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New Results on Rare Beauty Decays

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Abstract

We summarize new results on rare beauty decays from experiments at DORIS, LEP, and the Tevatron Collider. Charmless hadronic decays are observed at the 3.1 σ level by ARGUS, and at the 3.5 σ level by ALEPH, but no specific decay mode has been unambiguously identified. Upper limits on charmless hadronic decays of B_d, $B^\pm$, B_s, and Λ_b are given, as well as new limits on $B_s \to \phi\gamma$, $\Lambda_b \to \Lambda\gamma$, and $B^\pm \to \mu^+\mu^-K^\pm$.

1. Introduction

Beauty hadrons decay most of the time via the dominant $b \to cW^*$ quark transition. A great deal of experimental and theoretical work has been devoted to these decays, including, as an example, $B \to \bar{D}^*\ell\nu$. Much less is known experimentally about decay modes due to other, comparatively infrequent, quark transitions. These rare transitions (and some corresponding decay channels) include:‡

- $b \to uW^*$ ($b \to u$ transition; $B_d \to \pi^+\pi^-$; $B_s \to K^-\pi^+$; $\Lambda_b \to p\pi^-$)
- $b \to s\,gluon$ (hadronic "penguin" transition; $B_d \to K^+\pi^-$; $B_s \to K^+K^-$; $\Lambda_b \to pK^-$)
- $b \to d\,gluon$ (CKM-suppressed hadronic "penguin" transition; $B_d \to \pi^+\pi^-$; $B_s \to K^-\pi^+$; $\Lambda_b \to p\pi^-$)
- $b \to s\gamma$ (electromagnetic "penguin" transition; $B_s \to \phi\gamma$; $\Lambda_b \to \Lambda\gamma$)
- $b \to d\gamma$ (CKM-suppressed electromagnetic "penguin" transition; $B_s \to K^*\gamma$)
- $b \to s\ell^+\ell^-$ (flavor-changing neutral current transition; $B^+ \to \mu^+\mu^-K^+$)
- $b \to d\ell^+\ell^-$ (CKM-suppressed FCNC transition; $B^+ \to \mu^+\mu^-\pi^+$)

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‡ Throughout this report, charge-conjugate modes are also implied.

In this report, we will summarize some recent experimental results on most of the above-listed processes, as submitted to this conference by the ARGUS, ALEPH, DELPHI, OPAL, L3, and CDF Collaborations.

2. Charmless Hadronic Beauty Decays

Charmless hadronic B decays were first observed by the CLEO Collaboration [1]. They measured the branching ratio $BR(B_d \to \pi^+\pi^-, K^+\pi^-) = (2.4^{+0.8}_{-0.7} \pm 0.2) \times 10^{-5}$, but were unable to obtain statistically significant signals in the individual modes. New searches for charmless hadronic beauty decays at DORIS and LEP are reported in this section.

2.1. *Search for $b \to s\,gluon$ (ARGUS) [2]*

ARGUS has searched for charmless B decays that can arise from $b \to s\,gluon$ transitions. Their strategy was to use fully-reconstructed $\Upsilon(4S) \to B\bar{B}$ events.

The search was conducted in the channels $B \to (K^\pm, K^0_s)n\pi^\pm$, with $1 \le n \le 7$ (this B is called the "tagged" B). The decays considered for the second B in the event (the "tagging" B) were the semi-leptonic modes $B \to D^{(*)}\ell^-\bar{\nu}$, and the hadronic modes $B \to D^{(*)}\pi^-, D^{(*)}\rho^-$, and $D^{(*)}a_1^-$.

In a data sample of 209K $\Upsilon(4S)$ decays, 7 candidate

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events were found in the signal region. In five of these events, the decay products of the tagged B include a D or a ψ', consistent with a $b \to cW^*$ transition. In the remaining two candidate events, no charm or charmonium state was found in the decay products of the tagged B.

The continuum background, evaluated from data collected below the $\Upsilon(4S)$ resonance, is 0.03 ± 0.02 events. The probability for this background to fluctuate to the two observed events is 8×10^{-4}. The combinatorial background from $\Upsilon(4S)$ decays is less than 0.01 events. The overall background probability is therefore $\leq 9 \times 10^{-4}$, a $\approx 3.1\sigma$ effect.

One of the candidate events includes a decay consistent with the mode $B_d \to K^+\pi^-$. However, this decay is also consistent with the decay hypothesis $B_d \to \pi^+\pi^-$, with a probability of 8% relative to the $K^+\pi^-$ hypothesis. The second candidate event contains a possible decay $B^- \to K^-4\pi^\pm$, but, with approximately the same probability, this decay is also consistent with $B^- \to 5\pi^\pm$. We conclude that there is evidence, at the 3.1σ level, for charmless hadronic B decays. However, there is no significant separation between modes arising from $b \to s\,gluon$ transitions compared to $b \to d\,gluon$ or $b \to uW^*$ transitions.

This difficulty to unambiguously identify specific decay modes was already mentioned in connection with the original CLEO observation, and will arise again with the ALEPH results. However, particle identification in DELPHI (see section 2.2.2) illustrates a possible solution.

2.2. *Results from LEP*

All four LEP experiments have searched for charmless hadronic beauty decays, with B_d, B_u, B_s, and Λ_b all produced in $Z^0 \to b\bar{b}$ events. The number of charmless decays expected is limited: taking the CLEO branching ratio of 2.4×10^{-5} [1] for $BR(B_d \to \pi^+\pi^-, K^+K^-)$, the present LEP data sample of ≈ 1.6M $Z^0 \to hadrons$ events, and a typical reconstruction efficiency of 28%, we expect ~ 7 $B \to \pi^+\pi^-, K^+K^-$ decays produced with ~ 2 detected. Nonetheless, a number of features of the events at LEP make the search worthwhile, in ways which are complementary to the work at CLEO and ARGUS:

- The data from LEP can provide new information on B_s and Λ_b decays.
- The large boost of the b hadron in $Z^0 \to b\bar{b}$ events, combined with the precision measurement capability of silicon vertex detectors, provides the possibility for observing separated, well-identified decay vertices.
- In the events at LEP, there is very little overlap between the tracks from the b hadron decay and those from the $\bar{b}$ hadron decay.
- Particle id, particularly with the ring imaging Cherenkov detector (RICH) of the DELPHI experiment, will potentially allow unambiguous determination of the decay modes.

All these points will be illustrated below.

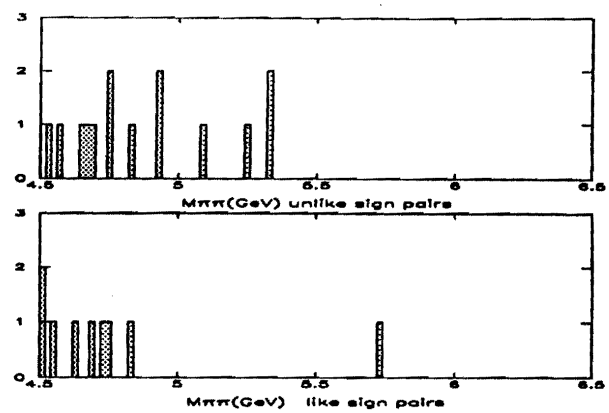

Figure 1. Invariant mass distribution for $B \to h^+h^-$ candidates in ALEPH, with each particle assigned the $\pi^\pm$ mass. Also shown is the corresponding distribution for like-sign pairs.

2.2.1. Results from ALEPH [3] ALEPH searched for charmless hadronic beauty decays in the channel with two oppositely-charged hadrons, h^+h^-. Particular use is made of the silicon vertex detector.

Background with one or two tracks originating from the primary vertex is suppressed by vertexing and momentum requirements. The background whereby the two tracks originate from a b hadron decay which includes charm is suppressed by demanding that the h^+h^- invariant mass be significantly above the kinematic limit for $b \to c$ decays (4.8 GeV/c^2 for b meson decays and 5.0 GeV/c^2 for b baryon decays, taking each hadron to have the $\pi^\pm$ mass).

In a data sample of 1.6M $Z^0 \to hadrons$ events, three $B \to h^+h^-$ candidates in the signal region are found, as shown in figure 1. Also shown is the corresponding distribution for like-sign pairs, with one candidate found. The efficiency for this search is about 28%, and the mass resolution is ≈ 40 MeV/c^2.

From Monte Carlo studies, we expect 0.07 ± 0.04 background events to populate the h^+h^- signal region. The corresponding binomial probability to observe three or more background events in the data is 1.8×10^{-4}. We conclude that charmless hadronic beauty decays have been observed in ALEPH with a statistical significance of 3.5σ.

One of these events is shown in figure 2. The h^+h^- has a $\pi^+\pi^-$ mass of 5.34 ± 0.05 GeV/c^2, a momentum of 40 GeV/c, and a decay length of 0.95 cm, with a decay length significance of 73σ.

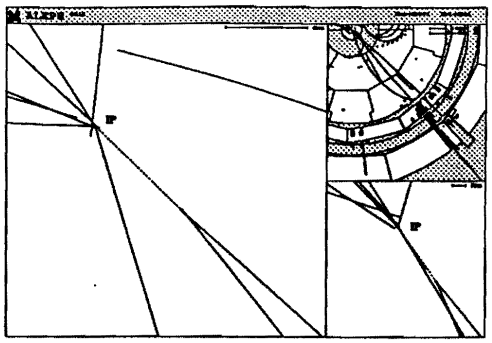

Figure 2. A $B \to h^+h^-$ candidate decay in ALEPH. Two magnified orthogonal views, close to the interaction point (IP), are shown, along with a partial $r-\phi$ view of the event.

Decay Mode	Upper Limits ALEPH [10^{-5}]	DELPHI [10^{-5}]	OPAL [10^{-5}]	L3 [10^{-5}]	PDG94 [10^{-5}]
$B_d \to \pi^+\pi^-$	7.5	5.5	4.7		2.9
$B_d \to K^+\pi^-$	7.5	12	8.1		2.6
$B_d \to K^+K^-$	3.2	16			0.7
$B_d \to p\bar{p}$	3.2				3.4
$B_d \to \eta\pi^0$				84	180
$B_d \to \eta\eta$				210	
$B_s \to \pi^+\pi^-$	25				
$B_s \to K^-\pi^+$	25	39	26		
$B_s \to K^+K^-$	11	52	14		
$B_s \to p\bar{p}$	11				
$\Lambda_b \to p\pi^-$	16				
$\Lambda_b \to pK^-$	16				

Table 1. Branching ratio upper limits (90% C.L.) for two-body charmless hadronic decays of B_d, B_s, and Λ_b. PDG94 refers to [4].

To try to identify the specific decay channels for the candidate decays, a χ^2 probability P_{χ^2}, based on the h^+h^- invariant mass, the dE/dx for each track, and the corresponding resolutions, is used. Unfortunately, each of the three candidate decays satisfies two or more decay hypotheses, with $P_{\chi^2} > 0.1$, so there is no unambiguous identification of a decay channel. For example, the decay illustrated in figure 2 is consistent with the channels $B_d \to K\pi$, $B_s \to \pi\pi$, and $B_s \to K\pi$. Therefore, we set branching ratio upper limits for specific decay modes, as given in Table 1. For comparison, the limits compiled in the "Review of Particle Properties" [4] are also shown.

2.2.2. Results from DELPHI [5] DELPHI has searched for charmless hadronic B decays in the channels $B \to n_1\pi^\pm$, $n_2K^\pm$, and $K^\pm m\pi^\pm$, with $2 \le n_1 \le 4$, $2 \le n_2 \le 3$, and $1 \le m \le 3$. They have used both their silicon vertex detector and RICH for this analysis, which is based on a data sample of 1.7M $Z^0 \to$ *hadrons* events.

In the two-body modes (which include the two-prong channels $\pi\pi, K\pi$, and KK, as well as the three and four-prong channels $\pi\rho, K\rho, Ka_1, \pi K^*$ and $K\phi$), three candidate decays are found with a background, estimated from Monte Carlo, of 0.34 ± 0.08 decays. The corresponding statistical significance for a possible combined signal is at the 2.5σ level. No individual decay channel is observed with a significant signal. Also, in the three and four-body modes, no signal is observed above background. Consequently, branching ratio upper limits are reported in Table 1 (for two-prong modes) and Table 2 (for three and four-prong modes).

Decay Mode	Upper Limits DELPHI [10^{-5}]	PDG94 [4] [10^{-5}]
$B_d \to K^+a_1$	51	
$B_d \to \pi^+\pi^+\pi^-\pi^-$	28	67
$B_d \to K^+\pi^+\pi^-\pi^-$	27	
$B^- \to \rho^0\pi^-$	26	15
$B^- \to K^{*0}\pi^-$	48	15
$B^- \to K^-\rho^0$	19	8
$B^- \to K^-\phi$	44	9
$B^- \to \pi^+\pi^-\pi^-$	22	19
$B^- \to K^-\pi^+\pi^-$	40	19
$B^- \to K^+K^-K^-$	31	35
$B_s \to K^+a_1$	169	
$B_s \to K^+\pi^+\pi^-\pi^-$	91	

Table 2. Branching ratio upper limits (90% C.L.) from DELPHI on two, three, and four-body charmless hadronic B decays.

One of the two-body candidate decays, in the mode $B^- \to \pi^-\bar{K}^{*0}(892)$, with $\bar{K}^{*0}(892) \to K^-\pi^+$, is of interest as it illustrates the power of the RICH for particle identification. The RICH data for this decay, as well as the dE/dx data, is shown in figure 3. The RICH allows for the unambiguous identification of the three particles.

2.2.3. Results from OPAL [6] In a data sample of 1.9M multihadronic Z^0 decays, OPAL has searched for the decays $B_d \to \pi^+\pi^-$, $B_d \to K^+\pi^-$, $B_s \to K^-\pi^+$, and $B_s \to K^+K^-$. Mass resolutions are 137 to 152 MeV/c^2, and the efficiencies range from 20 to 24%. The background is estimated from a fit to the invariant mass distribution outside of the signal region. No signal is observed above the estimated background in any of the four channels. The upper limits on the corresponding branching ratios are given in Table 1.

2.2.4. Results from L3 [7] Taking advantage of its BGO electromagnetic calorimeter, L3 has searched for charmless hadronic B decays into the all-photon final states $B_d \to \eta\eta$ and $\eta\pi^0$, with $\eta \to \gamma\gamma$ and $\pi^0 \to \gamma\gamma$. In a data sample of 1.2M hadronic Z^0 decays, with B mass resolutions of ~ 112 MeV/c^2, and efficiencies of $\sim 3.5\%$ (not including $BR(\eta \to \gamma\gamma)$, no candidates are found in the signal region for either channel. The corresponding

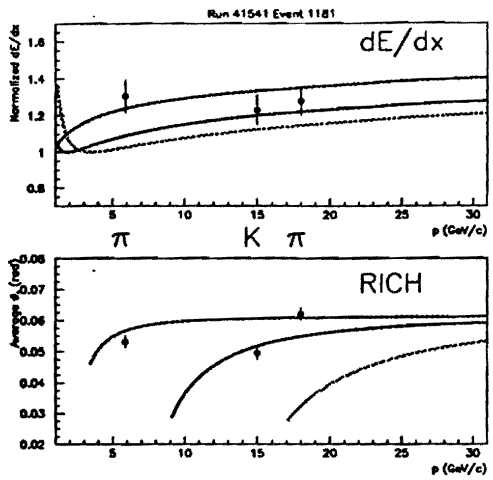

Figure 3. Particle id with the DELPHI dE/dx and RICH systems. The curves give the expected values for π, K, and p, as a function of momentum. The data points correspond to the three particles in the candidate decay $B^- \to \pi^- \bar{K}^{*0}$, with $\bar{K}^{*0} \to K^-\pi^+$.

Decay Mode	Upper Limits ALEPH [10^{-5}]	PDG94 [4] [10^{-5}]
$B_s \to \phi\gamma$	29	-
$\Lambda_b \to \Lambda\gamma$	56	-

Table 3. Branching ratio upper limits (90% C.L.) on $b \to s\gamma$ decay modes from ALEPH.

branching ratio upper limits are listed in Table 1.

3. Search for $b \to s\gamma$ transitions in B_s and Λ_b decays (ALEPH) [8]

A search in ALEPH has been conducted for electromagnetic penguin transitions via the decays $B_s \to \phi\gamma$ (with $\phi \to K^+K^-$), and $\Lambda_b \to \Lambda\gamma$ (with $\Lambda \to p\pi^-$). In a data sample of 1.8M hadronic Z^0 decays, no candidates have been found in either channel. The search efficiencies were 17% and 10%, respectively (not including $BR(\phi \to K^+K^-)$ or $BR(\Lambda \to p\pi^-)$), with mass resolutions $\sim 140\ MeV/c^2$. The derived branching ratio upper limits are given in Table 3.

4. Search for $B^\pm \to \mu^+\mu^-K^\pm$ (CDF) [9]

The CDF Collaboration has looked for evidence for the flavor-changing neutral current transition $b \to s\ell^+\ell^-$ by searching for $B^\pm \to \mu^+\mu^-K^\pm$ decays at the Tevatron Collider. A silicon vertex detector is used to identify the displaced B decay vertex and thereby substantially reduce the combinatorial background.

$B^\pm$ decays to $J/\psi K^\pm$, with $J/\psi \to \mu^+\mu^-$, are used for normalization. These decays are identified by restricting the $\mu^+\mu^-$ invariant mass $M_{\mu\mu}$ to the J/ψ region $3.017 \leq M_{\mu\mu} \leq 3.177\,GeV/c^2$. 50.3 ± 9.4 such decays are observed above background.

When $M_{\mu\mu}$ is in one of two non-ψ regions, $3.3 \leq M_{\mu\mu} \leq 3.6\,GeV/c^2$ or $3.8 \leq M_{\mu\mu} \leq 4.5\,GeV/c^2$, the $\mu^+\mu^-K^\pm$ invariant mass distribution shows no significant B signal above background. Hence it is found that $BR(B^\pm \to \mu^+\mu^-K^\pm, partial) < 7.4 \times 10^{-6}$ at the 90% confidence level, where "partial" refers to the sum of the two non-ψ $M_{\mu\mu}$ regions given above. A theoretical calculation [10], based on heavy quark effective theory, is used to extrapolate this "partial" result to the full allowed region in $M_{\mu\mu}$. Then $BR(B^\pm \to \mu^+\mu^-K^\pm) < 3.2 \times 10^{-5}$, again at the 90% confidence level. This is a factor of 5.3 below the PDG94 limit [4] of 17×10^{-5}.

5. Conclusions

Following the first observation by CLEO, there have been "sightings" of charmless hadronic beauty decays by ARGUS at DORIS (3.1σ effect) and ALEPH at LEP (3.5σ effect). However, there has been no unambiguous determination of a specific decay mode. The particle id result from DELPHI's RICH shows promise in this area. The expected factor of two increase in the LEP data sample this year will clearly help the LEP efforts.

Many new branching ratio upper limits for charmless hadronic beauty decays have been established at LEP, particularly in the realm of B_s and Λ_b decays. However, these limits are still far above the values expected by theory, in the absence of new physics.

New branching ratio upper limits have been set for decays mediated by flavor-changing neutral currents: $B^\pm \to \mu^+\mu^-K^\pm$ by CDF; $B_s \to \phi\gamma$ and $\Lambda_b \to \Lambda\gamma$ by ALEPH. In the absence of new physics, these limits are above the expected values.

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