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Searches for Rare B Decays with the ALEPH Detector

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ALEPH Collaboration

Invited talk at the XXVIII International Conference on High Energy Physics, ***Warsaw,*** *Poland, 25–31 July, 1996.*

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New results on searches for rare beauty decays are presented which are based on the complete LEP I data sample collected by the ALEPH experiment. An attempt has been made to measure the inclusive charmless semileptonic branching ratio of B hadrons with a novel technique which allows to reduce the model dependence of the result compared to previous methods. The searches for charmless hadronic B decays and for the rare leptonic decay $B^+ \to \tau^+\nu_\tau$ are updated. Charmless two-body decays have been observed with high significance. With the same method as used for the $B^+ \to \tau^+\nu_\tau$ search, a first limit on the inclusive FCNC process $B \to X_s\nu\bar{\nu}$ has been derived.

1 Introduction

At the end of the LEP I running period, the ALEPH experiment [1] has collected $4.1 \cdot 10^6$ hadronic Z^0 decays with fully operational silicon vertex detector [2]. The data were taken in the years 1991–95 and correspond to about $0.9 \cdot 10^6$ $Z^0 \to b\bar{b}$ events. Based on this data set, searches for rare decays of B hadrons have been updated and improved by new analysis methods.

2 Charmless Semileptonic B Decays

The search for charmless semileptonic B decays is motivated by the opportunity to determine the CKM matrix element $|V_{ub}|$ by measuring of the branching ratios for these decays.

Charmless semileptonic B decays have first been observed by the CLEO [3] and ARGUS [4] experiments from the analysis of the endpoint region of the inclusive lepton spectrum. The error on the inclusive branching fraction for $b \to u\ell\nu$ and on the extracted ratio $|V_{ub}|/|V_{cb}|$ is dominated by systematics due to the model assumptions needed to extrapolate the decay rate from the endpoint region. The present average from inclusive measurements at the $\Upsilon(4S)$ resonance is $|V_{ub}|/|V_{cb}| = 0.08 \pm 0.02$ [5].

Recently CLEO [6] has also observed signals of charmless semileptonic B decays in exclusive channels. The model dependence in the determination of $|V_{ub}|$ from the exclusive decay rates turns out to be still as large as 25%, like for the inclusive search.

ALEPH has developed a novel selection method [7] in order to reduce the model dependence in the determination of the inclusive $b \to u\ell\nu$ branching ratio. This approach avoids the restriction to a small region at the endpoint of the lepton spectrum by using a multivariate analysis to discriminate between signal and $b \to c$ background over the whole kinematic range.

The analysis proceeds in several steps. A 98 % pure sample of 48000 $b\bar{b}$ events is selected using a b lifetime tag [8] in the event hemisphere opposite to an identified lepton with momentum greater than 3 GeV.

In these events, tracks from the hypothetical semileptonic B hadron decay, $B \to X\ell\nu$, are selected. Charged and neutral particles from the hadronic part of the decay are distinguished from fragmentation particles on the basis of their kinematic properties (momentum, rapidity, decay angles, track impact parameter) by using a neural network algorithm. Purities of 60 and 70% are achieved for $b \to u\ell\nu$ and $b \to c\ell\nu$ decays, respectively, at 80% selection efficiency. The neutrino 4-momentum is reconstructed as the missing momentum and energy in the lepton hemisphere determined from a comparison with the opposite hemisphere.

From the B decay candidate tracks, including the charged lepton and the reconstructed neutrino, the B momentum can be estimated with an uncertainty of $\sigma(p_B) = 4.5$ GeV and an average polar angle deviation of 4.2°. In the B candidate rest frame, kinematic information from the charged lepton, the reconstructed neutrino and the hadronic final state is combined in a neural network algorithm with two hidden layers to discrminate between the inclusive $b \to u\ell\nu$ signal and

$b \to c$ background. The 20 discriminating variables, including the charged lepton energy, energy fraction and transverse momentum with respect to the B direction and track multiplicity, invariant masses and transverse momenta relative to the lepton direction for the hadronic system, are well described by the Monte Carlo simulation and were selected such that they are insensitive to B decay model assumptions

The distribution of the neural network output NN_{bu} is shown in figure 1 for data and for the Monte Carlo prediction normalized to the data. While in the background region, $NN_{bu} < 0.5$, data and Monte Carlo are in good agreement, there is a clear excess of 267 ± 90 events above the expected $b \to c$ background in the signal region, $NN_{bu} > 0.5$, which contains 60% of the $b \to u\ell\nu$ contribution. Fitting the data in the signal region with the prediction gives for the inclusive charmless semileptonic branching ratio a preliminary value of

$$BR(B \to X_u \ell\nu) = (1.6 \pm 0.4_{\text{stat}}) \cdot 10^{-3}$$

which is in agreement with the results from the $\Upsilon(4S)$ for $|V_{ub}|/|V_{cb}|$.

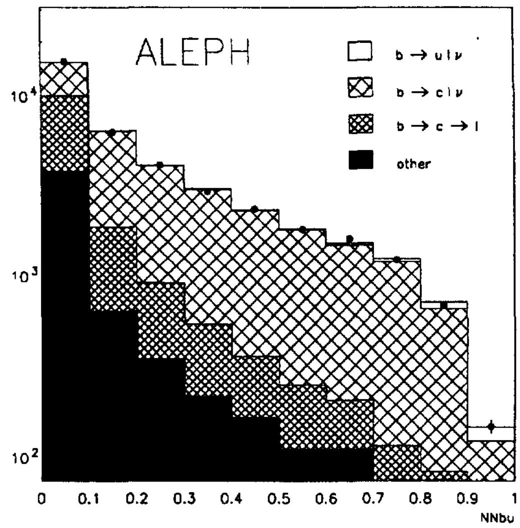

Figure 1: Neural network output NN_{bu} for data (full circles) and Monte Carlo prediction normalized to the same number of entries.

For the simulation of $B \to X_u \ell\nu$ decays over the whole kinematic range, a hybrid model was used. While at low hadronic recoil energy (< 1.6 GeV) exclusive final states ($X_u = \pi, \rho, \omega, \eta$ etc.) were generated with JETSET Monte Carlo, non-resonant multi-pion final states at larger recoil (85% of all $b \to u\ell\nu$ decays) were described by an inclusive quark model (ACCMM[9] with parameters fit to CLEO data). Variations of the parameters of the hybrid model and the use of an alternative inclusive $b \to u\ell\nu$ lepton spectrum predicted by QCD sum rules [10] result in a systematic uncertainty in the branching ratio of ±12%.

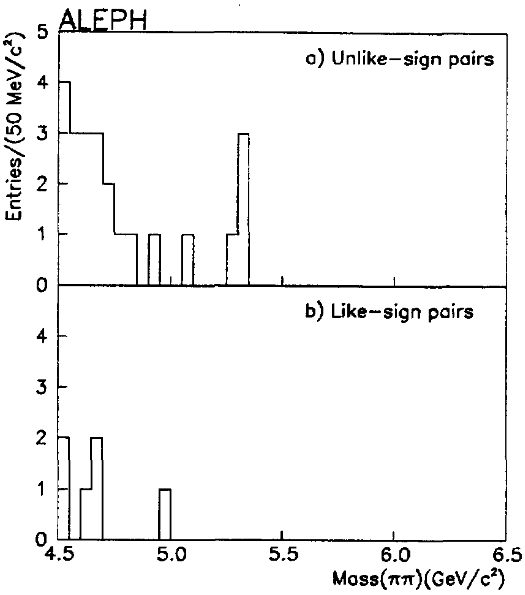

Figure 2: Invariant mass distribution for candidate track pairs under the pion hypothesis, for a) opposite-sign and b) like-sign charge combinations.

The lepton spectra for the simulation of the $b \to c\ell\nu$ and $b \to c \to s\ell\nu$ background were obtained by fitting model predictions to data from the $\Upsilon(4S)$ resonance and from the $c\bar{c}$ threshold. Systematic errors are determined by using different models. The dominant systematic errors in the background modelling come from uncertainties in the semileptonic branching ratios and in the topological branching ratios for D mesons. The preliminary total systematic error on the $b \to u\ell\nu$ branching ratio from these studies is ±25 %.

Table 1: The numbers of candidate events with χ^2-probability > 10% for a given decay hypothesis greater than 10% (see text) and 90% C.L. upper limits on the branching ratios ($BR \times 10^5$) for charmless hadronic two-body decay modes of beauty hadrons from ALEPH in comparison with other experiments and with standard-model expectations.

	# candidates w. prob(χ^2) > 0.10	ALEPH [11] this conf.	CLEO [12] 1995	DELPHI [13] 1996	OPAL [14] 1994	Standard Model [15]
# $b\bar{b}$ events		0.9×10^6	2.6×10^6	0.6×10^6	0.3×10^6	
$\overline{B}^0_d \to \pi^+\pi^-$	2	< 4.1	< 2.0	< 4.5	< 4.7	1.0 – 2.6
$\overline{B}^0_s \to \pi^+\pi^-$	3	< 17	–	–	–	–
$\overline{B}^0_d \to K^-\pi^+$	1	< 3.0	< 1.7	< 9.0	< 8.1	1.0 – 2.0
$\overline{B}^0_s \to K^+\pi^-$	4	< 21	–	–	< 26	1.4 – 1.8
$\overline{B}^0_d \to K^+K^-$	0	< 1.8	< 0.4	< 12	–	–
$\overline{B}^0_s \to K^+K^-$	0	< 5.9	–	–	< 14	0.6 – 2.1
$\overline{B}^0_d \to p\bar{p}$	0	< 1.8	–	–	–	–
$\overline{B}^0_s \to p\bar{p}$	0	< 5.9	–	–	–	–
$\Lambda_b \to p\pi^-$	0	< 5.0	–	–	–	–
$\Lambda_b \to pK^-$	0	< 5.0	–	< 36	–	–

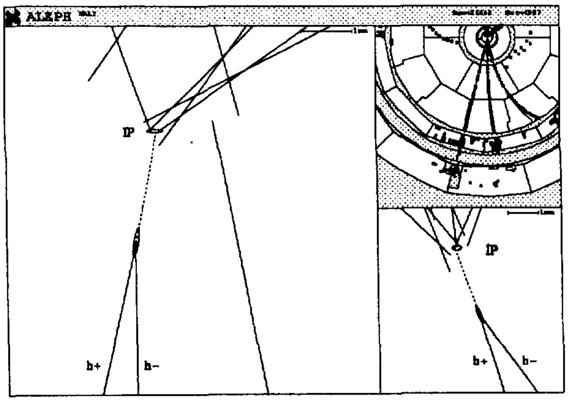

Figure 3: Display of a $B \to h^+h^-$ candidate event in the ALEPH detector with the vertex region enlarged (most likely hypothesis: $\overline{B}^0_d \to K^+\pi^-$).

3 Charmless Hadronic B Decays

3.1 Observation of Hadronic Two-Body Decays

A search has been performed [11] for charmless hadronic beauty decays of the type $B \to h^+h^-$, where a B hadron, $B^0_{d,s}$ or Λ_b, decays into a two-body final state consisting of $\pi^\pm$, $K^\pm$ and p (see Table 1). The decays $\overline{B}^0_d \to \pi^+\pi^-$, $\overline{B}^0_s \to K^+\pi^-$ and $\Lambda_b \to p\pi^-$ proceed predominantly via a $b \to u$ tree level process while gluonic penguin graphs dominate for the decay modes $\overline{B}^0_d \to \pi^+K^-$, $\overline{B}^0_s \to K^+K^-$ and $\Lambda_b \to pK^-$ (charge conjugate processes are implied).

At LEP energies, the large boost of the B hadron, combined with high-precision 3D track coordinate reconstruction in the ALEPH silicon vertex detector [2], allows to efficiently identify displaced common vertexes of the two final-state particles from B decay.

A combination of strict kinematic and vertex topology criteria was applied. This includes requirements for large reconstructed B momentum ($p_B > 30$ GeV) and for large decay length significance ($\ell/\sigma_\ell > 6$). The cuts are chosen to eliminate combinatorial background in the invariant mass region of the B candidates. The signal mass region (under the $\pi^+\pi^-$ hypothesis) is defined to lie 3 standard deviations above the kinematic limit of 5 GeV for track pairs from $b \to c$ decays, with a mass resolution of $\sigma_m = 44$ GeV.

In the signal region of the invariant mass distribution for the selected unlike-sign track pairs (see figure 2), four clean $B \to h^+h^-$ candidates with well separated decay vertex are observed (see, for example, figure 3). The four rare decay candidates have been found at a rate of one per year between 1991 and 95. In the same mass range, there are no like-sign candidates which are an indication for combinatorial background.

The combinatorial background contamination was estimated in an extensive Monte Carlo study using a sample of $Z^0 \to q\bar{q}$ events without $b \to u$ decays which, passed through the full detector simulation after a preselection, is equivalent to 320 times the number of data events. Five background events were found in the signal region. With a safety factor of 3 which accounts for possible underestimation of background in the simulation, this corresponds to a combinatorial background contribution in the data of 0.05 ± 0.02 events. The (binomial) probability that the signal could be caused by a background fluctuation is $9 \cdot 10^{-7}$.

Table 2: Selection efficiencies ε, numbers of candidate events and 90% C.L. upper limits on the branching ratios ($BR \times 10^4$) for charmless hadronic multi-body decay modes of B mesons in comparison with the 1996 PDG limits.

Channel	ε [%]	#ev.	ALEPH limit	PDG 96 limit [17]
$B^+ \to \pi^+\pi^+\pi^-$	7.0	0	0.50	1.9
$B^0 \to 2\pi^+2\pi^-$	3.0	2	2.6	2.8
$B^+ \to 3\pi^+2\pi^-$	4.3	4	2.8	8.6
$B^0 \to 3\pi^+3\pi^-$	1.2	2	6.6	30
$B^+ \to p\bar{p}\pi^+$	4.2	0	0.84	1.6
$B^0 \to p\bar{p}\pi^+\pi^-$	2.4	0	1.5	2.5
$B^+ \to p\bar{p}\, 2\pi^+\pi^-$	1.6	1	3.7	5.2
$B^0 \to \pi^+\pi^-\pi^0$	2.8	1	2.2	7.2
$B^+ \to 2\pi^+\pi^-\pi^0$	1.2	0	2.9	40
$B^0 \to 2\pi^+2\pi^-\pi^0$	0.3	0	12	90
$B+ \to \rho^0\pi^+$	11	0	0.32	0.43
$B^0 \to \rho^0\rho^0$	8.5	0	0.40	2.8
$B^0 \to a_1^\pm\pi^\mp$	2.3	1	2.4	4.9
$B^+ \to a_1^+\rho^0$	2.5	0	1.3	6.2
$B^0 \to a_1^+a_1^-$	0.6	0	5.7	28
$B^+ \to p\overline{\Delta}^0$	4.7	0	0.76	3.8
$B^+ \to \bar{p}\Delta^{++}$	13	0	0.26	1.5
$B^0 \to \Delta^0\overline{\Delta}^0$	0.9	0	3.8	15
$B^0 \to \Delta^{++}\Delta^{--}$	7.4	0	0.47	1.1
$B^0 \to \rho^\pm\pi^\mp$	5.4	3	1.8	0.88
$B^0 \to \rho^0\pi^0$	4.2	0	0.84	0.24
$B^+ \to \rho^+\rho^0$	2.9	0	1.2	10
$B^+ \to \omega\pi^+$	6.2	0	0.57	4.0
$B^+ \to \eta\pi^+$	2.2	0	1.6	7.0

Assuming equal partial widths for related decay processes of B_d^0, B_s^0 and Λ_b (tree vs. penguin-graph dominated decays), the average inclusive branching ratio for charmless hadronic two-body decays of B hadrons is determined from the observed number of events to

$$BR(B \to h^+h^-) = (1.7^{+1.0}_{-0.7} \pm 0.2) \cdot 10^{-5}$$

which is consistent with the CLEO [12] and DELPHI [13] measurements. The largest source of systematic uncertainty is background from charmless B decays involving neutrals, in particular $B_d^0 \to \pi^\pm\rho^\mp$, with $\rho^\mp \to \pi^\mp\pi^0$, which can contribute a fraction of up to 7% to the observed signal.

The four $B \to h^+h^-$ signal events cannot be unambiguously associated to specific final states. Discrimination of exclusive decay channels is rather done on a probabilistic basis. With an unbinned maximum-likelihood fit based on the expected dE/dx and invariant mass distributions for the individual final states, the fraction of tree-diagram dominated charmless B decays is determined to be

$$\frac{BR(B^0_{d(s)} \to \pi^+\pi^-(K^-))}{BR(B^0_{d(s)} \to h^+h^-)} = 1.0^{+0.0+0.0}_{-0.3-0.1},$$

or greater than 40% at 95% C.L.

3.2 *Limits on Exclusive Channels*

In order to classify the four selected events according to the exclusive decay channels they may originate from, a χ^2-probability is determined for each decay hypothesis based on the dE/dx and invariant mass measurements for the final state particles. For each decay mode, the number of events with corresponding χ^2-probability exceeding an optimized cut value of 10% is counted. The derived 90% C.L. upper limits on the branching ratios for the exclusive decay modes (see Table 1) are the best among the LEP experiments.

Several classes of charmless hadronic multi-body decays of B_d^0 and $B^\pm$ mesons have also been searched for [16], including final states with a π^0, with light meson resonances and with baryons. The selection criteria are similar to the ones for the two-body decay modes but optimized for the individual final states and the specific background processes. The cuts are chosen to eliminate combinatorial background in the $\pm 3\sigma_m$ signal regions around the B mass ($\pm 2\sigma_m$ for final states involving a π^0) where the mass resolution σ_m depends on the decay mode. Charged final state particles are identified by dE/dx cuts.

The selection efficiencies, numbers of candidate events and 90% C.L. upper limits on the branching ratios for the studied rare decay channels are given in Table 2. No background subtraction was performed. The new ALEPH limits improve upon most of the 1996 PDG limits [17]. Standard model predictions [15] for the investigated branching ratios range between 10^{-5} and 10^{-6}.

4 Limits on $B^+ \to \tau^+\nu_\tau$ and $b \to s\nu\bar{\nu}$ Decays

The rare leptonic decay $B^+ \to \tau^+\nu_\tau$ is of interest for future determinations of the CKM matrix element $|V_{ub}|$ or of the B decay constant f_B. Standard model predictions for the branching ratio are

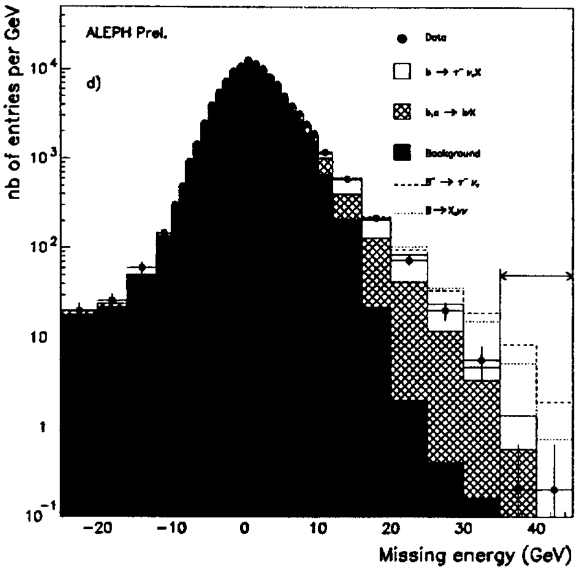

Figure 4: Missing energy distribution for the $B^+ \to \tau^+\nu_\tau$ and the inclusive $B \to X_s\nu\bar{\nu}$ search. Monte Carlo predictions for both processes corresponding to branching ratios of 1% and 0.3%, respectively, are indicated, together with the expected background contributions.

on the order of 10^{-5}. This could, however, be enhanced by contributions from new heavy bosons, like a charged Higgs, mediating the decay.

The search procedure has been developed for the measurement of the inclusive semileptonic $B \to \tau^+\nu_\tau X$ branching fraction [18]. Measurements for both decay modes have been updated for the 1991–95 data sample [19]. Since only hadronic $\tau^+ \to \bar{\nu}_\tau X_{\text{had}}$ decays are accepted, the final state contains two neutrinos in both cases and the signature is large missing energy E_{miss} in one event hemisphere. Background due to limited detector resolution and hermiticity and from semileptonic charm and beauty decays is suppressed by a lepton veto in the missing energy hemisphere and by applying a b lifetime tag [8] in the opposite hemisphere.

The optimized signal regions for $B \to \tau^+\nu_\tau X$ and $B^+ \to \tau^+\nu_\tau$ in the missing energy spectrum (compare figure 4) are $16 < E_{\text{miss}} < 35$ GeV and $35 < E_{\text{miss}} < 50$ GeV, respectively. The event selection is also optimized separately for each of the two decay modes. Fitting the Monte Carlo predictions for signal and backgrounds to the data in the signal region, one obtains the updated branching ratio measurement

$$BR(B \to \tau^+\nu_\tau X) = (2.41 \pm 0.21 \pm 0.34)\%.$$

The updated 90% C.L. upper limit

$$BR(B^+ \to \tau^+\nu_\tau) < 1.6 \cdot 10^{-3}$$

is extracted from the number of events in the corresponding signal region without background subtraction and takes into account systematic uncertainties in the B^+ production rate and in the selection efficiency due to the b fragmentation function. The result improves on the previous best limit which was also obtained by ALEPH [18].

A competing process for the $B^+ \to \tau^+\nu_\tau$ search is the inclusive FCNC decay $B \to X_s\nu\bar{\nu}$ which can be searched for with the same missing-energy method [20]. The process $b \to s\nu\bar{\nu}$, which in the standard model proceeds via weak penguin and box diagrams, is interesting because it can provide a theoretically clean determination of the CKM matrix element $|V_{ts}|$; NLO QCD calculations of the decay rate exist [21]. Standard model predictions for the branching ratio are on the order of $5 \cdot 10^{-5}$.

The selection efficiency for $B \to X_s\nu\bar{\nu}$ decays depends on the shape of the missing energy spectrum for these events (compare figure 4). The energy spectrum of the two neutrinos from $b \to s\nu\bar{\nu}$ was taken from [20] and the hadronic system X_s generated with JETSET. A preliminary 90% C.L. upper limit of

$$BR(B \to X_s\nu\bar{\nu}) < 7.7 \cdot 10^{-4}$$

is derived. With the same selection, the limit for inclusive $B \to X_s\nu\bar{\nu}$ decays is lower than for $B^+ \to \tau^+\nu_\tau$ since in the latter case only B^+ mesons and semi-hadronic τ decays contribute.

5 Conclusions

For the measurement of the inclusive charmless semileptonic branching ratio of B hadrons a new selection method has been developed which has the potential for a considerable reduction of the model dependence affecting previous results. Charmless hadronic two-body decays of B hadrons have been observed with high significance. Upper limits on exclusive charmless hadronic decay modes and on the rare leptonic decay $B^+ \to \tau^+\nu_\tau$ have been improved. A first limit on the inclusive FCNC process $b \to s\nu\bar{\nu}$ has been derived.

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