Reconstruction of semileptonic b→u decays

ARGUS Collaboration

H. Albrecht, H. Ehrlichmann, R. Gläser, G. Harder, A. Krüger, A. Nau, A.W. Nilsson, A. Nippe, T. Oest, M. Reidenbach, M. Schäfer, W. Schmidt-Parzefall, H. Schröder, H.D. Schulz, F. Sefkow, R. Wurth
DESY, W-2000 Hamburg, FRG

R.D. Appuhn, A. Drescher, C. Hast, G. Herrera, H. Kolanoski, A. Lange, A. Lindner, R. Mankel, H. Scheck, G. Schweda, B. Spaan, A. Walther, D. Wegener
Institut für Physik [1], Universität Dortmund, W-4600 Dortmund, FRG

M. Paulini, K. Reim, U. Volland, H. Wegener
Physikalisches Institut [2], Universität Erlangen-Nürnberg, W-8520 Erlangen, FRG

W. Funk, J. Stiewe, S. Werner
Institut für Hochenergiephysik [3], Universität Heidelberg, W-6900 Heidelberg, FRG

S. Ball, J.C. Gabriel, C. Geyer, A. Hölscher, W. Hofmann, B. Holzer, S. Khan, J. Spengler
Max-Planck-Institut für Kernphysik, Heidelberg, W-6900 Heidelberg, FRG

C.E.K. Charlesworth [4], K.W. Edwards [5], H. Kapitza [5], P. Krieger [4], R. Kutschke [4], D.B. MacFarlane [6], K.W. McLean [6], R.S. Orr [4], J.A. Parsons [4], P.M. Patel [6], J.D. Prentice [4], S.C. Seidel [4], J.D. Swain [6], G. Tsipolitis [6], K. Tzamariudaki [6], T.-S. Yoon [4]
Institute of Particle Physics [7], Canada

T. Ruf, S. Schael, K.R. Schubert, K. Strahl, R. Waldi, S. Weseler
Institut für Experimentelle Kernphysik [8], Universität Karlsruhe, W-7500 Karlsruhe, FRG

B. Boštjančič, G. Kernel, P. Križan [9], E. Križnič, T. Živko
Institut J. Stefan and Oddelek za fiziko [10], Univerza v Ljubljani, YU-61111 Ljubljana, Yugoslavia

H.I. Cronström, L. Jönsson
Institute of Physics [11], University of Lund, S-223 62 Lund, Sweden

A. Babaev, M. Danilov, B. Fominykh, A. Golutvin, I. Gorelov, V. Lubimov, A. Rostovtsev, A. Semenov, S. Semenov, V. Shevchenko, V. Soloshenko, V. Tchistilin, I. Tichomirov, Yu. Zaitsev
Institute of Theoretical and Experimental Physics, SU-117 259 Moscow, USSR

R. Childers and C.W. Darden
University of South Carolina [12], Columbia, SC, USA

0370-2693/91/$ 03.50 © 1991 – Elsevier Science Publishers B.V. (North-Holland)

Received 14 November 1990

Using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY we have updated our result on charmless semileptonic B decays and searched for direct evidence for $b \to u$ transitions through reconstruction of complete events. This approach has successfully identified two $\Upsilon(4S)$ events which contain B meson decays to a non-charm final state. In one case, a B^0 meson is found in the channel $\pi^+\mu^-\bar{\nu}$, while in the other a decay $B^+ \to \omega\mu^+\nu$ is seen. These events show that the previously observed signal of charmless semileptonic B decays is due to $b \to u$ transitions from which we obtain $|V_{ub}/V_{cb}| = 0.11 \pm 0.012$ using the model of Altarelli et al.

Leptons with momenta beyond the kinematic limit for $b \to c\ell^-\bar{\nu}$ transitions [#1] have been observed in $\Upsilon(4S)$ decays [1,2]. These are thought to originate from $b \to u\ell^-\bar{\nu}$ transitions, thereby implying that the Kobayashi–Maskawa matrix element V_{ub} is non-zero. This conclusion has important consequences for the standard model description of the origin of CP violation, which requires a finite value for V_{ub} [3]. The direct observation of $b \to u$ transitions through reconstruction of exclusive B decays has not been successful so far [4,5].

In this paper, we report on an update of our inclusive analysis of $b \to u\ell\nu$ decays [1] and on a search for exclusive decays of this type using the ARGUS detector at the e^+e^- storage ring DORIS II. An attempt to determine branching fractions for exclusive semileptonic decays has only led to the upper limits $BR(B^- \to \rho^0\ell^-\bar{\nu}) < 1.1 \times 10^{-3}$ and $BR(\bar{B}^0 \to \pi^+\ell^-\bar{\nu}) < 0.9 \times 10^{-3}$ with 90% CL. Details of this analysis, based on the missing mass squared technique [6] and on strong continuum-suppressing cuts, can be found in ref. [7]. The model depending V_{ub} limits deduced from this result, e.g. $|V_{ub}| < 0.007$ (90% CL) using the model of WSB [8] are higher than the measured value for $|V_{ub}|$ [1].

The new inclusive analysis uses a sample containing 202 000 $\Upsilon(4S)$ decays collected during the period 1983 to 1989 and corresponding to an integrated luminosity of 237 pb^{-1}. The analysis leads to an updated value of $BR(B \to X_u\ell^+\nu, 2.3 < p_\ell < 2.6\ \mathrm{GeV}/c) / BR(B \to X\ell^+\nu, 2.0 < p_\ell < 2.3\ \mathrm{GeV}/c)$ and forms the basis of a further investigation, which explicitly demonstrates that there are $b \to u$ transitions beyond the kinematic limit for $b \to c$ transitions through the complete reconstruction of two $\Upsilon(4S) \to B\bar{B}^0$ events. In both cases, one of the B mesons is seen in a semileptonic channel containing non-charmed hadrons. The continuum sample for this analysis consists of 98 pb^{-1} collected at center-of-mass energies about 100 MeV below the $\Upsilon(4S)$ mass. The ARGUS detector and its particle identification capabilities have been described in detail elsewhere [9]. Event selection criteria are similar to those described in our published study of inclusive leptons from $\Upsilon(4S)$ decays [1].

In the search for semileptonic $b \to u$ transitions, background events containing leptons originating from the e^+e^- continuum or from $b \to c$ transitions must be strongly suppressed. This is achieved either by requiring a single fast lepton, and applying additional restrictions on event topology and missing momentum, or demanding two leptons. We concentrate first on the single-lepton sample, and return to the dilepton events below. Signal events for $b \to u$ transitions were selected by requiring a single lepton with momentum between 2.3 and 2.6 GeV/c, where the contribution from $b \to c$ transitions is small. As demonstrated in our previous paper [1], the dominant source of continuum background in this region can

[1] Supported by the German Bundesministerium für Forschung und Technologie, under contract number 054DO51P.
[2] Supported by the German Bundesministerium für Forschung und Technologie, under contract number 054ER12P.
[3] Supported by the German Bundesministerium für Forschung und Technologie, under contract number 054HD24P.
[4] University of Toronto, Toronto, Ontario, Canada M5S 1A7.
[5] Carleton University, Ottawa, Ontario, Canada K1S 5B6.
[6] McGill University, Montreal, Quebec, Canada H3A 2T8.
[7] Supported by the Natural Sciences and Engineering Research Council, Canada.
[8] Supported by the German Bundesministerium für Forschung und Technologie, under contract number 054KA17P.
[9] Supported by Alexander von Humboldt Stiftung, Bonn.
[10] Supported by Raziskovalna skupnost Slovenije and the Internationales Büro KfA, Jülich.
[11] Supported by the Swedish Research Council.
[12] Supported by the US Department of Energy, under contract DE-AS09-80ER10690.

[#1] References to a specific particle state should be interpreted as implying the charge-conjugate state also.

be sharply reduced by exploiting the different topologies of continuum and $\Upsilon(4S)$ events, and by using the fact that the presence of an energetic neutrino in the decay $B \to X_u \ell^+ \nu$ manifests itself as large missing momentum in the event. The topology requirement was implemented in the original study by demanding a large sum of momentum transverse to the lepton, in a restricted angular region perpendicular to the lepton direction. The probability that the event contained an energetic neutrino was greatly enhanced by demanding that the missing momentum, p_{miss}, exceeded 1.0 GeV/c. Furthermore, the neutrino and charged lepton were forced to be back-to-back by requiring the angle β between the lepton and missing momentum direction to satisfy $\cos\beta < -0.5$.

To enlarge the available sample further, and alternative analysis has been devised which increases the overall acceptance for $b \to u$ leptons. This is achieved by first exchanging the topological cut with a requirement that the cosine of the angle α between the direction of the lepton and the thrust axis of the rest of the event satisfies $|\cos\alpha| < 0.75$. As demonstrated in fig. 1, continuum events are strongly peaked near $|\cos\alpha| = 1$, reflecting the two-jet topology of these events, in contrast to the uniform distribution of $\Upsilon(4S)$ events. Secondly, the requirement that the lepton and the missing momentum be back-to-back was replaced by a restriction that the squared mass of the hadronic system recoiling against the lepton and missing momentum, $M_h^2 \approx [E_{\text{beam}} - E_{\ell^-} - p_{\text{miss}}]^2 - [\boldsymbol{p}_{\ell^-} + \boldsymbol{p}_{\text{miss}}]^2$, must lie in the interval $|M_h^2| < 1.5$ GeV$^2/c^4$. The detection efficiency for events which pass either the original, or the modified requirements amounts to (50 ± 7)%.

The lepton spectrum for events which satisfy either our original or the revised selection criteria is shown in fig. 2 for direct $\Upsilon(4S)$ decays and continuum data, respectively. In the signal region, defined as lepton momenta between 2.3 and 2.6 GeV/c, 109 leptons are observed in the $\Upsilon(4S)$ data. To obtain the number of leptons from direct $\Upsilon(4S)$ decays the continuum contribution has to be subtracted. This contribution is determined from the continuum data taking into account the different luminosities and center-of-

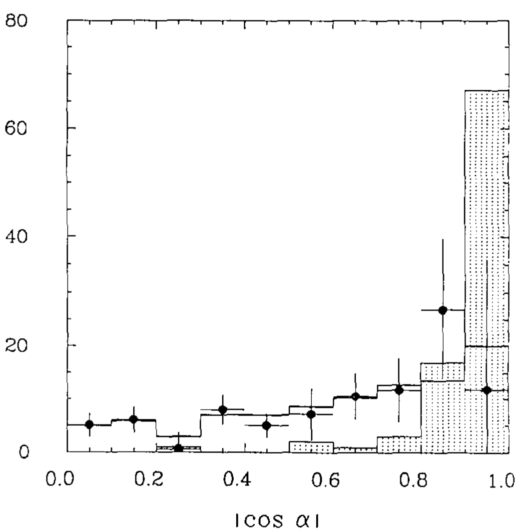

Fig. 1. Distribution of cos α for direct $\Upsilon(4S)$ decays (points with error bars), continuum events (shaded histogram, before scaling by the luminosity ratio 2.42), and Monte Carlo generated $\Upsilon(4S)$ events where one B decays via $\bar{B}^0 \to \rho^0 \ell \bar{\nu}$ (open histogram, normalized to the direct $\Upsilon(4S)$ data). α is the angle between the direction of the lepton $(3.2 < p_\ell < 2.6)$ and the thrust axis of the rest of the event.

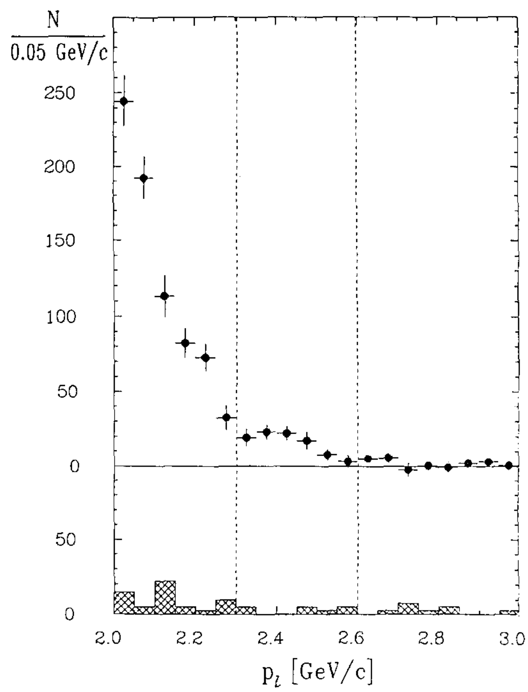

Fig. 2. Lepton momentum spectra for (a) $\Upsilon(4S)$ data after continuum subtraction and (b) scaled continuum.

mass energies for continuum and $\Upsilon(4S)$ data (table 1). Contributions from the tail of the $b \to c\ell^- \bar{\nu}$ process are small; the same is true for contributions from faked leptons and from J/ψ production in B decays where the J/ψ decays into a lepton pair of which only one lepton is observed (table 1).

An updated analysis of the dilepton events [1] results in 23 events having a lepton with momentum between 2.3 and 2.6 GeV/c which mainly come from $b \to u$ transitions (fig. 3 and table 1). Combining the single lepton sample with the dilepton one (fig. 4) there remains, after subtraction of all backgrounds, a combined signal of 77.1 ± 13.4 events from charmless B decays, containing a lepton with momentum in the range $2.3 < p_{\ell^-} < 2.6$ GeV/c (table 1). The shape of the spectrum in this interval is compatible with the predictions for semileptonic $b \to u\ell^- \bar{\nu}$ decays [8,10–12]. However, using only this restricted portion of the full momentum spectrum, it is not possible to discriminate between the available models. Events containing electrons or muons contribute about the same number of events to the signal, as expected from their similar acceptances. The observed lepton rate for $b \to u$ transitions in the momentum interval of $2.3 < p_{\ell^-} < 2.6$ GeV/c can be compared to the lepton rate from $\Upsilon(4S)$ decays in the range $2.0 < p_{\ell^-} < 2.3$ GeV/c:

$$\frac{BR(B \to X_u \ell^+ \nu,\ 2.3 < p_\ell < 2.6\ \mathrm{GeV}/c)}{BR(B \to X\ell^+ \nu,\ 2.0 < p_\ell < 2.3\ \mathrm{GeV}/c)} = (5.4 \pm 0.9 \pm 0.8)\%,$$

where the first error is determined from the errors on the event rates and the second error is due to the uncertainty in the detection efficiency. From this result the ratio $|V_{ub}/V_{cb}|$ can be calculated using model predictions for the semileptonic decay rates and lepton momentum spectra for $b \to u\ell^- \bar{\nu}$ and $b \to c\ell^- \bar{\nu}$. Using the ACM model [10] we obtain $|V_{ub}/V_{cb}| = 0.11 \pm 0.012$. Similar results are found using the WBS [8] ($|V_{ub}/V_{cb}| = 0.13 \pm 0.015$) and KS models [11] ($|V_{ub}/V_{cb}| = 0.11 \pm 0.012$), while the GISW prediction [12] yields a much larger value ($|V_{ub}/V_{cb}| = 0.20 \pm 0.023$).

In order to show that the excess of high momentum leptons ($2.3 < p_{\ell^-} < 2.6$ GeV/c) observed in the $\Upsilon(4S)$ data do indeed originate from $b \to u\ell^- \bar{\nu}$ transitions, we have made a systematic attempt to completely reconstruct the signal events. On the basis of Monte Carlo studies, and our previous experience with tagging B decays in the data, the reconstruction rate using all B decay channels involving D mesons is about 1.6%. Here D meson should be interpreted as D^0, D^+, D^{*0}, D^{*+} and their charge conjugate states. The final state of the B decay was required to contain no more than eight charged particles and six photons. Therefore we anticipate approximately one complete event in our combined single-lepton sample since the multiplicity of hadrons is small in the $b \to u\ell^- \bar{\nu}$ decays with high momentum leptons.

As a result of a search for a hadronic B tag in the indicated decay modes in the data, one fully reconstructed event was found, consistent with this expec-

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

$\Upsilon(4S)$		Single leptons		Dileptons	
		e	μ	e	μ
		52	57	12	11
backgrounds:	continuum (scaled)	10.7	19.9	0.8	0.8
	$b \to c$	5.5	6.3	1.2	1.3
	J/ψ	1.0	0.7	0.2	0.1
	fakes	1.3	2.8	0.8	1.5
total background		18.5 ± 3.1	29.7 ± 4.3	3.0 ± 1.0	3.7 ± 0.9
signal		33.5 ± 7.8	27.3 ± 8.7	0.9 ± 3.6	7.3 ± 3.4
combined signal			77.1 ± 13.4		

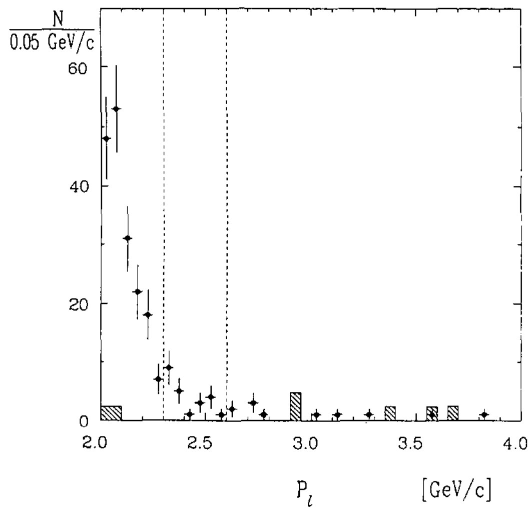

Fig. 3. Lepton momentum spectrum from dilepton events for $\Upsilon(4S)$ (crosses) and scaled continuum (histogram) data.

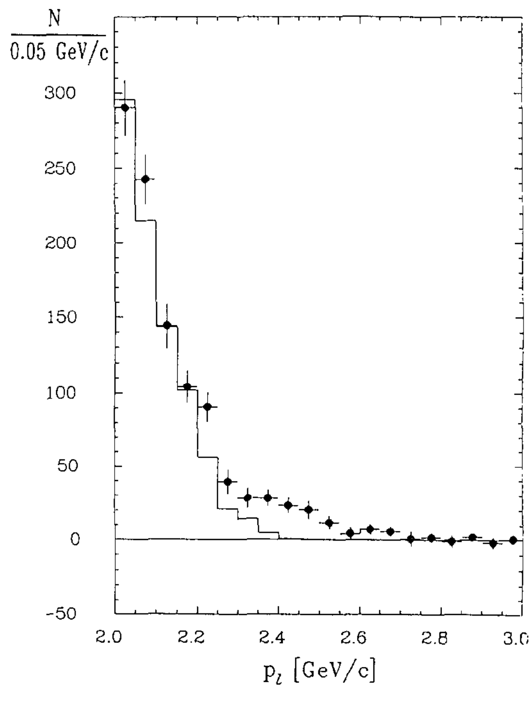

Fig. 4. Combined lepton momentum spectrum for direct $\Upsilon(4S)$ decays; the histogram shows the expected shape of the $b \to c$ contribution.

tation. The event is shown in fig. 5, and consists of a $\Upsilon(4S)$ decay into a pair of $\bar{B}^0$ mesons, indicating that one B^0 meson has oscillated into a $\bar{B}^0$. Thus, the event simultaneously demonstrates the existence of $b \to u$ transitions and $B^0\bar{B}^0$ mixing [13]. The hadronic $\bar{B}^0$ tag was reconstructed in the mode $\bar{B}^0 \to D^{*+}\rho^-$. The second $\bar{B}^0$ meson was seen in the channel $\bar{B}^0 \to \pi^+\mu^-\bar{\nu}$, representing the first direct observation of a $b \to u$ transition. Relevant kinetic quantities for this event are listed in table 2. All measurements of intermediate masses and momenta agree well with expected values. The mass of the B meson is obtained from an energy constraint fit.

Possible background sources to this event have been evaluated. The probability for mis-interpretation is substantially reduced by the existence of a charged D^* in the event. Also of particular importance is the fact that the missing momentum $p_{miss} = (2.667 \pm 0.034)$ GeV/c coincides within errors with the missing energy $E_{miss} = (2.711 \pm 0.027)$ GeV in the event. Since the missing momentum vector points into the barrel region of the detector, where no interaction is observed, we conclude that the missing particle is a neutrino. The μ^- lepton is well measured, with hits in all three layers of the muon chambers. If the lepton were actually faked by a hadron, the missing particle could also be a non-interacting K_L^0. However, this hypothesis is ruled out for most $b \to c$ decays, since such a hypothetical, high momentum K_L^0 would be beyond the kinematic limit for all but a sequence of two-body decays. Since the invariant mass formed by a missing K_L^0 with either the soft pion or the muon lies outside the charmed hadron region, the two-body channels can be safely rejected. The possibility that this decay proceeds via a "penguin" diagram in the channel $B^0 \to K_L^0\pi^-\pi^+$ cannot be excluded, but has a probability of less than 10^{-3} due to the smallness of the lepton fake rate and the "penguin" decay rate [14,15]. Misreconstruction of a continuum process is also very unlikely, with a probability estimated to be less than 10^{-3} by measuring the fake rate for hadronic B tags in the continuum data.

Therefore the only viable interpretation for this event is that we have observed a completely reconstructed $\Upsilon(4S)$ decay, where one $\bar{B}^0$ meson decays via a semileptonic $b \to u$ transition into $\pi^+\mu^-\bar{\nu}$. The event

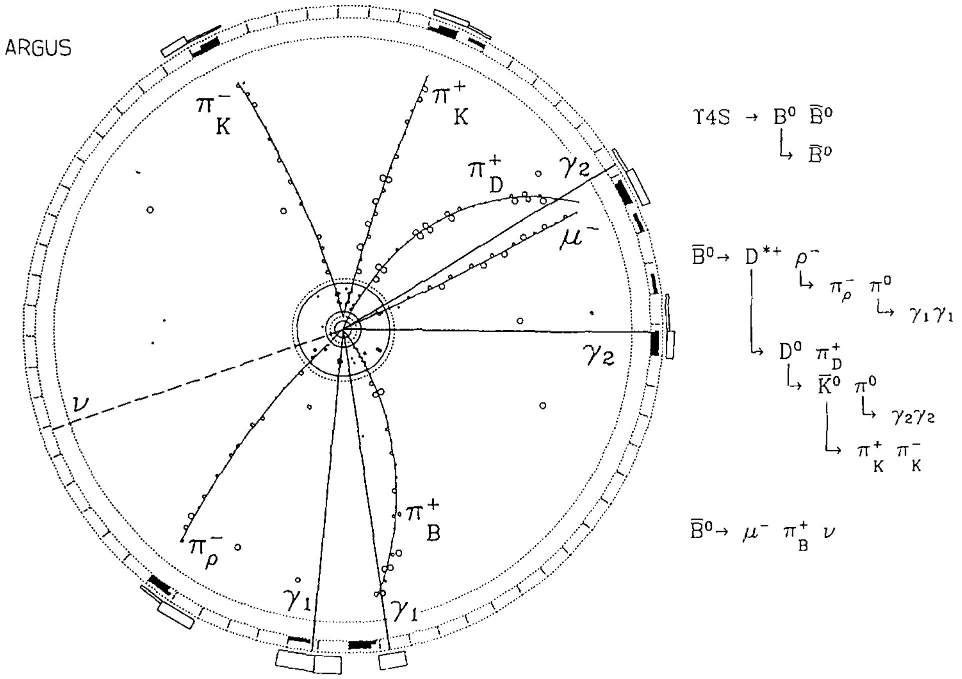

Fig. 5. Completely reconstructed event containing the decay $\Upsilon(4S)\to B^0\bar{B}^0$, $B^0\to\bar{B}^0$, where one $\bar{B}^0$ decays into $\pi^+\mu^-\bar{\nu}$ and the other into $D^{*+}\rho^-$.

Table 2
Kinematic quantities of the event in fig. 5, which contains the decay $\Upsilon(4S)\to B^0\bar{B}^0$, $B^0\to\bar{B}^0$, where one $\bar{B}^0$ decays into $\pi^+\mu^-\nu^-$ and the other into $D^{*+}\rho^-$.

	p(GeV/c)	Mass(MeV/c^2)	$\cos\theta$
$\bar{B}^0\to\pi_B^+\mu^-\bar{\nu}$			
π_B^+	0.213 ± 0.003		-0.423
μ^-	2.322 ± 0.026		0.205
$\bar{\nu}$	2.667 ± 0.034		-0.130
$\bar{B}^0\to D^{*+}\rho^-$	0.330 ± 0.021	5277.7 ± 3.3	-0.12
$D^{*+}\to\pi_D^+D^0$	2.278 ± 0.013	2010.0 ± 1.0	-0.62
π_D^+	0.204 ± 0.005		-0.72
$D^0\to\pi^0\bar{K}^0$	2.074 ± 0.014	1767 ± 62	-0.61
$\pi^0\to\gamma_2\gamma_2$	0.602 ± 0.045	114 ± 17	0.27
$\bar{K}^0\to\pi_K^+\pi_K^-$	2.041 ± 0.010	494.2 ± 4.1	-0.70
$\rho^-\to\pi_\rho^-\pi^0$	2.002 ± 0.159	747 ± 33	0.64
π_ρ^-	0.598 ± 0.003		0.43
$\pi^0\to\gamma_1\gamma_1$	1.518 ± 0.160	127 ± 22	0.69

is of remarkable simplicity and represents the first direct observation of $b\to u\ell^-\bar{\nu}$ transitions.

A second event in our sample can also be fully reconstructed, with the exception of a missing soft photon. In this case one B meson is found to decay in the mode $B^+\to\omega\mu^+\nu$ (fig. 6 and table 3). The high momentum μ^+ lepton again is well measured with hits in all three layers of muon chambers. The observed difference between the missing energy and the missing momentum in the event is about 100 MeV. The missing momentum vector points into the barrel region of the detector, where no interaction is observed, as expected for a neutrino. The second B^- meson most probably decays into the channel $D^{*0}\pi^+\pi^-\pi^-$, where $D^{*0}\to\pi^0D^0$. The reconstructed D^0 decays into a well identified, low momentum K^- and three charged pions. As indicated by the imbalance between the missing energy and momentum in the event, about 100 MeV of energy from the decay of the B^- meson is carried away by an unobserved photon which is needed to reconstruct the π^0 from the D^{*0} decay. Other interpretations of the event, where

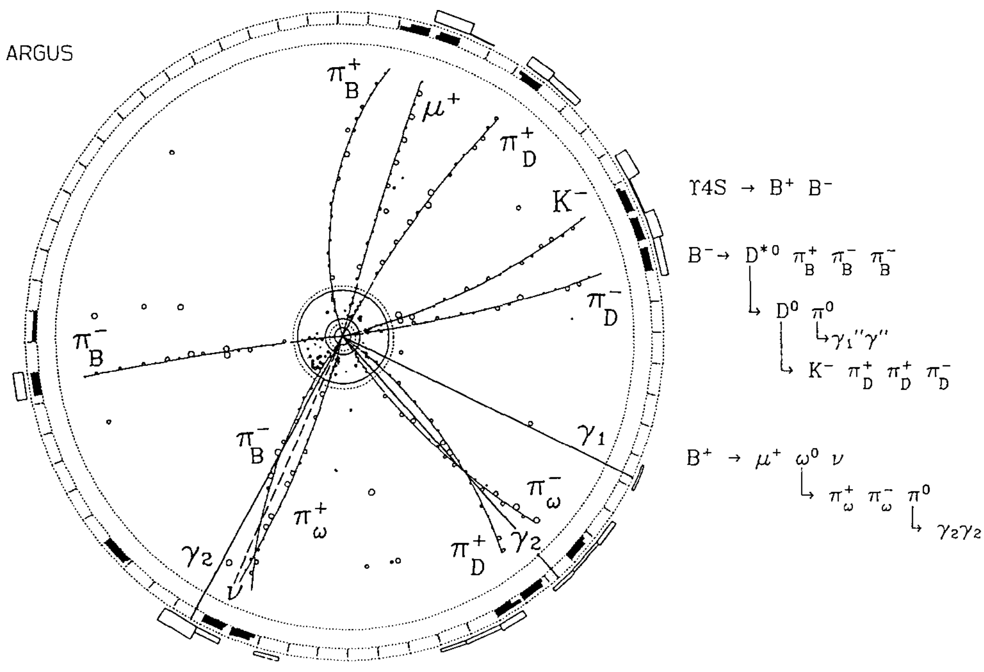

Fig. 6. $\Upsilon(4S)$ decay into B^+B^-, $B^+\to\omega\mu^+\nu$, $B^-\to D^{*0}\pi^+\pi^-\pi^-$.

Table 3
Kinematic quantities of the event in fig. 6, $\Upsilon(4S)\to B^+B^-$, where $B^+\to\omega\mu^+\nu$ and $B^-\to D^{*0}\pi^+\pi^-\pi^-$.

	p(GeV/c)	Mass(MeV/c^2)	$\cos\theta$
$B^+\to\omega\mu^+\nu$			
$\omega\to\pi^+_\omega\pi^-_\omega\pi^0$	1.517 ± 0.016	809 ± 20	-0.12
$\pi^0\to\gamma_2\gamma_2$	0.378 ± 0.049	193 ± 34	0.24
μ^+	2.368 ± 0.023		-0.03
ν	1.34		≈0.5
$B^-\to D^0\pi^+_B\pi^-_B\pi^-_B\gamma_1$			
$D^0\to K^-\pi^+_D\pi^+_D\pi^-_D$	1.988 ± 0.007	1853 ± 7	0.24
K^-	0.492 ± 0.006		-0.36
$\pi^+_B\pi^-_B\pi^-_B$	1.902 ± 0.012	1345 ± 10	-0.09
γ_1	0.105 ± 0.024		0.36

soft neutral particles are exchanged from one B meson to the other, are possible because of the missing photon. However, these alternatives do not change the conclusion that this event contains a B meson decay in a $b\to u$ channel.

In conclusion, we have explicitly shown that $b\to u\ell^-\nu$ transitions are responsible for the excess of leptons with momentum above $p_\ell=2.3$ GeV/c by completely reconstructing two $\Upsilon(4S)$ events containing semileptonic B meson decays into a π^+ or ω meson. In order to obtain a better measurement of the strength of the $b\to u$ coupling, more examples of exclusive $b\to u\ell^-\bar{\nu}$ decays will be needed. Their analysis would allow a discrimination between the proposed models for $b\to u\ell^-\bar{\nu}$ transitions, as has already been the case for $b\to c\ell^-\bar{\nu}$ decays [16]. The precise determination of the $b\to u$ coupling will then help to clarify our understanding of the Kobayashi–Maskawa and mass matrices.

It is a pleasure to thank U. Djuanda, E. Konrad, E. Michel, and W. Reinsch for their competent technical help in running the experiment and processing the data. We thank Dr. H. Nesemann, B. Sarau, and the DORIS group for the excellent operation of the storage ring. The visiting groups wish to thank the DESY directorate for the support and kind hospitality extended to them.

References

[1] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 234 (1990) 409.
[2] CLEO Collab., R. Fulton et al., Phys. Rev. Lett. 64 (1990) 16.
[3] See for example C. Jarlskog, Z. Phys. C 29 (1986) 491.
[4] CLEO Collab., C. Bebek et al., Phys. Rev. Lett. 62 (1989) 8.
[5] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 241 (1990) 278.
[6] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 197 (1987) 452.
[7] T. Ruf (ARGUS Collab.), PhD Thesis (1989), Universität Karlsruhe preprint IEKP-KA/89-5.
[8] M. Wirbel et al., Z. Phys. C 29 (1985) 637.
[9] ARGUS Collab., H. Albrecht et al., Nucl. Instrum. Methods A 275 (1989) 1.
[10] G. Altarelli et al., Nucl. Phys. B 208 (1982) 365.
[11] J.G. Körner and G.A. Schuler, Z. Phys. C 38 (1988) 511.
[12] B. Grinstein et al., Phys. Rev. Lett. 55 (1986) 298; N. Isgur et al., Phys. Rev. D 39 (1989) 799.
[13] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 192 (1987) 245.
[14] CLEO Collab., P. Avery et al., Phys. Lett. B 223 (1989) 470.
[15] ARGUS Collab., H. Albrecht et al., DESY report DESY 89-096 (1989).
[16] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 219 (1987) 121.