OBSERVATION OF SEMILEPTONIC CHARMLESS B MESON DECAYS

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A detailed study of the lepton momentum spectrum in $\Upsilon(4S)$ decays has been made using the ARGUS detector at the DORIS II e^+e^- storage ring at DESY. In the region from 2.3 to 2.6 GeV/c, which is above the endpoint for contributions from B decays via $b\to c$ transitions, we observe 41 ± 10 events in excess of known backgrounds. These events are interpreted as a signal for $b\to u$ transitions. A model dependent value of 0.10 ± 0.01 is obtained for the ratio of Cabibbo–Kobayashi–Maskawa matrix elements $|V_{ub}|/|V_{cb}|$, using the Altarelli et al. model.

Of fundamental importance for our understanding of the weak interaction is a determination of the strength of the couplings between third- and first- or second-generation quarks. The relationships among the quark–W boson couplings are expressed by the Cabibbo–Kobayashi–Maskawa mixing matrix [1,2], with its four experimentally determined free parameters. Two of these elements are directly accessible through a study of B meson decays, namely V_{ub} and V_{cb}, which determine the strength of $b\to u$ and $b\to c$ transitions respectively. The latter process is known to dominate, as demonstrated by prolific charmed hadron production in B meson decays. Previous searches for charmless B decays in semileptonic modes [3] have led to rather stringent limits on V_{ub}. Measurement of this coupling constant would greatly constrain our picture of weak-interaction physics. In particular, a non-zero value is essential for the Kobayashi–Maskawa explanation of the origin of CP violation [2].

In this letter, the results of a study of the lepton momentum spectrum in semileptonic B decays are reported. The signature for a decay via $b\to u$ transition would be seen as an excess of leptons with momenta above the kinematic limit for $b\to c$ decays. The data for this analysis were collected using the ARGUS detector, operating at the DORIS II e^+e^- storage ring at DESY. They comprise accumulated luminosities corresponding to 201 pb^{-1} on the $\Upsilon(4S)$ and 69 pb^{-1} in the nearby continuum at centre-of-mass energies below the open beauty threshold. The ARGUS detector is a universal 4π spectrometer described in more detail elsewhere [4].

Multihadron events in the data samples were selected by requiring a total multiplicity $(n_{ch}+n_\gamma/2)$ of 6 or more. Photons which deposited more than 80 MeV in the calorimeter, or which converted in the material of the detector, were included as a part of the neutral multiplicity (n_γ).

Lepton identification in ARGUS is made by coherently combining available information from several detector elements into a global likelihood ratio [4]. For electrons, this likelihood ratio (L_e) is con-

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structed from measurements of specific ionization in the main drift chamber, of time-of-flight, and of the size and lateral spread of the associated cluster in the electromagnetic calorimeter. A particle with $L_e > 0.7$ and a polar angle with respect to the beam axis in the interval $|\cos\theta_e| < 0.85$ was considered to be an electron. The angle cut restricts the electrons to a region of the detector with good momentum resolution. Contamination from photon conversions was significantly reduced by eliminating electron candidates which, when combined with an oppositely charged particle in the event consistent with the electron hypothesis, have an invariant mass of less than 100 MeV/c^2. The misidentification rate for hadrons has been determined to be $(0.5 \pm 0.2)\%$ with these requirements.

For muons, the quality of the match between the projected particle track and the associated hit in the muon chambers, located outside the magnet return yoke, is also used in forming the likelihood ratio (L_μ). A particle with at least one hit in the outer two layers of the muon chambers, a likelihood ratio (L_μ) greater than 0.7 and a polar angle in the interval $|\cos\theta_\mu| < 0.68$ was considered to be a muon. The more restrictive angle requirement eliminates the endcaps of the detector, where there is a significantly higher hadron misidentification rate. The misidentification rate for hadrons has been determined to be $(1.5 \pm 0.3)\%$ under these conditions.

Using these criteria, events containing one or more leptons were then selected. However, the electron sample still contains events from two-photon interactions, in addition to those from the desired annihilation channel. At large Q^2, two-photon scattering will result in one electron seen in the detector, while the other, with charge q_e, disappears down the beam pipe. The signature for such events is a missing momentum vector ($\boldsymbol{p}_{mis}$) which points along the beam pipe in a direction opposite to that of the particle with the large scatter. These can be efficiently eliminated by requiring $\cos\theta_{mis} \times q_e < 0.9$, which results in a 5% loss in acceptance for signal events in the electron channel alone.

In order to increase the sensitivity of searches for $b \to u$ transitions the strategy has been to use additional requirements which strongly suppress the continuum contribution, but which have a reasonably large efficiency for $b \to u$ decays. These requirements exploit the more spherical shape of $\Upsilon(4S)$ decays in comparison with continuum events and the existence of energetic leptons (including neutrinos) in semileptonic B meson decays. It is also natural at this point to divide the events into two samples: one consisting of those events containing exactly one lepton and the other containing those events with exactly two. The latter is already an intrinsically cleaner sample of B decays, requiring fewer additional cuts. The two samples are, by definition, independent.

Event shape suppression of the continuum contribution in the single-lepton sample was based on the scalar sum of momentum perpendicular to the lepton direction for particles which have an angle between 60° and 120° with respect to the lepton direction ($\sum p_T$). Since continuum events are largely two-jet events, and fast tracks coincide well with the jet axes, there should be few tracks perpendicular to the lepton direction, resulting in a smaller $\sum p_T$ on average. Shown in fig. 1 are the measured spectra of $\sum p_T$ for continuum and for $\Upsilon(4S)$ events, where the leptons were chosen in the momentum interval 2.0–2.3 GeV/c. The requirement that $\sum p_T$ exceeds 2 GeV/c reduces continuum background by a factor of 11, while the efficiency for $\Upsilon(4S)$ decays is 46%. The efficiency for $b \to c$ transitions was estimated using the WBS [5] and GISW [6] models to be 41% in both cases.

Semileptonic B decays produce a neutrino along with the charged lepton, resulting in missing momentum for the event. Many of the continuum leptons, particularly in the muon sample, are misidentified

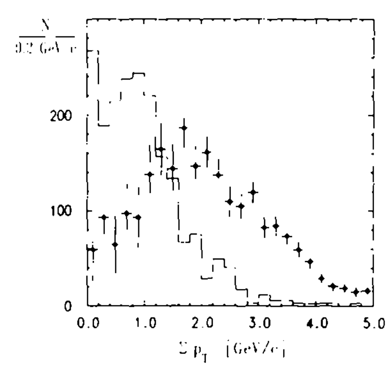

Fig. 1. Distribution of $\sum p_T$ for continuum (histogram) and direct $\Upsilon(4S)$ decays (crosses), for lepton momentum in the range 2.0–2.3 GeV/c.

hadrons, and so these events should have small missing momentum. A requirement of large p_{mis} also suppresses purely hadronic decays of the $\Upsilon(4S)$, such as a background from $B \to J/\psi X$, with $J/\psi \to \ell^+\ell^-$. Finally, since the neutrino energy spectrum is expected to be softer for $b \to c$ transitions than for $b \to u$, some suppression of the $b \to c$ background in the signal region would result from a cut on p_{mis}.

In addition to the large magnitude of missing momentum in semileptonic decays, there exists a strong correlation between the direction of the missing momentum and the lepton momentum direction, particularly for leptons in the endpoint region. The opening angle (β) between the lepton direction and the direction of missing momentum should peak at $\cos\beta = -1$ for signal events. The actual strength of the correlation depends on the quality of the detector, since the resolution for $\cos\beta$ is a function of the hermiticity of the experiment.

Shown in figs. 2a and 2b are comparisons between Monte Carlo predictions and direct $\Upsilon(4S)$ decays for the distributions of p_{mis} and $\cos\beta$ in the region $2.0 < p_\ell < 2.3$ GeV/c populated by $b \to c$ decays. Both the magnitude and angular correlation with $\boldsymbol{p}_{mis}$ are well described by the Monte Carlo. For comparison, the predicted p_{mis} and $\cos\beta$ distributions for $b \to u$ transitions are also shown. These were obtained by Monte Carlo calculation using the WBS model [5] for semileptonic B decays to π and ρ mesons. As previously indicated, the p_{mis} distribution is harder, and the angular correlation with the lepton momentum stronger, for $b \to u$ transitions. Therefore any reasonable restriction on these quantities is actually more efficient for $b \to u$ than for $b \to c$ decays.

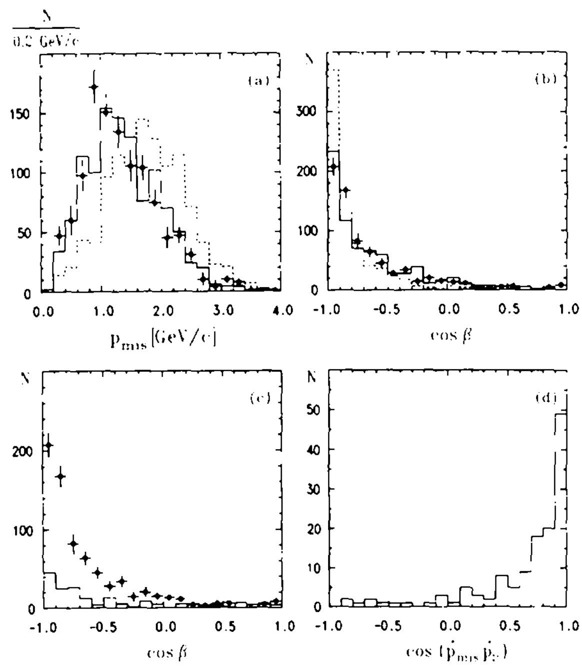

Fig. 2. Distribution of (a) p_{mis} and (b) $\cos\beta$ for direct $\Upsilon(4S)$ decays with leptons in the $b \to c$ range (crosses). Monte Carlo prediction for $b \to c$ (histogram) and $b \to u$ (dotted histogram) transitions. (c) Comparison of $\cos\beta$ distribution for events with a fast lepton (points) or fast hadron (histogram). (d) Opening angle distribution between $\boldsymbol{p}_{mis}$ and the known neutrino direction for a sample of $B^0 \to D^{*-}\ell^+\nu$ events.

In order to demonstrate that the observed peaking of $\cos\beta$ near -1 due to the neutrino and not an artifact, two tests have been performed. First, the analysis has been repeated, including the $\sum p_T$ cut, with a fast hadron substituted for the fast lepton. A comparison between the $\cos\beta$ distributions for fast leptons and hadrons is shown in fig. 2c. Since the relative scales are arbitrary, the distributions have been normalized in the interval $\cos\beta > 0$. The distribution shows a pronounced peaking towards $\cos\beta = -1$ in the case of the lepton, in strong contrast to selecting a fast hadron. The small rise in the hadron case is mainly due to a loss of photons caused by the overlap with charged particles in the calorimeter in the jet opposite to the fast hadron. The second check has been to examine the opening angle between the known neutrino direction and $\boldsymbol{p}_{mis}$ using our exclusive sample of $B^0 \to D^{*-}\ell\nu$. The result is shown in fig. 2d, where $\boldsymbol{p}_{mis}$ can be seen to coincide with $\boldsymbol{p}_\nu$ with approximately the same precision as seen in fig. 2b.

For the single-lepton analysis, the requirement was made that $1.0 < p_{mis} < 3.5$ GeV/c and $\cos\beta < -0.5$. The upper limit on p_{mis} retains all events from B decays, but is an additional means of suppressing two-photon contributions. The efficiency of the cut has been estimated to be 81% for $b \to u$ decays, while at the same time the background is reduced by a factor of 3.6.

The lepton momentum distribution after application of these cuts is shown in figs. 3a and 3b for direct $\Upsilon(4S)$ and continuum data respectively. The continuum background can be seen to have been dramatically suppressed. In order to search for events from semileptonic $b \to u$ decays, two intervals in the lepton

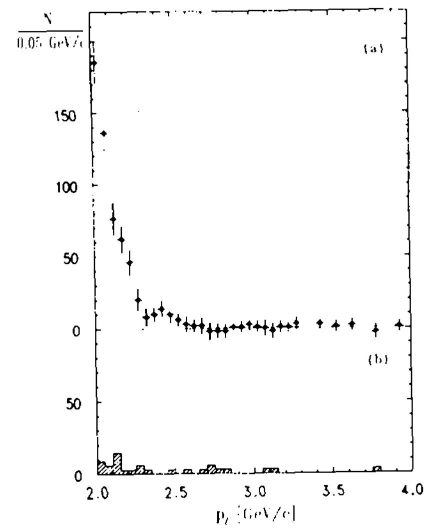

Fig. 3. Lepton momentum spectra for (a) direct Υ(4S) and (b) scaled continuum data.

momentum spectrum have been used. The first, 2.0–2.3 GeV/c, is dominated by b→c transitions and is used for normalization. Leptons from b→u transitions can have momenta up to 2.7 GeV/c. However, the fraction above 2.6 GeV/c is small. Therefore the actual search region for b→u decays was chosen to be between 2.3 and 2.6 GeV/c. In the signal region for b→u decays, 60 leptons are observed. In the continuum there are only 3 leptons in this range. However, as a conservative estimate we use the average level of the continuum background in the momentum interval 2.0–2.9 GeV/c, corresponding to 7.3 events in the signal region. This number must be scaled up by a factor of 2.9 in order to account for the difference in the integrated luminosities on the Υ(4S) and in the continuum. The same scaling factor is obtained by comparing the numbers of leptons produced above the kinematic limit for B decays. The total estimated background, broken down in detail in table 1, is 33.3 ± 5.2 events. Thus, there is an excess of 26.7 ± 9.3 leptons in the momentum region $2.3 < p_\ell < 2.6$ GeV/c. In the normalization region for b→c decays, 509 leptons (247 e and 262 μ) are observed after background subtraction.

Although the largest background remains the continuum contribution, there are a number of other sources from Υ(4S) decays themselves which must be considered. Perhaps the most critical of these could be the high-momentum tail of the contribution from b→c decays. This depends on the experimental resolution function, the uncertainty in the beam energy (estimated to be ± 3 MeV), and to a more limited extent on the model used for the semileptonic b→c decays.

The resolution function for muons has been checked by studying QED μ-pair events. There is virtually no high momentum tail in the distribution of muon momentum. The same is true for estimates of the electron response function which was studied using Bhabha events. The agreement between data and Monte Carlo is excellent. The extrapolation to the lower momenta of the b→u analysis is reliable, since this is still a regime where drift chamber resolution

Table 1
Observed single lepton and dilepton events in the momentum interval $2.3 < p_\ell < 2.6$ GeV/c and estimated backgrounds.

	Single leptons		Dileptons	
	e	μ	e	μ
Υ(4S)	31	29	11	10
backgrounds: continuum (scaled)	6.8	14.5	1.0	1.0
b→c	4.0	4.4	1.1	1.2
J/ψ	0.6	0.4	0.2	0.1
fakes	0.9	1.7	0.7	1.4
total background	12.3 ± 2.8	21.0 ± 4.0	3.0 ± 1.0	3.7 ± 1.1
signal	18.7 ± 6.2	8.0 ± 6.7	8.0 ± 3.5	6.3 ± 3.4

dominates the precision of the momentum determination. As a final check, a scan of all candidate events showed that lepton tracks are isolated and well measured. Comparing the available models for b→c decays [7,8], and varying the D/D* ratio within experimental limits, the uncertainty in the background from b→c decays in the signal region is estimated to be 20%.

Another source of background is B→J/ψX decays, followed by J/ψ→$\ell^+\ell^-$. As a means of suppressing these contributions, the invariant mass of a lepton and any other oppositely charged track consistent with a lepton hypothesis was required to be more than 100 MeV/c^2 away from the J/ψ mass. Since the inclusive branching ratio is reasonably well known, as is the relevant fraction of two-body decays [9], the residual background can be reliably predicted. The contribution of misidentified hadrons to the background has been obtained from the observed spectrum for hadrons in Υ(4S) decays, folded with the misidentification rates note above. Using the detector Monte Carlo, the probability that a kaon decay-in-flight to a fast forward-going muon causes the momentum to be reconstructed in the signal region has been demonstrated to be negligible. The background to the electron sample from asymmetric photon conversions is likewise estimated to be small.

An alternative approach to obtaining a largely background-free sample of leptons is to require not one, but exactly two leptons in the event. For the second lepton, the momentum was restricted to lie anywhere within the b→c range $1.2<p_\ell<2.3$ GeV/c and the polar angle interval was increased to $|\cos\theta_\ell|<0.90$. The small continuum contamination for dilepton events was further suppressed by requiring that the opening angle, $\theta_{\ell\ell}$, between the two leptons satisfy the requirement $\cos\theta_{\ell\ell}>-0.8$. Converted photons were removed by the restriction that $\cos\theta_{e^+e^-}$ be less than 0.95. The J/ψ decays were removed as in the first sample. Finally, the missing momentum in the event was required to lie in the interval $1.0<p_{mis}<3.5$ GeV/c. Once again, the lower limit suppresses continuum events and all neutrinoless decays, and the upper limit suppresses two-photon events.

The resulting momentum spectrum is shown in fig. 4, where the five events observed in the continuum are indicated by the histogram. There is no continuum event in the b→u signal region. However, once

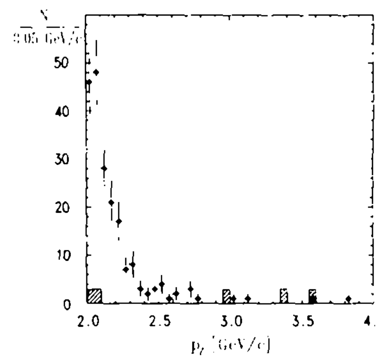

Fig. 4. Lepton momentum spectrum from dilepton events for Υ(4S) (crosses) and scaled continuum (histogram) data.

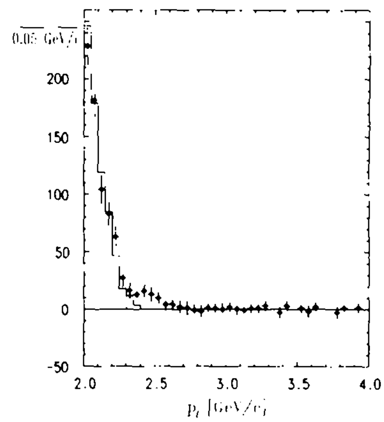

Fig. 5. Combined lepton momentum spectrum for direct Υ(4S) decays: the histogram is a b→c contribution normalized in the region 2.0–2.3 GeV/c.

more we subtract the average level of continuum in the 2–2.9 GeV/c range. The b→u momentum interval is populated in the Υ(4S) data by 21 events, with an estimated background of 6.7±2.2. There are 9 eμ, 6 ee and 6 μμ candidates, representing a reasonable division of the signal. Four events are like-sign dileptons. This is consistent with the expectation from cascade decays and mixing. Table 1 gives a detailed breakdown of the known background sources. After background subtraction there are 153.7 leptons (78.3 e and 75.4 μ) in the 2.0–2.3 GeV/c range.

Thus a comparable excess of electrons and muons is seen in both the single lepton and dilepton samples for the momentum interval 2.3–2.6 GeV/c. In total, there are 81 leptons in this range with a background estimated to be only 40.0 ± 5.3 events. The resulting lepton momentum spectrum is shown in fig. 5. The uncertainty of the background is dominated by the error in the continuum contribution. In the momentum interval 2.4–2.6 GeV/c, where the b→c background vanishes completely, 49 leptons remain with an estimated background of 18.2 ± 3.3.

Assuming that the ϒ(4S) decays only to B$\bar{\text{B}}$ pairs, we interpret the observed excess of leptons beyond the endpoint for b→c decays as a signal for b→u transitions. Taking into account that the estimated efficiency for b→u transitions is 1.3 times larger than for b→c transitions we obtain the ratio of semileptonic branching ratios in the studied momentum intervals:

$$\frac{BR_{s\ell}(2.3-2.6)}{BR_{s\ell}(2.0-2.3)} = (4.7 \pm 1.2)\% ,$$

where the statistical and systematic errors are added in quadrature. The error does not include the uncertainty due to the model dependence of the efficiency calculations for b→u transitions. The main uncertainty comes from the requirements on p_{mis}. However, since the estimated efficiency for this cut is large (81%), the result cannot be substantially smaller than that quoted above.

In order to calculate $|V_{ub}|/|V_{cb}|$ one must know the fractions of the lepton spectra for b→u and b→c transitions in the selected momentum intervals. These fractions are different for electrons and muons because of electron bremsstrahlung. The lepton spectrum in B decays is measured experimentally, and is well described by theoretical models for b→c transitions. The fraction of the spectrum in the normalization region 2.0–2.3 GeV/c is, therefore, quite well known. After correcting for electron bremsstrahlung, the average fraction for electrons and muons is about 6%. For b→u transitions, the corresponding partial width in the signal region is very model dependent. This leads to a considerable difference in the values of $|V_{ub}|/|V_{cb}|$ extracted from the data using different models. The results are shown in table 2. They were obtained neglecting a small b→u contribution in the normalization region below 2.3 GeV/c.

Table 2
$|V_{ub}|/|V_{cb}|$ ratio for different models (the errors are non-gaussian).

Model	Reference	$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$
ACM	[7]	0.10 ± 0.01
WBS	[5]	0.12 ± 0.02
KS	[8]	0.09 ± 0.01
GISW	[6]	0.18 ± 0.02

In summary, a detailed study of the lepton momentum spectrum in B decays has been made, with particular attention to the endpoint region where a signal for b→u transitions might be seen. After background suppression 81 leptons are observed in the momentum interval 2.3–2.6 GeV/c, with a background estimated to be only 40.0 ± 5.3 events. Thus there is a signal of 41.0 ± 10.4 events. This is a clear observation for an excess of leptons beyond the kinematic limit for b→c transitions. If interpreted as a signal of a b→u coupling, the observed event rate leads to a model-dependent value for the ratio of the Cabibbo–Kobayashi–Maskawa matrix elements $|V_{ub}|/|V_{cb}|$ of about 10%.

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