Study of inclusive semileptonic B meson decays

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Using the ARGUS detector at the e^+e^- storage ring DORIS-II, we have measured the inclusive semileptonic decays of B-mesons into electrons and muons. The data originate from 220.5 events/pb on the $\Upsilon(4S)$ resonance. We find $BR(B\to e^+\nu_e X) = (10.3\pm0.6\pm0.2)\%$ and $BR(B\to \mu^+\nu_\mu X) = (10.0\pm0.6\pm0.2)\%$ using the model of Altarelli et al. for extrapolating over all lepton momenta, and $BR(B\to e^+\nu_e X) = (9.9\pm0.6)\%$, $BR(B\to\mu^+\nu_\mu X) = (9.7\pm0.6)\%$ using the model of Grinstein et al. For semileptonic decays into baryons, we obtain an upper limit of $BR(B\to\bar{p}e^+\nu X) < 0.16\%$ (90% CL).

Semileptonic B-meson decays are sensitive to fundamental parameters of the standard model and to hadronisation properties of quarks. The momentum spectrum of inclusive decays $D\to\ell\nu X$ probes the ratio of the Cabibbo–Kobayashi–Maskawa matrix elements V_{ab}, V_{cb} and the space–time structure of the $b\to cW$, $b\to uW$ vertices. The absolute decay rate $B\to\ell\nu X$ is determined by the absolute values of $|V_{cb}|$ and $|V_{ub}|$. The branching fractions $BR(B\to\ell\nu X)$ probe the total rate of nonleptonic B-meson decays; spectator models for these decays with QCD corrections lead to expectations of $BR(B\to\ell\nu X)$ between 0.12 and 0.17 [1].

Experimentally, semileptonic B-meson decays have already been studied by several groups [2–8]. We report here on the inclusive analysis of decays collected with the ARGUS detector [9] at the e^+e^- storage ring DORIS-II at DESY. This analysis uses integrated luminosities of 220.5 events/pb on the $\Upsilon(4S)$ resonance and 80.7 events/pb in the nearby continuum. Cuts to suppress continuum events are kept on a modest level in order to ensure minimum bias on the determination of V_{cb}. As a consequence, the information on V_{ub} in this analysis is small since continuum events dominate the V_{ub}-sensitive lepton momentum region between 2.35 and 2.6 GeV/c. A different approach has been taken in an accompanying analysis [7] with very drastic cuts against continuum, leading to the observation of a non-zero result on $|V_{ub}|$.

In both the $\Upsilon(4S)$ and the nearby continuum sample, multihadron events are selected by requiring $n_{ch}\geqslant 4$ and $n_{ch}+n_\gamma/2\geqslant 6$, where n_{ch} is the number of charged particles from the interaction region within radial and longitudinal distances from the interaction centre of <1.5 cm and <5 cm, respectively, which fit to a common main vertex. n_γ is the number of photons with $E_\gamma > 50$ MeV. Converted photons are excluded from this counting of charged particles and included as neutrals. The only additional cuts against continuum, $\gamma\gamma$, and beam-gas or beam–wall events are the following: Events are rejected if they contain a photon of visible energy above 3.3 GeV or a charged particle, identified as a hadron, with $p>2.8$ GeV/c (which are, taking into account the experimental resolution, well above the kinematic limit for $\Upsilon(4S)$ decays). They are also rejected if $\sum p_i/\sqrt{2} > 2.5\sum p_{z,i}^2/s+0.35$ or if an electron (positron) occurs in coincidence with $Q_e\cos\theta_{miss}<0.95$, where p_i and $p_{z,i}$ are the momenta and their z-components of all charged and neutral particles observed, s in E_{cm}^2, Q_e is the charge of the detected electron (positron), and θ_{miss} is the polar angle of the missing momentum vector in the event. After these cuts, 697 810 events remain on the $\Upsilon(4S)$ resonance and 194 741 events in the continuum. The continuum subtraction, performed with the help of both the integrated luminosities from Bhabha events and the number of events with charged particles of $p>2.8$ GeV/c leads to

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$N(\Upsilon(4S)) = 186\,000 \pm 9\ 000$. We assume that all $\Upsilon(4S)$ decay to $B\bar{B}$.

Electrons and muons are selected in the detector barrel region, $|\cos\theta| < 0.7$. Electrons are identified by specific ionisation in the drift chamber, by time-of-flight, and by the energy deposition as well as the lateral energy distribution in the shower counters [9]. In the momentum range between 1.4 and 3.0 GeV/c, the identification has an efficiency of $(89 \pm 2)\%$ and a hadron misidentification probability of $(0.4 \pm 0.2)\%$. The efficiency has been determined from radiative Bhabha events (91%) corrected for overlaps in high-multiplicity events (2%). The misidentification is determined from direct $\Upsilon(1S)$ decays. In the momentum range as given above, there are 16 069 electron candidates in the $\Upsilon(4S)$ sample, with a momentum spectrum as shown in fig. 1, and 2 257 in the continuum sample.

Muons are identified with the help of the ARGUS muon chambers [9]. At least one hit in the two outer layers of the muon chambers close to the extrapolated track of the muon candidate is required. Between 1.4 and 3.0 GeV/c, there are 18 142 muon candidates in the on-resonance sample and 2802 in the continuum sample. The efficiency has been studied by radiative muon pair events and cosmic rays. Above 2 GeV/c it has a constant value of $(81 \pm 3)\%$. The hadron misidentification probability is $(1.5 \pm 0.3)\%$, again determined from direct $\Upsilon(1S)$ decays.

The momentum spectra of electron and muon candidates in the continuum sample are shown in fig. 2. A polynomial function $dN/dp = \exp(\sum_{n=0}^{5} a_n p^n)$ has been fitted to both distributions between 1.4 and 3.0 GeV/c. The best fits are also shown in the figure. These functions, taking properly into account the error matrices on $(a_0 ... a_5)$, are then used to describe the continuum contributions to electron and muon candidates in our fit of the on-resonance sample. Misidentified hadrons in continuum events are automatically included in this description. The continuum scaling factors $\alpha_i (i = e, \mu)$ in

$$\frac{dN_i}{dp}\,[\text{on resonance}] = \frac{dN_i}{dp}\,[\Upsilon(4S)] + \alpha_i \frac{dN_i}{dp}\,[\text{off resonance}]$$

can be obtained from the number of electron and muon candidates above 2.8 GeV/c. We find

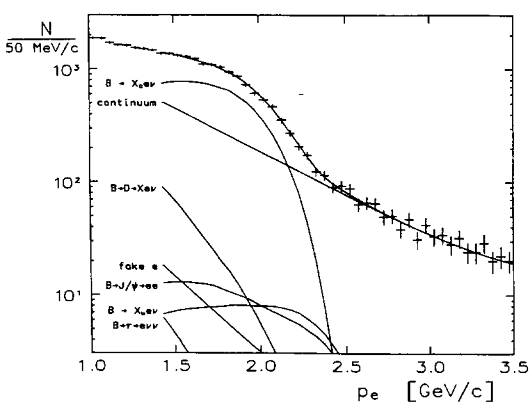

Fig. 1. Momentum distribution of electrons at the $\Upsilon(4S)$ energy. The various expected contributions are illustrated.

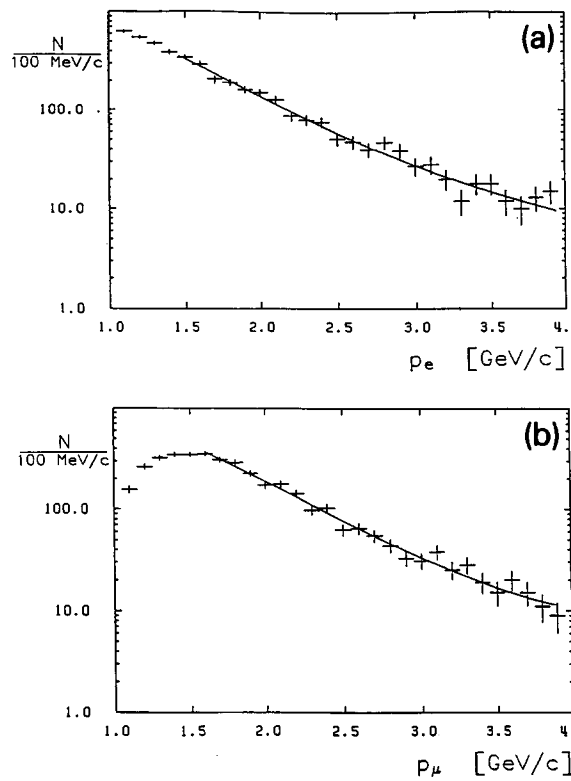

Fig. 2. Momentum distribution of electrons (a) and muons (b) in the continuum below the $\Upsilon(4S)$ energy. The solid lines give the results of the fit described in the text.

$\alpha_e=2.67\pm0.07$ and $\alpha_\mu=2.61\pm0.12$ compared to $\alpha_B=2.63\pm0.04$ used for the determination of the number of $B\bar{B}$ events. Detailed trigger and track chamber efficiency studies have not given any evidence for a difference between the three α values. We use a conservative common constraint of 2.63 ± 0.12 in the fit of the on-resonance data. We also include contributions of misidentified hadrons from B-decays and of secondary leptons from $B\to J/\psi\to \ell\ell$ and $B\to D\to \ell$ cascades [#1]. Fig. 1 shows all contributions for electrons. After additional corrections for efficiency and in the electron case for external and internal bremsstrahlung [#2] one obtains the final momentum spectra [#3] in the $\Upsilon(4S)$ rest frame as shown in fig. 3.

For a determination of the inclusive branching fraction $BR(B\to \ell\nu X)$ and the branching ratio $\Gamma(b\to u\ell^-\bar{\nu})/\Gamma(b\to c\ell^-\bar{\nu})$, we have to use hadronisation models to extrapolate to low momenta, since leptons form the cascade decays contribute significantly to the lepton spectrum below $p_\ell=1.4$ GeV/c, introducing large uncertainties due to the not very well known branching ratios. We consider two classes of models: Exclusive descriptions of $B\to D\ell\nu$, $B\to D^*\ell\nu$ and other decays with the help of form factors [10,13,14] and the inclusive description of $b\to c\ell\bar{\nu}$, $b\to u\ell\bar{\nu}$ including the b-quark motion in the B-meson rest frame and gluonic radiation [15]. In addition we have to take into account the experimental momentum resolution and the B-meson motion in the $\Upsilon(4S)$ rest frame.

We have fitted the lepton momentum spectra of four models, together with the continuum and background contributions described above, to the electron and muon spectra on resonance. The models of Wirbel et al., WSB [10], and Körner and Schuler, KS [13], include only the lightest hadron states D, D*, π and ρ. We therefore restrict the fit range to 1.9–3.0 GeV/c. The models of Grinstein et al., GISW [14], and Altarelli et al., ACM [15], are fitted over the full momentum range of 1.4–3.0 GeV/c. In the WSB, KB, and GISW models all parameters are fixed. ACM has been fitted with three free parameters, the c-quark mass m_c, the u-quark mass m_u, and the Fermi momentum p_F of the b-quark in the B-meson. The fit results are given in tables 1 and 2. In the following, we first comment on table 1 and the determination of $|V_{cb}|$, and then on table 2 with $|V_{ub}/V_{cb}|$.

All four models fit the experimental momentum spectra well, i.e. the spectra are consistent with the V−A structure of b-quark decays. WSB and KS fit well above 1.9 GeV/c where D and D* should dominate the $b\to c$ transitions. In this momentum range, we can approximate for these two models

$$\Gamma(B\to \ell\nu X_c)=\Gamma(B\to D\ell\nu)+\Gamma(B\to D^*\ell\nu)$$
$$=|V_{cb}|^2[\hat{\Gamma}(B\to D\ell\nu)+\hat{\Gamma}(B\to D^*\ell\nu)]$$

and use the reduced rates $\hat{\Gamma}$ together with the experimental B-meson mean life of (1.13 ± 0.15)ps [16] for determinations of $|V_{cb}|$. The obtained $|V_{cb}|$ values are given in table 1. the error on the B-meson mean life increases the error on $|V_{cb}|$ to ±0.003. The table gives also the extrapolated branching fractions $BR(B\to e^+\nu_e X)$ and $BR(B\to \mu^+\nu_\mu X)$ for these two models, where X is only the sum of D, D*, ρ/ω and

#1 We use $BR(B\to D^0X, D^0\to \ell X)=(3.4\pm0.5)\%$, $BR(B\to D^+X, D^+\to \ell X)=(4.2\pm0.7)\%$, $BR(B\to D_sX, D_s\to \ell X)=(0.9\pm0.5)\%$, $BR(B\to J/\psi X, J/\psi\to \ell\ell)=(0.15\pm0.05)\%$, $BR(B\to \tau X, \tau\to \ell X)=(0.40\pm0.05)\%$. The momentum dependence of $D\to \ell\nu X$ is taken from ref. [10] and is in good agreement with experimental data.

#2 The prompt photon radiation in $b\to ce^-\bar{\nu}\gamma$ was taken into account [11] in analogy to $\mu^-\to \nu_\mu e^-\bar{\nu}\gamma$ [12] with a massive ν_μ. The effect is equivalent to external bremsstrahlung in a radiator of 0.015 radiation lengths.

#3 Tables of dN/dp can be obtained from the authors.

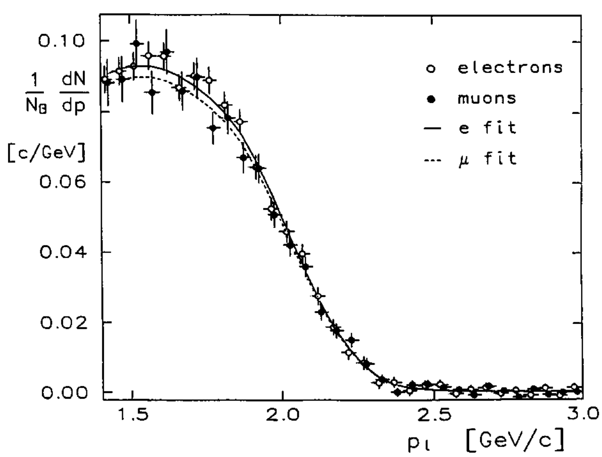

Fig. 3. Corrected momentum distribution of electrons and muons from $\Upsilon(4S)$ decays. The solid and dashed lines are the fits of the GISW model to the electron and muon data respectively.

Table 1
Results on $B_e = BR(B\to e^+\nu X)$, $B_\mu = BR(B\to \mu^+\nu X)$ and V_{cb} for different theoretical models. The quoted errors are statistical and systematic, added in quadrature. The additional error in the ACM case is due to the free parameters in this model. The errors on V_{cb} are from B_e and B_μ alone, additional uncertainties are discussed in the text. The B_e and B_μ values have different meaning for the four models; they include the final states as given in column 2.

Model	X states included	Sample	ξ^2/d.f. (best fit)	B_e [%]	B_μ [%]	V_{cb}
WSB [a),b)]	D*, D, ρ/ω, π	e+μ	34.1/33	(8.6±0.7)	(8.8±0.7)	0.051±0.001
KS [a),c)]	D*, D, ρ/ω, π	e+μ	33.8/33	(8.3±0.7)	(8.5±0.7)	0.047±0.001
GISW [d),e)]	1S, 2S, 1P	e+μ	48.8/53	9.9±0.6	9.9±0.6	0.046±0.001
ACM [d),f)]	c, u	e+μ	47.1/51	10.3±0.6±0.2	10.0±0.6±0.2	0.047±0.001

a) these models are fitted to leptons with $p > 1.9$ GeV/c. b) Ref. [10]. c) Ref. [13].
d) these models are fitted to leptons with $p > 1.4$ GeV/c. e) Ref. [14]. f) Ref. [15].

Table 2
Results on $R_{uc} = \Gamma(B\to \ell^+\nu X_u)/\Gamma(D\to \ell^+\nu X_c)$ from ARGUS data for different theoretical models.

Model	States included	Sample	p_{min} (b→c) [GeV/c]	p_{min} (b→u) [GeV/c]	R_{uc}	$\lvert V_{ub}/V_{cb}\rvert$
GISW [a)]	1S, 2S, 1P	e	1.40	1.40	0.003±0.015	
		μ	1.40	1.40	0.032±0.017	
		e+μ	1.40	1.40	0.014±0.011	
		e+μ	1.40	2.35	0.022±0.015	$0.14\pm^{0.05}_{0.06}$
WSB [b)]	D*,D, ρ/ω, π	e+μ	1.90	1.90	0.011±0.009	
		e+μ	1.90	2.35	0.012±0.010	$0.10\pm^{0.04}_{0.06}$
KS [c)]	D*, D, ρ/ω, π	e+μ	1.90	1.90	0.010±0.006	
		e+μ	1.90	2.35	0.011±0.007	$0.10\pm^{0.02}_{0.04}$
ACM [d)]	c, u	e+μ	1.40	1.40	0.018±0.006	
		e+μ	1.40	2.35	0.017±0.013	$0.09\pm^{0.03}_{0.05}$

a) Ref. [14]. b) Ref. [10]. c) Ref. [13]. d) Ref. [15].

π. The GISW model includes all important final states, and fits the full momentum range of fig. 3. Including the B mean life error and the quoted model uncertainty [14], we obtain

$$|V_{cb}| = 0.046 \pm 0.006 \quad \text{(GISW)} .$$

The ACM model describes semileptonic b-quark decays. For $b\to c\ell\bar{\nu}$ it gives the following lepton energy spectrum in the b-quark frame:

$$\frac{d\Gamma(b\to c\ell^-\bar{\nu})}{dx} = |V_{cb}|^2 \frac{G_F^2 m_b^5}{96\pi^3} \times\left(\frac{x^2(1-r_c^2-x)^2[(1-x)(3-2x)+(3-x)r_c^2]}{(1-x)^3} + G(x)\right),$$

where $x = 2E_\ell/m_b$, $r_c = m_c/m_b$ and $G(x)$ is a gluon-radiation correction. The $b\to u\ell\bar{\nu}$ decays are described accordingly. For the spectrum in the B-meson rest frame, the model describes the b-quark motion with a variable b-quark momentum distributed as

$$f(p) = \frac{4p^2}{\sqrt{\pi}\, p_F^3} \exp(-p^2/p_F^2) ,$$

where p_F is the Fermi momentum. The spectator quark mass is fixed to be $m_{sp} = 0.15$ GeV/c^2. The b-quark mass is variable with

$$\langle m_b \rangle \simeq m_B - \langle \sqrt{m_{sp}^2 + p^2} \rangle .$$

The observed spectrum is insensitive to m_u since $|V_{ub}/V_{cb}|^2 \ll 1$. The parameters m_c and p_F are fitted to be $m_c = (1.65 \pm 0.07)$ GeV/c^2 and $p_F = (0.26 \pm 0.06)$ GeV/c with a strong correlation as shown in fig. 4. The p_F result corresponds to $\langle m_b \rangle = (4.95 \pm 0.07)$ GeV/c^2, and the quark mass difference, taking into account the correlation, is $\langle m_b \rangle - m_c = (3.30 \pm 0.02)$ GeV/c^2. The CKM matrix element V_{cb} is obtained from the integral over the energy spectrum

$$\Gamma(B \to \ell \nu X) = \frac{G_F^2 m_b^5}{192\pi^3} (f_c |V_{cb}|^2 + f_u |V_{ub}|^2)$$

using the approximation [17]

$$f_q \simeq (1 - 8r_q^2 - 12 r_q^4 \ln r_q^2) \times \left(1 - \frac{2}{3} \frac{\alpha_s(m_b^2)}{\pi} [(\pi^2 - \tfrac{31}{4})(1 - r_q)^2 + \tfrac{3}{2}]\right),$$

where $r_q = m_q/m_b$. The r_q parameters obtained from the fit at the lepton spectra result in $f_c = 0.38 \pm 0.03$ and $0.80 < f_u < 0.82$ for $0 < m_u < 0.4$ GeV/c^2 using $\alpha_s = 0.23$. For evaluating $|V_{cb}|$ one has to take into account a correlation between m_b^5 and f_c. Assuming an error of ± 0.3 GeV/c^2 on $\langle m_b \rangle$, but keeping the above error of ± 0.02 GeV/c^2 on $\langle m_b \rangle - m_c$, we obtain

$$|V_{cb}| = 0.047 \pm 0.004 \quad (\text{ACM}),$$

including the error from the B-meson mean lifetime. The agreement with the GISW result is remarkable.

The large continuum contribution in the momentum region above 2.35 GeV/c (see fig. 1), leads to only a weak V_{ub} sensitivity of the inclusive analysis.

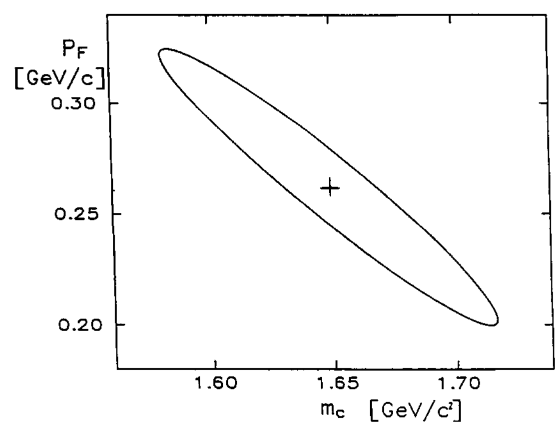

Fig. 4. Best fit and 1σ contour for p_F and m_c in the ACM model.

Table 2 shows the fit results of the four models for $R_{uc} = \Gamma(B \to X_u \ell^+ \nu)/\Gamma(B \to X_c \ell^+ \nu)$. The results agree with those of the ARGUS analysis with drastically reduced continuum [7], but the errors are much larger. As shown explicitly for the GISW case, electrons and muons give slightly different results, but agree within 1.3 standard deviations. The meaning of X_u and X_c is different for the different models. For WSB and KS we have $X_c = D + D^*$, $X_u = \pi + \rho$, for GISW anything evaluated on the meson level, and for ACM anything on the quark level. The quotient $|V_{ub}/V_{cb}|$ follows from $R_{uc} = F_{uc} |V_{ub}/V_{cb}|^5$ where F_{uc} is the model-dependent ratio of reduced rates. This ratio is $F_{uc} = f_u/f_c = 2.1$ for ACM, $F_{uc} = \hat{\Gamma}(\text{all u-mesons})/\hat{\Gamma}(\text{all c-mesons}) = 1.05$ for GISW, and $F_{uc} = (\hat{\Gamma}_\rho + \hat{\Gamma}_\pi)/(\hat{\Gamma}_{D^*} + \hat{\Gamma}_D) = 1.12$ for WSB and 1.18 for KS.

Within the obtained sensitivity, $|V_{ub}/V_{cb}|$ does not depend on m_u in the range between 0 and 0.4 GeV/c^2. The results also agree with each other if the V_{ub} part is fitted above 2.35 GeV/c or in the full momentum range. There is a slight tendency of larger $|V_{ub}|$ results above 2.35 GeV/c in the form-factor models.

The branching fraction results B_e and B_μ in table 1 are much lower than the expected value in quark-spectator models [1]. This could imply that there are contributions to the lepton spectrum in the range below 1.4 GeV/c which is not accessible in this experiment. One mechanism which would lead to low momentum leptons is the decay of B mesons into a lepton and a baryon. In the following we describe a search for these decays.

In multihadron events with $n_{ch} \geq 4$ and $n_\gamma \geq 2$ we have selected antiproton candidates with $0.4 < p < 1.2$ GeV/c, $|\cos\theta| < 0.9$, $p_\perp > 0.06$ GeV/c and $\Delta r < 15$ cm. The chosen momentum range ensures almost unique identification by time-of-flight and dE/dx. The cut on Δr, the distance of closest approach of the $\bar{p}$ track to the main vertex, is weak enough to keep all $\bar{p}$ from hyperon decays, but reduces considerably backscattered protons from the outer detector. This study was restricted to antiprotons because of the very high proton background from interactions in the vacuum pipe and the drift chamber walls.

In events with a $\bar{p}$, we demanded in addition two oppositely charged leptons from the primary vertex, an electron or muon with $1.5 < p_{e,\mu} < 2.3$ GeV/c and an electron with $0.4 < p_e < 1.5$ GeV/c. For kinematic reasons, only the low momentum lepton can come from B→baryon+lepton decays. The search for those leptons has to be limited to electrons, because of the rapid decrease of the muon efficiency below 1.5 GeV/c. We further demanded $|\cos\theta_e|<0.85$ and $|\cos\theta_\mu|<0.65$ to minimize misidentification, and $|\cos(\bar{p}, \ell^\pm)|<0.9$, $-0.5<\cos(\ell^\pm, e^\mp)<0.9$ against background from continuum events.

After these cuts, there remain two candidate events. The slow electrons in these events have momenta of 0.55 GeV/c and 0.57 GeV/c, respectively. Both fast leptons are electrons with $m(e^+e^-)\neq m(J/\psi)$. Both events are consistent with $B\bar{B}$ events, but a semileptonic B decay into baryons is not the only possibility to explain their properties. Semileptonic Λ_c and D decays are not fully removed by the cuts, and there is also a small background from faked leptons or antiprotons. We estimate the background to be of the order of one event. In deriving a conservative upper limit, we regard the two observed events as semileptonic B decays into baryons. After acceptance correction we obtain $BR(B\to\bar{p}e^+X)<1.0\times10^{-3}$ for electrons with $0.4<p<1.5$ GeV/c. The extrapolation to the full lepton momentum range requires a model for the baryon–antibaryon system. As a conservative lower limit for the acceptance, we use a heavy mass system like $\Sigma_c(2500)\Delta(1232)$, which leads to a fraction of 63% for $p_e>0.4$ GeV/c. We thus obtain $BR(B\to\bar{p}e^+\nu X)<0.16\%$(90% CL). This value is very low compared to the inclusive branching fractions $BR(B\to e^+\nu_e X)$ as obtained by the GISW and ACM model extrapolations in table 1. These values can therefore be considered inclusive even with the presence of baryons in the final state.

To conclude, an inclusive study of leptons from direct $\Upsilon(4S)$ decays has led to results on $BR(B\to e^+\nu_e X)$, $BR(B\to\mu^+\nu_\mu X)$, $BR(B\to\bar{p}e^+X)$ and V_{cb}. The extracted values for V_{cb} are model-dependent, but the hadron form factor model of GISW and the quark decay model of ACM lead to the consistent results of $|V_{cb}|=0.046\pm0.006$ and 0.047 ± 0.004, respectively. The obtained branching fractions are smaller than in previous experiments [2,3,5,8]. The electron–muon average $BR(B\to\ell\nu X)$ is $(10.2\pm0.5\pm0.2)\%$ in the ACM model extrapolation and $(9.8\pm0.5)\%$ in the GISW model extrapolation. These values are outside of the expected range of the spectator model [1] and indicate that nonleptonic B-meson decays are not yet well understood.

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