Study of High Momentum η' Production in $B \to \eta' X_s$

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We measure the branching fraction for the charmless semi-inclusive process $B \to \eta' X_s$, where the η' meson has a momentum in the range 2.0 to 2.7 GeV/c in the $\Upsilon(4S)$ center-of-mass frame and X_s represents a system comprising a kaon and zero to four pions. We find $\mathcal{B}(B \to \eta' X_s) = [3.9 \pm 0.8(\text{stat}) \pm 0.5(\text{syst}) \pm 0.8(\text{model})] \times 10^{-4}$. We also obtain the X_s mass spectrum and find that it fits models predicting high masses.

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The production of high momentum η' mesons in B meson decays is expected to be dominated by the $B \to \eta' X_s$ process, where X_s is a strange hadronic system, generated by the $b \to sg^*$ transition as depicted in Figs. 1(a)–1(c). Figure 1(d) shows the color-suppressed modes $\overline{B}^0 \to \eta' D^{(*)0}$, which are significant sources of background and which have been measured for the first time recently [1]. Contributions from $b \to u$ transitions and other sources of η' are expected to be negligible [2].

The large inclusive η' production branching fraction measured by the CLEO Collaboration [3] prompted intense theoretical activity, which focused the special character of the η' meson as receiving much of its mass from the QCD anomaly [4–6]. A later measurement by CLEO confirmed the large η' production, measuring $\mathcal{B}(B \to \eta' X_{nc}) = [4.6 \pm 1.1(\mathrm{stat}) \pm 0.4(\mathrm{syst}) \pm 0.5(\mathrm{bkg})] \times 10^{-4}$ [7], where X_{nc} denotes a charmless recoiling hadronic system including X_s.

We present results for the branching fraction of $B \to \eta' X_s$ and the fully background-subtracted mass spectrum of X_s. The signal is analyzed for η' momentum between 2.0 and 2.7 GeV$/c$ in the center-of-mass (c.m.) frame to suppress background coming from $b \to c \to \eta'$ cascades such as $B \to D_s X$ with $D_s \to \eta' X$, $B \to DX$ with $D \to \eta' X$, $B \to \Lambda_c X$ with $\Lambda_c \to \eta' X$. The improvement of the measurement, based on a better background suppression and the tagging of the strangeness of the recoiling hadronic mass can provide important clues to the dynamics of the transition $b \to sg^*$ and to the structure of the isosinglet pseudoscalar mesons.

Our analysis is based on data collected with the *BABAR* detector [8] at the PEP-II asymmetric e^+e^- collider located at the Stanford Linear Accelerator Center. An integrated luminosity of 81.4 fb^{-1}, corresponding to 88.4×10^6 $B\overline{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance (on-resonance) and 9.6 fb^{-1} were recorded 40 MeV below this resonance (off-resonance), for continuum background studies.

Two tracking devices are used for the detection of charged particles: a silicon vertex tracker consisting of five layers of double-sided silicon microstrip detectors, and a 40-layer central drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter. Charged-particle identification is provided by the average energy loss (dE/dx) in the tracking devices, and by an internally reflecting ring-imaging Cherenkov detector covering the central region.

We select $B\overline{B}$ events by requiring at least four charged tracks and a value of the ratio of the second to zeroth Fox-Wolfram moment [9] less than 0.5. We form a B candidate by combining an $\eta' \to \eta\pi^+\pi^-$, where the η decays into $\gamma\gamma$, with a K^+ or a K^0_S that is reconstructed in the $\pi^+\pi^-$ channel, and up to four pions, of which at most one is a π^0, leading to 16 possible channels [10]:

$$
\begin{aligned}
&B^+ \to \eta' K^+(+\pi^0) && B^0 \to \eta' K^0_S(+\pi^0),\\
&B^+ \to \eta' K^+\pi^+\pi^-(+\pi^0) && B^0 \to \eta' K^0_S\pi^+\pi^-(+\pi^0),\\
&B^+ \to \eta' K^0_S\pi^+(+\pi^0) && B^0 \to \eta' K^+\pi^-(+\pi^0),\\
&B^+ \to \eta' K^0_S\pi^+\pi^+\pi^-(+\pi^0) && B^0 \to \eta' K^+\pi^-\pi^+\pi^-(+\pi^0).
\end{aligned}
$$

The masses of the $\eta \to \gamma\gamma$, $K^0_S \to \pi^+\pi^-$, and $\pi^0 \to \gamma\gamma$ candidates are required to lie within 3σ ($\sigma = 16$, 3, and 6 MeV$/c^2$, respectively) of their known values and are then kinematically constrained to their nominal masses.

To identify the s quark in the X_s system, we require a K^0_S or a track consistent with a charged kaon. The charged-kaon selection has been optimized to suppress background from $B \to \eta'\pi$, $\eta'\rho$, and $\eta' a_1$ decays. For the K^0_S, we require the angle α between the momentum of the K^0_S candidate and its flight direction to be less than 0.05 radians, as it peaks at zero for true K^0_S particles.

We require candidates for $B \to \eta' X_s$ to be consistent with a B decay, based on the beam-energy-substituted mass $m_{\mathrm{ES}} = \sqrt{(s/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and the energy

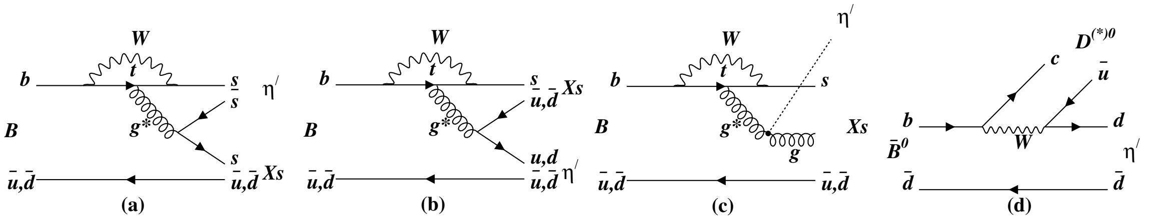

FIG. 1. Lowest order diagrams for (a)–(c) $B \to \eta' X_s$ and (d) the color-suppressed background $\overline{B}^0 \to \eta' D^{(*)0}$.

difference $\Delta E = E_B^* - \sqrt{s}/2$, where E and $\mathbf{p}$ denote the energy and momentum of the particles, the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and the B candidate, respectively, the asterisk denotes the $\Upsilon(4S)$ rest frame, and $\sqrt{s}$ is the e^+e^- c.m. energy [11]. In addition, the cosine of the angle between the thrust axis of the B candidate and that of the rest of the event in the c.m. frame ($\cos\theta_T^*$) is used to remove continuum background, which is peaked near $|\cos\theta_T^*| = 1$, while signal events are uniformly distributed. We require $m_{\rm ES} > 5.265$ GeV$/c^2$, $|\Delta E| < 0.1$ GeV, and $|\cos\theta_T^*| < 0.8$. For each event, we select the candidate with the smallest χ^2, with χ^2 defined by

$$\chi^2 = (m_{\rm ES} - M_B)^2/\sigma^2(m_{\rm ES}) + (\Delta E)^2/\sigma^2(\Delta E),$$

where M_B is the B-meson mass and where the resolutions $\sigma(m_{\rm ES}) = 3$ MeV$/c^2$ and $\sigma(\Delta E) = 25$ MeV are obtained from Monte Carlo simulation. The remaining continuum background is subtracted with the use of off-resonance data.

The background contribution from color-suppressed modes $\overline{B}^0 \to \eta' D^{(*)0}$ is estimated from a Monte Carlo simulation which uses our measurement of its branching fraction, $\mathcal{B}(\overline{B}^0 \to \eta' D^{(*)0}) = [1.7 \pm 0.4({\rm stat}) \pm 0.2({\rm syst})] \times 10^{-4}$ [1].

To determine efficiencies, we model the signal using a combination of the two-body mode $B \to \eta' K$ and, for X_s masses above the $K\pi$ threshold, a nonresonant hard spectrum derived from the theoretical predictions [4–6], which are based on the anomalous η'-gluon-gluon coupling and which favor high-mass X_s systems. The fraction of the two-body mode is constrained in the simulation model to be between 10% and 15% [12,13]. When not forming a K meson, the X_s fragments into $s\bar{q}$ and $s\bar{q}g$ ($q = u, d$). We find that the overall efficiency is $(6.0 \pm 0.2)\%$ for the $K^\pm$ modes and $(4.7 \pm 0.1)\%$ for the K_S^0 modes, including the branching fraction $\mathcal{B}(K_S^0 \to \pi^+\pi^-)$.

The branching fraction of $B \to \eta' X_s$ is computed through a fit to the number of η' signal events, with η' momentum between 2.0 and 2.7 GeV$/c$, both for on-resonance and off-resonance data. To parametrize the background, we use a Gaussian function for the signal and a second order polynomial. For the fit of the off-resonance data sample, we constrain the mass and width of the η' to the values obtained with on-resonance data. Figure 2 shows the fits of the $\eta\pi\pi$ invariant-mass distributions for the $K^\pm$ and K_S^0 modes. The fitted yields are reported in Table I.

The semi-inclusive branching fraction is computed by performing a weighted average of the results obtained for the $K^\pm$ and K_S^0 modes. The detection efficiencies are corrected to account for the η' and η branching fractions to the channel we observe. For the K_S^0 modes, we convert the result so it corresponds to K^0 and $\overline{K}^0$. The final state X_s includes both K^+- and K^0-tagged decays. Assuming that their branching fractions are equal, we obtain $\mathcal{B}(B \to \eta' X_s) = [3.9 \pm 0.8({\rm stat}) \pm 0.5({\rm syst}) \pm 0.8({\rm model})] \times 10^{-4}$. We obtain the systematic error by combining the sources listed in Table II; of the total error 8% is common to all the $\eta' K n\pi$ combinations.

TABLE I. Results of the fits for $K^\pm$ and K_S^0 modes. Yields for on-resonance data ($Y_{\rm ON}$), off-resonance data ($Y_{\rm OFF}$), expectation from color-suppressed background ($Y_{\rm CS}$) and on-resonance data after background subtraction (Y) are given. A luminosity scale factor, $f = 8.48$, is applied to the off-resonance yield.

	$K^\pm$ modes	K_S^0 modes
$Y_{\rm ON}$	577.0 ± 34.0	367.0 ± 34.0
$Y_{\rm OFF}$	18.9 ± 8.5	21.7 ± 8.4
$Y_{\rm CS}$	63.6 ± 11.4	26.9 ± 4.5
Y	353.1 ± 80.5	156.1 ± 79.1

The largest uncertainty arises from our model of the X_s system. To estimate that uncertainty, we use an alternative model which consists of a combination of resonant modes: $\eta' K$, $\eta' K^*(892)$, $\eta' K_1(1270)$, $\eta' K_1(1400)$, $\eta' K^*(1410)$, $\eta' K_2^*(1430)$, $\eta' K_3^*(1780)$, and $\eta' K_4^*(2045)$. The efficiency discrepancy between the models and our knowledge of the resonant sector lead us to assign a 20% systematic uncertainty. Other systematic uncertainties include track reconstruction efficiency, reconstruction efficiencies of $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, and $K_S^0 \to \pi^+\pi^-$ candidates, charged-kaon identification efficiency, secondary branching fractions, number of $B\overline{B}$ events ($N_{B\overline{B}}$), the size of our Monte Carlo sample, and subtraction of the background from $\overline{B}^0 \to \eta' D^{(*)0}$.

To explore the X_s mass distribution, we select B candidates for which the mass of the η' is within 3 standard deviations of the known value and subtract the continuum contribution by using on-resonance data in the sideband $5.200 < m_{\rm ES} < 5.265$ GeV$/c^2$. The continuum background scaling factor ($\mathcal{A}$), from the sideband to signal

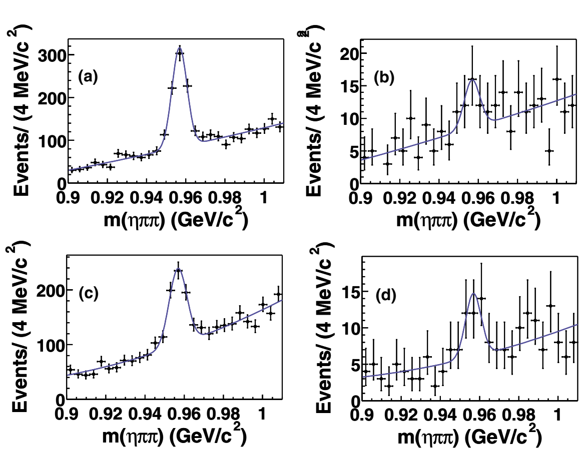

FIG. 2 (color online). Fits to the $\eta\pi\pi$ invariant mass for on-resonance (a),(c) and off-resonance (b),(d) data samples, for the modes (a),(b) $K^\pm$ and (c),(d) K_S^0.

TABLE II. Contribution of different sources to the systematic error for modes with a $K^{\pm}$ or K_S^0.

Source	$K^{\pm}$ syst (%)	K_S^0 syst (%)
Tracking	3.4	3.3
η, π^0 detection	7.0	8.2
K/K_S^0 ID	2.5	4.3
$\mathcal{B}(\eta' \to \eta_{\gamma\gamma}\pi\pi)$	3.4	3.4
$N_{B\overline{B}}$	1.1	1.1
MC sample size	3.0	3.0
$\eta' D^{(*)0}$ subtraction	3.0	2.9
Total	12.1	13.5
Model	20	20

regions, is computed from off-resonance data to be 0.591 ± 0.118. The resulting mass distributions are shown in Fig. 3 for all B modes and separately for the B^0 modes. The peak at $m(X_s) \simeq 500$ MeV$/c^2$ corresponds to the two body mode $B \to \eta' K$.

To obtain the full X_s spectrum, we fit the η' mass distribution in bins of X_s mass. The efficiency, averaged over the charged and neutral kaons, as a function of $m(X_s)$, is shown in Fig. 4. The correction for the feed across between bins is included in the efficiencies.

According to simulations, the X_s system is correctly reconstructed for 85% (60%) of the candidates in the region $m(X_s) < 1.5$ GeV$/c^2$ [$m(X_s) > 1.5$ GeV$/c^2$]. For correctly reconstructed events, the experimental resolution varies from 5 to 15 MeV$/c^2$ for low and high masses, respectively. In the case of misreconstructed events, the resolution ranges from 100 to 150 MeV$/c^2$. Table III shows the fitted yields for the raw signal, the sideband region, the expected color-suppressed background, and the yield after full background subtraction, as a function of $m(X_s)$.

The branching fraction as a function of $m(X_s)$, obtained from the fully background-subtracted yield (Table III), is shown in Fig. 5. We compare data and simulation by forming a χ^2 difference. The χ^2 probability for the nonresonant X_s model [Fig. 5(a)] to fit the data is 61%, while it is close to $\sim 10^{-7}$ for the equal mixture of resonances [Fig. 5(b)]. We find improved agreement with the resonant model if the weights of K_3^* and K_4^* are increased by a factor of 1.5, leading to a probability of 2%.

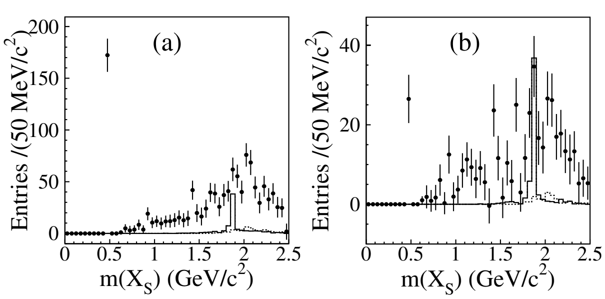

FIG. 3. Continuum-subtracted $Kn\pi$ invariant-mass distributions for (a) all B modes and (b) B^0 modes, including combinatorial background. Solid and dashed histograms represent expected backgrounds from $\overline{B}^0 \to \eta' D^0$ and $\overline{B}^0 \to \eta' D^{*0}$, respectively.

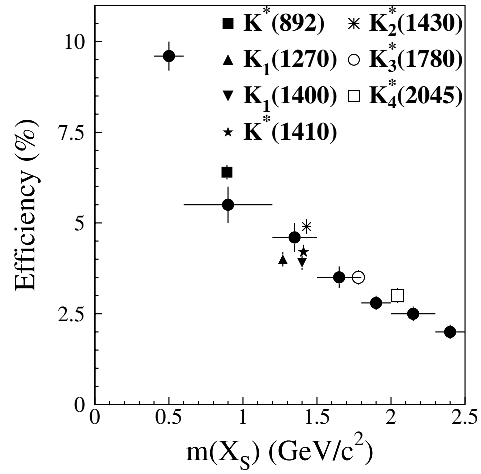

FIG. 4. Variation of the efficiency averaged over charged and neutral kaons with $m(X_s)$. The filled circles indicate the efficiency for nonresonant X_s simulation. The other symbols denote the values for the resonances.

As a consistency check of the method, we measure the two-body decay modes ($X_s = K^{\pm}, K_S^0$) and find 171.0 ± 14.0 and 27.1 ± 5.6 events in on-resonance data for $\eta' K^{\pm}$ and $\eta' K_S^0$, respectively, and no η' signal events for both channels in off-resonance data, leading to the branching fractions $\mathcal{B}(B^{\pm} \to \eta' K^{\pm}) = [6.9 \pm 0.6(\text{stat})] \times 10^{-5}$ and $\mathcal{B}(B^0 \to \eta' K^0) = [5.6 \pm 1.2(\text{stat})] \times 10^{-5}$. These values are fully compatible with what has been measured by recent exclusive analyses [12,13].

In summary, we have measured the branching fraction, $\mathcal{B}(B \to \eta' X_s) = [3.9 \pm 0.8(\text{stat}) \pm 0.5(\text{syst}) \pm 0.8(\text{model})] \times 10^{-4}$, for $2.0 < p^*(\eta') < 2.7$ GeV$/c$. We have also derived the $m(X_s)$ spectrum and found that the data tend to confirm models predicting a peak at high masses and seem to disfavor predictions based

TABLE III. Fitted yields for on-resonance data and color-suppressed background for different $m(X_s)$ ranges in GeV$/c^2$. The sideband yields (Y_{SB}) must be corrected by the sideband to the signal region scaling factor (see text) before subtraction.

$m(X_s)$ range	Y_{ON}	Y_{SB}	Y_{CS}	Y
[0.4, 0.6]	200 ± 15	46.1 ± 8.8	$\cdots$	172.8 ± 15.9
[0.6, 1.2]	120 ± 14	100 ± 13	$\cdots$	60.9 ± 16.0
[1.2, 1.5]	114 ± 15	112 ± 14	1.1 ± 0.3	46.7 ± 17.1
[1.5, 1.8]	150 ± 18	163 ± 17	7.7 ± 1.6	46.0 ± 20.7
[1.8, 2.0]	140 ± 17	93 ± 15	47.4 ± 9.6	37.6 ± 21.4
[2.0, 2.3]	149 ± 20	142 ± 18	26.2 ± 4.5	38.9 ± 23.1
[2.3, 2.5]	80 ± 14	70 ± 14	4.9 ± 0.9	33.7 ± 16.3

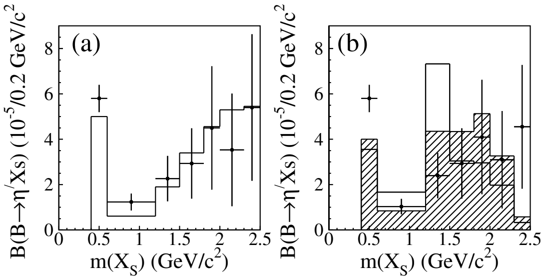

FIG. 5. Branching fractions as a function of $m(X_s)$. Both (a) and (b) show the same data, though the efficiency used in (a) is derived from the nonresonant model, while the efficiency in (b) comes from the model with a combination of resonances. The errors include bin-to-bin systematics; an additional systematic error of ~8% (not shown) is common to all points. (a) The open histogram represents the expectation from nonresonant $m(X_s)$ simulation. (b) The open histogram represents the expectation from a mixture of resonant modes with equal proportions. The hatched histogram results if some heavy resonances are enhanced.

only on the diagram of Figs. 1(a) and 1(b) for which $m(X_s)$ peaks near 1.4–1.5 GeV$/c^2$ [14].

Among the various theoretical conjectures to explain this production, an $\eta' gg$ coupling due to the QCD anomaly has been widely suggested as a likely explanation. However, the $\eta' gg$ form factor initially proposed [4] is disfavored by recent studies of the inclusive production $\Upsilon(1S) \to \eta' X$ [15,16]. A recently updated approach [6] exploiting the same η' gluon anomaly could in principle account for the observed branching fraction and the $m(X_s)$ spectrum.

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