Study of *B* Meson Decays with Excited η and η' Mesons

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Using 383×10^6 $B\bar{B}$ pairs from the *BABAR* data sample, we report results for branching fractions of six charged B-meson decay modes, where a charged kaon recoils against a charmless resonance decaying to $K\bar{K}^*$ or $\eta\pi\pi$ final states with mass in the range (1.2–1.8) GeV/c^2. We observe a significant enhancement at the low $K\bar{K}^*$ invariant mass which is interpreted as $B^+ \to \eta(1475)K^+$, find evidence for the decay $B^+ \to \eta(1295)K^+$, and place upper limits on the decays $B^+ \to \eta(1405)K^+$, $B^+ \to f_1(1285)K^+$, $B^+ \to f_1(1420)K^+$, and $B^+ \to \phi(1680)K^+$.

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Charmless hadronic B-meson decays have been of particular interest due to their sensitivity to weak interaction dynamics. The first observed gluonic-penguin–dominated decays, such as $B \to \eta' K$ and $B \to \pi K$ [1], allowed the study of CP violation in these decays with potential sensitivity to new physics [2,3]. The relatively large $B \to \eta' K$ decay rate was also a topic of debate. However, little is known about the B-meson decays to excited states of the η and η' mesons. There are three candidates for the first excited states $\eta(1295)$, $\eta(1405)$, and $\eta(1475)$ [4], and there is a possibility that they might include a gluonium admixture [5]. This part of the pseudoscalar meson spectrum remains uncertain after a few decades of studies [5–11]. A search for B-meson decays to these pseudoscalar states is the focus of this Letter.

The η and η' candidates and their excited counterparts, which we call generically η_X in this Letter, have the quantum numbers $J^P = 0^-$ and decay strongly to at least three pseudoscalar mesons. Thus we look for the $\eta_X \to K\bar{K}\pi$ and $\eta\pi\pi$ final states. In the former case, the resonant structure $K\bar{K}^* + \bar{K}K^*$ is of particular interest, and we refer to it as $K\bar{K}^*$. Previously, the $K^*K^+K^-$ final state has been studied by *BABAR* inclusively [12]. The $J^P = 1^+$ mesons $f_1(1285)$ and $f_1(1420)$ and $J^P = 1^-$ meson $\phi(1680)$ also appear in the mass range (1.2–1.8) GeV/c^2 in these final states. These resonances are considered in our search for the decays $B^+ \to \eta_X K^+$ and referred to by the generic nomenclature η_X as well. Hermitian conjugation is implied throughout this Letter unless stated otherwise.

The $B \to \eta_X K$ decay mechanism is expected to be dominated by the $b \to s$ gluonic-loop penguin diagram, similar to the $B \to \eta' K$ decay. The expected branching fractions differ significantly depending on the η_X state [4], following a pattern that early naive factorization models were unable to predict [13]. The first attempt at unraveling the pattern in the branching fractions of B-meson decays with η and η' [14] suggested including the interference within the quark flavor octet among other possible scenarios, but the predictions did not match the experimental data. More recent calculations find a larger predicted rate for $B \to \eta' K$, in agreement with data, with inclusion of higher-order corrections [15] or "charming-penguin" contributions [16]; large theoretical uncertainties persist, partly due to insufficient experimental data. An admixture of a bound two-gluon state, gluonium, in η_X could also explain the enhancement of the branching fractions.

Although the $\eta(1295)$, $\eta(1405)$, and $\eta(1475)$ states are considered well-established [4], their nature is still unknown. Partial wave analyses of the $K\bar{K}\pi$ and $\eta\pi\pi$ spectra from past experiments, such as studies in Refs. [7–10], conclude that the meson spectrum in the (1.2–1.8) GeV/c^2 range is described by a linear combination of the resonant states and a nonresonant phase-space contribution. The analyses in Refs. [7,8] found that mass spectrum description without interference between the resonant and nonresonant contributions is preferred. Therefore, in our analysis we adopt the model of three spin-zero resonances $\eta(1295)$, $\eta(1405)$, and $\eta(1475)$, three spin-one resonances $f_1(1285)$, $f_1(1420)$, and $\phi(1680)$, and a phase-space nonresonant contribution without interference with the above states. Only four resonances are considered in each final state, $K\bar{K}^*$ or $\eta\pi\pi$, according to their dominant decay modes as discussed below.

We use a sample of $(383 \pm 4) \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ events collected with the *BABAR* detector [17] at the PEP-II e^+e^- asymmetric-energy storage rings with the e^+e^- center-of-mass energy $\sqrt{s} = 10.58$ GeV. Momenta of charged particles are measured in a tracking system consisting of a silicon vertex tracker with five double-sided layers and a 40-layer drift chamber, both within the 1.5-T magnetic field of a solenoid. Identification of charged particles is provided by measurements of the energy loss in the tracking devices and by a ring-imaging Cherenkov detector. Photons are detected by a CsI(Tl) electromagnetic calorimeter.

We search for $B^+ \to \eta_X K^+$ where η_X decays to $K\bar{K}^*$ and $\eta\pi^+\pi^-$. We reconstruct $K\bar{K}^* \to \overset{(-)}{K}{}^0 K^\pm \pi^\mp$, $\overset{(-)}{K}{}^0 \to K_S^0 \to \pi^+\pi^-$, and $\eta \to \gamma\gamma$. Isospin symmetry implies that the final states $K^0K^-\pi^+ + \bar{K}^0K^+\pi^-$ and $\eta\pi^+\pi^-$ constitute two-thirds of $\eta_X \to K\bar{K}^*$ and $\eta_X \to \eta\pi\pi$, respectively.

We identify B-meson candidates using two kinematic variables: $m_{\mathrm{ES}} = \sqrt{s/4 - \mathbf{p}_B^2}$ and $\Delta E = \sqrt{s}/2 - E_B$, where $(E_B, \mathbf{p}_B)$ is the four-momentum of the B candidate in the e^+e^- center-of-mass frame. We require $m_{\mathrm{ES}} > 5.25$ GeV/c^2 and $|\Delta E| < 0.1$ GeV. The requirements on the invariant masses are $1.35 < m_{K\bar{K}^*} < 1.8$ GeV/c^2, $1.2 < m_{\eta\pi\pi} < 1.5$ GeV/c^2, $|m_{\pi\pi} - m_{K^0}| < 12$ MeV/c^2, and $510 < m_{\gamma\gamma} < 570$ MeV/c^2. The η_X invariant mass range is chosen to include the broad spectrum of states without extending it above the charm background production threshold.

We require the photon energies be at least 100 MeV. For the K_S^0 candidates, we require the cosine of the angle between the flight direction from the interaction point and the momentum direction to be greater than 0.995 and the measured proper decay time to be greater than 5 times its uncertainty. In the $\eta_X \to K\bar{K}^* + \bar{K}K^* \to K\bar{K}\pi$ decay channel, we require the $\bar{K}\pi$ or $K\pi$ invariant mass to satisfy $0.85 < m_{K\pi} < 0.95$ GeV/c^2 for either $K^\pm\pi^\mp$ or $\overset{(-)}{K}{}^0\pi^\mp$ combinations.

We use the angle θ_T between the B-candidate thrust axis and that of the rest of the event and a Fisher discriminant $\mathcal{F}_L$ to reject the dominant $e^+e^- \to$ quark-antiquark background [18]. Both variables are calculated in the e^+e^- center-of-mass frame. The discriminant combines the polar angles of the B-candidate momentum vector and its thrust axis with respect to the beam axis and two moments of the energy flow around the B-candidate thrust axis [18].

We suppress the background from B decays into states with D or $c\bar{c}$ mesons by applying vetoes on the invariant masses of their decay products. The remaining background (less than 10%) comes from random combinations of tracks from B decays and from $B^+ \to K\bar{K}^* K^+$. When more than one candidate is reconstructed, we select the one with the lowest combined χ^2 of the charged-track vertex fit and of the invariant mass of the K_S^0 or η candidate relative to the PDG values [4].

We define the helicity angle $\theta_{\mathcal{H}}$ as the angle between the direction of the B meson and the normal vector to the η_X three-body decay plane in the η_X rest frame. The ideal distribution is uniform, $\mathcal{H}^2$, or $(1 - \mathcal{H}^2)$ for η_X with $J^P = 0^-$, 1^-, or 1^+, respectively, where $\mathcal{H} = \cos\theta_{\mathcal{H}}$. The observed angular distribution can be parametrized as a product of the ideal angular distribution for a given spin and parity multiplied by an empirical acceptance function parametrized as a polynomial $P(|\mathcal{H}|)$.

We use an unbinned, extended maximum-likelihood fit to extract the event yields n_j and the parameters $\boldsymbol{\zeta}$ of the probability density functions (PDFs) $\mathcal{P}_j$. The index j represents six event categories used in our data model: the $B^+ \to \eta_X K^+$ signal (four categories in each of the two η_X decay channels as shown in Table I), combinatorial background (mostly $e^+e^- \to q\bar{q}$ production with a few percent admixture of misreconstructed B-meson decays), and a possible background from $B \to K\bar{K}^* K$ (in the $\eta_X \to K\bar{K}^*$ channel) or other B backgrounds (in the $\eta_X \to \eta\pi\pi$ channel). The likelihood $\mathcal{L}_i$ for each candidate i is defined as $\mathcal{L}_i = \sum_j n_j \mathcal{P}_j(\boldsymbol{x}_i, \boldsymbol{\zeta})$, where the PDF is formed from the observables $\boldsymbol{x} = \{m_{\rm ES}, \Delta E, \mathcal{F}_L, \mathcal{H}, m\}$. Here m is the invariant mass of the η_X candidate.

We use a relativistic spin-J Breit-Wigner amplitude parametrization for the invariant mass of an η_X resonance with the nominal mass and width parameters quoted in Table I. We model the decay kinematics as $\eta_X \to K\bar{K}^* \to K\bar{K}\pi$ and $\eta_X \to a_0(980)\pi \to \eta\pi\pi$. For the $\eta_X \to K\bar{K}^*$ mode, the η_X invariant mass parametrization is corrected for phase space of the $B^+ \to K\bar{K}^* K^+$ decay and averaged over the $\bar{K}^* \to \bar{K}\pi$ invariant mass values. We ignore the interference between the overlapping resonances because it averages to zero for resonances with different quantum numbers or because these resonances have different final states, such as $\eta(1405)$ and $\eta(1475)$. The former decays mainly to $a_0(980)\pi$ (or direct $K\bar{K}\pi$) and the latter mainly to $K\bar{K}^*$ [4]. We also ignore the interference between the resonant and nonresonant decays based on indications from previous studies of η_X decays [7,8] and due to potentially different three-body structure. This interference effect would only increase the significance estimate because the hypothesis of zero yield is not affected and the likelihood of the nominal fit could only improve. The significance is defined as the square root of the change in $2\ln\mathcal{L}$ when the yield is constrained to zero in the likelihood $\mathcal{L}$.

The signal PDF for a given candidate i is the product of the PDFs for each of the discriminating variables. The

TABLE I. Summary of results for the $B^+ \to \eta_X K^+$ process studied with six B-decay modes and eight decay channels with the signal resonance and nonresonant model discussed in text, where $\eta_X \to K\bar{K}^* \to K_S^0 K^\pm \pi^\mp$ in the upper part and $\eta_X \to \eta\pi^+\pi^-$ in the lower part. The mass m_0 and width Γ of six η_X states are quoted [4] with errors in parentheses. The number of signal events $n_{\rm sig}$ with the significance of the observed signal in parentheses, the product of the branching fractions $\mathcal{B}$ and the corresponding daughter branching fractions, the $B^+ \to f_1(1285)K^+$ branching fraction, the corresponding 90% C.L. upper limits, and selection efficiencies ϵ obtained from MC simulation are shown. The systematic uncertainties are quoted last.

$\eta_X \to K\bar{K}^*$	$\eta(1475)$	$\phi(1680)$	$\eta(1405)$	$f_1(1420)$
m_0/Γ [4], MeV	1476(4)/87(9)	1680(20)/150(50)	1409.8(2.5)/51.1(3.4)	1426.3(0.9)/54.9(2.6)
$n_{\rm sig}$	$155^{+21+11}_{-19-6}(7.5\sigma)$	$17^{+6}_{-9} \pm 7$	$-12^{+8}_{-5} \pm 1$	$36^{+13}_{-14} \pm 7$
90% C.L.	<192	<39	<12	<56
$\mathcal{B}(B^+ \to \eta_X K^+)\mathcal{B}(\eta_X \to K\bar{K}^*)$	$(13.8^{+1.8+1.0}_{-1.7-0.6})10^{-6}$	$(1.5^{+0.5+0.7}_{-0.8-0.6})10^{-6}$	$(-1.2^{+0.9}_{-0.5} \pm 0.1)10^{-6}$	$(2.7^{+0.9}_{-1.0} \pm 0.5)10^{-6}$
90% C.L.	$<17 \times 10^{-6}$	$<3.4 \times 10^{-6}$	$<1.2 \times 10^{-6}$	$<4.1 \times 10^{-6}$
ϵ (%)	8.8 ± 0.1	9.0 ± 0.2	8.4 ± 0.3	10.7 ± 0.3
$\eta_X \to \eta\pi\pi$	$\eta(1295)$	$f_1(1285)$	$\eta(1405)$	$f_1(1420)$
m_0/Γ [4], MeV	1294(4)/55(5)	1281.8(0.6)/24.2(1.1)		
$n_{\rm sig}$	$131^{+35}_{-33} \pm 10(3.5\sigma)$	$-30^{+21}_{-19} \pm 14$	$-14^{+36}_{-33} \pm 6$	$49^{+35}_{-34} \pm 11$
90% C.L.	<179	<30	<54	<99
$\mathcal{B}(B^+ \to \eta_X K^+)\mathcal{B}(\eta_X \to \eta\pi\pi)$	$(2.9^{+0.8}_{-0.7} \pm 0.2)10^{-6}$	$(-0.8^{+0.6}_{-0.5} \pm 0.4)10^{-6}$	$(-0.3^{+0.9}_{-0.8} \pm 0.1)10^{-6}$	$(1.4 \pm 1.0 \pm 0.3)10^{-6}$
90% C.L.	$<4.0 \times 10^{-6}$	$<0.8 \times 10^{-6}$	$<1.3 \times 10^{-6}$	$<2.9 \times 10^{-6}$
$\mathcal{B}(B \to f_1(1285)K^+)$	$\cdots$	$(-1.5^{+1.1}_{-1.0} \pm 1.2)10^{-6}$	$\cdots$	$\cdots$
90% C.L.	$\cdots$	$<2.0 \times 10^{-6}$	$\cdots$	$\cdots$
ϵ (%)	17.6 ± 0.3	14.1 ± 0.9	16.5 ± 1.2	13.5 ± 0.6

combinatorial background PDF is the product of the PDFs for independent variables. The signal and background PDFs are illustrated in Fig. 1. We use a sum of Gaussian functions for the parametrization of the signal PDFs for ΔE, $m_{\rm ES}$, and $\mathcal{F}_L$. For the combinatorial background, we use polynomials, except for $m_{\rm ES}$ and $\mathcal{F}_L$ distributions, which are parametrized by an empirical phase-space function and by Gaussian functions, respectively. The nonresonant $B \to K\bar{K}^* K$ background is parametrized the same as the signal, except for the quantity m, which is described by a phase-space function.

The PDF parameters (ζ) of the combinatorial background are left free to vary in the fit, except for the parameters that describe $\mathcal{F}_L$ and the $m_{\rm ES}$ end point, which are fixed to the values extracted from the data sideband region ($m_{\rm ES} < 5.27$ GeV$/c^2$ or $|\Delta E| > 0.07$ GeV). The PDF parameters for other event categories are taken from Monte Carlo (MC) simulation [19] and adjusted with $B \to \bar{D}\pi$ calibration data samples. We allow the yields to become negative as long as the total likelihood function remains positive in the allowed ranges of the observables. We study the goodness of fit and validate the fit procedure using MC simulation and generated samples.

In Table I, we present the results of the fit. We observe a large charmless contribution in the $B^+ \to (K\bar{K}^*)K^+$ decay with a significant enhancement at the low $K\bar{K}^*$ invariant mass, which is interpreted as $\eta(1475) \to K\bar{K}^*$ from the decay $B^+ \to \eta(1475)K^+$. We also see evidence for a nonzero $B^+ \to \eta(1295)K^+$ yield in the $\eta(1295) \to \eta\pi\pi$ channel. The significances are more than 7.5 and 3.5 standard deviations, respectively, including systematic uncertainties. The significance of the $B^+ \to \eta(1295)K^+$ yield is obtained in the fit when all yields are restricted to be positive, thus reducing the significance from the nominal fit. The significance is calculated within the model of resonant and nonresonant signal contributions discussed above and in earlier work [4,7,8]. We quote 90% confidence level (C.L.) upper limits, taken to be the values below which lies 90% of the total of the likelihood integral in the positive branching fraction or yield region.

We repeat the fit by varying the fixed parameters in ζ within their uncertainties to obtain the associated systematic uncertainties. The biases from the presence of fake combinations or other imperfections in the signal PDF model are estimated with MC simulation. Additional systematic uncertainties originate from other potential B backgrounds, which we estimate can contribute at most a few events to the signal component. As a cross-check, we repeat the fit with the particle identification on the recoil kaon reversed in order to enhance the $B^+ \to \eta_X\pi^+$ topology by more than a factor of 10 compared to the nominal reconstruction and find no evidence for such a decay. The systematic uncertainties in selection efficiencies are dominated by those in particle identification, track finding, and K^0_S and η selection. Other systematic effects arise from event-selection criteria and the estimation of the number of B mesons.

The states $\eta(1475)$, $\phi(1680)$, and $f_1(1420)$ are expected to decay into the $K\bar{K}\pi$ final state through $K\bar{K}^*$ [4]. We cross-check the $K\bar{K}^*$ dominance by removing the $\bar{K}\pi$ mass requirement and find consistent results. With the present data set, we are unable to resolve intermediate states in the $\eta\pi\pi$ modes, such as $\rho^0(770)$ and $a_0^{\pm}(980)$ resonances.

In the projection plots in Fig. 1, for illustration purposes, the signal fraction is enhanced with a requirement on the signal-to-background probability ratio, calculated with the plotted variable excluded. The m projection plot in Fig. 1(e) implies a possible difference of the signal resonance parameters from the assumed values. We repeat the fit with the $\eta(1475)$ resonance parameters m_0 and Γ unconstrained while constraining other fit parameters to the values from the nominal fit. We find the m_0 and Γ central values to be larger but still consistent with the nominal

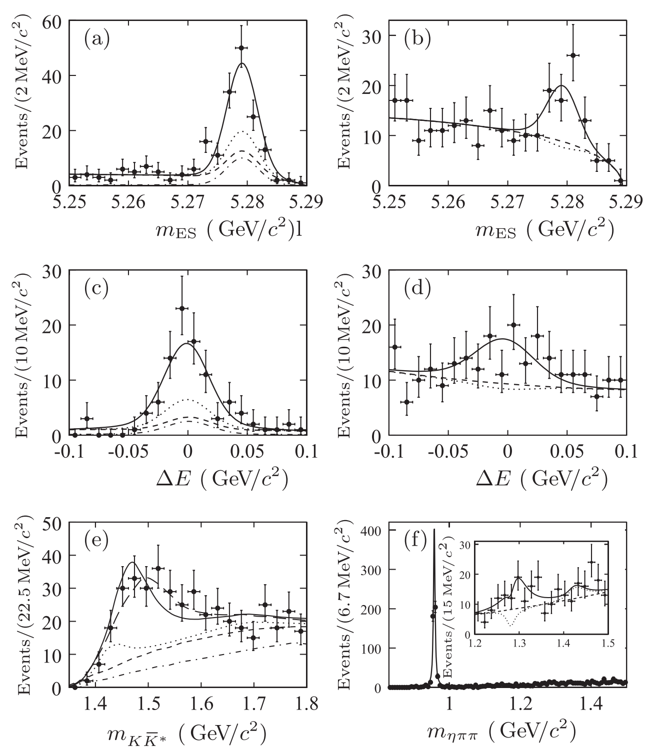

FIG. 1. Projections for $B^+ \to K\bar{K}^*K^+$ (left column) and $B^+ \to \eta\pi\pi K^+$ (right column) of (a),(b) $m_{\rm ES}$, (c),(d) ΔE, and (e),(f) m with a requirement applied on the signal-to-background probability ratio calculated with all variables except the one being plotted. The extended mass region in (f) includes the η' resonance as a cross-check. The nominal region is shown in the inset. The solid (dashed) lines show the signal-plus-background (background) PDF projections. The dotted line shows the total PDF projection excluding the $\eta(1475)K^+$ (left) or $\eta(1295)K^+$ (right) final states. The dashed-dotted lines indicate the nonresonant component. The long-dashed line in (e) represents the cross-check with the $\eta(1475)$ resonance mass (m_0) and width (Γ) parameters unconstrained, both resulting in larger values.

values within statistical uncertainties (1482 ± 10 and 108 ± 20 MeV, respectively). We also repeat the fit with the m range extended up to 2.5 GeV$/c^2$ and find good extrapolation of the fit results in the full range, apart from the narrow charm production contribution just above the 1.8 GeV$/c^2$ threshold.

In summary, we have measured product branching fractions $\mathcal{B}(B^+ \to \eta_X K^+) \times \mathcal{B}(\eta_X \to K\bar{K}^*, \eta\pi\pi)$ for six B-decay modes that have not been studied previously, where η_X stands for $\eta(1295)$, $\eta(1405)$, $\eta(1475)$, $f_1(1285)$, $f_1(1420)$, or $\phi(1680)$. We observe a significant enhancement at the low $K\bar{K}^*$ invariant mass which is interpreted as $B^+ \to \eta(1475)K^+$ and find evidence for the decay $B^+ \to \eta(1295)K^+$. These decays could be used to either test weak dynamics in the predominant $b \to s$ gluonic-loop penguin transition or study the η_X composition, including potential gluonium admixture.

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