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## Rapid Communications

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# Improved upper limit on flavor-changing neutral-current decays of the *b* quark

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We report the results of a new search for flavor-changing neutral-current decays of the *b* quark, and present a 90%-confidence-level upper limit for the branching fraction for $B \rightarrow l^+l^-X$ of $1.2 \times 10^{-3}$.

Because the experimental absence of strangeness-changing neutral currents has played such an important role in the development of weak-interaction theory, it is natural to search for flavor-changing neutral currents (FCNC's) in the weak decays of mesons containing charm or *b* quarks. The standard model predicts that the lowest-order contributions due to the $Z^0$ vanish, and that the contributions from penguin diagrams and from higher-order weak diagrams lead to branching ratios for $b \rightarrow l^+l^-X$ of not more than $3 \times 10^{-6}$.[1] However, some nonstandard models predict substantial FCNC's in *b* decay. For example, if there were no *t* quark, and the *b* quark were a member of a left-handed singlet, then, as Kane and Peskin have shown,[2] the ratio $\Gamma(b\to l^+l^-X)/\Gamma(b\to l\nu X)$ must exceed 0.12, which gives $1.3\times10^{-2}$ for the branching fraction for $b\to l^+l^-X$. In string-inspired $E_6$ models FCNC's may be present, but the branching ratio for $b\to l^+l^-X$ is difficult to predict.[3]

Upper limits on the branching ratio for $b\to l^+l^-X$ have been set by several experiments.[4,5] The CLEO limit, $\frac{1}{2}[B(b\to\mu^+\mu^-X)+B(b\to e^+e^-X)] < 3.1\times10^{-3}$ at 90% confidence level, is substantially below the Kane-Peskin limit, and rules out the five-quark model. The limits set by other groups are weaker. In this Rapid Communication, we describe the analysis of a new data sample, and present an independent, improved upper limit on the branching ratio for $B\to l^+l^-X$.

Our approach is to search a sample of $\Upsilon(4S)$ decays for the final states $\mu^+\mu^-X$ and $e^+e^-X$. There are several expected sources of dilepton events. All can be reliably calculated and, in varying degrees, can be suppressed by kinematic cuts. Any excess in opposite-sign dilepton events in data, beyond the expectations from conventional sources, is attributed to FCNC's.

The data sample was collected with the CLEO detector at the Cornell Electron Storage Ring (CESR), and included 86000 $B\bar{B}$ events and 260000 continuum events from an integrated luminosity of 78 $\mathrm{pb}^{-1}$ at the $\Upsilon(4S)$. The detector, as used during this running period, differs only slightly from that described by Andrews *et al.*[6] Charged-particle tracks are reconstructed with a 10-layer precision drift chamber (vertex detector), followed by a 17-layer drift chamber, both in a 1.0-T axial magnetic field created by a 2-m-diameter superconducting solenoid. In addition to being used for track finding, the 17-layer chamber provides a measurement of specific ionization ($dE/dx$) for each track. Beyond the solenoid there are eight identical particle-identification octants. Each octant contains a three-layer planar drift chamber, a pressurized proportional-wire-chamber (PWC) system for measuring $dE/dx$, an array of 12 time-of-flight scintillators, and a 44-layer lead and proportional-tube shower counter. The octants are surrounded by 0.6 to 0.9 m of iron to absorb hadrons. Finally, there are two orthogonal wire-chamber layers outside the iron for muon identification. The vertex detector and the $dE/dx$ measurement capability of the 17-layer drift chamber are new features since the description of Ref. 6; all other aspects of the detector are as described there.

Identification of electrons is performed by a maximum-likelihood technique, using information from several detector components: $dE/dx$ from the 17-layer drift chamber, $dE/dx$ from the pressurized PWC system, time of flight and pulse height from the scintillation counters, and shower-development information from the shower counters. The identification algorithm was developed by comparing particles known to be electrons with particles known to be hadrons. Electron identification is performed over 46% of the solid angle, for all momenta above 0.6 GeV/$c$. The average identification efficiency between 1.5 and 3.0 GeV/$c$ is approximately 85%.

Particles are identified as muons if their tracks, as found in the central tracking chambers, project to within 0.32 m of the point defined by an orthogonal pair of struck wires in the muon chambers. Muon identification is performed over 75% of the solid angle. The momentum threshold for identification varies from 1.1 to 1.9 GeV/$c$, depending on the thickness of iron to be traversed. Above 1.9 GeV/$c$, the identification efficiency is 90%.

The probability of a hadron being misidentified as a lepton ($\mu$ or $e$) was determined by examining high-momentum tracks from three-gluon decays of the $\Upsilon(1S)$. It is believed that these decays will produce no real leptons, and so the fraction of particles identified as leptons determines the misidentification probability. With this approach, electrons from Dalitz decays of $\pi^0$ are classified as misidentified hadrons. For muons, the misidentification probability was also determined by a Monte Carlo simulation, and the results agreed to 13%, well within our assumed systematic error of ±20%. Typical misidentification probabilities are 1.3% for muons and 0.5% for electrons.

It is necessary to model the FCNC decays $B\to l^+l^-X$ to determine the efficiency with which they are detected. For this purpose we use a spectator-quark model for the decay $b\to l^+l^-s$, with a current-current interaction. For the lepton current we follow the Weinberg-Salam model. It is less clear what to do for the hadron current, and consequently we consider four possibilities: $V$, $A$, $V+A$, and $V-A$ couplings. In addition, we consider a constant matrix element (i.e., three-body phase space). We use $s$-quark masses between 150 and 500 MeV.

There are four conventional sources of real dilepton events which must be calculated and subtracted. (i) Both the $B$ and the $\bar{B}$ from $\Upsilon(4S)\to B\bar{B}$ decay semileptonically ("parallel decays"). (ii) Either the $B$ or the $\bar{B}$ decays semileptonically to charm, followed by the semileptonic decay of the charmed state, e.g., $B\to\bar{D}l^+\nu$, $\bar{D}\to Kl^-\nu$ ("cascade decays"). (iii) Either the $B$ or the $\bar{B}$ decays to $\psi$, followed by the leptonic decay of $\psi$, i.e., $B\to\psi X$, $\psi\to l^+l^-$ ("$\psi$ decays"). (In this category we include detected lepton pairs with one coming from the $\psi$ and the other coming from semileptonic decay of the other $B$.) (iv) The $D$ and $\bar{D}$ meson from the production of $c\bar{c}$ in the continuum under $\Upsilon(4S)$ both decay semileptonically ("continuum dileptons").

Parallel decays are readily calculated[5] from the single-lepton yield, which we obtain from the same data sample and with the same analysis techniques. A 10% correction is applied for the loss of opposite-sign dileptons due to $B^0\bar{B}^0$ mixing of 20%.[7] The calculation of cascade decays requires in addition the semileptonic decay branching ratio of $D^0$ and $D^+$,[8] the lepton momentum spectrum in semileptonic $D$ decay,[9] and the $D$ momentum spectrum in semileptonic $B$ decay.[10] The calculation of $\psi$ decays requires the branching ratio for $B\to\psi X$ and the momentum distribution of the $\psi$'s from that reaction.[11] Finally, the calculation of continuum dileptons requires the $D$ momentum spectrum for continuum-produced charm[10] along with the lepton momentum spectrum[9] and branching ratios[8] for semileptonic $D$ decay.

The initial requirements for an event to be classified as a dilepton event are that it is a hadronic event with five or more charged tracks, and that it includes two identified like-kind, oppositely charged leptons, i.e., $e^+e^-$ or $\mu^+\mu^-$. The momentum of each lepton must be below 3.0 GeV/*c* and above 1.5 GeV/*c*. Since all particles from *B* decay are below 3.0 GeV/*c*, the upper-momentum requirement eliminates a small fraction of the background from continuum events, and also events with badly measured tracks, while resulting in a negligible loss of FCNC events. The lower-momentum requirement strongly reduces cascade decays, $\psi$ decays, and continuum dileptons, with small loss of FCNC or parallel-decay events. At this stage in the analysis, the bulk of events are parallel decays.

If both leptons from an FCNC event are energetic enough to pass our momentum cut, they will tend to be back to back. This behavior is a consequence of momentum conservation, and depends only weakly on the particular matrix element chosen to describe the FCNC process. In contrast, the directions of the leptons from parallel decays are uncorrelated. By requiring that the angle between the two leptons exceeds 135°, we eliminate 82% of the parallel decays, and lose only 28% of the FCNC events.

Having required the leptons to be back to back, we use them to define an axis, the direction of $\mathbf{P}_{l^+}-\mathbf{P}_{l^-}$. For events in which one *B* decays by FCNC, the other *B* in the event will decay isotropically with respect to this axis. In contrast, continuum dileptons are jetlike, and have little momentum transverse to the axis. We can discriminate between these cases with a variable $S_\perp$ defined by

$$S_\perp = \frac{\sum P_j \sin\theta_j}{\sum P_i} \ .$$

$P_i$ is the momentum of the *i*th charged particle in the event. The sum in the denominator extends over all charged particles excluding the two leptons. The sum in the numerator extends only over charged particles in the cone $45° < \theta_j < 135°$, where $\theta_j$ is the angle between the lepton axis and the momentum vector of the *j*th charged particle. Imposing a cut of $S_\perp \geq 0.4$ eliminates 75% of the remaining continuum dileptons and 44% of the remaining parallel decays, while losing only 16% of the remaining FCNC events.

Summarizing, our selection requirements of FCNC events are (1) hadronic event with five or more charged tracks, (2) an identified $\mu^+\mu^-$ or $e^+e^-$, (3) both lepton momenta between 1.5 and 3.0 GeV/*c*, (4) included angle between the leptons greater than 135°, and (5) $S_\perp \geq 0.4$.

TABLE I. Observed and calculated numbers of dileptons (see text).

| | $\mu^+\mu^-+e^+e^-$ | $\mu^\pm e^\mp$ |
|---|---|---|
| Observed events | 20 | 13 |
| Lepton misidentifications | 3.2 ± 0.6 | 1.8 ± 0.4 |
| Observed − misident | 16.8 ± 4.5 | 11.2 ± 3.6 |
| Expected from conventional sources | | |
| Parallel decays | 6.0 ± 0.8 | 6.1 ± 0.8 |
| Cascade decays | 3.6 ± 0.6 | 1.5 ± 0.3 |
| $\psi$ decays | 3.1 ± 0.4 | 0.1 ± 0.1 |
| Continuum dileptons | 0.8 ± 0.2 | 0.8 ± 0.2 |
| Sum of conventional sources | 13.5 ± 1.7 | 8.5 ± 1.3 |
| Excess of (observed − misident) over conventional sources | 3.3 ± 4.8 | 2.7 ± 3.8 |

The results are shown in Table I. The number of apparent dilepton events in which one or both of the identified leptons is a misidentified hadron is computed using the misidentification probabilities previously described and the measured number of high-momentum tracks. These estimates are subtracted from the number of observed dilepton events to give the number of true dilepton events shown in Table I. The numbers of dilepton events expected from conventional sources are also shown in Table I. The errors on these numbers reflect the uncertainties in the background calculation due to uncertainties in branching ratios, in lepton detection efficiencies, and in modeling event shapes for the $S_\perp$ computation. The error in the sum of conventional sources includes an additional 10% systematic error, allowing for correlations among the errors in the separate sources. The excess of the number

TABLE II. Upper limits on the FCNC's branching ratio for five models of FCNC's and three choices of *s*-quark mass. Limits are at 90% confidence level.

| | $\frac{1}{2}[B(B\rightarrow\mu^+\mu^-X)+B(B\rightarrow e^+e^-X)]$ $(10^{-3})$ | | |
|---|---|---|---|
| $m_s$ (MeV) / Hadronic current | 150 | 300 | 500 |
| $V-A$ | 0.7 | 0.7 | 0.7 |
| $V+A$ | 0.8 | 0.7 | 0.8 |
| $V$ | 0.7 | 1.0 | 1.2 |
| $A$ | 0.7 | 0.7 | 0.6 |
| Three-body phase space | 0.6 | 0.6 | 0.6 |

of true dilepton events over that expected from conventional sources is 3.3 ± 4.8. Thus, there is no evidence for FCNC events.

Table I also lists the number of observed $\mu^{\pm}e^{\mp}$ events, the contribution of lepton misidentifications to this number, and the calculated number of $\mu^{\pm}e^{\mp}$ events from conventional sources. The agreement between observation and calculation provides a check on our procedures for calculating the background from conventional sources.

The observed excess of $3.3 \pm 4.8$ $\mu^+\mu^-$ and $e^+e^-$ events corresponds to a 90%-confidence-level upper limit of 10.2 events. The limits on the FCNC branching ratio implied by this number are listed in Table II, for five different models for FCNC's, and three choices of the $s$-quark mass. The weakest limit is obtained for a pure $V$ hadronic current and an $s$-quark mass of 500 MeV, and is

$$\frac{B(B\rightarrow\mu^+\mu^-X)+B(B\rightarrow e^+e^-X)}{2} < 1.2\times10^{-3} .$$

In summary, we have searched for the FCNC decay $b\rightarrow l^+l^-X$. We find no evidence for it, and place an upper limit on the branching ratio of $1.2\times10^{-3}$.

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