INCLUSIVE ELECTRON PRODUCTION FROM HEAVY QUARKS IN e^+e^- ANNIHILATION AT 34.6 GeV CENTER OF MASS ENERGY

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The production of electrons by bottom and charm hadrons has been studied in e^+e^- annihilation at 34.6 GeV center of mass energy. It is observed that the b quark fragmentation function is peaked at large values of the scaling variable z with $\langle z_b \rangle = 0.84^{+0.15}_{-0.10}{}^{+0.15}_{-0.11}$. For c quarks $\langle z_c \rangle = 0.57^{+0.10}_{-0.09}{}^{+0.05}_{-0.06}$ is observed. A forward–backward charge asymmetry of $A = -0.25 \pm 0.22$ was measured in b production.

The majority of hadronic events from electron–positron annihilation at high energies is believed to arise from quark pair production $e^+e^- \to q\bar{q}$, with the quarks subsequently fragmenting to produce hadrons. Heavy quark (charm and bottom) production in this scheme is especially interesting since the production of heavy quark pairs in the fragmentation process is expected to be small at PETRA energies; hence hadrons containing heavy quarks are believed to contain a primary quark. These hadrons carry information about the original production of quarks and the first stage of fragmentation. Hadrons containing heavy quarks have been observed to have semi-leptonic decays [1–4], and so the production rates and momentum spectra of leptons observed in hadron events furnish information on the heavy quarks.

It has been observed [5–8] that $D^{*\pm}$ charmed mesons retain a large fraction of the charmed quark momenta in the fragmentation process. Measurements of leptons have also shown [9–14] that bottom hadrons carry on the average an even larger fraction of the original quark momentum. These observations are consistent with theoretical ideas [15–17] that heavy quarks are expected to have harder fragmentation functions than light quarks, that is a hadron containing a heavy quark is expected to carry a large fraction of the heavy quark's original momentum. In this letter we present a determination of the bottom and charmed quark fragmentation functions based on inclusive electron spectra.

The experiment was carried out at the DESY storage ring PETRA using the TASSO detector [18,19]. The data were collected at center of mass energies W between 32.9 GeV and 36.8 GeV with an average $\bar{W}$ of 34.6 GeV and correspond to an integrated luminosity of 72.1 pb^{-1}. Hadronic events were selected using charged particle information as described previously [20,21] giving 20331 events. To reduce further the background from two photon interactions and radiative Bhabha scattering, each of these events was required (a) to have at least 5% of its charged momentum in each $\pm Z$ hemisphere, where Z is the beam axis direction and (b) to have an aplanarity $A \geq 0.0005$, where aplanarity is calculated from charged tracks and is defined as $A = \frac{3}{2}Q_1$, and $Q_3 \geq Q_2 \geq Q_1$ are the normalized eigenvalues of the momentum tensor [22]. These cuts selected 18 999 events which contained 1506 (136) electron candidates in the momentum range $1 \leq p \leq 10$ GeV/c ($4 \leq p \leq 10$ GeV/c).

Electrons were detected in lead-liquid argon shower counters located above and below the TASSO magnet coil. These counters cover 40% of the solid angle. They consist of a system of towers and strips described in detail previously [19]. The towers are composed of signal plates of $\approx 7 \times 7$ cm^2 (front towers) and $\approx 14 \times 14$ cm^2 (back towers) stacked so as to point at the interaction region. Four front towers are followed by one back tower. The ≈ 2 cm wide copper strips are plated onto epoxy circuit board and run orthogonal to the beam axis (Z = constant) and parallel to it (ϕ = constant). The first active layer of the counter is at a radial distance of 178 cm from the interaction point. The towers provide easy pattern recognition and a measurement of the total shower energy with a resolution of $\sigma_E/E = 0.136/\sqrt{E} + 0.03$, E in GeV, and the

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strips provide an accurate angular resolution of better than 6 mrad. (These values are for electrons of energy greater than 1 GeV). Charged particle momenta are measured over the solid angle of the shower counters with a cylindrical drift chamber giving a momentum resolution of $\sigma_p/p = 0.016(1+p^2)^{1/2}$, p in GeV/c.

Electron showers are separated from hadron showers and from hadrons with nearby photons using several measurements of the shower properties. In brief:

(1) The momentum of the charged track was required to agree with the total shower energy measured in the front and back towers.

(2) The extrapolated position of the charged track was required to agree with the position of the shower measured in the strips.

(3) The longitudinal development (depth) of the shower measured in front towers, back towers and strips was required to be consistent with an electron shower.

(4) The lateral distribution (width) of the shower energy measured in the strips was required to be consistent with an electron shower. The precise criteria follow:

(1) A χ^2 value was defined to measure the agreement between track momentum and shower energy. The measured track momentum p_{meas} and the measured shower energy E_{meas} were combined to find a value p_{fit} (E_{fit}) representing the electron momentum (energy) by minimizing $\chi^2 = [(p_{\mathrm{meas}} - p_{\mathrm{fit}})/\sigma_p(p_{\mathrm{fit}})]^2 + [(E_{\mathrm{meas}} - E_{\mathrm{fit}})/\sigma_E(E_{\mathrm{fit}})]^2$ with respect to p_{fit}. If the shower energy was less than the track momentum (as tends to be the case for hadronic showers) the energy and momentum were required to be consistent by demanding a χ^2 value less than 6.0.

(2) All of the strips struck by a shower were used to determine the energy weighted position of the shower. The differences in position in the two directions ΔZ and $\Delta\phi$ (cm) between the extrapolated track position and the shower position were found. The errors on these quantities were measured in two photon scattering events $e^+e^- \to e^+e^-e^+e^-$ and Bhabha scattering events $e^+e^- \to e^+e^-$ to be $\sigma_Z = 0.48/p + 1.27$ cm and $\sigma_\phi = 0.77/p + 0.53$ cm where p is the momentum of the charged track measured in GeV/c. This error contains the multiple scattering error, the error on the position measurement of the shower, and the error on the extrapolated track position (which is important in the case of σ_Z). The condition $(\Delta Z/\sigma_Z)^2 + (\Delta\phi/\sigma_\phi)^2 < 26$ was required to be satisfied.

(3) The longitudinal development of the shower was required to be consistent with that of an electron by examining E_F and E_B, the front tower and back tower summed energies. It was required that $(E_B/E_F) < 0.80 + 0.10p$.

(4) The cluster was required to have most of its energy concentrated in a small lateral region by demanding that the energies E_Z and E_ϕ measured in the two strips closest to the extrapolated track position (in the two directions Z and ϕ) be large. The requirements were that $E_Z/E_{\mathrm{min}} > -0.64 + 1.22\,p$ and that $E_\phi/E_{\mathrm{min}} > -1.43 + 1.13p$ where E_{min} is the mean energy deposited by a minimum ionizing particle traversing the counter at normal incidence.

The efficiency for detecting an electron with these cuts was determined from two photon scattering events $e^+e^- \to e^+e^-e^+e^-$ for electron momenta $1 \leqslant p \leqslant 5$ GeV/c, and is approximately constant in this range with a value of 82%.

The major sources of background in the electron sample are showers induced by charged hadrons resembling electron showers, charged hadrons and photons accidentally arriving at nearly the same location in the counter, and photon conversions into electron pairs which were not recognized as such. A hybrid Monte Carlo method was used to estimate the backgrounds due to hadrons. Single simulated hadron showers were generated with the aid of the hadronic shower Monte Carlo program Gheisha [23]. All electromagnetic particles (including those produced in the course of a hadronic shower) were treated with the electromagnetic shower Monte Carlo program EGS [24]. The detector response to these showers was simulated in detail; drift times were generated for the wires of the drift chamber and deposited energies were generated for the towers and strips of the shower counters. This simulated shower was then imbedded into a real event by combining the drift times (taking the shortest drift time if the same wire fired in both data and Monte Carlo) and by summing the energy deposits in the liquid argon. The resultant event was then passed through the analysis chain used for the real data. The thrust axis was determined using all charged tracks including the imbedded track. The momentum p and transverse momentum p_T with respect to the thrust axis of the simulated hadron were determined. At a given p and p_T, the energy deposit distributions associated with the simulated hadrons were found to agree with those of the charged tracks in hadronic events. The hybrid method enabled us to simulate not only hadronic showers, but also the overlapping of hadronic showers with photons as occurs in a jet environment. Using this method it was estimated that (1.0 ± 0.3)% of all hadrons with momentum $p \geqslant 2.0$ GeV/c and $p_T \geqslant 1.0$ GeV/c pass the electron selection criteria. This number increases to (1.5 ± 0.4)% for hadrons closer to the jet axis with momentum $p \geqslant 1.0$ GeV/c and $p_T < 1.0$ GeV/c. These fractions are consistent with estimates obtained from the pions observed in the decays $\tau \to$ hadrons and $K^0 \to \pi^+\pi^-$.

Electrons from photon conversion and from the Dalitz decay of the π^0 were suppressed by a search for oppositely charged pairs of particles with an invariant mass below 0.080 GeV (assuming electron masses for the particles) and a common vertex at a radial distance between 8 cm and 35 cm from the interaction point. This radial region includes all regions of the detector between the beam pipe and the inner wall of the drift chamber. The background from conversion electrons not found by this search was estimated by simulating full events in the drift chamber, followed by the same pattern recognition and analysis used in the data. Of the conversion electrons in the momentum range $1 \leqslant p \leqslant 10$ GeV/c approximately 65% are recognized and removed. After removing the detected conversion electrons 1110 (117) electron candidates remained in the momentum range $1 \leqslant p \leqslant 10$ GeV/c ($4 \leqslant p \leqslant 10$ GeV/c).

The studies of background showed that of these electron candidates 52% (69%) are prompt electrons from semi-leptonic decays, 30% (26%) are hadronic background and 18% (5%) are conversion electrons which were not recognized in the momentum ranges $1 \leqslant p \leqslant 10$ GeV/c ($4 \leqslant p \leqslant 10$ GeV/c). This is shown in fig. 1, where the electron candidates are shown as

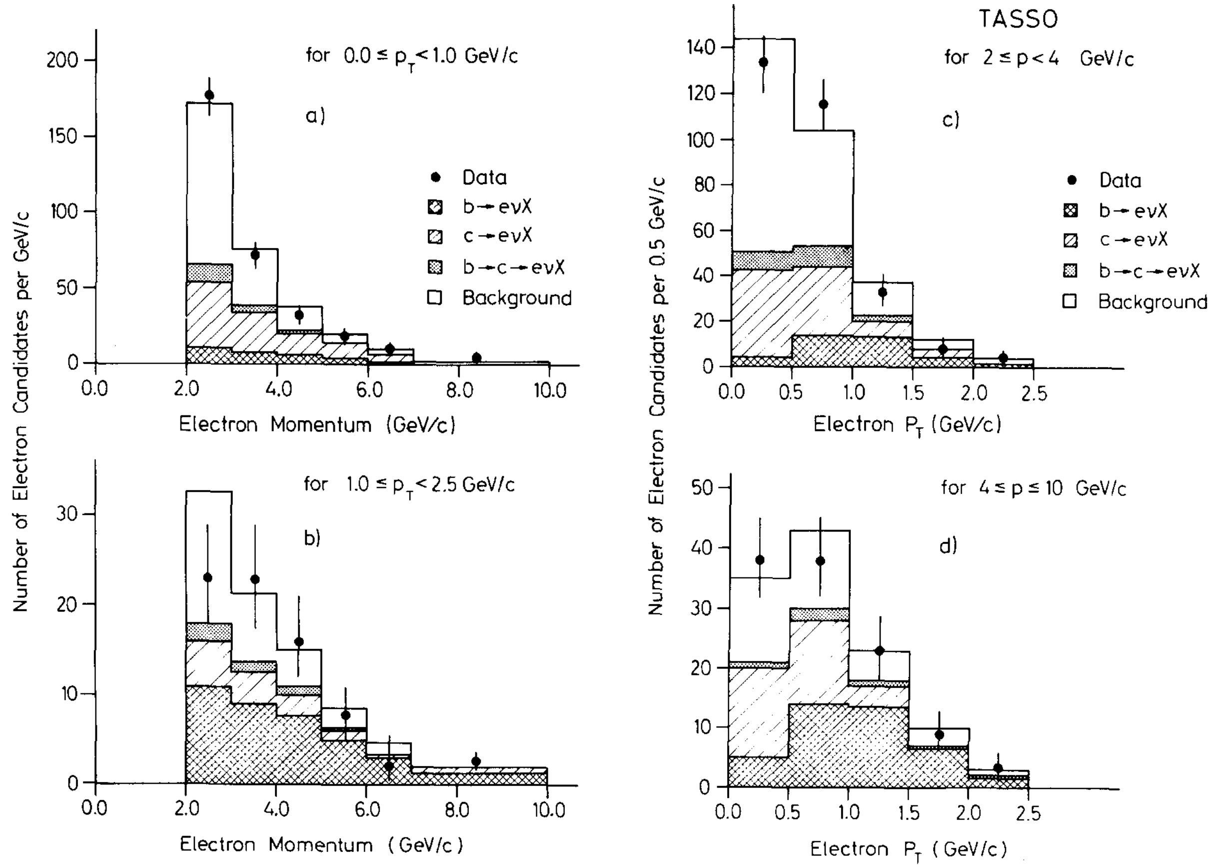

Fig. 1. p and p_T spectra of electron candidates. (a) $0.0 \leqslant p_T < 1.0$ GeV/c, (b) $1.0 \leqslant p_T < 2.5$ GeV/c, (c) $2 \leqslant p < 4$ GeV/c, (d) $4 \leqslant p \leqslant 10$ GeV/c. The points with error bars represent the data. The histograms show the fitted contributions from $b \to e\nu X$ (hatched), from $c \to e\nu X$ (diagonally hatched), and from $b \to c \to e\nu X$ (dotted), and the background contribution.

points with error bars and the background contribution is shown in white.

The efficiency for finding a prompt electron was determined using the same hybrid method, this time imbedding a single simulated electron track and shower produced with EGS [24] into real events. The electron detection efficiency for electrons with momentum $p \geqslant 2.0$ GeV/c and $p_T \geqslant 1.0$ GeV/c (these are isolated tracks) is approximately 82% as also seen in the two photon events $e^+e^- \to e^+e^-e^+e^-$, and falls to approximately 73% for electrons with momentum $p \geqslant 1.0$ GeV/c and $p_T < 1.0$ GeV/c (these tracks are near the jet axis).

A useful variable for separating the contribution of charmed hadrons and bottom hadrons to the lepton rate is the transverse momentum p_T. As bottom hadrons are more massive than charmed hadrons, their decay can produce a lepton at a larger p_T. Therefore seven bins were defined in p, ($1 \leqslant p < 2, 2 \leqslant p < 3, 3 \leqslant p < 4, 4 \leqslant p < 5, 5 \leqslant p < 6, 6 \leqslant p < 7, 7 \leqslant p \leqslant 10$ GeV/c) and four bins were defined *in* p_T ($0.0 \leqslant p_T \leqslant 0.5, 0.5 \leqslant p_T \leqslant 1.0, 1.0 \leqslant p_T \leqslant 1.5, 1.5 \leqslant p_T \leqslant 2.5$). A prompt electron rate was then estimated for each bin by subtracting the various background contributions from the electron candidates.

The fragmentation functions of heavy quark flavors were parameterized by

$$f(z) = \frac{N}{z[1 - 1/z - \epsilon/(1-z)]^2}, \quad \text{for } z \geqslant z_{\min},$$
$$= 0, \quad \text{for } z < z_{\min}, \quad (1)$$

as proposed by Peterson et al. [17], where N is a normalization factor chosen such that $\int f(z)\,dz = 1$, ϵ is a parameter describing the fragmentation, and $f(z)$ is the probability of finding a hadron containing the original quark at z, defined as

$$z = (E + p_\parallel)_{\text{hadron}}/(E + p_\parallel)_{\text{quark}},$$

where E is the energy of the quark or hadron, $p_\parallel$ is the longitudinal momentum of the quark or hadron measured relative to the original quark direction and $z_{\min}$ is the minimum value that z can take on. (Due to finite hadron masses $z_{\min}$ is not zero.) The use of formula (1) gives us a convenient way of expressing our results.

A fit to the background subtracted electron distributions was made considering three different classes of events:

(1) Semi-leptonic decay of bottom hadrons in $b\bar{b}$ events.

(2) Semi-leptonic decay of charmed hadrons in $c\bar{c}$ events.

(3) Semi-leptonic decay of charmed hadrons resulting from the decay of bottom hadrons in $b\bar{b}$ events (cascade decay).

The lepton spectra were estimated using our standard Monte Carlo event simulation [25] with independent jet fragmentation [26], first and second order QCD as calculated by FKSS [27] and radiative corrections as calculated by Berends and Kleiss [28]. The generated lepton spectra of D and B mesons in the center of mass frame are in agreement with the results from DELCO [2] and CLEO [4], respectively. The spectrum of leptons from the cascade decay of B mesons to D mesons to leptons is in agreement with expectations from the D spectra from B meson decay as measured by CLEO [29].

Four parameters were allowed to vary in the fit: ϵ_c and ϵ_b the longitudinal fragmentation function parameters for charmed quarks and bottom quarks, and $BR(c \to e\nu X)$ as well as $BR(b \to e\nu X)$ the average semileptonic branching ratios of charmed hadrons and bottom hadrons into electrons, respectively. The fit was performed by generating electron p and p_T spectra with a flat fragmentation function and weighting these spectra with the fragmentation functions and branching ratios to predict the contents of the set of bins given before. The distribution of prompt electrons in the momentum range $1 \leqslant p < 10$ GeV/c was taken into the fit, with the exception of the bins ($1 \leqslant p < 2$ GeV/c, $0 \leqslant p_T < 1$ GeV/c) and ($2 \leqslant p < 3$ GeV/c, $0 \leqslant p_T < 0.5$ GeV/c) where the hadronic background is above 65% of the total rate. We obtain

$$BR(c \to e\nu X) = 0.092 \pm 0.022(\text{stat.}) \pm 0.040(\text{syst.}),$$

$$BR(b \to e\nu X) = 0.111 \pm 0.034 \pm 0.040,$$

$$\epsilon_b = 0.005^{-0.005}_{+0.022}{}^{-0.005}_{+0.020},$$

$$\epsilon_c = 0.19^{-0.13}_{+0.29}{}^{-0.08}_{+0.17},$$

where the statistical errors are those defined by an increase in χ^2 value of 1.0. The four parameters are correlated, and the statistical errors take this into account by being given as the outer limits of the projection of the four dimensional surface where the χ^2 has increased by 1.0. The χ^2 value for this fit is 16.3 for 21 degrees of freedom. The various contributions from the fit to the electron rate are shown in fig. 1. Systematic errors were estimated by varying the overall estimate of the hadronic background by ±30%, by varying the estimate of the converted photon background by ±20% and by varying the regions of p and p_T used in the fit.

The average semi-leptonic branching ratios into electrons are comparable to the results from the charm and bottom threshold energy regions [1–4] as well as to the higher energy data [9–14,30].

The values of ϵ_c and ϵ_b correspond to average values of z of

$$\langle z_b \rangle = 0.84^{+0.15}_{-0.10}{}^{+0.15}_{-0.11} ,$$

$$\langle z_c \rangle = 0.57^{+0.10}_{-0.09}{}^{+0.05}_{-0.06} .$$

These results agree with previous measurements [9–14].

One further topic of interest is that of possible weak-electromagnetic interference effects. Quarks are expected to have an asymmetry in their production angular distribution due to weak-electromagnetic interference, similar to, but larger than the asymmetry observed in the process $e^+e^- \to \mu^+\mu^-$ [‡1]. We analyzed the data in terms of the angular distribution of the event thrust axis, which according to Monte Carlo studies [32] measures the original quark direction within 8° accuracy. The p and p_T of the electron and an event shape variable (described below) are used to determine the probability that the event arose from an $e^+e^- \to b\bar{b}$ event or an $e^+e^- \to c\bar{c}$ event. The charge of the electron found in the jet is used to decide whether the jet originated from a quark or an antiquark (an e^- tags b and $\bar{c}$ quarks).

The event shape variable used is motivated by the observation that near threshold, $b\bar{b}$ events have high sphericities [29]. This variable is calculated in the following way: all of the particles which fall within a cone of half-opening angle 40° about the thrust axis are considered, and divided into two jets of particles. The particles of each jet are then boosted by a Lorentz transformation into the rest frame of a hypothetical particle travelling along the thrust axis with velocity $\beta = 0.64$. (This boost brings the particles toward the quark rest frame). The value of β was chosen to maximize the separation of $b\bar{b}$ events from $c\bar{c}$ events. The sphericities S_1 and S_2 of the two jets in their boosted frames are calculated, and the product $S_1 \times S_2$ is taken as a measure of how likely the event was to have come from an $e^+e^- \to b\bar{b}$ event or an $e^+e^- \to c\bar{c}$ event. For the standard Monte Carlo events the requirement $S_1 \times S_2 > 0.1$ yields a sample of events of which 37% arise from bottom quark pair production and selects 27% of all $b\bar{b}$ events produced. Requiring that $S_1 \times S_2 > 0.2$ yields a sample of events of which 48% arise from bottom quark pair production and selects 9% of all $b\bar{b}$ events produced.

‡1 For a recent summary see ref. [31].

A maximum likelihood fit was performed to the angular distribution θ between the incoming electron beam and the thrust axis in the same (opposite) hemisphere as the detected electron (positron). The function to be maximized was

$$W(A_b, A_c) = \sum \ln[F(p, p_T, S_1 \times S_2, \cos\theta)] ,$$

where the sum is over the same electron candidates used above, and

$$F(p, p_T, S_1 \times S_2, \cos\theta)$$
$$= f_b(p, p_T, S_1 \times S_2)(1 + \tfrac{8}{3}A_b \cos\theta + \cos^2\theta)$$
$$+ f_c(p, p_T, S_1 \times S_2)(1 - \tfrac{8}{3}A_c \cos\theta + \cos^2\theta)$$
$$+ f_g(p, p_T, S_1 \times S_2)(1 + \cos^2\theta)$$
$$+ f_{b\to c}(p, p_T, S_1 \times S_2)(1 - \tfrac{8}{3}A_b \cos\theta + \cos^2\theta). \quad (2)$$

A_b and A_c are the forward–backward asymmetries of bottom and charmed quarks respectively for the full angular range, $f_b(p, p_T, S_1 \times S_2)$ is the fraction of events, with the particular values of p, p_T and $S_1 \times S_2$, which come from original bottom quark production, $f_c(p, p_T, S_1 \times S_2)$ is the fraction of events which come from original charmed quark production, $f_g(p, p_T, S_1 \times S_2)$ is the fraction of events which come from background sources (this distribution is assumed to have the symmetric form $1 + \cos^2\theta$), and $f_{b\to c}(p, p_T, S_1 \times S_2)$ is the fraction of $b\bar{b}$ events in which one or both of the bottom quarks has subsequently decayed to a charmed quark, and where this charmed quark produced an observable electron. These fractions were determined from Monte Carlo events generated with the fragmentation parameters determined above.

The fit of eq. (2) to the data yields

$A_b = -0.25 \pm 0.22$,

$A_c = +0.05 \pm 0.24$,

The errors given here are statistical only and the systematic errors are small compared to the statistical errors. These values are to be compared to the values given by the standard electroweak theory of $A_b = -0.25$ and $A_c = -0.14$. When the results for the bottom quark asymmetry are combined with our previous results from muons [12] of $A_b = -0.375 \pm 0.275$, we obtain a combined value of $A_b = -0.30 \pm 0.18$. Asymmetry measurements have been reported by other experiments [30,11,14]. The results from the MARK J group can be directly compared and are $A_b = -0.21 \pm 0.19$ and $A_c = -0.16 \pm 0.09$. We have been informed of a similar measurement by the JADE Collaboration.

In conclusion, the b fragmentation function is found to be peaked at large z with $\langle z_b \rangle = 0.84\,^{+0.15}_{-0.10}\,^{+0.15}_{-0.11}$ which shows that the b quark fragmentation function is hard. The c fragmentation function also has a large mean z of $\langle z_c \rangle = 0.57\,^{+0.10}_{-0.09}\,^{+0.05}_{-0.06}$. The angular distributions of the jets of particles associated with heavy quark production are found to be in agreement with the standard electroweak theory.

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