## Study of high momentum $\eta^{\prime}$ production in $B \rightarrow \eta^{\prime} X_{s}$

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We measure the branching fraction for the charmless semi-inclusive process $B \rightarrow \eta^{\prime} X_{s}$, where the $\eta^{\prime}$ meson has a momentum in the range 2.0 to $2.7 \mathrm{GeV} / c$ in the $\Upsilon(4 S)$ center-of-mass frame and $X_{s}$ represents a system comprising a kaon and zero to four pions. We find $\mathcal{B}\left(B \rightarrow \eta^{\prime} X_{s}\right)=$
$(3.9 \pm 0.8($ stat $) \pm 0.5($ syst $) \pm 0.8($ model $)) \times 10^{-4}$. We also obtain the $X_{s}$ mass distribution and find that it tends to favor models predicting high masses.

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


FIG. 1: Lowest order diagrams for (a,b,c) $B \rightarrow \eta^{\prime} X_{s}$ and (d) the color-suppressed background $\bar{B}^{0} \rightarrow \eta^{\prime} D^{(*) 0}$.

The large $B \rightarrow \eta^{\prime} X_{s}$ branching fraction measured by the CLEO collaboration [3], prompted intense theoretical activity, which focused the special character of the $\eta^{\prime}$ meson as receiving much of its mass from the QCD anomaly.

A later measurement by CLEO confirmed the large $\eta^{\prime}$ production, measuring $\mathcal{B}\left(B \rightarrow \eta^{\prime} X_{n c}\right)=(4.6 \pm$ $1.1($ stat $) \pm 0.4($ syst $) \pm 0.5(\mathrm{bkg})) \times 10^{-4}$ [8], where $X_{n c}$ denotes a charmless recoiling hadronic system.
The rate for $B \rightarrow \eta^{\prime} X_{s}$ and especially the fully background-subtracted distribution of the mass of $X_{s}$ can provide important clues to the dynamics of weak decays and to the structure of the isosinglet pseudoscalar mesons.

We present results for the branching fraction $\mathcal{B}(B \rightarrow$ $\eta^{\prime} X_{s}$ ) and the mass spectrum of $X_{s}$. The signal is analyzed for $\eta^{\prime}$ momentumbetween 2.0 and $2.7 \mathrm{GeV} / c$ in the CM to suppress background coming from $b \rightarrow c \rightarrow \eta^{\prime}$ cascades such as $B \rightarrow D_{s} X$ with $D_{s} \rightarrow \eta^{\prime} X, B \rightarrow D X$ with $D \rightarrow \eta^{\prime} X, B \rightarrow \Lambda_{c} X$ with $\Lambda_{c} \rightarrow \eta^{\prime} X$. Our analysis is based on data collected with the BABAR detector [9] at the PEP-II asymmetric $e^{+} e^{-}$collider located at the Stanford Linear Accelerator Center. An integrated luminosity of $81.4 \mathrm{fb}^{-1}$, corresponding to 88.4 million $B \bar{B}$ pairs, was recorded at the $\Upsilon(4 S)$ resonance (on-resonance) and 9.6
$\mathrm{fb}^{-1}$ were recorded 40 MeV below this resonance (offresonance), 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 $\operatorname{CsI}(\mathrm{Tl})$ electromagnetic calorimeter. Charged-particle identification is provided by the average energy loss $(d E / d x)$ in the tracking devices, and by an internally reflecting ring-imaging Cherenkov detector covering the central region.

We select $B \bar{B}$ events by requiring at least four charged tracks and a value of the ratio of the second to zeroth Fox-Wolfram moment 10] less than 0.5.

We form a $B$ candidate by combining an $\eta^{\prime} \rightarrow \eta \pi^{+} \pi^{-}$, where the $\eta$ decays into $\gamma \gamma$, with a $K^{+}$or a $K_{S}^{0}$ that is reconstructed in the $\pi^{+} \pi^{-}$channel, and up to four pions, of which at most one is a $\pi^{0}$, leading to 16 possible channels 11]:

$$
\begin{array}{ll}
B^{+} \rightarrow \eta^{\prime} K^{+}\left(+\pi^{0}\right) & B^{0} \rightarrow \eta^{\prime} K_{S}^{0}\left(+\pi^{0}\right) \\
B^{+} \rightarrow \eta^{\prime} K^{+} \pi^{+} \pi^{-}\left(+\pi^{0}\right) & B^{0} \rightarrow \eta^{\prime} K_{S}^{0} \pi^{+} \pi^{-}\left(+\pi^{0}\right) \\
B^{+} \rightarrow \eta^{\prime} K_{S}^{0} \pi^{+}\left(+\pi^{0}\right) & B^{0} \rightarrow \eta^{\prime} K^{+} \pi^{-}\left(+\pi^{0}\right) \\
B^{+} \rightarrow \eta^{\prime} K_{S}^{0} \pi^{+} \pi^{+} \pi^{-}\left(+\pi^{0}\right) & B^{0} \rightarrow \eta^{\prime} K^{+} \pi^{-} \pi^{+} \pi^{-}\left(+\pi^{0}\right)
\end{array}
$$

The mass of the $\eta \rightarrow \gamma \gamma, K_{S}^{0} \rightarrow \pi^{+} \pi^{-}$and $\pi^{0} \rightarrow \gamma \gamma$ candidates are required to lie within $3 \sigma$ ( $\sigma=16,3$ and $6 \mathrm{MeV} / c^{2}$ 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 $K_{S}^{0}$ or a track consistent with a charged kaon. The charged-kaon selection has been optimized to reduce background from $B \rightarrow \eta^{\prime} \pi, \eta^{\prime} \rho$, and $\eta^{\prime} a_{1}$ decays. For the $K_{S}^{0}$, we require the angle $\alpha$ between the momentum of the $K_{S}^{0}$ candidate and its flight direction to be less than 0.05 radians, as it peaks at zero for true $K_{S}^{0}$ particles.

We require candidates for $B \rightarrow \eta^{\prime} X_{s}$ to be consistent with a $B$ decay, based on the beam-energy-substituted mass, $m_{\mathrm{ES}}=\sqrt{\left(s / 2+\mathbf{p}_{0} \cdot \mathbf{p}_{B}\right)^{2} / E_{0}^{2}-\mathbf{p}_{B}^{2}}$ and the energy 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 $\Upsilon(4 S)$ and the $B$ candidate, respectively, the asterisk denotes the $\Upsilon(4 S)$ rest frame, and $\sqrt{s}$ is the $e^{+} e^{-}$center-of-mass energy. 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 center-of-mass frame $\left(\cos \theta_{T}^{*}\right)$ is used to remove continuum background, which is peaked near $\left|\cos \theta_{T}^{*}\right|=1$, while signal events are uniformly distributed. We require $m_{\mathrm{ES}}>5.265 \mathrm{GeV} / c^{2}$, $|\Delta E|<0.1 \mathrm{GeV}$, and $\left|\cos \theta_{T}^{*}\right|<0.8$. For each event, we select the candidate with the smallest $\chi^{2}$, with $\chi^{2}$ defined by


FIG. 2: Fits to the $\eta \pi \pi$ invariant mass for on-resonance (top) and off-resonance (bottom) data samples, for the modes (a,b) $K^{ \pm}$and (c,d) $K_{S}^{0}$.

$$
\chi^{2}=\left(m_{\mathrm{ES}}-M_{B}\right)^{2} / \sigma^{2}\left(m_{\mathrm{ES}}\right)+(\Delta E)^{2} / \sigma^{2}(\Delta E)
$$

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

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

To determine efficiencies, we model the signal using a combination of the two-body mode $B \rightarrow \eta^{\prime} K$ and, for $X_{s}$ masses above the $K \pi$ threshold, a non-resonant derived from the theoretical predictions [4, [5, [6], which are based on the anomalous $\eta^{\prime}$-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 $15 \%$ [13, 14]. 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 $\mathcal{B}\left(K_{S}^{0} \rightarrow \pi^{+} \pi^{-}\right)$.

The branching fraction of $B \rightarrow \eta^{\prime} X_{s}$ is computed through a fit to the number of $\eta^{\prime}$ signal events, with $\eta^{\prime}$ momentum between 2.0 and $2.7 \mathrm{GeV} / c$, both for onresonance and off-resonance data. To parameterize the background, we use a Gaussian function for the signal and a second order polynomial. For the fit of the offresonance data sample, we constrain the mass and width of the $\eta^{\prime}$ 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 【
The semi-inclusive branching fraction is computed by

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

|  | $K^{ \pm}$modes | $K_{S}^{0}$ modes |
| :--- | :---: | :---: |
| $Y_{\mathrm{ON}}$ | $577.0 \pm 34.0$ | $367.0 \pm 34.0$ |
| $Y_{\mathrm{OFF}}$ | $18.9 \pm 8.5$ | $21.7 \pm 8.4$ |
| $Y_{\mathrm{CS}}$ | $63.6 \pm 11.4$ | $26.9 \pm 4.5$ |
| $Y$ | $353.1 \pm 80.5$ | $156.1 \pm 79.1$ |

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 |
| $\eta, \pi^{0}$ detection | 7.0 | 8.2 |
| $K / K_{S}^{0}$ ID | 2.5 | 4.3 |
| $\mathcal{B}\left(\eta^{\prime} \rightarrow \eta_{\gamma \gamma} \pi \pi\right)$ | 3.4 | 3.4 |
| $N_{B \bar{B}}$ | 1.1 | 1.1 |
| MC sample size | 3.0 | 3.0 |
| $\eta^{\prime} D^{(*) 0}$ subtraction | 3.0 | 2.9 |
| Total | 12.1 | 13.5 |
| Model | 20 | 20 |

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 $\eta^{\prime}$ and $\eta$ branching fractions to the channel we observe. For the $K_{S}^{0}$ modes, we convert the result so it corresponds to $K^{0}$ and $\bar{K}^{0}$. The final state $X_{s}$ includes both $K^{+}$- and $K^{0}$-tagged decays. Assuming that their branching fractions are equal, we obtain $\mathcal{B}\left(B \rightarrow \eta^{\prime} X_{s}\right)=(3.9 \pm 0.8$ (stat) $\pm 0.5$ (syst) $\pm$ $0.8($ model $)) \times 10^{-4}$. We obtain the systematic error by combining the sources listed in Table $\llbracket$

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: $\eta^{\prime} K, \eta^{\prime} K^{*}(892), \eta^{\prime} K_{1}(1270), \eta^{\prime} K_{1}(1400)$, $\eta^{\prime} K^{*}(1410), \eta^{\prime} K_{2}^{*}(1430), \eta^{\prime} K_{3}^{*}(1780)$, and $\eta^{\prime} K_{4}^{*}(2045)$. The variability of the efficiency 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 $\pi^{0} \rightarrow \gamma \gamma, \eta \rightarrow \gamma \gamma$, and $K_{S}^{0} \rightarrow \pi^{+} \pi^{-}$candidates, charged-kaon identification efficiency, secondary branching fractions, number of $B \bar{B}$ events $\left(N_{B} \bar{B}\right)$, the size of our Monte-Carlo sample, and subtraction of the background from $\bar{B}^{0} \rightarrow \eta^{\prime} D^{(*) 0}$.

To explore the $X_{s}$ mass distribution, we select $B$ candidates for which the mass of the $\eta^{\prime}$ is within three standard deviations of the known value, and subtract the continuum contribution by using on-resonance data in the sideband $5.200<m_{\mathrm{ES}}<5.265 \mathrm{GeV} / c^{2}$. The contin-


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


FIG. 4: Variation of efficiency with $m\left(X_{s}\right)$. The filled circles indicate the efficiency for non-resonant $X_{s}$ simulation. The other symbols denote the values for the resonances.
uum background scaling factor $(\mathcal{A})$, from the sideband to signal regions, is computed from off-resonance data to be $0.591 \pm 0.118$. The resulting mass distributions are shown in Fig. 3 for all $B$ modes and separately for the $B^{0}$ modes. The peak at $m\left(X_{s}\right) \simeq 500 \mathrm{MeV} / c^{2}$ corresponds to the two body mode $B \rightarrow \eta^{\prime} K$.

To obtain the full $X_{s}$ spectrum, we fit the $\eta^{\prime}$ mass distribution in bins of $X_{s}$ mass. The efficiency, averaged over the charged and neutral kaons, as a function of $m\left(X_{s}\right)$, 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 $m\left(X_{s}\right)<1.5 \mathrm{GeV} / c^{2}\left(m\left(X_{s}\right)>1.5 \mathrm{GeV} / c^{2}\right)$. For correctly reconstructed events, the experimental resolution varies from 5 to $15 \mathrm{MeV} / c^{2}$ for low and high masses, respectively. In the case of misreconstructed events, the resolution ranges from 100 to $150 \mathrm{MeV} / c^{2}$. 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

TABLE III: Fitted yields for on-resonance data and colorsuppressed background for different $m\left(X_{s}\right)$ ranges in $\mathrm{GeV} / c^{2}$. The sideband yields ( $Y_{S B}$ ) must be corrected by the sideband to signal region scaling factor (see text) before subtraction.

| $m\left(X_{s}\right)$ range | $Y_{O N}$ | $Y_{S B}$ | $Y_{C S}$ | $Y$ |
| :---: | :---: | :---: | :---: | :---: |
| $[0.4,0.6]$ | $200 \pm 15$ | $46.1 \pm 8.8$ | - | $172.8 \pm 15.9$ |
| $[0.6,1.2]$ | $120 \pm 14$ | $100 \pm 13$ | - | $60.9 \pm 16.0$ |
| $[1.2,1.5]$ | $114 \pm 15$ | $112 \pm 14$ | $1.1 \pm 0.3$ | $46.7 \pm 17.1$ |
| $[1.5,1.8]$ | $150 \pm 18$ | $163 \pm 17$ | $7.7 \pm 1.6$ | $46.0 \pm 20.7$ |
| $[1.8,2.0]$ | $140 \pm 17$ | $93 \pm 15$ | $47.4 \pm 9.6$ | $37.6 \pm 21.4$ |
| $[2.0,2.3]$ | $149 \pm 20$ | $142 \pm 18$ | $26.2 \pm 4.5$ | $38.9 \pm 23.1$ |
| $[2.3,2.5]$ | $80 \pm 14$ | $70 \pm 14$ | $4.9 \pm 0.9$ | $33.7 \pm 16.3$ |



FIG. 5: Branching fractions as a function of $m\left(X_{s}\right)$. Both (a) and (b) show the same data, though the efficiency used in (a) is derived from the non-resonant model, while that in (b) the efficiency comes from the model with a combination of resonances. The errors include bin-to-bin systematics; an additional systematic error of $\sim 8 \%$ (not shown) is common to all points. (a) The open histogram represents the expectation from non-resonant $m\left(X_{s}\right)$ 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. The equal mixture provides a good approximation to what is predicted in 12].
of $m\left(X_{s}\right)$.
The branching fraction as a function of $m\left(X_{s}\right)$, obtained from the fully background-subtracted yield (Table III), is shown in Fig. 5

We compare data and simulation by forming a $\chi^{2}$ difference. The $\chi^{2}$ 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 $2 \%$.

As a consistency check of the method, we measure the two-body decay modes $\left(X_{s}=K^{ \pm}, K_{S}^{0}\right)$, and find $171.0 \pm$ 14.0 and $27.1 \pm 5.6$ events in on-resonance data for $\eta^{\prime} K^{ \pm}$ and $\eta^{\prime} K_{S}^{0}$ respectively, and no $\eta^{\prime}$ signal events for both channels in off-resonance data, leading to the branching fractions $\mathcal{B}\left(B^{ \pm} \rightarrow \eta^{\prime} K^{ \pm}\right)=(6.9 \pm 0.6($ stat $)) \times 10^{-5}$ and $\mathcal{B}\left(B^{0} \rightarrow \eta^{\prime} K^{0}\right)=(5.6 \pm 1.2($ stat $)) \times 10^{-5}$. These values
are fully compatible with what has been measured by recent exclusive analyses 13, 14].

In summary, we have measured the branching fraction, $\mathcal{B}\left(B \rightarrow \eta^{\prime} X_{s}\right)=(3.9 \pm 0.8($ stat $) \pm 0.5($ syst $) \pm 0.8($ model $)) \times$ $10^{-4}$, for $2.0<p^{*}\left(\eta^{\prime}\right)<2.7 \mathrm{GeV} / c$. We have also derived the $m\left(X_{s}\right)$ spectrum and found that the data tends to confirm models predicting a peak at high masses and seems to disfavor predictions based only on the diagram of Fig. [1 $\mathrm{a}, \mathrm{b})$ for which $m\left(X_{s}\right)$ peaks near 1.4-1.5 GeV/c $c^{2}$ 12.

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

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