Rare B decays with photons in the final state

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Abstract

A search for rare decays of B_d^0 and B_s^0 mesons with photons in the final state has been performed in more than three million hadronic decays of the Z collected by the L3 detector at LEP. Eight exclusive channels have been investigated:

$$B_d^0 \rightarrow \eta\eta, B_d^0 \rightarrow \eta\pi^0, B_d^0 \rightarrow \pi^0\pi^0, B_d^0 \rightarrow \gamma\gamma,$$

$$B_s^0 \rightarrow \eta\eta, B_s^0 \rightarrow \eta\pi^0, B_s^0 \rightarrow \pi^0\pi^0, B_s^0 \rightarrow \gamma\gamma.$$

No candidate has been observed in any of these channels and thus upper limits at 90% confidence level have been set on the branching ratios. These are the first experimental limits on $B_d^0 \rightarrow \gamma\gamma$, $B_d^0 \rightarrow \eta\eta$ and on all the B_s^0 modes.

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1 Introduction

Rare B hadron decays are an important test of the Standard Model as well as its extensions and constitute a challenge to detectors' capabilities. High efficiencies and background rejection power are needed to look for a few possible candidates in millions of collected events.

Rare B decays can be searched for at present and future B factories as well as at LEP where $\approx 540,000$ B_d^0 are available in three million hadronic decays of the Z collected by the L3 detector in the years from 1991 through 1994. Moreover $\approx 160,000$ B_s^0 are available in the same data sample while they are not accessible at the $\Upsilon(4S)$ centre of mass energy. Charge conjugate mesons $\bar{B}_d^0$ and $\bar{B}_s^0$ are also implied throughout this paper.

This paper describes the search for eight rare exclusive decay modes: $B_{d,s}^0 \rightarrow \eta\eta$, $\eta\pi^0$, $\pi^0\pi^0$ and $B_{d,s}^0 \rightarrow \gamma\gamma$. η 's and π^0 's have been detected by means of their decays into pairs of photons. These searches have been performed with the L3 detector (described in detail in Reference [1]) whose BGO crystal electromagnetic calorimeter has an energy resolution less than 2% and an angular resolution better than 0.5° for electromagnetic clusters with energies above 1 GeV. Photons are identified using a charged track veto and a study of the consistency of the lateral shower shape with electromagnetic energy deposition as expected from test beam studies.

2 $B_{d,s}^0 \rightarrow \eta\eta, \eta\pi^0, \pi^0\pi^0$ decays

In the Standard Model, the neutral charmless $B_{d,s}^0$ decays can occur through a variety of processes such as Cabibbo-suppressed $b \rightarrow u$ transition [2] with a further color suppression with respect to the charged modes [3] or one loop diagrams with a heavy quark and a virtual $W^\pm$ boson [4, 3]. Contributions can also arise from electroweak penguins [5].

These decay modes can give information on new physics beyond the Standard Model, since in models with charged Higgs additional diagrams are allowed and can add constructively to the $W^\pm$ boson loop [6]. Minimal Supersymmetric extensions of the Standard Model predict superpartners that could also affect the expected decay rates [7]. A set of diagrams is shown in Reference [4].

The Standard Model theoretical predictions for the branching ratios of the neutral charmless $B_{d,s}^0$ decays range from 10^{-5} to 10^{-8} [3, 9]. No predictions for extensions to the Standard Model exist. The existing ARGUS and CLEO limits at 90% confidence level on these decays are $\text{Br}(B_d^0 \rightarrow \eta\pi^0) < 1.8 \times 10^{-3}$ [10] and $\text{Br}(B_d^0 \rightarrow \pi^0\pi^0) < 9.1 \times 10^{-6}$ [11], respectively.

Since the hard fragmentation of the b quark gives on average 70% of the beam energy to the $B_{d,s}^0$ meson, the η/π^0 are likely to have high momentum and the two photons from their decay can have a small opening angle, merging in a single cluster in the electromagnetic calorimeter. This analysis has been performed in the different final state configurations which have shown the best acceptance and background rejection capability:

- $B_{d,s}^0 \rightarrow \eta\eta$: four detected photons in the final state or one η detected as a photon pair and the other as a single cluster,
- $B_{d,s}^0 \rightarrow \eta\pi^0$: the η detected as a photon pair and the π^0 as a single cluster,
- $B_{d,s}^0 \rightarrow \pi^0\pi^0$: both π^0 's detected as single clusters.

After the photon and the cluster identification, the global kinematics has been investigated to reject the combinatoric background:

- The opening angle of the two light mesons is expected to be small, while for random combinations it is peaked toward large values.
- The hard fragmentation of the b quark gives high energy to the $B_{d,s}^0$ meson candidate, whereas background tends to be at low energies.
- The cosine of the angle in the $B_{d,s}^0$ candidate rest frame between the direction of one decay product and the $B_{d,s}^0$ candidate flight direction is peaked for the background, while it is expected to be more isotropic for the signal.
- In decay modes where an η is detected as a photon pair, a cut on the invariant mass of these photons can be applied.
- A constrained fit to the $B_{d,s}^0$ mass, taking into account the energy and angular resolutions of the calorimeter, has been performed for the $B_{d,s}^0 \rightarrow \pi^0\pi^0$ search. The χ^2 of this fit shows large values for background and small ones for signal.

The invariant mass of all the photons and/or clusters from the $B_{d,s}^0$ candidates, has been calculated for all the decay modes. The resolution was calculated as the width, σ , of a Gaussian fit to the distribution of this invariant mass for events in signal Monte Carlo surviving the cuts. The invariant mass spectra for data are shown in Figure 1 together with the resolutions.

Since no candidate event has been found in data in a $\pm 2\sigma$ window around the fit mass of the $B_{d,s}^0$ meson, for any of the eight modes, upper limits at 90% confidence level on the branching ratios have been set and are reported in the upper part of Table 1. Further details on this analysis can be found in Reference [12].

3 $B_{d,s}^0 \rightarrow \gamma\gamma$ decays

$B_{d,s}^0 \rightarrow \gamma\gamma$ decays have a clean experimental signature but large theoretical uncertainties affect the few present calculations. These decays can occur via a second order weak transitions with gluonic penguins contributions and are described by diagrams like the ones reported in References [13].

The expected Standard Model value for the branching ratio is of the order of 10^{-7} [14, 15] and can be significantly enhanced [14] from the existence of charged Higgs bosons expected in extensions to the Standard Model. The search for $B_{d,s}^0 \rightarrow \gamma\gamma$, like the $b \rightarrow s\gamma$ studies, is thus a window on new physics beyond the Standard Model.

Once further calculations on the $B_{d,s}^0 \rightarrow \gamma\gamma$ processes are performed, the possible observation of $B_{d,s}^0 \rightarrow \gamma\gamma$ decays could give a measurement of the Cabibbo-Kobayashi-Maskawa matrix elements ratio $|V_{ts}|^2/|V_{td}|^2$ from the relation:

$$\frac{\text{Br}(B_d^0 \rightarrow \gamma\gamma)}{\text{Br}(B_s^0 \rightarrow \gamma\gamma)} = \frac{|V_{td}|^2}{|V_{ts}|^2} \frac{f_{B_d^0}^2}{f_{B_s^0}^2}.$$

This approach is complementary to the study of $B^0\bar{B}^0$ mixing.

A search for $B_{d,s}^0 \rightarrow \gamma\gamma$ decays has been performed using the L3 detector at LEP [13]. After the identification of photons, the main background is the combinatoric one, which has been reduced with cuts on the $B_{d,s}^0$ candidate energy and photons' opening angle. In order to

separate $b\bar{b}$ events from other hadronic events, a multidimensional analysis based on a neural network approach described elsewhere [16] is used.

Figure 2 shows the invariant mass spectra of the two selected photons after the application of all the cuts, for the $B_{d,s}^0$ Monte Carlo, the background Monte Carlo and the data sample. The resolutions σ are calculated with a Gaussian fit to the $B_{d,s}^0$ Monte Carlo invariant mass distribution. No event is observed in a $\pm 2\sigma$ window around the $B_{d,s}^0$ mass and the upper limits at 90% confidence level on the branching ratios reported in the lower part of Table 1 have been set.

A $B_{d,s}^0 \rightarrow \pi^0\pi^0$ decay can fake a $B_{d,s}^0 \rightarrow \gamma\gamma$ decay, if the two photons from π^0 decay merge into a single cluster. In calculating the limits on the branching ratio of $B_{d,s}^0 \rightarrow \gamma\gamma$ the conservative assumption that the contribution from $B_{d,s}^0 \rightarrow \pi^0\pi^0$ is negligible has been made and vice-versa. A complementary analysis not relying on the neural network $b\bar{b}$ selection has been performed as a cross-check [17]. This analysis uses photon selection and global kinematic variables similar to those used in the search for $B_{d,s}^0 \rightarrow \eta\eta, \eta\pi^0, \pi^0\pi^0$ decays. A single variable function based on a multidimensional approach has been used to discriminate the signal from the background events, obtaining compatible results with the analysis described above.

Process	Resolution	Efficiency	L3 upper limit 90% C.L.	Other upper limit 90% C.L.
$B_d^0 \rightarrow \eta\eta$ (I)	107 ± 10 MeV	$2.5 \pm 0.2^{+0.2}_{-0.2}$ %		
$B_d^0 \rightarrow \eta\eta$ (II)	146 ± 11 MeV	$4.6 \pm 0.3^{+0.02}_{-0.2}$ %		
$B_d^0 \rightarrow \eta\eta$			4.1×10^{-4}	-
$B_d^0 \rightarrow \eta\pi^0$	79 ± 5 MeV	$4.5 \pm 0.3^{+0.05}_{-0.03}$ %	2.5×10^{-4}	1.8×10^{-3}
$B_d^0 \rightarrow \pi^0\pi^0$	97 ± 4 MeV	$7.6 \pm 0.4^{+0.2}_{-0.5}$ %	6.0×10^{-5}	9.1×10^{-6}
$B_s^0 \rightarrow \eta\eta$ (I)	101 ± 10 MeV	$2.4 \pm 0.2^{+0.2}_{-0.2}$ %		
$B_s^0 \rightarrow \eta\eta$ (II)	129 ± 8 MeV	$4.8 \pm 0.3^{+0.2}_{-0.3}$ %		
$B_s^0 \rightarrow \eta\eta$			1.5×10^{-3}	-
$B_s^0 \rightarrow \eta\pi^0$	81 ± 1 MeV	$4.3 \pm 0.3^{+0.02}_{-0.1}$ %	1.0×10^{-3}	-
$B_s^0 \rightarrow \pi^0\pi^0$	99 ± 4 MeV	$8.3 \pm 0.4^{+0.4}_{-0.7}$ %	2.1×10^{-4}	-
$B_d^0 \rightarrow \gamma\gamma$	73 ± 3 MeV	$11.8 \pm 0.5 \pm 0.7\%$	3.9×10^{-5}	-
$B_s^0 \rightarrow \gamma\gamma$	72 ± 3 MeV	$11.8 \pm 0.5 \pm 0.7\%$	1.5×10^{-4}	-

Table 1: Resolutions, efficiencies and upper limits for B_d^0 and B_s^0 branching ratios. The (I) and (II) modes for the $B_{d,s}^0 \rightarrow \eta\eta$ channel refer respectively to the search for a four photon final state or one with a photon pair and a single cluster. The first error on the efficiencies is statistical, the second systematic.

4 Conclusions

A search for rare decays of B_d^0 and B_s^0 mesons with photons in the final state has been performed in more than three million hadronic decays of the Z collected by L3 detector at LEP. Eight exclusive modes have been studied:

$$B_{d,s}^0 \rightarrow \eta\eta, B_{d,s}^0 \rightarrow \eta\pi^0, B_{d,s}^0 \rightarrow \pi^0\pi^0, B_{d,s}^0 \rightarrow \gamma\gamma.$$

No evidence for those decays has been observed and thus upper limits at 90% confidence level have been set on their branching ratios. These limits, the resolutions and the efficiencies with

their errors are summarised in Table 1. The $B_d^0 \rightarrow \gamma\gamma$, $B_d^0 \rightarrow \eta\eta$ and all the B_s^0 limits are the first ones set while the $B_d^0 \rightarrow \eta\pi^0$ limit improves the existing one by almost an order of magnitude.

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Figure 1: Invariant mass spectra for data and the expected resolutions from the $B_{d,s}^0$ Monte Carlo (arbitrary units) after the application of all the cuts. a) $B_{d,s}^0 \rightarrow \eta\eta$ in four photons, b) $B_{d,s}^0 \rightarrow \eta\eta$ in a photon pair and one single cluster, c) $B_{d,s}^0 \rightarrow \eta\pi^0$, d) $B_{d,s}^0 \rightarrow \pi^0\pi^0$ before the application of the χ^2 cut.

Figure 2: Invariant mass spectra for data and the expected resolutions from the B_d^0 and B_s^0 Monte Carlo. All the cuts are applied.