Observation of High Momentum $\eta'$ Production in $B$ Decays

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Browder, T.E.; Bloom, Kenneth A.; and Collaboration, CLEO, "Observation of High Momentum $\eta'$ Production in $B$ Decays" (1998). *Kenneth Bloom Publications*. 138.  
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Observation of High Momentum $\gamma'$ Production in $B$ Decays

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0031-9007/98/81(9)/1786(5)$15.00 © 1998 The American Physical Society
We report the first observation of $B \rightarrow \eta' X$ transitions with high momentum $\eta'$ mesons. We observe $39.0 \pm 11.6$ $B$ decay events with $2.0 < p_{\eta'} < 2.7$ GeV/c, the high momentum region where background from $b \rightarrow c$ processes is suppressed. We discuss the physical interpretation of the signal, including the possibility that it is due to $b \rightarrow s g^*$ transitions. Given that interpretation, we find $B(B \rightarrow \eta'X) = [6.2 \pm 1.6 \text{(stat)} \pm 1.3 \text{(syst)}^{-0.5}_{+0.6} \text{(bkg)}] \times 10^{-4}$ for $2.0 < p_{\eta'} < 2.7$ GeV/c.

PACS numbers: 13.25.Hw

Effective flavor changing neutral current decays of the type $b \rightarrow s g^*$, 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 $B \rightarrow \bar{B}$ mixing [1]. CLEO has reported the observation of signals in $\bar{B}^0 \rightarrow K^- \pi^+$ [2] and $B^- \rightarrow K^- \eta'$ [3], exclusive modes which are expected to be dominated by the gluonic penguin amplitude. The inclusive decay $B \rightarrow \eta'X$, where the collection of particles $X$ contains a single $s$ quark, is another signature of $b \rightarrow s g^*$ (followed by $g^* \rightarrow \gamma \pi\pi$, $d\bar{d}$, or $s\bar{s}$). Here we report the observation of the inclusive process $B \rightarrow \eta'X$ and examine these data for evidence of $b \rightarrow s g^*$.

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 $3.3 \times 10^6$ $B\bar{B}$ pairs. Another data sample with an integrated luminosity of 1.6 fb$^{-1}$ was taken at an energy 60 MeV below the $Y(4S)$ resonance and is used to subtract the continuum background.

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

We search for $\eta'$s with momenta in the range $2.0 < p < 2.7$ GeV/c, beyond the kinematic limit for most $b \rightarrow c$ 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 $b \rightarrow s g^*$. However, $b \rightarrow u$ decays with $\eta'$ mesons, such as $B^- \rightarrow \pi^- \eta'$, and color-suppressed $b \rightarrow c$ decays, such as $B^0 \rightarrow D^0 \eta'$, also populate this interval. Methods for discriminating among these possibilities will be discussed later.

To isolate the signal, we require $M_{\eta'\pi^+\pi^-} < 1.5$ GeV/c for events with requirements on $R_2$ (the ratio of second to zeroth Fox-Wolfram moments) and $\theta_S$ (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.](image)
spherical events. The variable \( \cos \theta_S \) is isotropic for signal events and peaks near \( \cos \theta_S = \pm 1 \) for continuum.

We require \( R_3 < 0.45 \) and \( |\cos \theta_S| < 0.6 \).

The \( \eta^+ \pi^- \) mass spectrum in the high momentum window \( 2.0 < p_{\eta^+} < 2.7 \text{ GeV/c} \) for the on-resonance and off-resonance samples is shown in Fig. 1. A fit to the \( \eta^i \) peak finds \( 50.7 \pm 8.6 \) events on the \( \Upsilon(4S) \) resonance and \( 6.1 \pm 4.1 \) off-resonance (unscaled). After accounting for the differences in luminosity of the two samples, this gives an excess of \( 39.0 \pm 11.6 \) 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 \( \eta^i \). 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 \( B^- \rightarrow \eta^i K^- \) [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: \( \eta^i \) from secondary decays \( b \rightarrow c, c \rightarrow \eta^i \); color-allowed \( b \rightarrow c \); color-suppressed \( b \rightarrow c \); \( b \rightarrow u \); and \( b \rightarrow s g^* \).

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

We have also considered the possibility of color-allowed \( b \rightarrow c \) backgrounds such as \( B \rightarrow D^0 \eta^i \). We have searched for this decay in a lower \( \eta^i \) momentum range, modeling the decay with three-body phase space. This search gives an upper limit of \( B(B \rightarrow D^0 \eta^i \pi^0) < 1.3 \times 10^{-3} \), corresponding to a background of fewer than 1.4 events in the signal region. Thus, neither secondary decays nor color-allowed \( b \rightarrow c \) decays are a significant source of the high momentum \( \eta^i \) signal.

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

Further information on \( b \rightarrow u \) comes from the \( M(X_s) \) distribution. The dominant \( b \rightarrow u \) modes with an \( \eta^i \) are expected to have \( X_s \) mass below 1.8 GeV, where we see no strong evidence for a signal. The theoretical expectation for \( b \rightarrow u \) [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 \( M(X_s) > 1.8 \text{ GeV} \) and \( 2.0 < p_{\eta^i} < 2.7 \text{ GeV} \) is likely to be much smaller.

Experimental searches for the color-suppressed \( b \rightarrow c \) modes \( \bar{B}^0 \rightarrow D^{(*)} \eta^i \) [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 \( (1.5–6.0) \times 10^{-3} \) [10], implying a yield of high momentum \( \eta^i \) 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 \( \bar{B}^0 \rightarrow D^0 \eta^i \) has a spike at the \( D^0 \) mass, while that for \( \bar{B}^0 \rightarrow D^{*0} \eta^i \) has a broader peak at the \( D^{*0} \) mass as shown in Fig. 3. This distribution limits the contribution of \( \bar{B}^0 \rightarrow D^0 \eta^i \) to 15% of the signal.

Information about \( \bar{B}^0 \rightarrow D^{*0} \eta^i \) 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. \( \bar{B}^0 \rightarrow D^{*0} \eta^i \) peaks sharply at the \( D^0 \) mass in this distribution as shown in Fig. 4. The absence of such a peak in the data limits \( \bar{B}^0 \rightarrow D^{*0} \eta^i \) to 26% of the signal. The limits on \( D^0 \eta^i \) and \( D^{*0} \eta^i \) constrain the total contribution.

**TABLE I.** Yield in \( M(X_s) \) bins for \( B \rightarrow \eta^i X_s \). 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 \( \eta^i \) 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 |
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 $\bar{B}^0 \to D^0 \eta'$, $B^0 \to D^{*0} \eta'$, and $\bar{B}^0 \to D^{*+}(2.2) \eta'$ [$D^{*+}(2.2)$ 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 $b \to s g^*$. Conventional $b \to s q \bar{q}$ operators predict an $X_s$ mass distribution that peaks near 1.5 GeV. This description fits the $M(X_s)$ spectrum poorly (1% C.L.). However, the process $b \to s g^*$ with $g^* \to g \eta'$ from the QCD anomaly, which has the attractive feature that it accounts for the large mass of the $\eta'$ relative to other members of its SU(3) multiplet, gives a three-body $g s \eta$ 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 $b \to s g^*$, and allow for a background from $D^{(*)0} \eta'$ assuming that these decays occur at rates consistent with standard expectations.

The detection efficiency for $b \to s g^*$ 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 $b \to s g^*$, so the computed $B \to X_s \eta'$ branching fraction depends on our assumption that the signal is $b \to s g^*$. The $b \to s g^*$ decays are modeled by allowing the JETSET Monte Carlo to hadronize the $s$ quark and gluon. We also generate a number of exclusive $b \to s g^*$ 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 $\eta'$ 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 $K^- \eta'$ and $K_0^* \eta'$ 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 $\eta'$ 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

| Mode                          | $\epsilon$    |
|-------------------------------|---------------|
| $B \to K \eta'$               | 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 |
| $B \to K_3^*(2200) \eta'$     | 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    |               |
| $b \to s g^*$ modes           | 0.055 ± 0.003 |
| $B \to \eta' s\bar{d}, \eta' s\bar{u}$ (JETSET hadronization) | 0.055 ± 0.003 |
possible contribution of color-suppressed $b \to c$ 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 $b \to s\eta^*$, we obtain $B(B \to \eta'X_c) = [6.2 \pm 1.6 \text{(stat)} \pm 1.3 \text{(syst)} \pm 0.2 \text{(bkg)}] \times 10^{-4}$ for $2.0 < p_{\eta'} < 2.7 \text{ GeV}/c$.

A number of interpretations have been proposed to account for the large branching fraction of $B \to \eta'X_c$. These include (1) conventional $b \to s\eta^*$ operators with constructive interference between the $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ components of the $\eta'$ [16,17], (II) $b \to c\pi\bar{s}$ decays enhanced by $c\bar{c}$ content in the $\eta'$ wave function [18,19], and (III) $b \to s\eta^*$, $g^* \to g\eta'$ from the $\eta'$ 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 $X_c$ mass distribution peaked near 1.5 GeV. Only scenario III gives a three-body $g\pi\pi X_c$ mass spectrum that peaks above 2 GeV.

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

In summary, we have observed a signal of $39.0 \pm 11.6$ events in high momentum $B \to \eta X_c$ production. The interpretation $b \to s\eta^*$ is consistent with all features in the data. Given that interpretation, the branching fraction is $B(B \to \eta'X_c) = [6.2 \pm 1.6 \text{(stat)} \pm 1.3 \text{(syst)} \pm 0.2 \text{(bkg)}] \times 10^{-4}$ for $2.0 < p_{\eta'} < 2.7 \text{ GeV}/c$.

We gratefully acknowledge the effort of the CESR staff. This work was supported by the National Science Foundation, the U.S. Department of Energy, Research Corporation, the Natural Sciences and Engineering Research Council of Canada, the A. P. Sloan Foundation, and the Swiss National Science Foundation.

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