Lepton-number violation in $B$ decays at $\text{BaBar}$

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We present results of searches for lepton-number and, in some cases also baryon-number, violation in $B$ decays using the full $\text{BaBar}$ dataset of 471 million $B\bar{B}$ pairs.

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1 Introduction

The observation of neutrino oscillations suggests that lepton flavour is not a conserved quantity. If neutrinos have mass, then the neutrino and antineutrino can be the same particle and processes involving lepton-number violation become possible. The most sensitive searches for lepton-number violation are currently found in neutrinoless double-beta decays \[1\]. However the nuclear environment of this type of search makes it difficult to extract the neutrino mass scale. Processes involving mesons decaying to lepton-number violating final states have been suggested as an alternative to the neutrinoless double-beta decay searches. Figure 1 shows an example Feynman diagram for a $B$ decay to a lepton-number violating final state via the exchange of an s-channel Majorana neutrino. It is however expected that these decays have extremely small unobservable probabilities and therefore the observation of a significant signal would be a clear sign of New Physics.

![Figure 1: Example diagram of a process with $\Delta L = 2$ due to the exchange of a Majorana neutrino][2].

In this paper, we present the results of analyses conducted by the $\text{B}A\overline{\text{B}}\text{A}$ collaboration for the following lepton-number violating $B$ decays: $B^0 \rightarrow \Lambda^0 \ell^-$, $B^+ \rightarrow \Lambda^0 \ell^+$ and $B^+ \rightarrow h^- \ell^+ \ell^+$, where $\ell^+$ and $\ell^+$ are either $e^+$ or $\mu^+$ leptons and $h$ is either a kaon, pion, $K^*$, $\rho$, or $D$ meson.

These analyses make use of the full $\text{B}A\overline{\text{B}}\text{A}$ $\Upsilon(4S)$ dataset. This consists of 471 million $B\overline{B}$ pairs collected by the $\text{B}A\overline{\text{B}}\text{A}$ detector at the PEP-II $B$ Factory, which collides $e^+e^-$ asymmetric-energy beams at the $\Upsilon(4S)$ resonance \[3\]. The $B$ meson candidates are characterised by two kinematic variables. We take advantage of the precise kinematic information for the beams to form the variables $m_{ES} = \sqrt{s} - p_B^{s2}$ and $\Delta E = E_B - \frac{\sqrt{s}}{2}$, where $(E_B, \vec{p}_B)$ is the $B$ meson four-momentum in the $e^+e^-$ centre-of-mass frame and $\sqrt{s}$ is the centre-of-mass energy. Signal events are expected to peak around the $B$ mass for $m_{ES}$ and around zero for $\Delta E$. There are two main types of backgrounds: the very abundant $q\overline{q}$ events, where $q$ is either a $u$, $d$, $s$ or $c$ quark, and
the background arising from $B$ decays to other final states. To distinguish $B$ meson candidates from the continuum $q\bar{q}$ background, variables describing the topology of the event are combined in a multivariate analyser (MVA), such as a neural network or a Fisher discriminant, in order to maximise their discriminating power. The variables $m_{ES}$, $\Delta E$ and the output of the MVA either have selection requirements placed upon them or are supplied as inputs to a maximum likelihood fit.

2 Lepton and baryon number violation in $B \to \Lambda_{(c)}e^-(\mu^-)$ decays

This is the first and only search for the decay modes $B^0 \to \Lambda_c^+ \ell^-$ and $B^- \to \Lambda^0 \ell^-$, where $\ell^-$ is either an electron or a muon. These decays are particularly interesting since a significant signal would not only be an indication of lepton-number violation but also of baryon-number violation. Figure 2 shows a typical Feynman diagram for the $B^0 \to \Lambda_c^+ \ell^-$ decays. We reconstruct $\Lambda_c^+ \to pK^-\pi^+$, which has a branching fraction of $\mathcal{B} \approx 5\%$, and $\Lambda^0 \to p\pi^-$, with branching fraction $\mathcal{B} \approx 64\%$. The baryon candidate is required to have originated from a common vertex with a lepton. A candidate event is also required to have more than four charged tracks. A neural network composed of six event shape variables is used to reduce remaining backgrounds.

![Feynman diagram](image)

Figure 2: Feynman diagram for the $B^0 \to \Lambda_c^+ \ell^-$ decay.

The signal $m_{ES}$ and $\Delta E$ distributions are parametrised in the fit to data with a Crystal Ball function PDF. For the $\Lambda_c^+$ decay modes, an additional parametric PDF is added to the fit to parametrise the distribution of the output of the MVA. Figure 3 shows projection plots for $m_{ES}$ and $\Delta E$ for the $B^- \to \Lambda^0 \ell^-$ decays, where the blue line is the overall fit and the black points with error bars correspond to the data distribution. We observe no significant signals in any of the modes and measure branching fraction upper limits in the range of $(3 - 180) \times 10^{-8}$ at 90% confidence.
level. The most sensitive decay was found to be $B^- \rightarrow \Lambda^0 e^-$ with a branching fraction upper limit of $\mathcal{B}_{90\%} < 3.2 \times 10^{-8}$ [4].

![Figure 3](image)

Figure 3: $m_{ES}$ and $\Delta E$ projection distributions for the decays $B^- \rightarrow \Lambda^0 \ell^-$, where $\ell$ is either an electron or a muon. The blue solid line is the overall fit and the black points with error bars correspond to data.

### 3 Lepton-number violation in $B^+ \rightarrow h^- \ell^+ \ell'^+$

Two different analyses were performed by BABAR, each with a different set of selection criteria. The first looked for the decays $B^+ \rightarrow h^- \ell^+ \ell'^+$, where $h$ is either a pion or a kaon and $\ell$ is a same-flavour electron or muon. The decay mechanism is fairly similar to the neutrinoless double-beta decays. Again candidate events are selected with more than four charged tracks originating from the same vertex and with same-sign charged leptons in the final state. In this analysis a veto is applied to remove backgrounds originating from the decay of a $B$ meson to $J/\psi$ or $\psi(2S)$ and a pion or kaon. Other types of backgrounds are reduced by forming a boosted decision tree using 18 event-shape variables.
The signal $m_{ES}$ and $\Delta E$ distributions are parametrised using a Gaussian PDF where the mean and width parameters are determined from a fit to the kinematically similar decay $B^+ \to J/\psi(\ell^+\ell^-)h^+$. Figure 4 shows the resultant fit (blue solid line) over the data points for $m_{ES}$ for all the $B^+ \to h^-\ell^+\ell^+$ decay modes. The green area is the overall signal. We do not observe significant signals for any of these modes and find 90% confidence level upper limits of the order of $10^{-8}$. In Figure 5 the branching fraction upper limits are plotted against the $\ell^+h^-$ invariant mass. If the decay of $B^+ \to h^-\ell^+\ell^+$ is governed by the exchange of a Majorana neutrino, then $m_{\ell^+h^-}$ is directly related to the neutrino mass [2].

![Figure 4: $m_{ES}$ projection distributions for the decays $B^+ \to h^-\ell^+\ell^+$, where $h$ is either a kaon or a pion and $\ell$ a same-flavour lepton. The blue solid line is the overall fit, the solid green shape the overall signal and the black points with error bars the data.](image)

The second analysis, performed recently by BaBar, searched for 11 decay modes: $B^+ \to \rho^-\ell^+\ell^+$, $B^+ \to K^{*-}(\to K^0\pi^-(K^-\pi^0))\ell^+\ell^+$, $B^+ \to D^-(\to K^-\pi^-\pi^+)\ell^+\ell^+$ and $B^+ \to K^-(\pi^-)e^+\mu^+$. The difference here is that the lepton $\ell$ may not be of the same flavour. These types of decays can occur if the Majorana neutrino oscillates during the exchange. Hence $B^+ \to h^-e^+\mu^+$ decays, where $h$ here can be any of the above listed final-state mesons, are also lepton-flavour violating. Most of these decays, except for the few listed above, have only been previously studied by the CLEO Collaboration, which published upper limits at 90% confidence level for final states containing a $\pi$, $K$, $\rho$ or $K^*$ of order $(1.0 - 8.3) \times 10^{-6}$ [5]. The Belle Collaboration, and LHCb in the $\mu^+\mu^+$ case only, both measured upper limits for the decays to $D$ mesons of the order of $10^{-6}$ [6] [7].
Figure 5: Upper limits for the $B^+ \rightarrow h^-\ell^+\ell^+$ decays plotted against the $h^-\ell^+$ invariant mass. If the decay process proceeds via the exchange of a Majorana neutrino then this quantity is related to the neutrino mass.

The analysis follows a similar procedure to the previously mentioned analysis, only that selections are tailored to select efficiently all 11 decay modes in one selection procedure. The boosted decision tree in this analysis only includes 9 event-shape variables. Signal $m_{ES}$ and $\Delta E$ distributions are modelled in the fit to data using a Crystal Ball function. Figure 6 shows projections of fit variables for data, for the fit (blue solid line) and overall signal (green solid area) using $B^+ \rightarrow K^-e^+\mu^+$ as an example. Preliminary results show that no significant signal is found in any of the channels, and 90% confidence level upper-limits are set ranging between $(1.5 - 26.4) \times 10^{-7}$. Figure 7 shows a plot of all the upper-limit measurements to date made by the different collaborations, including the new BABAR preliminary upper limits, which are indicated with solid magenta triangles. We have the most stringent upper limits for the following decays: $B^+ \rightarrow \pi^-e^+\mu^+$, $B^+ \rightarrow K^-e^+\mu^+$, and all the decays to $\rho$ or $K^*$. Our results for the upper limits in the decays to a $D$ meson are comparable to the results obtained by both Belle and LHCb. This plot also shows that we still hold the most stringent upper limits in the decays to $\Lambda(c)$ and $K^-(\pi^-)e^+e^+$. Our $B^+ \rightarrow K^-\mu^+\mu^+$ upper limit is comparable to the upper limit obtained by the LHCb Collaboration.

4 Conclusion

BABAR has searched for many lepton-number violating decays; however no significant signal was found for any of the decay modes. Our measurements give more stringent 90% confidence level upper limits compared to the other experiments for most
Figure 6: $m_{ES}$ and $\Delta E$ projection distributions for the decay $B^+ \rightarrow K^- e^+ \mu^+$. The blue solid line is the overall fit, the solid green shape the overall signal and the black markers indicate the data points.

Figure 7: Summary of all 90% confidence-level upper limits for all the lepton-number violating $B$ decays measured. Blue circles indicate the published $\text{BaBar}$ measurements and solid magenta triangles the new preliminary results. Other measurements include the CLEO Collaboration (black diamonds), Belle (red squares) and LHCb (open triangles). Note that LHCb upper limits are quoted at 95% confidence level.

of the decays studied. Our best sensitivity to branching fractions for these modes is of the order of $10^{-8}$. Higher luminosity experiments such as Belle-II and LHCb can still increase the sensitivity to these decays. However, the higher background levels can make study of these rare decays more difficult. Some future experiments will be specifically designed to look for lepton-number violation and lepton-flavour violation. One of these is the Mu2e experiment at Fermilab, which will search for muons converting to electrons. The goal of the experiment is to be able to reach a sensitivity to this type of process of the order of $10^{-17}$. Other experiments specifically designed
for these types of searches include neutrinoless double-beta decay experiments.

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