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Abstract

With the ARGUS detector at the e^+e^- storage ring DORIS II, we have determined decay fraction and electron momentum spectrum of the inclusive decay mode $B \to e\nu X$. Using lepton tags from the second B meson in 209000 $\Upsilon(4S) \to B\overline{B}$ decays, we could determine the spectrum for all electron momenta $p_e > 0.6$ GeV/c. Including the small extrapolation to $p_e > 0$, we find the model-independent decay fraction $\mathcal{B}(B \to e\nu X) = (9.6 \pm 0.5 \pm 0.4)\%$. Adding D meson tags, our result is $(9.7 \pm 0.5 \pm 0.4)\%$.

Measurements of semileptonic B meson decays are essentially the only way for a determination of the CKM matrix elements V_{cb} and V_{ub} which are two of the 18 constants of Nature in the framework of the Standard Model. For V_{cb}, exclusive and inclusive decays give comparable precision; recent results [1-9] of the inclusive fraction $\mathcal{B}(B \to \ell\nu X)$ are summarized in Table 1. All these results are obtained from measurements of about half the lepton spectrum, requiring p_ℓ to be larger than about 1.4 GeV/c if measured on the $\Upsilon(4S)$ or similar p and p_t cuts on the Z^0 resonance. Extrapolations down to $p_\ell = 0$ are performed with the help of various models [10-14]; the results in Table 1 are dominantly obtained with those models [10, 11] which give the largest decay fraction. Their average, $(10.5 \pm 0.3)\%$, is significantly lower than expectations from spectator models which, even with the largest conceivable QCD corrections [15], give values above 12%.

Table 1: Recent measurements of inclusive semileptonic decay fractions $\mathcal{B}(B \to \ell\nu X)$.

Experiment	Energy	Ref.	Lepton	Result(%)
ARGUS	$m(\Upsilon 4S)$	[1]	e, μ	$10.2 \pm 0.5 \pm 0.2$
Crystal Ball	$m(\Upsilon 4S)$	[2]	e	$11.7 \pm 0.4 \pm 1.0$
CLEO	$m(\Upsilon 4S)$	[3]	e, μ	$10.5 \pm 0.2 \pm 0.4$
CUSB	$m(\Upsilon 4S)$	[4]	e	$10.0 \pm 0.4 \pm 0.3$
ALEPH	$m(Z^0)$	[5]	e, μ	$10.3 \pm 0.7 \pm 0.5$
DELPHI	$m(Z^0)$	[6]	e, μ	10.1 ± 0.7
L3	$m(Z^0)$	[7]	e, μ	$11.9 \pm 0.3 \pm 0.6$
OPAL	$m(Z^0)$	[8, 9]	e, μ	10.6 ± 0.6

There have been some theoretical efforts to explain the discrepancy. Unexpected large non-spectator effects are discussed in ref. [15]. A hybrid model [16] combines duality for large hadron masses in the final state with bound state calculations for the low masses. A model with two Higgs doublets [17] leads to $b \to H^- c$ decays with $H^- \to \tau^-\nu$ which decrease $\mathcal{B}(B \to e\nu X)$ and $\mathcal{B}(B \to \mu\nu X)$ but enhance $\mathcal{B}(B \to \tau\nu X)$. The discrepancy could, however, be an experimental problem, i. e. the fraction of decay leptons with $p_\ell < 1.4$ GeV/c could be larger than assumed by the extrapolation models used. Semileptonic decays with baryons cannot solve the problem; their contribution has been determined [1] to be negligible. We have therefore tried to measure the lepton momentum spectrum down to the lowest accessible momenta, and in this paper we describe the results obtained with electrons down to 0.6 GeV/c.

Inclusive measurements of B decay leptons suffer from two major background contributions at low momenta, $c \to \ell\nu X$ decays from either continuum c quarks or from $b \to c \to \ell\nu X$ cascades.

Both backgrounds can be considerably reduced by tags from the second B meson in $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ events. Using electrons and muons in the momentum interval between 1.4 and 2.3 GeV/c as tags, the first background from $e^+e^- \to c\bar{c}$ is strongly reduced, and the cascade background is identified by its charge sign. Electrons with a like-sign lepton tag are mainly cascade electrons, and those with an opposite-sign lepton tag are mainly primary. The main corrections arise from $B\overline{B}$ oscillations and from events where both leptons originate from the same B meson. The first of these corrections is well known, and the latter can be determined experimentally from the distribution of the angle between the two leptons.

The experiment has been performed with the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The storage ring is described in ref. [18], ARGUS and its performance in ref. [19]. The data sample used for this analysis has been collected between 1983 and 1992. Its integrated luminosity is 246/pb on the $\Upsilon(4S)$ resonance, corresponding to 209000 $\Upsilon(4S)$ decays, and 97/pb in the nearby continuum. We restrict our lepton spectrum analysis to electrons because their identification extends to much lower momenta than that of muons. In a multihadron environment, electrons are well identified down to 0.6 GeV/c, whereas muon identification in ARGUS reaches a comparable quality only above 1.3 GeV/c. The analysis of even smaller electron momenta would suffer from the large hadronic background in $B\overline{B}$ events.

Multihadron events are selected by requiring $N_{ch} + N_\gamma/2 > 5.0$, where N_{ch} is the number of charged particles and N_γ is the number of photons with $E_\gamma > 80$ MeV. Pairs from converted photons are not included in N_{ch} but are counted as one photon. Electron and muon candidates are selected in the angular range $|\cos\theta| < 0.90$ and are identified by the standard ARGUS particle identification [19] requiring an electron or muon likelihood > 0.7. Contamination from photon conversion is removed by eliminating e^+ and e^- candidates which are partners in a pair with an invariant mass of less than 100 MeV/c^2.

The observed electron momentum spectra between 0.6 and 2.5 GeV/c with like-sign and opposite-sign lepton tags (e or μ) between 1.4 and 2.3 GeV/c are linear combinations of primary and secondary B-meson decay electrons owing to $B\overline{B}$ oscillations. Before separating them into primary and secondary, the two observed electron spectra have to be corrected for the following six background contributions:

1. Electrons from non-$\Upsilon(4S)$ events,
2. Misidentified hadrons in the electron spectra as well as in the e and μ tags,
3. Leptons from decays $B \to J/\psi X$, $J/\psi \to \ell^+\ell^-$, or with $\psi(2S)$,
4. Leptons from cascades $B \to \tau \to \ell$ and $B \to D_s \to \ell$,
5. Photon conversion and $\pi^0 \to \gamma e^+e^-$ decays if only one electron of the pair is detected,
6. Cascade decays with both leptons from the same B meson (only for the e spectrum with unlike-sign e or μ tags).

The main backgrounds are determined from the data themselves, only the small contributions (3) and (4) are estimated by a Monte Carlo simulation. The cascade decays with both leptons

from the same B meson (6) would contribute a large background if we would include all unlike-sign lepton pair events in our analysis. However, the decay kinematics of these cascade events favours opposite directions for both leptons whereas the lepton pairs from two different B mesons have an isotropic opening angle distribution. The cascade background is reduced by a factor of 15 if we apply a cut on the opening angle α, $\cos\alpha(e^\pm\ell^\mp) > 0$, and the remaining contribution can be determined from the data themselves from their opening angle distribution. We therefore continue in the following with the like-sign-tag electron spectra for all opening angles and the unlike-sign-tag spectra with the condition $\cos\alpha(e^\pm\ell^\mp) > 0$. In total, there are 1387 unlike-sign pair candidates in our momentum and opening angle range.

The continuum background (1) is subtracted by scaling the observed off-resonance spectra with the pertinent luminosity ratio. The momentum dependent misidentification of hadrons as electrons (2) is obtained from clean pion samples in K^0_S decays, kaon samples in ϕ meson decays, and antiprotons in $\overline{\Lambda}^0$ decays. The observed hadron spectra in lepton-tagged events are multiplied by these misidentification probabilities and subtracted from the electron spectra. Misidentification in the lepton tags is subtracted with the help of electron-hadron events, where the hadrons have a momentum between 1.4 and 2.3 GeV/c, and the average misidentification rates of $(0.4 \pm 0.2)\%$ for e and $(1.8 \pm 0.5)\%$ for μ in this momentum range. The electron spectrum with unlike-sign tags after corrections (1) and (2) is shown in Fig. 1.

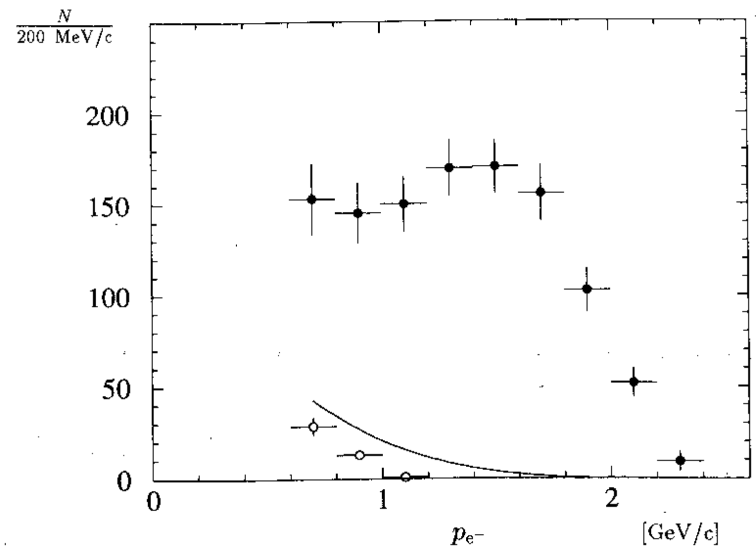

Fig. 1: Electron momentum spectrum with opposite-sign tags and $\cos\alpha(e^\pm\ell^\mp) > 0$ after background subtraction from continuum and hadron misidentification (full circles). The solid line shows the summed background from D_s and τ decays, from γ conversion, and from $\pi^0 \to \gamma e^+e^-$ decays. The open circles give the background with both leptons from the same B meson.

Background (3) arises from J/ψ or $\psi(2S) \to e^+e^-$ decays or from events with only one lepton from the J/ψ or $\psi(2S)$. The first contribution is negligible after the cut $\cos\alpha\ (e^+e^-) > 0$; the data contain only three e^+e^- events in the J/ψ mass region. The second contribution is estimated by Monte Carlo simulation. It contains 15 ± 4 events with the tag lepton from J/ψ or $\psi(2S)$ and 3 ± 3 with the studied electron. The backgrounds (4) are also obtained from a Monte Carlo simulation using the BSW model [12] with $\mathcal{B}(B \to \tau\nu X) = (2.8 \pm 0.2)\%$ [20], $\mathcal{B}(\tau \to e\nu\bar{\nu})$ from ref. [21], $\mathcal{B}(B \to D_s X) = (10.8 \pm 1.8)\%$ [22], and $\mathcal{B}(D_s \to e\nu X) = (8.1 \pm 0.9)\%$ [23]. Background from photon conversion (5) has been determined from the data using pair rates from B events and the probabilites to detect only one electron from radiative Bhabba events. Fig. 1 shows the sum of corrections (3) to (5) as a solid line.

The contribution from lepton pairs originating from the same B meson (6) is determined from the distributions of the opening angle between the two leptons as function of the electron momentum. As an example, the opening angle distribution is shown in Fig. 2 for the electron momentum bin between 0.6 and 0.8 GeV/c after continuum and fakes subtraction. Each of these angular distributions in p_e bins of 0.2 GeV/c width is decomposed in a part with lepton pairs from the same B and a part with pairs from two different B mesons. This is achieved by a fit of two Monte Carlo distributions [11] to the data in the whole angular range; the background from the same B meson is strongly peaked at $\cos\alpha(e^\pm\ell^\mp) = -1$ whereas the signal distribution is constant. The angular range with $\cos\alpha > 0$ contains only a small background of pairs from the same B meson. Its amount depends only weakly on the D^{**} fraction in primary semileptonic B decays; this dependence is included in the systematic error. The results are shown as open circles in Fig. 1. Above $p_e = 1.2$ GeV/c, the background (6) is zero.

Table 2: Event and background summary for the electrons above 0.6 GeV/c with both signs of tags.

	unlike-sign tags $\cos\alpha(e^\pm\ell^\mp) > 0$	like-sign tags all α
Total number of electrons	1387 ± 37	1319 ± 36
Backgrounds:		
(1) Continuum	$193 \pm 22 \pm 4$	$246 \pm 25 \pm 5$
(2) Hadrons misidentified as electrons	$45 \pm 1 \pm 6$	$90 \pm 2 \pm 10$
Hadrons misidentified as lepton tags	$37 \pm 2 \pm 9$	$65 \pm 4 \pm 15$
(3) $B \to J/\psi(\psi(2S))X$, $J/\psi(\psi(2S)) \to \ell^+\ell^-$	$21 \pm 3 \pm 5$	$36 \pm 6 \pm 7$
(4) $B \to D_s X$, $D_s \to e\nu X$	34 ± 7	6 ± 2
$B \to (\tau\nu X)_{\mathrm{Standard}}$, $\tau \to e\nu\bar{\nu}$	36 ± 5	6 ± 2
(5) Photon conversion	18 ± 6	55 ± 11
$\pi^0 \to \gamma e^+e^-$	5 ± 3	17 ± 6
(6) Tag leptons from the same B	$42 \pm 6 \pm 5$	
Background subtracted numbers	$956 \pm 45 \pm 14$	$798 \pm 46 \pm 20$

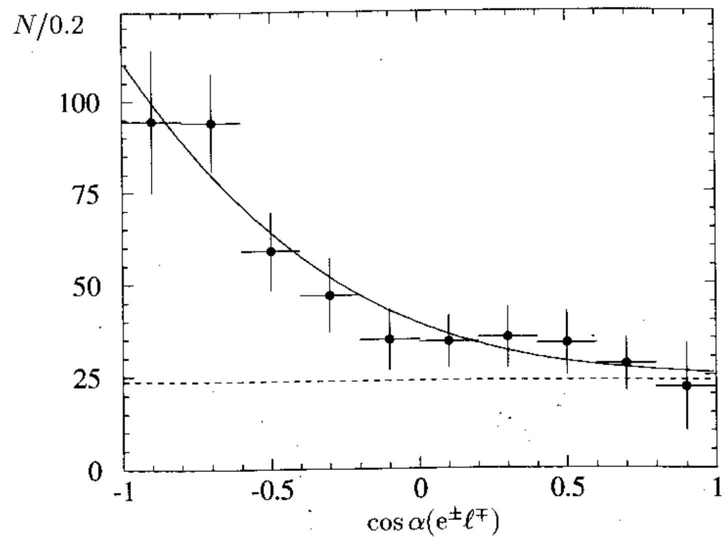

Fig. 2: Distribution of the opening angle between the electron and the tag lepton for the momentum interval $p_e = 0.6 - 0.8$ GeV/c, after continuum and misidentification subtraction. The dashed line shows the contribution of lepton pairs from two different B mesons, the solid line describes the lepton pairs from the same B meson.

A summary of all background determinations is given in Table 2. The final corrected spectrum with the like-sign tags is shown in Fig. 3. The two electron spectra after corrections (1) to (6) can be written as

$$\frac{dN(e^\pm\ell^\mp,\ \cos\alpha > 0)}{dp} = N_B \cdot \frac{\eta_e(p)}{2} \cdot \eta_{tag} \cdot \left[\frac{d\mathcal{B}(b \to e\nu X)}{dp} \cdot (1-\chi) + \frac{d\mathcal{B}(b \to c \to e\nu X)}{dp} \cdot \chi\right],$$

$$\frac{dN(e^\pm\ell^\pm,\ \mathrm{all}\ \alpha)}{dp} = N_B \cdot \eta_e(p) \cdot \eta_{tag} \cdot \left[\frac{d\mathcal{B}(b \to e\nu X)}{dp} \cdot \chi + \frac{d\mathcal{B}(b \to c \to e\nu X)}{dp} \cdot (1-\chi)\right],$$

where N_B is the number of B mesons in the data sample, η_e is the momentum dependent electron efficiency, η_{tag} is the tagging efficiency integrated over all μ and e momenta between 1.4 and 2.3 GeV/c, and χ describes $B\bar{B}$ oscillations, $\chi = f_0 \cdot \chi_0$ with $f_0 = N(B^0\bar{B}^0)/N(\Upsilon 4S) = 0.50$ and $\chi_0 = \mathcal{B}(B^0 \to \ell^- X)/\mathcal{B}(B^0 \to \ell^\pm X) = 0.171 \pm 0.048$ [24]. The product $N_B \cdot \eta_{tag} = N_{tag}$ is equal to the number of all single lepton events with e and μ momenta in our tag range. It is obtained from the same data sample using the same set of correction criteria (1) to (5) as in the lepton-pair analysis. Dividing by N_{tag} and resolving the linear equation set for $d\mathcal{B}(b \to e\nu X)/dp$ and $d\mathcal{B}(b \to c \to e\nu X)/dp$ leads to the final results as shown in Figs. 4 and 5. The actual resolving procedure takes into account that there is also a small number of tags, about 5%, from cascade leptons with different tagging efficiencies and different oscillation dilutions for neutral and charged

B mesons, and that $\eta_e(p)$ is a matrix with bins of true momenta and observed momenta. This efficiency matrix has been determined by the Monte Carlo simulation using external and internal bremsstrahlung, momentum resolution of the detector, and electron reconstruction efficiencies as determined experimentally from radiative Bhabha events.

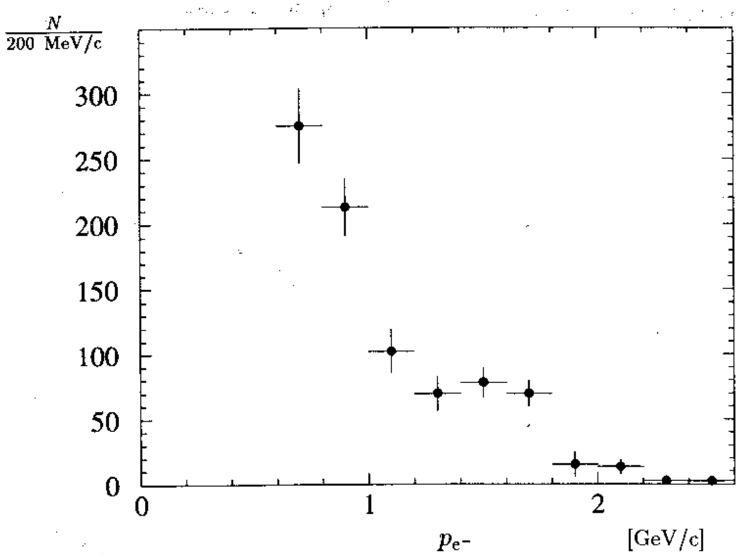

Fig. 3: Electron momentum spectrum with like-sign tags after background subtraction from continuum, hadron misidentification, γ conversion, and $\pi^0 \to \gamma e^+e^-$ decays.

Integration of the obtained electron spectrum in Fig. 4 leads to

$$\mathcal{B}(B \to e\nu X,\ p_e > 0.6\ \ \text{GeV/c}) = (9.1 \pm 0.5 \pm 0.4)\%\ ,$$

where the statistical error takes into account correlations between neighbouring bins arising from the efficiency matrix and the systematic error is dominated by contributions from the background determination (Table 2) and the error on χ_0. The result is independent of any B meson decay model. Extrapolation to $p_e = 0$ requires a model, but the momentum region below 0.6 GeV/c turns out to contain only $(5.7 \pm 1.0)\%$ of all electrons owing to the constraint $d\mathcal{B}/dp = 0$ at $p = 0$. Our final result

$$\mathcal{B}(B \to e\nu X) = (9.6 \pm 0.5 \pm 0.4)\%\ ,$$

is therefore essentially model-independent.

The ACCMM model [10] with parameters as found in our inclusive analysis [1] describes the data points in Fig. 4 very well. The χ^2 value is 12.0 for 8 degrees of freedom and the integral obtained by the fit is $\mathcal{B}(B \to e\nu X) = (9.6 \pm 0.5 \pm 0.4)\%$. With GSIW [11] we obtain $\chi^2 = 4.0$ and $\mathcal{B}(B \to e\nu X) = (9.9 \pm 0.5 \pm 0.4)\%$. Both fits are shown as curves in Fig. 4.

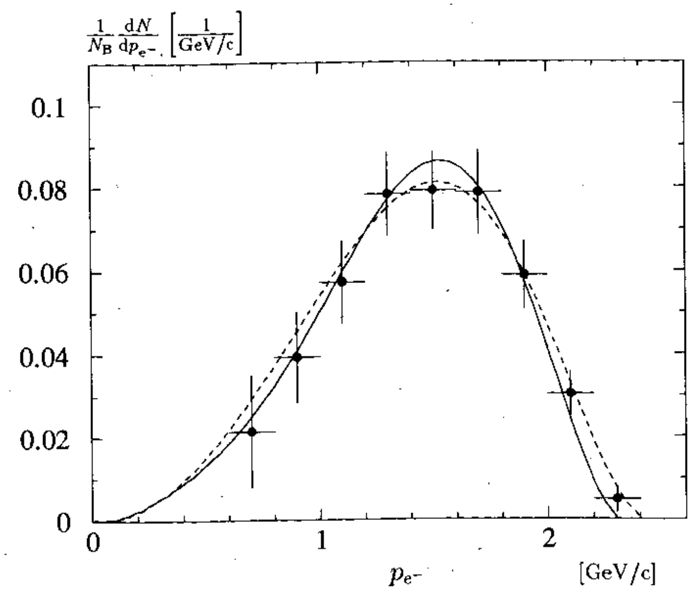

Fig. 4: Final result for the electron spectrum of primary $B \to e\nu X$ decays, all backgrounds subtracted and corrected for efficiency, momentum resolution, external and internal bremsstrahlung. The solid line is the fit of the ACCMM model to the data, the dashed line that of the ISGW model.

The curve in Fig. 5 is the fit of a model for secondary decays to the data points. This model uses the momentum spectrum of inclusive D^0 and D^+ production in B meson decays as observed by ARGUS [25] and $D \to e\nu X$ decays described by BSW [12]. The fit gives a total secondary decay fraction

$$\mathcal{B}(B \to \overline{D} \to e^-) = (7.9 \pm 0.8 \pm 1.0)\%,$$

where the systematic error contains the systematic errors on the data points in Fig. 5, the experimental errors in the D^0 and D^+ spectra, and the BSW model uncertainty in the electron spectrum of $D \to e\nu X$ decays. The result does not include secondary electrons of the opposite sign from the decay chain $B \to \overline{D}D_s$, $D_s \to e^+\nu X$. Within errors, it is compatible with the expectation $\mathcal{B}(B \to \overline{D} \to e^-) = (9.8 \pm 1.4)\%$ [26].

Our model-independent result for $\mathcal{B}(B \to e\nu X)$ as well as the good agreement with the models which were used so far for extrapolating the inclusive lepton measurements [1-9] do not resolve the disagreement with the QCD-inspired expectations for $\mathcal{B}(B \to e\nu X)$ around 12% or higher. One of the non-Standard explanations for the disagreement can be tested with the help of the data presented here. The low momentum part of the electron spectrum contains cascades $B \to \tau\nu X$, $\tau \to e\nu\overline{\nu}$. We have therefore fitted the spectrum in Fig. 4, where the cascades $B \to (\tau\nu X)_{\text{Standard}}$, $\tau \to e\nu\overline{\nu}$ are already subtracted, with a superposition of $B \to e\nu X$ and $B \to (\tau\nu X)_{\text{non-Standard}}$, $\tau \to e\nu\overline{\nu}$. Assuming the same spectrum for both types of $B \to \tau$ decays, the result is

$$\mathcal{B}(\mathrm{B} \to \tau\nu \mathrm{X})_{\text{non-Standard}} = (0.0 \pm 3.2)\% ,$$

corresponding to a 90% CL upper limit of 5.2%. Assuming this upper limit for $\mathrm{B} \to \tau\nu\mathrm{X}$ decays in addition to decays from Standard lepton universality, the fit requires a reduction of $\mathcal{B}(\mathrm{B} \to e\nu\mathrm{X})$ to $(8.8 \pm 0.5 \pm 0.4)\%$. On the other hand, a non-Standard $\mathrm{B} \to \tau$ contribution at a level of 5.2% reduces a 12% decay fraction of $\mathrm{B} \to e\nu\mathrm{X}$ to only 11.4%. We conclude that our observed electron spectrum is inconsistent with the Higgs doublet explanation of the lepton deficit in ref. [17].

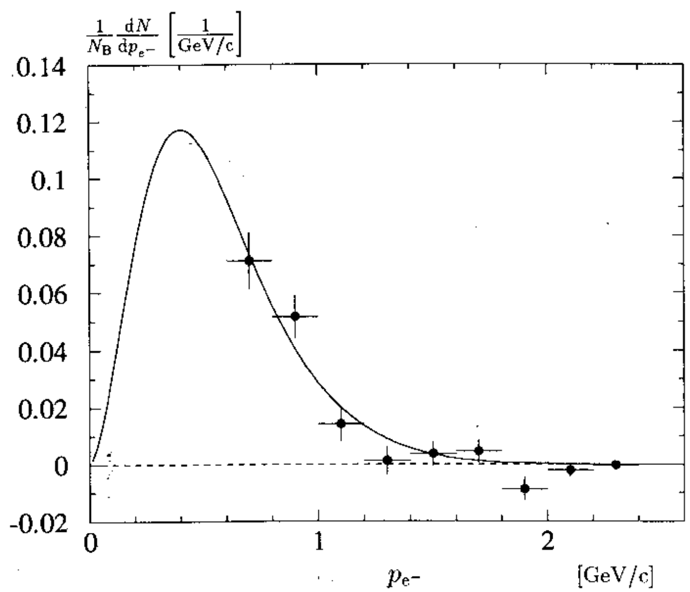

Fig. 5: Final result for the electron spectrum of cascade decays $\mathrm{B} \to \overline{\mathrm{D}} \to e\nu\mathrm{X}$, all backgrounds subtracted and corrected for efficiency, momentum resolution, and bremsstrahlung. The curve represents the fit to a cascade decay model as described in the text.

We have tried an additional model-independent method [27] for a determination of $\mathcal{B}(\mathrm{B} \to e\nu\mathrm{X})$ using D^0 and D^{*+} meson tags. With reconstructed D^0 mesons in the decay mode $\mathrm{K}^-\pi^+$ and D^{*+} in the mode $(\mathrm{K}^-\pi^+)\pi^+$, both with the momentum cut $x_p = p(\mathrm{D},\mathrm{D}^*)/p_{\max} < 0.5$, we obtain $237 \pm 41 \pm 12$ electrons above 1.2 GeV/c, $213 \pm 42 \pm 13$ muons above 1.2 GeV/c, and $442 \pm 84 \pm 27$ electrons in the full momentum range including the small extrapolation to $p_e = 0$. These numbers are corrected for acceptance and background; they originate only from primary $\mathrm{B} \to \ell\nu\mathrm{X}$ decays. Averaging electrons and muons, we obtain

$$\frac{\mathcal{B}(\mathrm{B} \to \ell\nu\mathrm{X},\ p_\ell > 1.2\ \mathrm{GeV/c})}{\mathcal{B}(\mathrm{B} \to e\nu\mathrm{X},\ \text{all } p_e)} = 0.51 \pm 0.12 \pm 0.04 .$$

The combination of this ratio with the efficiency-corrected and luminosity-normalized number of inclusive electrons above 1.2 GeV/c leads to

$$\mathcal{B}(\mathrm{B} \to e\nu\mathrm{X}) = (11.2 \pm 2.8 \pm 1.1)\% .$$

To conclude, we have determined a model-independent inclusive decay fraction $\mathcal{B}(\mathrm{B} \to e\nu\mathrm{X})$ with the help of tags from the second B meson in events $e^+e^- \to \Upsilon(4S) \to \mathrm{B}\overline{\mathrm{B}}$. Both tag methods used, inclusive semileptonic decays with lepton momenta between 1.4 and 2.3 GeV/c and D^0 and $\mathrm{D}^{*\pm}$ mesons from inclusive decays $\mathrm{B} \to \mathrm{DX}$, are flavour-specific and therefore distinguish between primary and cascade electrons. The result with lepton tags, $(9.6 \pm 0.5 \pm 0.4)\%$, has significantly smaller errors than the result with meson tags, $(11.2 \pm 2.8 \pm 1.1)\%$. The average of the two methods is $\mathcal{B}(\mathrm{B} \to e\nu\mathrm{X}) = (9.7 \pm 0.5 \pm 0.4)\%$. This result confirms earlier inclusive measurements [1-9] which had to rely strongly on decay models for extrapolating into the unobserved lepton momentum range and excludes a semileptonic decay fraction of $\geq 12\%$ as expected by the quark decay assumption even with large QCD corrections [15]. One of the explanations for this discrepancy, a non-Standard Higgs contribution to B meson decays into τ leptons [17], is excluded by our electron spectrum.

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