Search for $B^0$ Decays to Invisible Final States and to $\nu\gamma$
We establish upper limits on branching fractions for $B^0$ decays to final states where the decay products are purely invisible (i.e., no observable final state particles) and for $B^0_s$ decays to $\phi\phi$. Within the standard model, these decays have branching fractions that are below current experimental sensitivity, but various models of physics beyond the standard model predict significant contributions from these channels. Using $88.5 \times 10^6$ $B\bar{B}$ pairs collected at the $Y(4S)$ resonance by the BABAR...
This Letter describes a novel search for “disappearance decays” of $B^0$ mesons [1], where the $B^0$ decay contains no observable final state particles, or such “invisible” decay products plus a single photon. Invisible decay products are particles that are neither charged nor would generate a signal in an electromagnetic calorimeter. These include neutrinos, as well as exotic, hypothetical particles (such as neutralinos). The rate for invisible $B$ decays is negligibly small within the standard model (SM) of particle physics but can be larger in several models of new physics. The SM decay $B^0 \rightarrow \nu \bar{\nu}$, which would give such an invisible experimental signature, is strongly helicity-suppressed by a factor of order $(m_\tau/m_\rho)^2$ [2]. When combined with the weak coupling constant $G_F$, the resulting branching fraction is necessarily well below the range of present experimental observability. The SM expectation for the $B^0 \rightarrow \nu \bar{\nu} \gamma$ branching fraction is predicted to be of order $10^{-9}$ with very little hadronic uncertainty [3]. An experimental observation of an invisible $(\gamma + \gamma)$ decay of a $B^0$ with current experimental sensitivity would thus be a clear sign of beyond-SM physics, as it could not be accommodated within SM theoretical uncertainty. No quantitative experimental bounds on $B^0$ to invisible or $\nu \bar{\nu} \gamma$ have been previously established; however, a reinterpretation of data used for previous constraints on $b \rightarrow s \nu \bar{\nu}$ and other modes could potentially imply upper limits on the quark-level process of this decay [4].

Several models of new physics can give significant branching fractions for invisible decays of the $B^0$. A phenomenological model motivated by the observation of an anomalous number of dimuon events by the NuTeV experiment allows for an invisible $B^0$ decay to a $\nu \bar{\nu} \chi^0_n$ final state, where $\chi^0_n$ is a neutralino, with a branching fraction in the $10^{-7}$ to $10^{-6}$ range [5,6]. Also, models with large extra dimensions, which would provide a possible solution to the hierarchy problem, can also have the effect of producing significant, although small, rates for invisible $B^0$ decays [7–9].

The data used in this analysis were collected with the BABAR detector at the PEP-II $e^+e^-$ storage ring at the Stanford Linear Accelerator Center, we establish upper limits at the 90% confidence level of $22 \times 10^{-5}$ for the branching fraction of $B^0 \rightarrow \nu \bar{\nu} \gamma$.实验结果表明，$B^0$ mesons decay into invisible final states at a rate consistent with the SM expectations. Invisible decays are characterized by the absence of any detectable final state particles, or the presence of a single photon and an invisible particle combination. These decays are of particular interest as they can serve as signatures for new physics beyond the Standard Model (SM). 

The BABAR detector, operating at the PEP-II $e^+e^-$ collider at SLAC, exploits these invisible signatures to search for new physics. The data used in this analysis consist of an integrated luminosity of 81.5 fb$^{-1}$, accumulated at the Y(4S) resonance, containing 88.5 ± 1.0 $\times 10^6$ $B\bar{B}$ pair events, and 9.6 fb$^{-1}$ accumulated at a center-of-mass (c.m.) energy about 30 MeV below $B\bar{B}$ threshold. The asymmetric energy distributions of the PEP-II $e^+$ and $e^-$ beams result in a Lorentz boost $\beta\gamma = 0.55$ of the $B\bar{B}$ pairs.

A detailed description of the BABAR detector is presented in Ref. [10]. Charged particle momenta are measured in a tracking system consisting of a 5-layer double-sided silicon vertex tracker (SVT) and a 40-layer hexagonal-cell wire drift chamber (DCH). The SVT and DCH operate within a 1.5 T solenoidal field and have a combined solid angle coverage in the c.m. frame of 90.5%. Photons and long-lived neutral hadrons are detected and their energies are measured in a CsI(Tl) electromagnetic calorimeter (EMC), which has a solid angle coverage in the c.m. frame of 90.9%. Muons are identified in the instrumented flux return (IFR), composed of resistive plate chambers and layers of iron that return the magnetic flux of the solenoid. A detector of internally reflected Cherenkov light (DIRC) is used for identification of charged kaons and pions. A GEANT4 [11] based Monte Carlo simulation of the BABAR detector response was used to optimize the signal selection criteria and evaluate the signal detection efficiency.

The detection of invisible $B$ decays uses the fact that $B$ mesons are created in pairs, due to flavor conservation in $e^+e^-$ interactions. If one $B$ is reconstructed in an event, one can thus infer that another $B$ has been produced. This technique has been exploited in several BABAR analyses [12,13]. We reconstruct events in which a $B^0$ decays to $D^{(*)} \rightarrow \ell^+\nu$, then look for consistency with an invisible decay of the other neutral $B$ (no observable final state particles) in the rest of the event. In order to help reject non-$B\bar{B}$ background, $R_2$, the ratio of the second and zeroth Fox-Wolfram moments, is required to be less than 0.5 [14].

We reconstruct $D^{(*)}$ in the decay modes $D^+ \rightarrow K^+\pi^-\pi^-$ and $D^{*-} \rightarrow D^0\pi^-$, where, in the latter case, $D^0$ is reconstructed in the decay modes $K^-\pi^+, K^+\pi^-\pi^0$, or $K^-\pi^+\pi^-\pi^-$. To form $D^{(*)}$ candidates in these decay modes, $K^+$ candidates are combined with other tracks and $\pi^0$ candidates in the event. We identify $K^+$ candidates using Cherenkov-light information from the DIRC and energy-loss information $(dE/dx)$ from the DCH and SVT. The $\pi^0$ candidates are composed of pairs of photons in the EMC. Each photon must have a reconstructed energy above 30 MeV in the laboratory frame, and the sum of their energies must be greater than 200 MeV. The $\pi^0$ candidates must have an invariant mass between 115 and 150 MeV/$c^2$. A mass-constrained fit is imposed on $\pi^0$ candidates in order to improve the resolution on the reconstructed invariant mass of the parent $D$ meson.

We require the $D^{(*)}$ and $D^-$ candidates to have reconstructed invariant masses within 20 MeV/$c^2$ of their respective nominal masses [15], except for $D^0$ decays with a $\pi^0$ daughter, which must be within 35 MeV/$c^2$ of the nominal $D^0$ mass. Mass-constrained fits are applied to $D^0$ and $D^-$ candidates in order to improve the
measurement of the momentum of each \( D \). The difference in reconstructed mass between \( D^{(*)} \) decay candidates and their \( D^0 \) daughters must be less than 150 MeV/c^2. All \( D^{(*)} \) candidates must have a total momentum between 0.5 and 2.5 GeV/c in the c.m. frame.

Tracks selected as lepton candidates must pass either electron or muon selection criteria. We identify electron candidates using energy and cluster shape information from the EMC and Cherenkov angle information from the DIRC. Muons are identified using information from the IFR and EMC. Both electrons and muons must also have a momentum of at least 1 GeV/c and a minimum of 20 DCH measurements.

To select \( B^0 \rightarrow D^{(*)} \ell^+ \nu \) candidates, we require a \( D^{(*)} \) candidate and a lepton candidate to be consistent with production at a common point in space. We then calculate the cosine of the angle between the \( D^{(*)} \) and the hypothesized \( B^0 \) candidate, under the assumption that the only particle missing is a neutrino:

\[
\cos \theta_{B,D^{(*)}\ell^+\nu} = \frac{(2E_B E_{D^{(*)}\ell^+\nu} - m_B^2 - m_{D^{(*)}\ell^+\nu}^2)}{2|\vec{p}_B||\vec{p}_{D^{(*)}\ell^+\nu}|}.
\]

The energy \( E_{D^{(*)}\ell^+\nu} \) and mass \( m_{D^{(*)}\ell^+\nu} \) of the \( D^{(*)} \ell^+\nu \) combination are determined from reconstructed momentum information, and \( m_B \) is the nominal \( B^0 \) mass. The \( B^0 \) momentum \( |\vec{p}_B| \) and energy \( E_B \) are determined from beam parameters. When the assumption that a neutrino is the only missing particle is incorrect, \( \cos \theta_{B,D^{(*)}\ell^+\nu} \) can fall outside the region \([-1, 1]\). We thus require the \( D^{(*)} \ell^+ \nu \) combination to satisfy \(-2.5 < \cos \theta_{B,D^{(*)}\ell^+\nu} < 1.1\). The asymmetric cut admits higher mass \( D^* \) states where the additional decay products are lost and allows for detector energy and momentum resolution. When more than one such \( D^{(*)} \ell^+\nu \) candidate is reconstructed in an event, the one with the smallest value of \( |\cos \theta_{B,D^{(*)}\ell^+\nu}| \) is taken. We reconstruct a total of 126 108 \( B^0 \rightarrow D^{(*)} \ell^+ \nu \) candidate events in the data sample, with a purity of approximately 66%.

We consider events with no charged tracks besides those of a \( B^0 \rightarrow D^{(*)} \ell^+ \nu \) candidate. Removing all decay products of the \( D^{(*)} \ell^+ \nu \) candidate from consideration, we count the number of remaining EMC clusters consistent with a \( K^0_{L2} \) hypothesis, \( N_{\text{extr}}^{K^0_{L2}} \), and with a photon hypothesis, \( N_{\text{extr}}^\gamma \). Because of accelerator-induced background and detector noise, the optimal requirements on \( N_{\text{extr}}^{K^0_{L2}} \) and \( N_{\text{extr}}^\gamma \) are loose. For \( B^0 \rightarrow \text{invisible} \) candidates, we require that \( N_{\text{extr}}^{K^0_{L2}} < 3 \) and \( N_{\text{extr}}^\gamma < 3 \). For \( B^0 \rightarrow \nu \bar{\nu} \gamma \) candidates, we require only that there be one remaining photon candidate with energy greater than 1.2 GeV in the c.m. frame.

The total energy in the EMC, in the c.m. frame, of photon clusters that remain after the decay products of the \( D^{(*)} \ell^+ \nu \) candidate are removed, is denoted by \( E_{\text{extra}} \). For \( B^0 \rightarrow \nu \bar{\nu} \gamma \), the energy of the highest-energy photon remaining in the event (the hypothesized signal photon) is also removed from \( E_{\text{extra}} \). In both \( B^0 \rightarrow \text{invisible} \) and \( B^0 \rightarrow \nu \bar{\nu} \gamma \), this variable is strongly peaked near zero for signal, whereas for the background it is less strongly peaked, as seen in Fig. 1. The background can peak near zero due to events in which all charged and neutral particles from the signal \( B^0 \) are either outside the fiducial volume of the detector or are unreconstructed. For \( B^0 \rightarrow \nu \bar{\nu} \gamma \), the background shape increases at large \( E_{\text{extra}} \) due to photons arising from misreconstructed \( \pi^0 \) decays, and the best-fit amount of signal is slightly (but not significantly) negative. We construct probability density functions (PDFs) for the \( E_{\text{extra}} \) distribution for signal (\( \mathcal{F}_{\text{sig}} \)) and background (\( \mathcal{F}_{\text{bkgd}} \)) using detailed simulation of signal and background data. The background from accelerator and detector noise is modeled using randomly triggered events in data. The two PDFs are combined into an extended maximum likelihood function \( L \), defined as a function of the free parameters \( N_{\text{sig}} \) and \( N_{\text{bkgd}} \):

\[
L(N_{\text{sig}}, N_{\text{bkgd}}) = \frac{e^{-(N_{\text{sig}}+N_{\text{bkgd}})}}{N!} \prod_{i=1}^{N} \left[ N_{\text{sig}} \mathcal{F}_{\text{sig}}(E_i) + N_{\text{bkgd}} \mathcal{F}_{\text{bkgd}}(E_i) \right],
\]
Of signal events that contain a reconstructed track momentum resolution, and the total number of events in the data sample. The total systematic uncertainty on the number of signal events are 7.4 and 4.3 events for $B^0 \rightarrow \text{invisible}$ and $B^0 \rightarrow \nu \bar{\nu} \gamma$, respectively. Other systematic uncertainties include the efficiency for reconstructing the charged tracks in the $B^0 \rightarrow D^{(*)} \ell^+ \nu \gamma$ decay, the charged track momentum resolution, and the total number of $B\bar{B}$ events in the data sample. The total systematic uncertainties on the efficiency are 10.9% and 11.1% and on the fitted number of signal events are 7.4 and 4.3 events for $B^0 \rightarrow \text{invisible}$ and $B^0 \rightarrow \nu \bar{\nu} \gamma$, respectively.

To determine 90% confidence level (C.L.) upper limits on the branching fractions of $B^0 \rightarrow \text{invisible}$ and $B^0 \rightarrow \nu \bar{\nu} \gamma$, we generate 8000 Monte Carlo experiments, each parametrized by the fitted numbers of signal and background events, the efficiency, and the number of $B\bar{B}$ events in the data sample. Errors are incorporated into the simulated experiments via a convolution of the systematic effects (treated as Gaussian distributions) and the statistical error (taken from the non-Gaussian likelihood function from the fit).

The resulting upper limits on the branching fractions are

$$B(B^0 \rightarrow \text{invisible}) < 22 \times 10^{-5}$$

and

$$B(B^0 \rightarrow \nu \bar{\nu} \gamma) < 4.7 \times 10^{-5} \text{ at 90% C.L.}$$

If the $B^0 \rightarrow \text{invisible}$ branching fraction were zero, the probability of observing an equal or larger signal yield would be 6%.

We perform validation cross-checks on the results of this analysis. To check the measurement of the efficiency for reconstructing $B^0 \rightarrow D^{(*)} \ell^+ \nu$ decays (which was determined using Monte Carlo simulation), we select a data sample in which a $B^0$ and a $B^0$ are both reconstructed as decays to $D^{(*)} \ell \nu$ in the same event. Using the ratio of such “double tag” data events to events where just a single $D^{(*)} \ell \nu$ is reconstructed and the number of $B\bar{B}$ events in the full data sample, we determine the efficiency for $B^0 \rightarrow D^{(*)} \ell^+ \nu$ reconstruction in data. The result is consistent with that obtained from Monte Carlo simulation.

We also search for the unphysical modes $B^0 \rightarrow \text{invisible}$ and $B^\pm \rightarrow \nu \bar{\nu} \gamma$ (which would violate charge conservation) to check that their resulting signal is consistent with zero. For these modes, we reconstruct...
$B^\pm \rightarrow D^0 \ell \nu X^0$, where $X^0$ can be a photon, $\pi^0$, or nothing. The $D^0$ is reconstructed in the same three decay modes as in $B^0 \rightarrow D^{(*)-} \ell^+ \nu$, and similar criteria are enforced for the reconstructed $B$ as for the neutral $B$ modes. All systematic errors are considered, and the double tags validation above is also performed for $B^\pm$ reconstruction. The resulting fitted values of $N_{\text{sig}}$ are $-6^{+10}_{-9}(\text{stat}) \pm 6(\text{syst})$ for $B^0 \rightarrow \text{invisible}$ and $8^{+2}_{-3}(\text{stat}) \pm 4(\text{syst})$ for $B^\pm \rightarrow \nu \bar{\nu} \gamma$, which are both consistent with zero. Figure 3 shows the $E_{\text{extra}}$ distributions for the two validation modes.

In summary, we obtain limits on branching fractions for $B^0$ decays to an invisible final state and for $B^0$ decays to $\nu \bar{\nu} \gamma$. The upper limits at 90% confidence level are $2.2 \times 10^{-5}$ and $4.7 \times 10^{-5}$ for the $B^0 \rightarrow \text{invisible}$ and $B^0 \rightarrow \nu \bar{\nu} \gamma$ branching fractions, respectively. The latter limit assumes a photon momentum distribution predicted by the constituent quark model for $B^0 \rightarrow \nu \bar{\nu} \gamma$ decay [3], whereas the $B^0 \rightarrow \text{invisible}$ limit is not decay-model dependent.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from the A.P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

References:
[1] Charge-conjugate decay modes are implied throughout this Letter.
[12] BABAR Collaboration, B. Aubert et al., BABAR-CONF-03/06, hep-ex/0304020.