obtained from unbinned, extended maximum likelihood (ML) fits to data collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- collider located at the Stanford Linear Accelerator Center. The *BABAR* detector and relevant details specific to this analysis are described elsewhere [7, 8]. The analysis uses 211 fb^{-1} of data recorded at the $\Upsilon(4S)$ resonance, corresponding to 232 million $B\bar{B}$ pairs, and closely follows the approach described in Ref. [8].

We select η' , K^* , ρ , η , K_S^0 and π^0 candidates through the decays $\eta' \rightarrow \eta \pi^+ \pi^-$ ($\eta'_{\eta\pi\pi}$), $\eta' \rightarrow \rho^0 \gamma$ ($\eta'_{\rho\gamma}$), $K^{*0} \rightarrow K^+ \pi^-$, $K^{*+} \rightarrow K_S^0 \pi^+$ ($K_{K^0\pi^+}^{*+}$), $K^{*+} \rightarrow K^+ \pi^0$ ($K_{K^+\pi^0}^{*+}$), ρ^0 (and f_0) $\rightarrow \pi^+ \pi^-$, $\rho^+ \rightarrow \pi^+ \pi^0$, $\eta \rightarrow \gamma\gamma$, $K_S^0 \rightarrow \pi^+ \pi^-$ and $\pi^0 \rightarrow \gamma\gamma$. We impose the following requirements on candidate invariant masses, in MeV/c^2 :

$910 < (m_{\eta\pi\pi}, m_{\rho\gamma}) < 1000$ for η' , $755 < m_{K\pi} < 1035$ for the K^* , $510 < m_{\pi\pi^0} < 1070$ for ρ^+ and $510 < m_{\pi\pi} < 1060$ for ρ^0 (f_0), $490 < m_{\gamma\gamma} < 600$ for η , $486 < m_{\pi\pi} < 510$ for K_S^0 and $120 < m_{\gamma\gamma} < 150$ for π^0 . For the masses of the η' , K^* and ρ , which will be included as observables in the ML fit described below, the selection is wide enough to allow for a parameterization of the background. For K_S^0 candidates we require a flight distance of at least three times its estimated uncertainty.

We also use the helicity-frame decay angle θ_H of K^* , ρ , and $f_0(980)$. The helicity frame is defined as the vector meson rest frame with polar axis along the direction of the boost from the B rest frame. The angle θ_H is the angle between the polar axis and the flight direction of the charged resonance daughter. For K^{*0} and ρ^0 the kaon candidate and the positively charged pion, respectively, are used to define that angle. We use mode dependent selection criteria on $\cos \theta_H$, with the lower bound between -0.95 and -0.70 and the upper bound of either 0.95 or 1.00 . Decay modes suffering from higher combinatoric background due to low momentum pions have the tighter cuts applied. The helicity has a $\cos^2 \theta_H$ distribution for K^* and ρ signal events and is flat for the $f_0(980)$.

All charged pion candidates are required to have particle identification (PID) consistent with pions and inconsistent with protons, kaons, and electrons. No such requirement is made of K_S^0 daughters. Charged kaon candidates are required to have PID consistent with kaons and inconsistent with pions, protons and electrons.

We form B meson candidates by combining an η' candidate with either a K^* or ρ candidate. B meson candidates are characterized kinematically by the energy substituted mass, $m_{\text{ES}} = (s/4 - \mathbf{p}_B^2)^{1/2}$ and the energy difference $\Delta E = E_B - \sqrt{s}/2$ where (E_B, \mathbf{p}_B) is the four-momentum of the B candidate, expressed in the $\Upsilon(4S)$ frame and \sqrt{s} is the e^+e^- center of mass energy. Signal events peak at zero for ΔE and at the B mass for m_{ES} , with typical resolutions of 20 MeV and $3.0 \text{ MeV}/c^2$, respectively. We require $5.25 \leq m_{\text{ES}} \leq 5.29 \text{ GeV}/c^2$ for all modes, $-0.2 \leq \Delta E \leq 0.150 \text{ GeV}$ for modes where the vector meson decay includes a neutral pion and $-0.2 \leq \Delta E \leq 0.125 \text{ GeV}$ otherwise.

Backgrounds arise primarily from random combinations of particles in continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) events. To reject these events, we employ the angle θ_T in the $\Upsilon(4S)$ frame between the thrust axis of the B candidate's daughters and that of the remaining particles in the event. Continuum events are produced well above threshold, with a jet-like topology resulting in a distribution of $|\cos\theta_T|$ that is sharply peaked near 1 for candidates formed in such events. Events containing true $\Upsilon(4S)$ decays are produced near threshold with particles distributed isotropically, resulting in a uniform distribution of $|\cos\theta_T|$. We require $|\cos\theta_T| < 0.9$ for decays with $\eta'_{\eta\pi\pi}$, and $|\cos\theta_T| < 0.75$ for the higher-background $\eta'_{\rho\gamma}$ decays. Due to large backgrounds in $\eta'_{\rho\gamma}$, we only use the $\eta'_{\eta\pi\pi}$ decay in reconstructing $B \rightarrow \eta'\rho/f_0(980)$.

Additional discrimination against continuum background occurs in the ML fit and is provided by a Fisher discriminant, \mathcal{F} . This is a linear combination of discriminating variables with weights chosen to maximize the separation between signal and continuum background. \mathcal{F} contains the angles of the B momentum and B thrust axis with respect to the beam axis, the B -flavor tagging category [9], and the zeroth and second angular moment of the energy flow in the rest of the event with respect to the B candidate thrust axis [8].

After selection, events containing multiple B candidates occur less than 30% of the time. In such cases, we choose the B candidate with the η' mass closest to the Particle Data Group (PDG) value [10].

We use Monte Carlo (MC) simulation [11] for an initial survey of background from $B\bar{B}$ events and to identify for detailed study any decays that are not rejected by candidate selection. The remaining background is composed almost entirely of charmless resonant B decays, especially $B \rightarrow \eta'K$. We account for B backgrounds by including in the ML fit an additional component which models these charmless, resonant decays. Backgrounds arising from charmed B decays have been studied and found to be negligible or accounted for by our continuum background model. Backgrounds from non-resonant B decays have been found to be consistent with zero.

We determine yields and charge asymmetries ($\mathcal{A}_{ch} = (n^+ - n^-)/(n^+ + n^-)$) for each decay chain from a ML fit with the observables ΔE , m_{ES} , \mathcal{F} , $m_{\eta'}$, the mass of the candidate vector meson m_V , and $\mathcal{H} \equiv \cos\theta_H$. For charged (neutral) B decays, n^\pm is defined as the number of B^\pm decays (final states with K^\pm). For each event i and hypothesis j (signal, continuum, $B\bar{B}$), we define the probability density function (PDF) as a simple product of the individual observable PDFs:

$$\mathcal{P}_j^i = \mathcal{P}_j(m_{ES}^i)\mathcal{P}_j(\Delta E^i)\mathcal{P}_j(\mathcal{F}^i)\mathcal{P}_j(m_{\eta'}^i)\mathcal{P}_j(m_V^i)\mathcal{P}_j(\mathcal{H}^i).$$

For the $\eta'\pi^+\pi^-$ final state, a fourth hypothesis is added to account explicitly for a possible $\eta'f_0$ signal.

The total likelihood function is then given by

$$\mathcal{L} = \frac{\exp(-\sum_j n_j)}{N!} \prod_i \left(\sum_j n_j \mathcal{P}_j^i \right),$$

where N is the number of events in the sample and n_j is the yield of events of hypothesis j to be found by maximizing \mathcal{L} . In addition to the yields and \mathcal{A}_{ch} for each hypothesis, parameters describing the continuum PDFs are also allowed to vary (see below).

We parameterize the PDFs for peaking observables with either a single or asymmetric Gaussian, sum of two Gaussians, or a Breit-Wigner as required. Slowly varying observables are described by low degree polynomials or phase-space motivated functions [8]. Several PDFs require linear combinations of peaking and non-peaking shapes. We parameterize the $f_0(980)$ mass and width using measured values [12].

For the signal and $B\bar{B}$ background components we determine the PDF parameters from simulation. Control samples with topologies similar to our signal (e.g., $B^- \rightarrow D^0\pi^-$) are used to verify and adjust simulated resolutions [8]. For the continuum background we obtain initial PDF parameters from data excluding the ΔE and m_{ES} signal region (sideband). We further refine the continuum PDFs by letting as many parameters as feasible vary in the fit to the full data. The final fitted continuum background PDF parameters are found to be in close agreement with their initial values.

We apply several tests to the fitting procedure for validation before implementing it on the data. In particular, we evaluate any possible bias in our event yields due to our neglect of small correlations between the observables, which our PDFs ignore by construction. We determine the bias by fitting ensembles of simulated continuum experiments generated from the PDF into which we embed the expected number of signal and $B\bar{B}$ background events randomly taken from samples of fully simulated MC events. Measured correlations in the sideband data (pure $q\bar{q}$) are found to be small. The measured biases for each decay chain are given in Table I.

We compute the branching fraction for each decay by subtracting the fit bias from the measured yield and dividing the result by the efficiency (determined from simulation and ancillary studies), the product of the daughter branching fractions, and the number of produced $B\bar{B}$ pairs. We assume equal decay rates of the $\Upsilon(4S)$ to B^+B^- and $B^0\bar{B}^0$. In Table I we show for each decay the measured branching fraction, event yield, efficiency and daughter branching fraction as well as \mathcal{A}_{ch} .

Measurements for separate decay chains are combined by adding the values of $-2\ln\mathcal{L}$ as functions of branching fraction, taking appropriate account of correlated and uncorrelated systematic uncertainties (described below) [8]. The significance is taken as the square root of the difference between the value of $-2\ln\mathcal{L}$ (including sys-

TABLE I: Summary of results showing (from left): fitted signal yield n before bias correction, fit bias, detection efficiency ε , product daughter branching fraction $\prod \mathcal{B}_i$ [10], significance S (including systematic uncertainties) in standard deviations, measured branching fraction \mathcal{B} and signal charge asymmetry \mathcal{A}_{ch} for each mode. The values in parentheses are 90% C.L. upper limits. The result for $B^0 \rightarrow \eta' f_0(980)(f_0 \rightarrow \pi^+ \pi^-)$ includes the branching fraction for $f_0 \rightarrow \pi^+ \pi^-$, which is not well known. Results in bold face represent combined fits to multiple decay chains (when present).

Mode	n (ev.)	Bias (ev.)	ε (%)	$\prod \mathcal{B}_i$ (%)	$S(\sigma)$	$\mathcal{B}(10^{-6})$	\mathcal{A}_{ch}
$B \rightarrow \eta' K^*$					5.6	$4.1_{-0.9}^{+1.0} \pm 0.5$	
$B^0 \rightarrow \eta' K^{*0}$					4.3	$3.8 \pm 1.1 \pm 0.5$	$-0.08 \pm 0.25 \pm 0.02$
$\eta'_{\eta\pi\pi} K^{*0}$	$22.6_{-6.7}^{+7.7}$	$+1.7 \pm 0.9$	19.0 ± 1.2	11.6	3.9	$4.1_{-1.3}^{+1.5}$	
$\eta'_{\rho\gamma} K^{*0}$	$35.1_{-12.7}^{+14.2}$	$+9.5 \pm 4.8$	16.9 ± 1.1	19.7	2.0	$3.3_{-1.6}^{+1.9}$	
$B^+ \rightarrow \eta' K^{*+}$					3.6	$4.9_{-1.7}^{+1.9} \pm 0.8$ (< 7.9)	$0.30_{-0.37}^{+0.33} \pm 0.02$
$\eta'_{\eta\pi\pi} K_{K^0\pi^+}^{*+}$	$11.2_{-4.5}^{+5.7}$	$+0.8 \pm 0.5$	18.0 ± 1.2	4.0	3.2	$6.2_{-2.7}^{+3.4}$	
$\eta'_{\rho\gamma} K_{K^0\pi^+}^{*+}$	$14.8_{-9.7}^{+11.2}$	$+2.9 \pm 1.5$	15.8 ± 1.1	6.8	1.2	$4.7_{-3.9}^{+4.5}$	
$\eta'_{\eta\pi\pi} K_{K^+\pi^0}^{*+}$	$5.2_{-3.6}^{+5.4}$	$+1.0 \pm 0.5$	10.7 ± 0.6	5.8	1.2	$2.9_{-2.6}^{+3.7}$	
$\eta'_{\rho\gamma} K_{K^+\pi^0}^{*+}$	$3.1_{-9.6}^{+12.1}$	-2.3 ± 1.3	8.0 ± 0.5	9.8	0.5	$2.9_{-5.4}^{+6.7}$	
$B^0 \rightarrow \eta' \rho^0$	$14.9_{-8.4}^{+10.6}$	$+11.2 \pm 5.7$	22.8 ± 1.4	17.5	0.3	$0.4_{-0.9-0.6}^{+1.2+1.6} (< 3.7)$	
$B^0 \rightarrow \eta' f_0(\rightarrow \pi^+ \pi^-)$	$-2.6_{-4.0}^{+6.0}$	-3.8 ± 2.0	25.4 ± 1.6	17.5	0.2	$0.1_{-0.4-0.4}^{+0.6+0.9} (< 1.5)$	
$B^+ \rightarrow \eta' \rho^+$	$57.3_{-14.7}^{+16.0}$	$+11.5 \pm 5.8$	13.0 ± 1.0	17.5	3.2	$8.7_{-2.8-1.3}^{+3.1+2.3} (< 14)$	$-0.04 \pm 0.28 \pm 0.02$

tematics) for zero signal and the minimum. For modes where the combined significance is less than 4 standard deviations, we quote 90% confidence level (C.L.) upper limits. We compute these as the branching fraction below which lies 90% of the total likelihood integral in the positive branching fraction domain.

For modes with evidence of a signal, we show in Fig. 1 projections onto m_{ES} and ΔE of subsamples (containing 63 – 85% of all signal events) enriched by a requirement on the ratio of the signal likelihood to the total likelihood. The likelihood is computed excluding the plotted variable. Figure 2 shows background-subtracted distributions of the K^{*0} mass and helicity obtained with the sPlot technique described in [13]. These plots illustrate that the $K\pi$ signal we observe is consistent with the $K^*(892)$ and is polarized as one would expect in a pseudoscalar-vector B decay.

Systematic uncertainties in this analysis are dominated by our knowledge of signal and $B\bar{B}$ background PDF modeling, along with the fit bias and the efficiencies of the track and neutral particle selections. Uncertainty due to continuum PDF modeling is largely incorporated into the statistical uncertainty since most continuum background parameters are allowed to vary in the fit. Uncertainties in the signal PDF parameters are estimated from comparisons between data and MC in control samples. Varying the signal PDF parameters within these errors results in a mode dependent variation in signal yield of between 0.1 and 1.6 events.

The uncertainty in the fit bias is taken to be half of the correction. We estimate the uncertainty from $B\bar{B}$

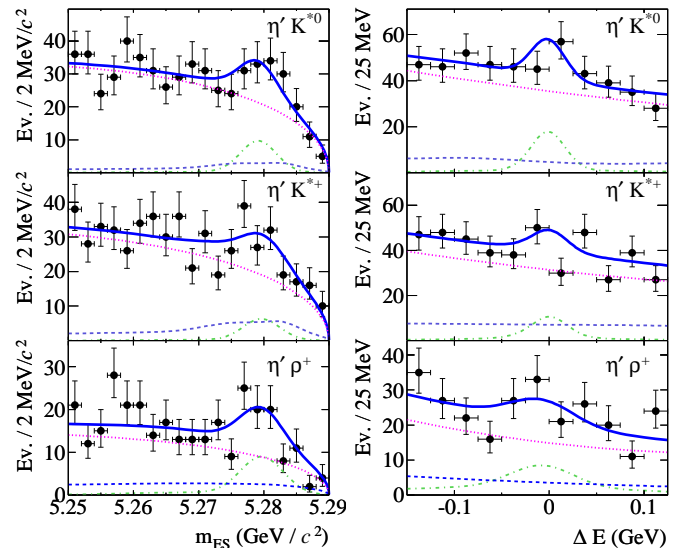


FIG. 1: (Color online) B candidate m_{ES} (left) and ΔE (right) projections obtained with a cut on the likelihood (see text) for $B^0 \rightarrow \eta' K^{*0}$ (top), $B^+ \rightarrow \eta' K^{*+}$ (middle) and $B^+ \rightarrow \eta' \rho^+$ (bottom). Submodes have been combined. The data are represented by points with uncertainties, full fit functions by solid curves, $B\bar{B}$ background by dashed, continuum by dotted and signal by dot-dashed curves. Depending on the decay, the plots contain 63 – 85% of all signal events.

modeling by taking half of the difference between the signal yield fitted with and without the $B\bar{B}$ component (0.2 to 10 events). The uncertainty due to non-resonant $B\bar{B}$ background is estimated by taking half the difference between the signal yield in the nominal fit and in a fit

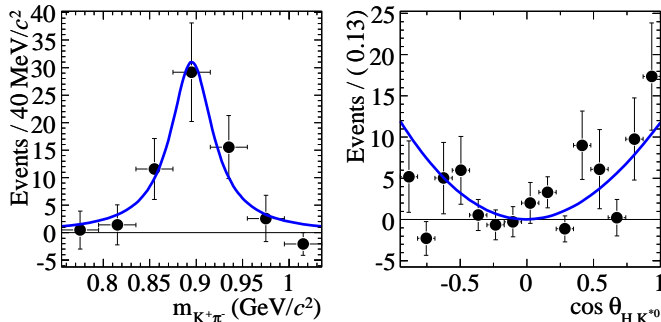


FIG. 2: (Color online) Distributions of the $K\pi$ mass (*left*) and helicity (*right*) for the decay $B^0 \rightarrow \eta' K^{*0}$. Points with error bars: data, background subtracted with the sPlot technique, solid curve: signal PDF.

in which a non-resonant background component has been added (0.7 to 4.8 events). Uncertainties in reconstruction efficiency are determined from supplementary studies of control samples. These include 0.8% per charged track (excluding daughters of the K_S^0), 1.5% per photon, and 1.9% for a K_S^0 . The systematic uncertainty in the number of $B\bar{B}$ pairs is 1.1% [14]. Published data [10] provide the uncertainties in the B -daughter product branching fractions (3.4%). Uncertainties in the event selection efficiency are 0.5–3% for the requirement on $\cos\theta_T$.

We assign a systematic uncertainty on \mathcal{A}_{ch} of 0.02, based on studies of inclusive samples of kaons and B decays. This is due primarily to asymmetries in charged kaon identification and slow pion reconstruction.

We present measurements for the decays $B^{+,0} \rightarrow \eta' K^{*+,0}$ and $B^+ \rightarrow \eta' \rho^+$. They allow the level of suppression of these decays, with respect to the enhanced $\eta' K$ and ηK^* , to be determined. A simultaneous fit of all charged and neutral $\eta' K^*$ submodes results in the observation of $B \rightarrow \eta' K^*$ with a total significance of 5.6σ , including systematics, as shown in Table I. The measurements place constraints on possible enhanced flavor-singlet contributions to these decays [2, 15]. These results are consistent with previous upper limits, where they existed. In all cases, predictions based on SU(3) flavor symmetry [4], QCD factorization [5] and perturbative QCD [6] are in excellent agreement with our measured central values. Values of \mathcal{A}_{ch} are consistent with zero in all channels.

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