Observation of B-Meson Semileptonic Decays to Noncharmed Final States

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We report the first evidence of charmless semileptonic decays of B mesons. In the momentum interval 2.4–2.6 GeV/c where the background from $b \to cl\nu$ is negligible, the average of the measured $b \to ue\nu$ and $b \to u\mu\nu$ partial branching ratios is $\Delta B_{ub}(2.4,2.6) = (1.8 \pm 0.4 \pm 0.3) \times 10^{-4}$. Inclusion of data from the interval 2.2–2.4 GeV/c, where the lepton yield is dominated by $b \to cl\nu$, gives $\Delta B_{ub}(2.2,2.6) = (3.3 \pm 0.8 \pm 0.8) \times 10^{-4}$. $|V_{ub}/V_{cb}|$ depends on the theoretical model of $b \to ul\nu$ decay and is approximately 0.1.

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CP violation can be understood within the three-generation standard model only if all elements of the Kobayashi-Maskawa[1] quark-mass-mixing matrix are nonzero.[2] There has been no confirmed evidence[3] for a nonzero value of V_{ub} from studies of hadronic or semileptonic[4] B decays. We report here the observation of leptons with momenta near and above the kinematic limit (2.46 GeV/c) for $b \to cl\nu$ in $\Upsilon(4S) \to B\bar{B}$ decays. Since the contribution of $b \to cl\nu$ decays in this region is small, we interpret this as evidence for $b \to ul\nu$ decays.

Our B-meson sample consists of 212 pb^{-1} of e^+e^- annihilation data obtained at the peak of the $\Upsilon(4S)$ resonance with the CLEO detector at the Cornell Electron Storage Ring (CESR). A total of 244000 $\Upsilon(4S)$ events were produced. An additional 101 pb^{-1}, accumulated at total energies 60 MeV below the resonance, provides a sample of pure continuum events. One-day off-resonance (OFF) runs were alternated with two-day on-resonance (ON) runs during the whole data-taking period to minimize systematic differences between the two data sets. We estimate the continuum contribution to the ON yields by scaling the OFF yields by $f = 2.08 \pm 0.01$, the ratio of the ON and OFF luminosities, corrected for the energy dependence of the continuum cross section.

The CLEO detector, our standard event-selection criteria, and lepton detection have been described previously.[5] The data sample consists of hadronic events with five or more charged tracks including an identified lepton ($e^{\pm}$ or $\mu^{\pm}$). For momenta near 2.5 GeV/c, the overall efficiency for identifying μ's is 60%, and the probability of misidentifying a hadron track as a μ is 1.1%. The cor-

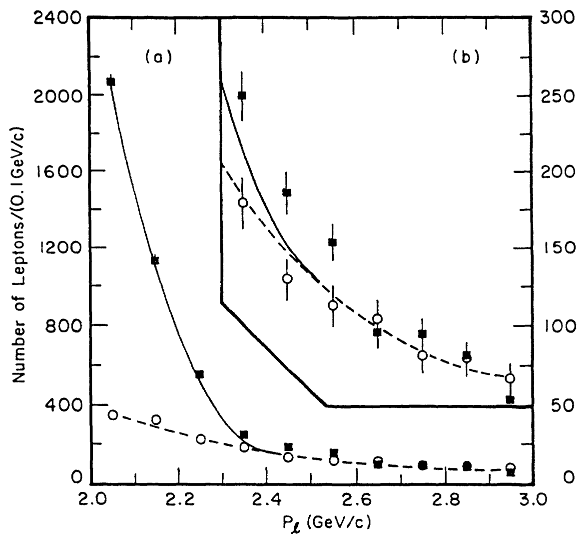

FIG. 1. Sum of the e and μ momentum spectra for ON data (filled squares), scaled OFF data (open circles), the fit to the OFF data (dashed line), and the fit to the OFF data plus the $b \to c l \nu$ yield (solid line). Note the different vertical scales in (a) and (b).

responding numbers for e's are 64% and 0.5%, respectively. To ensure the best possible momentum resolution, we impose strict track-quality cuts on lepton candidates.

Most of the observed leptons with momenta above 2.4 GeV/c are from continuum events. We use the Fox-Wolfram[6] event-shape parameter R_2 ($R_2 \equiv H_2/H_0$) to suppress continuum events with leptons. Nearly spherical $B\bar{B}$ events have R_2 values near zero, while two-jet continuum events have larger values of R_2. We calculate R_2 using charged tracks and neutrals and require $R_2 \leq 0.4$. We also analyze our data with limits of 0.3 and 0.5; within this range the results are insensitive to the limit. Monte Carlo simulations of continuum and B-decay events with high-momentum leptons predict that this requirement eliminates approximately 70% of the continuum yield, while retaining 90% of $b \to u l \nu$ events. We eliminate 93% of the background from $B \to \psi X$ decays by rejecting leptons that combine with any other track to give a mass within 60 MeV of the ψ mass.

Figure 1 shows the lepton momentum spectra for ON and OFF data after the R_2 cut. In the interval 2.4–2.6 GeV/c, where the contribution from $b \to c l \nu$ decays is minute, there is a substantial excess of ON data. To obtain the most accurate estimate of the continuum contribution, we fit the OFF lepton spectra by smooth functions as well as a Monte Carlo calculation of continuum charm production and decay. All approaches result in consistent good fits. This procedure significantly reduces the statistical uncertainty, but it introduces a modest systematic error, which we estimate from the spread in the fits. n_{ON} and n_{OFF}, the yields of lepton candidates from the ON and the fitted[7] OFF data, are given in Table I.

The number of leptons from $B\bar{B}$ events[8] is obtained by subtracting the estimated number of fake leptons (see Table I) from $y_s = n_{\mathrm{ON}} - f n_{\mathrm{OFF}}$. We obtain u_s, the yield of leptons from $b \to u l \nu$ decays, by subtracting the estimates of background leptons from $b \to c l \nu$, $B \to \psi' X$, and residual $B \to \psi X$ events, given in Table I. Except for a large $b \to c l \nu$ contribution for 2.2–2.4 GeV/c, all these backgrounds are small and their errors are inconsequential. Other potential backgrounds, such as leptons from D's, vector mesons, π^0 Dalitz decay, and mismeasured μ tracks from π or K decay, total less than one event. We find an excess of $u_s = 70 \pm 20 \pm 10$ leptons in the interval 2.4–2.6 GeV/c, which we attribute to $b \to u l \nu$ decays.[9]

We have estimated the contribution of $b \to c l \nu$ decays using the predicted lepton spectra of several theoretical models, ACCMM,[10] WSB,[11] and ISGW.[12] These predictions are smeared by our detector momentum resolution and corrected for QED effects.[13] They are normalized to the data in the momentum region 1.5–2.2 GeV/c, ignoring the small contribution from $b \to u l \nu$ suggested by our data, and extrapolated to the 2.4–2.6 GeV/c interval. All of the models give acceptable fits to our data.

Mismeasured tracks from the large number of $b \to c l \nu$ decays below 2.4 GeV/c are a possible background. The Gaussian tail of the momentum resolution ($\sigma_p \sim 23$

TABLE I. Lepton event yields, backgrounds, and the subtracted yields y_s and u_s.

Momentum	2.2–2.4 GeV/c	2.4–2.6 GeV/c
n_{ON}	$813.1 \pm 28.7 \pm 2.0$	$349.5 \pm 18.8 \pm 1.2$
n_{OFF}	$196.6 \pm 3.4 \pm 9.5$	$129.8 \pm 3.5 \pm 4.9$
Subtracted yield (y_s)	$404.2 \pm 29.5 \pm 19.9$	$79.5 \pm 20.2 \pm 10.3$
Fakes	$43.8 \pm 2.9 \pm 5.6$	$5.2 \pm 2.0 \pm 1.0$
Leptons from $B\bar{B}$	$360.4 \pm 29.6 \pm 20.7$	$74.3 \pm 20.3 \pm 10.3$
$b \to c l \nu$	$291.0 \pm 3.1 \pm 20.4$	$1.0 \pm 0.1 \pm 0.6$
$B \to \psi X$	$4.4 \pm 1.0 \pm 0.9$	$1.3 \pm 0.5 \pm 0.7$
$B \to \psi' X$	$3.4 \pm 0.8 \pm 1.1$	$1.6 \pm 0.6 \pm 0.8$
$b \to u l \nu$ (u_s)	$61.6 \pm 29.8 \pm 29.1$	$70.4 \pm 20.3 \pm 10.4$

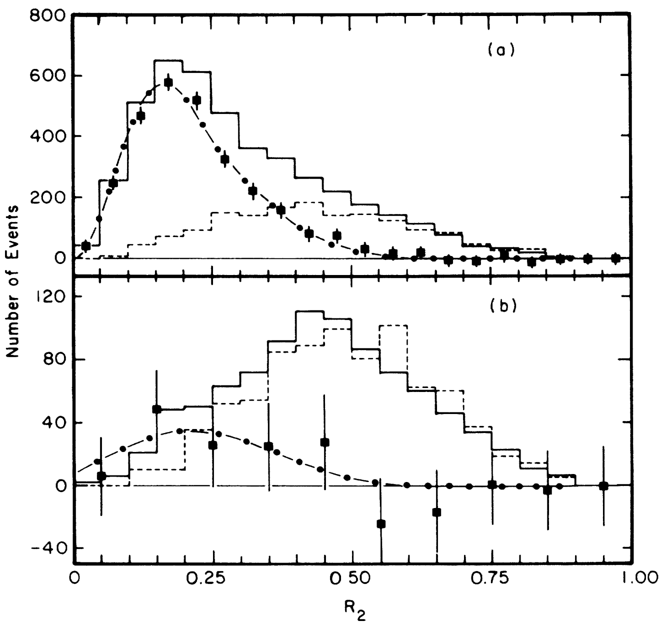

FIG. 2. R_2 distributions from ON data (solid histogram), OFF data (dashed histogram), the subtracted yield (filled squares), and Monte Carlo $B\bar{B}$ events (smooth dashed-dotted curve) for lepton momenta in the intervals (a) 2.0–2.2 GeV/c and (b) 2.4–2.6 GeV/c.

MeV/c in the end-point region) raises only very few leptons from $b \to c l \nu$ transitions to momenta above 2.4 GeV/c; this contribution is included in the estimate of $b \to c l \nu$. A larger background could potentially come from non-Gaussian tails due to incorrectly reconstructed tracks. However, μ pair tracks do not exhibit non-Gaussian tails; neither do e tracks from radiative Bhabha events reconstructed after being embedded in randomly selected hadronic events. Therefore, this potential background is negligible.

We can reduce the uncertainties in u_s by exploiting the differences in R_2 between $B\bar{B}$ and continuum events. The R_2 distributions for events with leptons in two momentum intervals are shown in Fig. 2. A large difference between the ON and OFF data is apparent in Fig. 2(a), where the $b \to c l \nu$ contribution is large. In Fig. 2(b), where the only B-decay contribution is from $b \to u l \nu$, there is also an excess at small R_2. To exploit these differences, we calculate $\langle R_2 \rangle$, the mean value of R_2, for lepton events with $R_2 \leq 0.4$. The values, $r_{\rm ON}$ and $r_{\rm OFF}$, obtained for the ON and OFF data are listed in Table II. To obtain r_B, our estimate of $\langle R_2 \rangle$ for $B\bar{B}$ events given in Table II, we use a Monte Carlo simulation of $B\bar{B}$ events with one B meson decaying in a $b \to u l \nu$ mode. The error in r_B is systematic and it is estimated from the spread of results for different models of $b \to u l \nu$ decays. We use these $\langle R_2 \rangle$ values to calculate y_r, an alternative to y_s for estimating the yield of lepton candidates,

$$y_r = n_{\rm ON} \frac{r_{\rm OFF} - r_{\rm ON}}{r_{\rm OFF} - r_B} . \qquad (1)$$

The statistical error in y_r is dominated by the errors in $r_{\rm ON}$ and $r_{\rm OFF}$, which do not appear in y_s, so the statistical errors in y_s and y_r are nearly independent. Table II includes y_r and u_r, the corresponding estimate of leptons from $b \to u l \nu$ decays, which is obtained from y_r by subtracting the fake leptons and B-decay backgrounds given in Table I. We calculate the average of y_r and y_s and the corresponding χ^2, taking the correlation between them into account. The correlation coefficient is $\rho = 0.17$ and the χ^2 is 0.3 for one degree of freedom. This value of χ^2 is evidence that y_s is not merely due to a fluctuation of the number of continuum events in the ON or OFF data, since the difference between the $\langle R_2 \rangle$ values of the ON and OFF data is also consistent with the $\langle R_2 \rangle$ expected for $B\bar{B}$ events. Table II gives $\langle y \rangle$ and $\langle u \rangle$, the corresponding yield of leptons from $B\bar{B}$ decay. We find $\langle u \rangle = 76 \pm 18 \pm 8$ in the interval 2.4–2.6 GeV/c.

Using the ISGW model to estimate the proportions of exclusive final states in the end-point region, we find overall detection efficiencies of $(42 \pm 4)\%$ and $(43 \pm 4)\%$ for e and μ events, respectively. The *average* of the $b \to u e \nu$ and $b \to u \mu \nu$ branching ratios is $\Delta B_{ub}(p) = (1.8 \pm 0.4 \pm 0.3) \times 10^{-4}$, where (p) denotes a partial branching ratio for leptons in the interval 2.4–2.6 GeV/c. We extract $|V_{ub}/V_{cb}|^2$ from $\Delta B_{ub}(p)$ using

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\Delta B_{ub}(p)}{B_{cb}} \frac{1}{d(p)} , \qquad (2)$$

where $d(p)$ is derived from theory and B_{cb} is the branch-

TABLE II. $\langle R_2 \rangle$ values from the ON and OFF data and for $B\bar{B}$ events. Yields derived from $\langle R_2 \rangle$ and the averages of these and the subtracted yields from Table I.

Momentum	2.2–2.4 GeV/c		2.4–2.6 GeV/c	
$r_{\rm ON}$	0.250 ± 0.003		0.278 ± 0.005	
$r_{\rm OFF}$	0.287 ± 0.006		0.302 ± 0.007	
r_B	0.213	± 0.007	0.216	± 0.010
Yield from $\langle R_2 \rangle$ (y_r)	406.5 ± 48.8	± 38.5	97.5 ± 29.3	± 11.3
$b \to u l \nu$ (u_r)	63.9 ± 49.0	± 43.9	88.4 ± 29.4	± 11.5
Average yield ($\langle y \rangle$)	404.6 ± 28.0	± 17.7	84.7 ± 17.8	± 8.1
$b \to u l \nu$ ($\langle u \rangle$)	62.0 ± 28.4	± 27.6	75.6 ± 18.0	± 8.2

TABLE III. $d(p)$ calculated from various theoretical models of $b \to ul\nu$ decay, the corresponding values of $|V_{ub}/V_{cb}|^2$, and weighted averages of the two momentum intervals.

	2.2–2.4 GeV/c		2.4–2.6 GeV/c		Average
Model	$d(p)$	$10^2 \lvert V_{ub}/V_{cb}\rvert^2$	$d(p)$	$10^2 \lvert V_{ub}/V_{cb}\rvert^2$	$10^2 \lvert V_{ub}/V_{cb}\rvert^2$
ISGW	0.12	1.3 ± 0.8	0.05	3.6 ± 1.0	2.2 ± 0.6
ACCMM	0.29	0.5 ± 0.3	0.13	1.4 ± 0.4	0.8 ± 0.2
WSB	0.20	0.8 ± 0.5	0.10	1.8 ± 0.5	1.3 ± 0.4
KS	0.27	0.6 ± 0.4	0.16	1.1 ± 0.3	0.9 ± 0.2
RDB			0.12	1.5 ± 0.4	

ing ratio for $b \to cl\nu$. In a particular theoretical model, $\Gamma(b \to cl\nu) = |V_{cb}|^2 \gamma_c$ and $\Gamma(b \to ul\nu) = |V_{ub}|^2 \gamma_u$, where Γ denotes the total width for the given semileptonic decay. If $f_u(p)$ is the fraction of the $b \to ul\nu$ momentum spectrum in the interval 2.4–2.6 GeV/c, then $d(p)$ is given by $d(p) = f_u(p)\gamma_\mu/\gamma_c$. For B_{cb}, we ignore the small contribution of $b \to ul\nu$ to the total semileptonic branching ratio and use[14] $B_{cb} = (10.2 \pm 0.2 \pm 0.7)\%$.

The values of $d(p)$ for various models and the resulting $|V_{ub}/V_{cb}|^2$ (with statistical and systematic errors added in quadrature) are given in Table III. The models differ in the way they treat the hadronization of the quarks. The WSB and KS (Ref. 15) models consider only the exclusive final states, $B \to \pi l\nu$ and $B \to \rho l\nu$. ISGW also include some higher-mass resonances. These are in contrast to the ACCMM model which is based on quark fragmentation. RDB (Ref. 16) argue that the lepton end-point region contains nonresonant multipion states in addition to the states considered by ISGW. Their model contains features of both the ISGW and the ACCMM models.

This evidence for $b \to ul\nu$ decays in the interval 2.4–2.6 GeV/c, where the $b \to cl\nu$ contribution is negligible, is supported by results at lower momenta. In the interval 2.2–2.4 GeV/c, the $b \to cl\nu$ contribution is significant so the uncertainty in the theoretical predictions for $b \to cl\nu$ becomes more important. However, the different model predictions agree within 10%. To estimate r_B, we use a mixture of $b \to cl\nu$ and $b \to ul\nu$ events in the Monte Carlo simulation. We find a net yield of $\langle u \rangle = 62 \pm 28 \pm 28$ leptons from $b \to ul\nu$ decays in this interval. The overall detection efficiencies are $(39 \pm 4)\%$ and $(43 \pm 4)\%$ for e's and μ's, respectively. The corresponding branching ratio is $\Delta B_{ub}(p) = (1.5 \pm 0.7 \pm 0.7) \times 10^{-4}$.

The values of $|V_{ub}/V_{cb}|^2$ given in Table III for 2.2–2.4 GeV/c are systematically smaller than those for 2.4–2.6 GeV/c. This difference may reflect some deficiency in the models used to subtract the large $b \to cl\nu$ contribution in the 2.2–2.4-GeV/c interval or in the models used to extract $|V_{ub}/V_{cb}|^2$ for the two momenta. Our principle evidence for $b \to ul\nu$ transitions is the observed lepton excess in the 2.4–2.6-GeV/c interval; it is independent of the theoretical models.

In conclusion, we have observed charmless semileptonic decays of B mesons. The value of $|V_{ub}/V_{cb}|$ obtained from our data is approximately 0.1; it is sensitive to the theoretical model.

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[7] The OFF yields obtained by counting events rather than fitting are $196 \pm 14 \pm 1$ and $117 \pm 11 \pm 1$ for 2.2–2.4 and 2.4–2.6 GeV/c, respectively.

[8] Evidence that these yields are from B decay comes from the interval 2.7–3.5 GeV/c, where we find 427 ON events and 222 OFF events, giving $y_s = -35 \pm 33$.

[9] The separate yields of e and μ events, after all subtractions, are $47 \pm 15 \pm 6$ and $24 \pm 14 \pm 8$, respectively, for 2.4–2.6 GeV/c, and $33 \pm 21 \pm 14$ and $29 \pm 21 \pm 21$, respectively, for 2.2–2.4 GeV/c.

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