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We report the first observation of $B \to \eta' X$ transitions with high momentum η' mesons. We observe 39.0 ± 11.6 B decay events with $2.0 < p_{\eta'} < 2.7$ GeV/c, the high momentum region where background from $b \to c$ processes is suppressed. We discuss the physical interpretation of the signal, including the possibility that it is due to $b \to sg^*$ transitions. Given that interpretation, we find $\mathcal{B}(B \to \eta' X_s) = [6.2 \pm 1.6(\text{stat}) \pm 1.3(\text{syst})^{+0.0}_{-1.5}(\text{bkg})] \times 10^{-4}$ for $2.0 < p_{\eta'} < 2.7$ GeV/c. [S0031-9007(98)06978-6]

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Effective flavor changing neutral current decays of the type $b \to sg^*$, gluonic penguins, are likely to be important in future studies of CP violation. These decay modes will be used to search for direct CP violation which arises from the interference of the W-tree diagram and the gluonic penguin. Gluonic penguins could also complicate the interpretation of some measurements of indirect CP violation induced by B-$\overline{B}$ mixing [1]. CLEO has reported the observation of signals in $\overline{B}^0 \to K^- \pi^+$ [2] and $B^- \to K^- \eta'$ [3], exclusive modes which are expected to be dominated by the gluonic penguin amplitude. The inclusive decay $B \to \eta' X$, where the collection of particles X contains a single s quark, is another signature of $b \to sg^*$ (followed by $g^* \to u\overline{u}$, $d\overline{d}$, or $s\overline{s}$). Here we report the observation of the inclusive process $B \to \eta' X$ and examine these data for evidence of $b \to sg^*$.

The data sample used in this analysis was collected with the CLEO II detector at the Cornell Electron Storage Ring. This detector is designed to measure charged particles and photons with high efficiency and precision [4]. The data sample has an integrated luminosity of 3.1 fb^{-1} and contains 3.3×10^6 $B\overline{B}$ pairs. Another data sample with an integrated luminosity of 1.6 fb^{-1} was taken at an energy 60 MeV below the $\Upsilon(4S)$ resonance and is used to subtract the continuum background.

To isolate the signal and reduce the large background from continuum production of η' mesons, we apply the B reconstruction technique that was previously used to isolate an inclusive signal for $b \to s\gamma$ [5]. This technique selects $B \to \eta' X$ events in which the decay products of X include a charged kaon candidate in order to enhance the probability of observing $b \to sg^*$.

We search for η''s with momenta in the range $2.0 < p < 2.7$ GeV/c, beyond the kinematic limit for most $b \to c$ decays. This range corresponds to a region in X mass from zero to 2.5 GeV. In this momentum range we should be sensitive to $b \to sg^*$. However, $b \to u$ decays with η' mesons, such as $B^- \to \pi^- \eta'$, and color-suppressed $b \to c$ decays, such as $\overline{B}^0 \to D^0 \eta'$, also populate this interval. Methods for discriminating among these possibilities will be discussed later.

Events are selected using standard criteria for hadronic final states. Candidate η' mesons are reconstructed in the $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$ mode. For each η candidate, the $\gamma\gamma$ invariant mass must be within 30 meV of the nominal η mass. The η candidate is kinematically constrained to the η mass and then combined with the charged pions to form the η' candidate.

We then form combinations of a charged kaon, an η', and n pions where $n \le 4$ (at most one of these pions is allowed to be neutral). Eight decay modes and their charge conjugates are considered: $B^- \to K^- \eta'$, $\overline{B}^0 \to K^- \eta' \pi^+$, $B^- \to K^- \eta' \pi^0$, $B^- \to K^- \eta' \pi^- \pi^+$, $\overline{B}^0 \to K^- \eta' \pi^+ \pi^0$, $\overline{B}^0 \to K^- \eta' \pi^+ \pi^- \pi^+$, $B^- \to K^- \eta' \pi^+ \pi^- \pi^0$, and $\overline{B}^0 \to K^- \eta' \pi^+ \pi^- \pi^+ \pi^0$. For the charged kaon candidate we require that dE/dx be within three standard deviations of the expected value. These combinations must be consistent in beam-constrained mass (M_B) and energy difference ($\Delta E = E_{\text{observed}} - E_{\text{beam}}$) with a B meson. (Here M_B denotes the invariant mass with the energy constrained to the beam energy.) We require $|\Delta E| < 0.1$ GeV and $M_B > 5.275$ GeV. In case of ambiguous hypotheses we choose the best candidate in each event on the basis of a χ^2 formed from M_B and ΔE.

Following Ref. [5], we suppress the jetlike continuum relative to the spherical $B\overline{B}$ events with requirements on R_2 (the ratio of second to zeroth Fox-Wolfram moments) and θ_S (the angle between the sphericity axis of the B candidate and the sphericity axis of the remainder of the event). R_2 is large for jetlike events and small for

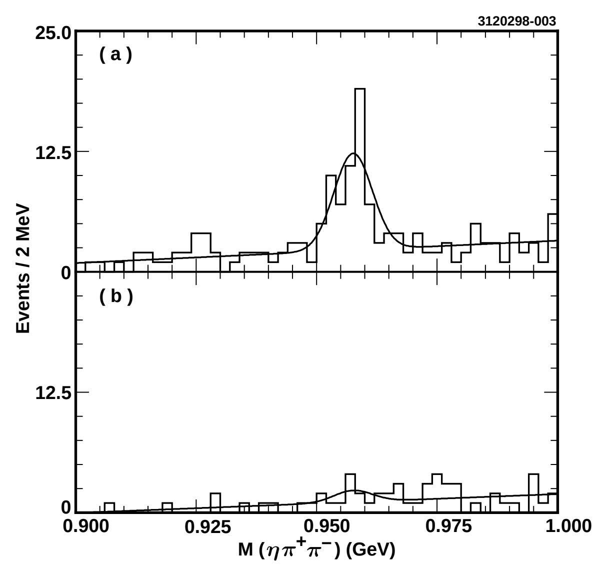

FIG. 1. The distribution of $\eta\pi^+\pi^-$ mass for (a) on-resonance data and (b) below-resonance data.

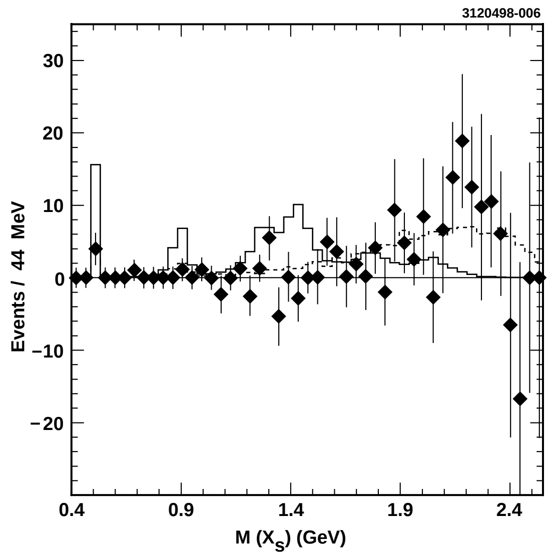

FIG. 2. The continuum-subtracted $M(X_s)$ distribution (points with error bars) with expected $M(X_s)$ distributions for a mixture of two-body $b \to sq\overline{q}$ (solid) and three-body $b \to sg^*$ with $g^* \to g\eta'$ simulated using JETSET (dashed). The data points have been corrected for the $M(X_s)$ dependent efficiency. Each simulation has been normalized to the data yield.

spherical events. The variable $\cos\theta_S$ is isotropic for signal events and peaks near $\cos\theta_S = \pm 1$ for continuum. We require $R_2 < 0.45$ and $|\cos\theta_S| < 0.6$.

The $\eta\pi^+\pi^-$ mass spectrum in the high momentum window $2.0 < p_{\eta'} < 2.7$ GeV$/c$ for the on-resonance and off-resonance samples is shown in Fig. 1. A fit to the η' peak finds 50.7 ± 8.6 events on the $\Upsilon(4S)$ resonance and 6.1 ± 4.1 off-resonance (unscaled). After accounting for the differences in luminosity of the two samples, this gives an excess of 39.0 ± 11.6 events. Other ways of determining the yield give consistent results. We estimate a systematic error of 3% from the uncertainty in the fitting procedure.

We now study the invariant mass spectrum $M(X_s)$ of the particles recoiling against the η'. The continuum-subtracted $M(X_s)$ distribution is shown in Fig. 2 and tabulated in Table I. The peak at the kaon mass due to the exclusive decay mode $B^- \to \eta' K^-$ [3] accounts for about 10% of the inclusive yield. There is no significant excess in the K^* mass region. The remainder of the yield comes from events with X_s mass near or above charm threshold. Five sources can contribute to this distribution: η' from secondary decays $b \to c$, $c \to \eta'$; color-allowed $b \to c$; color-suppressed $b \to c$; $b \to u$; and $b \to sg^*$.

TABLE I. Yield in $M(X_s)$ bins for $B \to \eta' X_s$. The off-resonance yields must be scaled by 1.908 to account for differences in energy and luminosity. The detection efficiency drops as $M(X_s)$ approaches 2.5 GeV because of the η' momentum cut.

$M(X_s)$ (GeV)	N (on)	N (off)	Yield
$0.4 < M(X_s) < 0.6$	4	0	4 ± 2
$0.6 < M(X_s) < 1.2$	2.7 ± 2.1	0.6 ± 1.1	1.6 ± 2.9
$1.2 < M(X_s) < 1.8$	18.0 ± 4.9	6.6 ± 3.2	5.4 ± 7.6
$1.8 < M(X_s) < 2.5$	26.0 ± 6.4	-0.8 ± 2.3	27.5 ± 7.8

Secondary decays have been reliably simulated with the Monte Carlo program. These include processes such as $\overline{B}^0 \to D^+\pi^-$, $D^+ \to \eta'\pi^+$ and $\overline{B}^0 \to D_s^- D^+$, $D_s^- \to \pi^-\eta'$. The yield from secondary sources is thus estimated to be less than 0.2 events.

We have also considered the possibility of color-allowed $b \to c$ backgrounds such as $B \to D\eta'\pi$. We have searched for this decay in a lower η' momentum range, modeling the decay with three-body phase space. This search gives an upper limit of $\mathcal{B}(B \to D\eta'\pi) < 1.3 \times 10^{-3}$, corresponding to a background of fewer than 1.4 events in the signal region. Thus, neither secondary decays nor color-allowed $b \to c$ decays are a significant source of the high momentum η' signal.

We next consider $b \to u$ modes. First, we check for the presence of an s quark in the final state by forming a χ^2 difference based on ΔE and the resolution-normalized dE/dx residual for the candidate kaon. The ΔE distribution for $b \to u$ modes is shifted above that for $b \to s$ modes because the kaon mass is attributed to a pion. A fit to this χ^2 difference, using $B \to \eta'\pi$, $\eta'\rho$, $\eta' a_1$ for the $b \to u$ contribution and a model of $b \to sg^*$ for the $b \to s$ contribution, gives the yields $f(b \to sg^*) = (82 \pm 20)\%$ and $f(b \to u) = (18 \pm 20)\%$.

Further information on $b \to u$ comes from the $M(X_s)$ distribution. The dominant $b \to u$ modes with an η' are expected to have X_s mass below 1.8 GeV, where we see no strong evidence for a signal. The theoretical expectation for $b \to u$ [6] from an inclusive calculation [6], or from a sum of the dominant exclusive modes [7], is (3.5–7.0)% of the signal yield. The contribution with $M(X_s) > 1.8$ GeV and $2.0 < p_{\eta'} < 2.7$ GeV is likely to be much smaller.

Experimental searches for the color-suppressed $b \to c$ modes $\overline{B}^0 \to D^{(*)}\eta'$ [8,9], while showing no evidence for them, place unrestrictive upper limits. Theoretical expectations for the branching fractions for these modes are in the range $(1.5–6.0) \times 10^{-5}$ [10], implying a yield of high momentum η' of (2.1–8.6)% of the observed yield.

To search for these modes in the data, we examine the $M(X_s)$ distribution for neutral modes. The mode $\overline{B}^0 \to D^0\eta'$ has a spike at the D^0 mass, while that for $\overline{B}^0 \to D^{*0}\eta'$ has a broader peak at the D^{*0} mass as shown in Fig. 3. This distribution limits the contribution of $\overline{B}^0 \to D^0\eta'$ to 15% of the signal.

Information about $\overline{B}^0 \to D^{*0}\eta'$ comes from the mass distribution obtained by removing a single pion (charged or neutral) from the X_s system, such that the remaining particles are consistent with coming from a D^0 decay. $\overline{B}^0 \to D^{*0}\eta'$ peaks sharply at the D mass in this distribution as shown in Fig. 4. The absence of such a peak in the data limits $\overline{B}^0 \to D^{*0}\eta'$ to 26% of the signal. The limits on $D^0\eta'$ and $D^{*0}\eta'$ constrain the total contribution

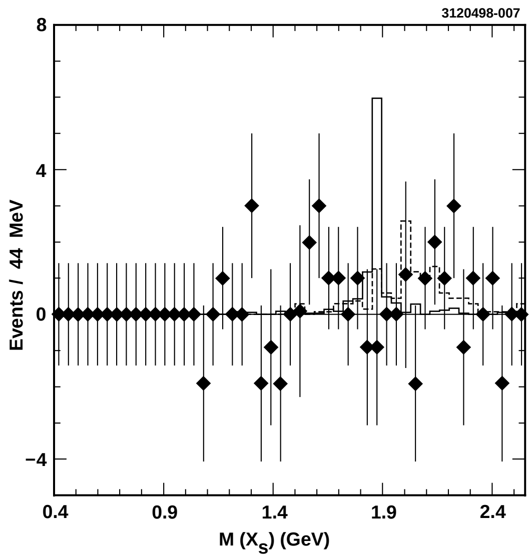

FIG. 3. The continuum-subtracted distribution of X_s mass for neutral modes with the expectations from $\overline{B}^0 \to D^0\eta'$ (solid) and $\overline{B}^0 \to D^{*0}\eta'$ (dashed) superimposed. The simulation has been normalized to the data yield.

of color-suppressed decay to be less than 41% of the signal.

We have also tried to describe the data in Fig. 2 with a combination of $\overline{B}^0 \to D^0\eta'$, $\overline{B}^0 \to D^{*0}\eta'$, and $\overline{B}^0 \to D^{**}(2.2)\eta'$ [$D^{**}(2.2)$ being a hypothetical broad state decaying into $D\pi$ and $D^*\pi$], and have found no combination with a confidence level above 2.7%. We conclude that while these modes could contribute to our signal, they are unlikely to account for it fully.

Finally, we consider $b \to sg^*$. Conventional $b \to sq\overline{q}$ operators predict an X_s mass distribution that peaks near 1.5 GeV. This description fits the $M(X_s)$ spectrum poorly

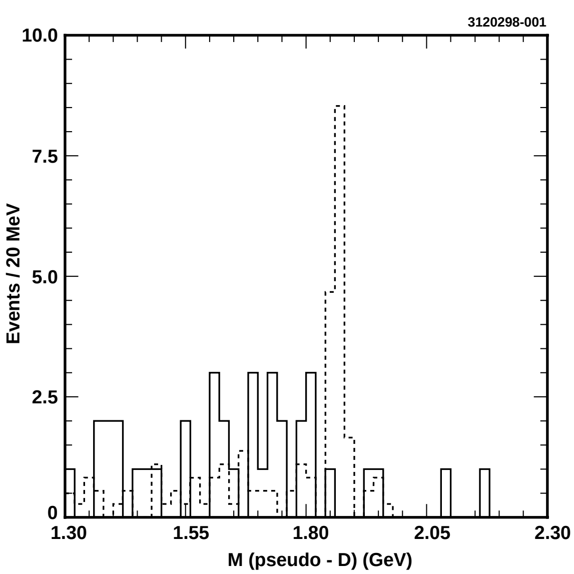

FIG. 4. The continuum-subtracted distribution of pseudo-D mass (solid) with the expectation from $\overline{B}^0 \to D^{*0}\eta'$ (dashed). The simulation has been normalized to the data yield.

(1% C.L.). However, the process $b \to sg^*$ with $g^* \to g\eta'$ from the QCD anomaly, which has the attractive feature that it accounts for the large mass of the η' relative to other members of its SU(3) multiplet, gives a three-body $gs\overline{q}$ mass spectrum that peaks above 2 GeV [6,11–14] as shown in Fig. 2. A fit of this model to the data gives a C.L. in the (25–72)% range.

In what follows, we shall compute the $B \to X_s\eta'$ branching fraction assuming that it is due to $b \to sg^*$, and allow for a background from $D^{[*(*)]}\eta'$ assuming that these decays occur at rates consistent with standard expectations.

The detection efficiency for $b \to sg^*$ and for the color-suppressed $b \to c$ decays are listed in Table II. We observe that the efficiency for the $b \to c$ decay mechanisms is half that for $b \to sg^*$, so the computed $B \to X_s\eta'$ branching fraction depends on our assumption that the signal is $b \to sg^*$. The $b \to sg^*$ decays are modeled by allowing the JETSET Monte Carlo to hadronize the s quark and gluon. We also generate a number of exclusive $b \to sg^*$ decay modes. The average efficiency for exclusive modes with equal weights is equal to the JETSET efficiency. The detection efficiency is averaged over B^0 and B^+ mesons and corrects for unobserved modes with K^0 mesons but does not include η' branching fractions. To determine the uncertainty in efficiency due to the modeling of the signal, we vary the relative weights of different modes (increasing the fractions of $K_3^*\eta'$ and $K_4^*\eta'$ to 50%); this leads to a systematic error of 16%. No attempt has been made to calculate the branching fraction for decays that lie outside the η' momentum window, as such a calculation would be extremely model dependent.

The dominant source of experimental systematic error is due to the modeling of the X_s system [15]. Other sources include the choice of background parametrization and the uncertainty in the tracking and photon detection. We have also included a second systematic error for the

TABLE II. Detection efficiency for $B \to \eta' X_s$ modes.

Mode	ϵ
$B \to K\eta'$	0.076 ± 0.006
$B \to K^*(892)\eta'$	0.058 ± 0.005
$B \to K_1(1270)\eta'$	0.050 ± 0.005
$B \to K_1^*(1406)\eta'$	0.053 ± 0.005
$B \to K_2^*(1429)\eta'$	0.051 ± 0.005
$B \to K_3^*(1774)\eta'$	0.046 ± 0.005
$B \to K_4^*(2200)\eta'$	0.046 ± 0.005
$B \to D^0\eta'$	0.025 ± 0.002
$B \to D^{*0}\eta'$	0.026 ± 0.002
$B \to D(2.2)\eta'$	0.011 ± 0.003
Equal mixture of exclusive $b \to sg^*$ modes	0.055 ± 0.003
$B \to \eta' s\overline{d}$, $\eta' s\overline{u}$ (JETSET hadronization)	0.055 ± 0.003

possible contribution of color-suppressed $b \rightarrow c$ modes. This is determined by using the largest model prediction for these modes and taking into account their lower acceptance. The theoretical predictions are multiplied by 1.5 as an estimate of the theoretical uncertainty. Assuming an average detection efficiency of 5.5%, appropriate for $b \rightarrow sg^*$, we obtain $\mathcal{B}(B \rightarrow \eta' X_s) = [6.2 \pm 1.6(\text{stat}) \pm 1.3(\text{syst})^{+0.0}_{-1.5}(\text{bkg})] \times 10^{-4}$ for $2.0 < p_{\eta'} < 2.7$ GeV/c.

A number of interpretations have been proposed to account for the large branching fraction of $B \rightarrow \eta' X_s$. These include (1) conventional $b \rightarrow sq\overline{q}$ operators with constructive interference between the $u\overline{u}$, $d\overline{d}$, and $s\overline{s}$ components of the η' [16,17], (II) $b \rightarrow c\overline{c}s$ decays enhanced by $c\overline{c}$ content in the η' wave function [18,19], and (III) $b \rightarrow sg^*$, $g^* \rightarrow g\eta'$ from the η' QCD anomaly [6,11–14]. The observed branching fraction is larger than what is expected from scenario I. Furthermore, scenarios I and II will give an X_s mass distribution peaked near 1.5 GeV. Only scenario III gives a three-body $gs\overline{q}\ X_s$ mass spectrum that peaks above 2 GeV.

We have also searched for high momentum $B \rightarrow \eta X_s$ decays, with $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^-\pi^+\pi^0$ and $2.1 < p_\eta < 2.7$ GeV. In the $\eta \rightarrow \gamma\gamma$ mode, we find a yield of 54 ± 26 events. In the $\eta \rightarrow \pi^-\pi^+\pi^0$ mode, we observe an excess of 4.9 ± 16.5 events. The limit obtained by combining the two η decay modes and allowing for systematic uncertainty is $\mathcal{B}(B \rightarrow \eta X_s) < 4.4 \times 10^{-4}$. The theoretical expectation is that this rate will be suppressed relative to $B \rightarrow \eta' X_s$ by $\tan^2 \theta_P$ ($\sim$0.1) [6,11] where θ_P is the pseudoscalar mixing angle, which is consistent with our result.

In summary, we have observed a signal of 39.0 ± 11.6 events in high momentum $B \rightarrow \eta' X_s$ production. The interpretation $b \rightarrow sg^*$ is consistent with all features in the data. Given that interpretation, the branching fraction is $\mathcal{B}(B \rightarrow \eta' X_s) = [6.2 \pm 1.6(\text{stat}) \pm 1.3(\text{syst})^{+0.0}_{-1.5}(\text{bkg})] \times 10^{-4}$ for $2.0 < p_{\eta'} < 2.7$ GeV/c.

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