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Search for the Decay $B^+ \to K^+ \nu\bar{\nu}$


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We search for the rare flavor-changing neutral-current decay $B^+ \rightarrow K^+ \nu \bar{\nu}$ in a data sample of $82 \text{ fb}^{-1}$ collected with the BABAR detector at the PEP-II $B$-factory. Signal events are selected by examining the properties of the system recoiling against either a reconstructed hadronic or semileptonic charged-$B$ decay. Using these two independent samples we obtain a combined limit of $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) < 5.2 \times 10^{-3}$.
10^{-5}$ at the 90\% confidence level. In addition, by selecting for pions rather than kaons, we obtain a limit of $\mathcal{B}(B^+ \to \pi^+ \nu \bar{\nu}) < 1.0 \times 10^{-4}$ using only the hadronic $B$ reconstruction method.

The presence of two neutrinos in the final state precludes the direct reconstruction of the $B^0 \to K^+ \nu \bar{\nu}$ signal mode. Instead, the $B^-$ meson from an $Y(4S) \to B^+ B^-$ event is reconstructed in one of many semileptonic or hadronic decay modes; then all remaining charged and neutral particles in that event are examined under the assumption that they are attributable to the decay of the accompanying $B$.

The $B^-$ reconstruction proceeds by combining a $D^0$ candidate with either a single identified charged lepton or a combination $X_{\text{had}}$ of charged and neutral hadrons. The resulting semileptonic and hadronic charged-$B$ samples are referred to as $B_{s\ell}$ and $B_{\text{had}}$ throughout this Letter. The $D^0$ candidates are reconstructed by selecting combinations of identified pions and kaons that yield an invariant mass within approximately $3\sigma$ of the expected $D^0$ mass in the modes $K^- \pi^+ + K^- \pi^+ \pi^0$, and $K^- \pi^+ \pi^+ \pi^-$. For $B_{\text{had}}$ reconstruction, $D^0 \to K^0_{s\ell} \pi^+ \pi^-$ is also used.

Photon candidates are obtained from EMC clusters with laboratory-frame energy greater than 30 MeV and no associated charged track. Photon pairs that combine to yield $\gamma \gamma$ invariant masses between 115 MeV/$c^2$ and 150 MeV/$c^2$ and total energy greater than 200 MeV are considered to be $\pi^0$ candidates.

The $B_{s\ell}$ candidates are reconstructed by combining a $D^0$ candidate having a momentum $p_{D}\ell > 0.5$ GeV/$c$ with a lepton candidate of momentum $p_{\ell}\ell > 1.35$ GeV/$c$ that satisfies either electron or muon identification criteria. The invariant mass, $m_{D\ell}$, of the $D^0 \ell$ candidate is required to be greater than 3.0 GeV/$c^2$. Under the assumption that the neutrino is the only missing particle, the cosine of the angle between the inferred direction of the reconstructed $B$ and that of the lepton, $D^0 \ell$ combination, described by the four vector $(E_{D\ell}, \mathbf{p}_{D\ell})$, is

$$\cos\theta_{B,D\ell} = \frac{2E_{\text{beam}} \cdot E_{D\ell} - m_B^2 - m_{D\ell}^2}{2|\mathbf{p}_{D\ell}| \cdot \sqrt{E_{\text{beam}}^2 - m_B^2}},$$

where $m_B$ is the nominal $B$ meson mass and $E_{\text{beam}}$ and $\sqrt{E_{\text{beam}}^2 - m_B^2}$ are the expected $B$-meson energy and momentum, respectively. We use $\cos\theta_{B,D\ell}$ to discriminate against combinatorial backgrounds, for which $|\cos\theta_{B,D\ell}|$ can exceed unity. We retain events in the interval $-2.5 < \cos\theta_{B,D\ell} < 1.1$ in order to maintain efficiency for $B^0 \to D^{\ast\pm} \ell^- \bar{\nu}$ decays in which a $\pi^0$ or photon has not been reconstructed as part of the $D\ell$ combination. However, events are vetoed if a charged $\pi$ consistent with $B^0 \to D^{\ast\pm} \ell^- \bar{\nu}$ is identified. If more than one $D\ell$ candidate is reconstructed in a given event, the candidate with the smallest $|\cos\theta_{B,D\ell}|$ is retained.
Reconstructed $B_{\text{had}}^-$ decays are obtained by combining a reconstructed $D^0$ candidate with a hadronic system $X_{\text{had}}$ composed of up to five mesons ($\pi^\pm$, $K^\pm$, and $\pi^0$), including up to two $\pi^0$ candidates. We define the kinematic variables $m_{\text{ES}} = \sqrt{E_{\text{beam}}^2 - p_B^2}$ and $\Delta E = E_B - E_{\text{beam}}$, where $p_B$ and $E_B$ are the momentum and the energy of the $B_{\text{had}}^-$ candidate. The $X_{\text{had}}$ system is selected by requiring that the resulting $B_{\text{had}}^-$ candidate lies within $-1.8 < \Delta E < 0.6$ GeV. If multiple $B_{\text{had}}^-$ candidates are identified in an event, only the one with $\Delta E$ closest to zero is retained. The $m_{\text{ES}}$ distribution of reconstructed $B_{\text{had}}^-$ candidates is shown in Fig. 1(b). $B_{\text{had}}^-$ candidates in the signal region, $5.272 < m_{\text{ES}} < 5.288$ GeV/c$^2$, are used for the $B^+ \rightarrow K^+ \nu \bar{\nu}$ signal selection. Candidates in the sideband region, $5.225 < m_{\text{ES}} < 5.265$ GeV/c$^2$, are retained for background studies.

Combinatorial backgrounds from continuum events are reduced in both the $B_{\text{sl}}^-$ and $B_{\text{had}}^-$ samples by requiring $|\cos \theta_T| < 0.8$, where $\theta_T$ is the angle between the thrust axes defined by the $B_{\text{sl}}^-$ or $B_{\text{had}}^-$ daughter particles, and by all other tracks and clusters in the event. Continuum events peak at $|\cos \theta_T| = 1$, while the distribution is approximately flat for $BB$ backgrounds. Events contain an EMC cluster that is not associated either with the decay daughters of the $B^-$ or with the signal track. Events are required to have $E_{\text{extra}} < 250$ MeV. The $E_{\text{extra}}$ distributions are shown in Fig. 2 for $B_{\text{sl}}^-$ and $B_{\text{had}}^-$ events with one additional track that has been identified as a kaon. The $B_{\text{had}}^-$ analysis additionally requires that there are six or fewer clusters contributing to $E_{\text{extra}}$, and that no pair of these clusters can be combined to form a $\pi^0$ candidate.

The total $B^+ \rightarrow K^+ \nu \bar{\nu}$ signal-selection efficiencies, including the $B^-$ reconstruction, are estimated to be $\varepsilon_K = (0.115 \pm 0.009)\%$ for $B_{\text{sl}}^-$ and $\varepsilon_K = (0.055 \pm 0.005)\%$ for $B_{\text{had}}^-$ events. The quoted errors are the quadratic sum of statistical and systematic uncertainties. Theoretical uncertainties in the $K^-$ energy spectrum result in a 1.3% uncertainty on the signal efficiency. This uncertainty is evaluated by comparing the $p_K$ spectrum of $B^+ \rightarrow K^+ \nu \bar{\nu}$ MC events generated with a phase-space model with the models given.

![FIG. 1](image1.png) (a) The $D^0$ mass distribution for $D^0 \rightarrow K^- \pi^+$ decays used for $B_{\text{sl}}^-$ reconstruction. Data are shown as points and the total background MC simulation is shown as a solid histogram. (b) The $m_{\text{ES}}$ distribution of $B_{\text{had}}^-$ events for data (points) and $BB$ MC simulation (solid histogram). Continuum background has been subtracted from the on-resonance data using off-resonance data. The hatched histogram represents the estimated combinatorial background from $BB$ decays.

![FIG. 2](image2.png) The $E_{\text{extra}}$ distribution for $B^+ \rightarrow K^+ \nu \bar{\nu}$ $B_{\text{sl}}^-$ (left) and $B_{\text{had}}^-$ (right) events. Events are required to have a reconstructed $B^-$ and exactly one additional track which has been identified as a kaon. No other signal-selection cuts have been applied. The data and background MC samples are represented by the points with error bars and solid histograms, respectively. The dotted line indicates the expected $B^+ \rightarrow K^+ \nu \bar{\nu}$ signal distribution from MC simulation.
in [3,4]. Additional systematic uncertainties associated with the $B^+ \rightarrow K^+ \nu \bar{\nu}$ signal candidate efficiencies include the single track efficiency (1.3%), PID (2%), and EMC-energy-modeling (3.8% for $B^\pi_{sl}$ and 2.3% for $B^\pi_{had}$). The EMC-energy-modeling systematic is determined by evaluating the effect of varying the MC $E_{extra}$ distribution within a range representing the observed level of agreement with data in events with a reconstructed $B^+ \rightarrow D^0 \ell^+ \nu$ (for the $B^\pi_{sl}$ sample) and in samples containing two or three additional tracks (for the $B^\pi_{had}$ sample).

Background events can arise either from $B^0 \bar{B}^0$ or continuum events in which the $B^-$ candidate is constructed from a random combination of particles, or peaking background events in which the accompanying $B^-$ (or in the case of $B^\pi_{sl}$, at least the $D^0$) has been correctly reconstructed.

In the $B^\pi_{sl}$ analysis, purely combinatorial backgrounds are estimated by examining sideband regions of the reconstructed $D^0$ invariant mass distribution, $m_{D^0}^{\text{reco}}$, defined by $3\sigma < |m_{D^0}^{\text{reco}} - m_{D^0}| < 10\sigma$ as is illustrated in Fig. 1(a) for the $D^0 \rightarrow K^- \pi^+$ mode. The sideband yields are scaled to the signal region under the assumption that the combinatorial component is flat throughout the $D^0$ mass distribution. This assumption has been validated using samples of events in which two or three tracks not associated with the $B^-$ reconstruction are present. The total combinatorial background in the $B^\pi_{sl}$ analysis is estimated to be $N^\text{bg}_{K^+} \geq 3.4 \pm 1.2$. Although the peaking background prediction in the $B^\pi_{sl}$ analysis have been studied in MC simulation and are shown in Figs. 2 and 3, the peaking background in the final selection is not subtracted.

In the $B^\pi_{had}$ analysis, the combinatorial background can be reliably estimated by extrapolating the observed yields in the $m_{ES}$ sideband region into the $m_{ES}$ signal region, indicated in Fig. 1(b), yielding $2.0 \pm 0.7$ events. The quoted uncertainty is dominated by the sideband data statistics but includes also the uncertainty in the combinatorial background shape, which is estimated by varying the shape over a range of possible models. The peaking background in the $B^\pi_{had}$ analysis consists only of $B^+ B^- \text{MC}$ events in which the $B^\pi_{had}$ has been correctly reconstructed and is estimated directly from $B^+ B^- \text{MC}$ simulation. MC yields are validated by direct comparison with data in samples of events in which the full signal selection is applied, except that either $E_{extra} > 0.5 \text{ GeV}$ or more than one track remains after the $B^-$ reconstruction. Uncertainties in the peaking background are dominated by the MC statistical uncertainty (42%). Other systematic errors include the overall $B^-$ yield (7%), the remaining track multiplicity (5%), the particle misidentification rates for the $K^\pm$ selection (6.3%), and the EMC-energy modeling (8%). The total peaking background in the $B^\pi_{had}$ analysis is estimated to be $1.9 \pm 0.9$. The total (combinatorial + peaking) background in the $B^\pi_{had}$ analysis is estimated to be $N^\text{bg}_{K^+} = 3.9 \pm 1.1$ events.

Optimization of the signal candidate selection and estimation of backgrounds and systematics were performed with the signal region in data concealed in order to avoid experimental bias. Unbinding of the signal region in data revealed a total of $N^\text{obs}_{K^+} = 6(3)$ $B^+ \rightarrow K^+ \nu \bar{\nu}$ candidate events in the $B^\pi_{sl}$ ($B^\pi_{had}$) analysis. The $p_K$ distributions for $B^+ \rightarrow K^+ \nu \bar{\nu}$ signal events are shown in Fig. 3. The $B^+ \rightarrow K^+ \nu \bar{\nu}$ branching fraction is calculated from

$$B(B^+ \rightarrow K^+ \nu \bar{\nu}) = \frac{N^\text{obs}_{K^+} - N^\text{bg}_{K^+}}{N_{B^+} \cdot e_{K}},$$

where $N^\text{obs}_{K^+}$ is the total number of observed events in the signal region. $N_{B^+} = (88.9 \pm 1.0) \times 10^6$ is the estimated number of $B^+$ mesons in the data sample and $e_{K}$ is the total efficiency.

Branching fraction upper limits are computed using a modified frequentist approach, based on Ref. [9], which models systematic uncertainties using Gaussian distributions. For both the $B^\pi_{sl}$ and $B^\pi_{had}$ searches, $B^+ \rightarrow K^+ \nu \bar{\nu}$ limits are set at the branching fraction value at which it is estimated that 90% of experiments would produce a yield that is greater than the number of signal events observed. Limits of $B(B^+ \rightarrow K^+ \nu \bar{\nu})_{sl} < 7.0 \times 10^{-5}$ and $B(B^+ \rightarrow K^+ \nu \bar{\nu})_{had} < 6.7 \times 10^{-5}$ are obtained for the $B^\pi_{sl}$ and $B^\pi_{had}$ searches, respectively. Since the two tag $B$ samples are statistically independent, we can combine the results of the two analyses to derive a limit of $B(B^+ \rightarrow K^+ \nu \bar{\nu}) < 5.2 \times 10^{-5}$ at the 90% C.L.

We also report a limit on the exclusive $B^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching fraction using only the $B^\pi_{had}$ sample. The same methodology as for the $B^+ \rightarrow K^+ \nu \bar{\nu}$ search is applied to the $B^+ \rightarrow \pi^+ \nu \bar{\nu}$ search except that the single additional track is required not to satisfy either kaon or electron PID criteria. The $E_{extra}$ and $p_{\pi}$ distributions for $B^+ \rightarrow \pi^+ \nu \bar{\nu}$ are shown in Fig. 4. The overall $B^+ \rightarrow \pi^+ \nu \bar{\nu}$ selection

![FIG. 3. The $p_K$ distribution for (a) $B^\pi_{had}$ and (b) $B^\pi_{sl}$ events after applying the full $B^+ \rightarrow K^+ \nu \bar{\nu}$ selection except for the $p_K > 1.25 \text{ GeV}/c$ requirement. The dotted line indicates the expected signal distribution from MC simulation. The data are represented by the points. The expected background distributions obtained from MC simulation are also plotted (solid histograms) although it should be noted that estimates of nonpeaking backgrounds are obtained directly from data and hence differ slightly from the MC estimates shown here.](101801-6)
efficiency is estimated to be $\varepsilon = (0.065 \pm 0.006)\%$, where the quoted uncertainties include an estimated 2% PID uncertainty, and other contributions to the systematic uncertainty are similar to $B^+ \to K^+ \nu \bar{\nu}$. The peaking and nonpeaking backgrounds are estimated to be $15.1 \pm 3.1$ events and $9.0 \pm 1.8$ events, respectively, with similar systematic uncertainties to the $B^+ \to K^+ \nu \bar{\nu}$ analysis. The search selects $N_{\text{obs}} = 21$ candidates in data with an estimated total background of $N_{\text{bg}} = 24.1 \pm 3.6$, resulting in an upper limit of $\mathcal{B}(B^+ \to \pi^+ \nu \bar{\nu})_{\text{had}} < 1.0 \times 10^{-4}$ at the 90% C.L.

We see no evidence for a signal in either of the reported decay modes. The $\mathcal{B}(B^+ \to K^+ \nu \bar{\nu})$ limit reported here is approximately 1 order of magnitude above the SM prediction. It is the most stringent experimental limit reported to date.

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