Inclusive D^0 and D^+ Production in e^+e^- Annihilation at 29 GeV

M. Derrick, E. Fernandez, R. Fries, L. Hyman, P. Kooijman, J. S. Loos, B. Musgrave, L. E. Price, J. Schlereth, K. Sugano, J. M. Weiss, and D. E. Wood
Argonne National Laboratory, Argonne, Illinois 60439

and

S. Ahlen, G. Baranko, P. Baringer, D. Blockus, B. Brabson, M. Daigo,[(a)] G. E. Forden, S. W. Gray, J.-P. Guilluad, C. Jung, H. Neal, H. Ogren, D. R. Rust, and M. Valdata-Nappi[(b)]
Indiana University, Bloomington, Indiana 47401

and

C. Akerlof, J. Chapman, D. Errede, N. Harnew, P. Kesten, S. Kooijman, D. I. Meyer, D. Nitz, D. Rubin, A. A. Seidl, R. Thun, T. Trinko, and M. Willutzky
University of Michigan, Ann Arbor, Michigan 48109

and

I. Beltrami, R. DeBonte, K. K. Gan, D. Koltick, F. J. Loeffler, U. Mallik, R. L. McIlwain, D. H. Miller, C. R. Ng, P. P. Ong, L. K. Rangan, E. I. Shibata, R. Stevens, and R. J. Wilson
Purdue University, West Lafayette, Indiana 47907

and

B. Cork
Lawrence Berkeley Laboratory, Berkeley, California 94720

and

L. Keller and J. Va'vra
Stanford Linear Accelerator Center, Stanford, California 94305
(Received 25 June 1984)

We have observed inclusive production of D^0 and D^+ mesons, and their charge conjugates, in e^+e^- annihilation at 29 GeV on the basis of a data sample of 106 pb^{-1}. These signals correspond to R values of $R(D^0+\bar{D}^0)=1.8\pm0.5$ and $R(D^++D^-)=1.2\pm0.4$. Taking the D^+ and D^0 data together, we measure a charge asymmetry of $A=-0.08\pm0.12$ for charmed quarks. A comparison of $R(D+\bar{D})$ with $R(D^*+\bar{D}^*)$ obtained via the process $D^{*+}\to D^0\pi^+$ gives a D/D^* ratio of $1.0^{+0.3}_{-0.2}$, indicating that direct D^* production dominates over direct D production.

PACS numbers: 14.40.Jz, 13.65.+i

The study of charm production[1-4] in e^+e^- annihilation at PEP and PETRA has largely relied on reconstruction of D^{*+} mesons through their transition $D^{*+}\to D^0\pi^+$. The low Q value of this process enables its detection without the requirement of exceptional resolution of the apparatus. Inclusive measurements of other D mesons, however, make exacting demands on resolution. We present here results for inclusive D^0 and D^+ production obtained with the high-resolution spectrometer (HRS) at PEP. Fragmentation functions and cross sections are compared with D^* data. We also present a measurement of the electroweak asymmetry for charmed quarks.

The data sample corresponds to an integrated luminosity of 106 ± 5 pb^{-1} obtained during the first two years of HRS operation at the PEP storage ring. The data were taken at a center-of-mass energy of 29 GeV. The HRS is a general purpose detector and is described elsewhere.[5] Substantial emphasis is placed on measurements of the charged-particle momenta and all the detector elements operate in a magnetic field of 1.62 T. The measured momentum resolution for high-momentum tracks at large angles is $\sigma_p/p\simeq2\times10^{-3}p$ (p in GeV/c).

The apparatus was triggered when two or more tracks were found by the trigger processor in the central drift chamber or when at least 4.8 GeV of energy was deposited in the barrel and end-cap calorimeters. Subsequently, to select one-photon annihilation events and to reduce beam-gas and two-photon backgrounds, the events were required to have a minimum charged multiplicity of 5 and a scalar sum of charged-track momenta greater than 7.8 GeV/c. No particle identification or shower-counter information was used for the analysis.

Figure 1(a) presents the $K^-\pi^*$ (and charge conjugate) mass spectrum for $z_D \geqslant 0.5$, where $z_D \equiv 2E_D/\sqrt{s}$, and for $|\cos\theta^*| < 0.7$, where θ^* is the D^0 decay angle in the helicity frame (D^0 rest frame with the z axis along the D^0 direction of flight). All reconstructed tracks coming from the vertex were tried in turn as both K and π. A clear signal is observed at $m_{D^0} = 1.861$ GeV/c^2. The $\cos\theta^*$ selection eliminates an angular region observed to be dominated by background.[6] Since the D^0 is spinless, the actual distribution in decay angle is isotropic and thus the efficiency correction is straightforward.[7]

The signal in Fig. 1(a) corresponds to 144 ±18 events. The observed mass of 1.861 ±0.004 GeV/c^2, including estimated systematic error, is consistent with the accepted value. The observed width σ_m of 0.013 ±0.002 GeV/c^2 is consistent with the apparatus resolution.

The inclusive $K^-\pi^+\pi^+$ effective mass spectrum for $z_D \geqslant 0.5$ is given in Fig. 1(b). A similar decay-angle cut of $|\cos\theta^*| > 0.3$ has been applied, where the decay angle is now defined by the normal to the three-body decay plane of the D^+ in the helicity frame. In this case the background is observed to lie preferentially in a plane which contains the D^+ direction of flight while the actual D^+ angular distribution must again be isotropic.[6]

The data of Fig. 1(b) give a signal of 123 ±23 events at the mass value of $m_{D^+} = 1.863$ ±0.004 GeV/c^2 with an observed σ_m of 0.013 ±0.003 GeV/c^2.

The D^0 fragmentation function has been measured from the data of Fig. 2 which shows the $K^-\pi^+$ spectra for several different intervals of z_D. For $z_D \geqslant 0.5$, a significant signal is measurable in each bin. The acceptance has been calculated with use of a Monte Carlo simulation[8] of the detector with the resulting efficiencies given in Table I. For $z_D \geqslant 0.5$, the average detection efficiency including the decay-angle cut for $D^0 \to K^-\pi^+$ is 0.39 ±0.01 and the corresponding efficiency for $D^+ \to K^- + \pi^+\pi^+$ is 0.23 ±0.04. With use of previously measured branching fractions,[9] the observed signals then correspond to cross sections of $\sigma(D^0 + \bar{D}^0) = 0.11 \pm 0.03$ nb and $\sigma(D^+ + D^-) = 0.08 \pm 0.03$ nb for $z_D \geqslant 0.5$. The cross-section errors are dominated by the current uncertainties in the branching fractions. The production ratio D^+/D^0 in this z range is 0.7 ±0.3.

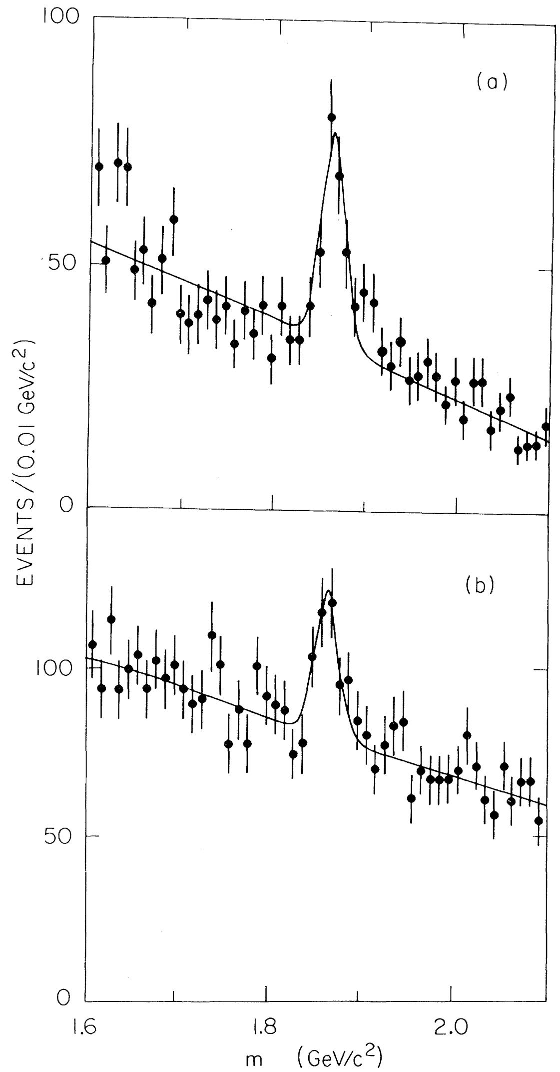

FIG. 1. (a) Invariant $K\pi$ mass distribution for $z_D \geqslant 0.5$ and $|\cos\theta^*| < 0.7$. (b) Invariant $K\pi\pi$ mass distribution for $z_D \geqslant 0.5$ and $|\cos\theta^*| > 0.3$.

Figure 3(a) shows the D^0 fragmentation function, $D(z) = (1/N)\,dN/dz$, where N is the number of observed events corrected for the acceptance. Although the acceptance calculation includes the effects of initial-state radiation, we use $\sqrt{s} = 29$ GeV in the definition of z. Also plotted in Fig. 3(a) are our simultaneous measurements of the D^* fragmentation function, reported elsewhere.[10] Fitting with the form of Peterson *et al.*,[11] which has been used empirically to characterize heavy-quark fragmentation functions, gives the parameter $\epsilon = 0.35^{+0.07}_{-0.06}$ which is the best-fit value for the combined D^0 and D^* data. The D^0 results alone give $\epsilon = 0.27^{+0.09}_{-0.07}$, in agreement with our D^* value from

TABLE I. D^0 and D^+ fragmentation.

z	Efficiency[a]	$\frac{s}{\beta}\frac{d\sigma}{dz}$ (μb GeV^2)	$D(z)=\frac{1}{N}\frac{dN}{dz}$
		D^0	
0.3–0.5	0.35	0.148 ±0.141	1.13 ±1.08
0.5–0.6	0.32	0.413 ±0.082	3.25 ±0.72
0.6–0.7	0.41	0.249 ±0.057	1.96 ±0.51
0.7–1.0	0.41	0.105 ±0.021	0.84 ±0.14
		D^+	
0.5–0.6	0.22	0.266 ±0.105	...
0.6–0.7	0.23	0.223 ±0.060	...
0.7–1.0	0.23	0.056 ±0.019	...

[a]Includes correction for decay-angle cuts.

Ref. 10 of $\epsilon=0.41^{+0.10}_{-0.08}$. The curve shown in Fig. 3(a) corresponds to $\epsilon=0.35$.

Figure 3(b) presents our D^0 and D^+ cross sections expressed as $(s/\beta)d\sigma/dz$. The D^+ and D^0 cross sections show the same z dependence within errors.

To extract the total cross sections for inclusive D^0 and D^+ production, the observed cross sections in the region $z_D \geqslant 0.5$ are extrapolated to the full range of z. We use the form plotted in Fig. 3(a) with $\epsilon=0.35$ because it includes our D^* measurements which extend over the full range in z. Other forms giving equally good fits to the D^0 and D^* data have been tried. The correction factor is 1.8 ±0.2, where the error includes our full estimate of this extrapolation uncertainty. The above cross sections, taken relative to the μ-pair cross section, then lead to R values for all z of

$$R(D^0+\bar{D}^0)=1.8\pm0.5$$

and

$$R(D^++D^-)=1.2\pm0.4.$$

Here we have corrected for initial-state radiation by

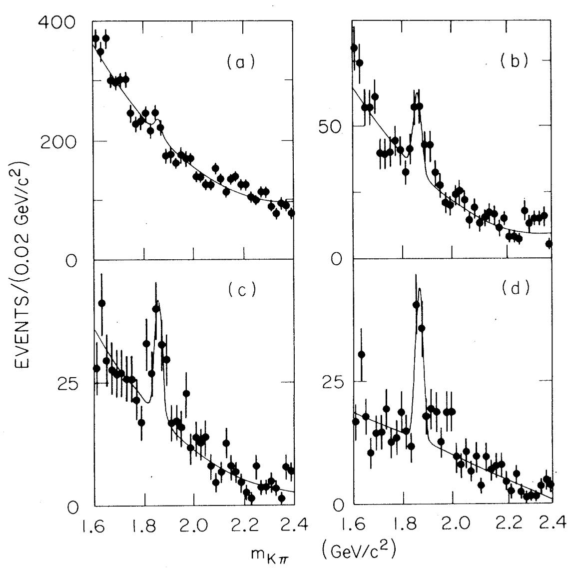

FIG. 2. $K\pi$ mass distribution for intervals (a) $0.3<z_D<0.5$; (b) $0.5<z_D<0.6$; (c) $0.6<z_D,0.7$; (d) $0.7<z_D<1.0$.

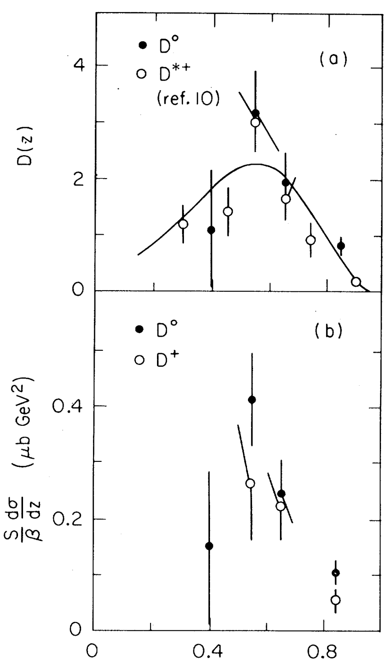

FIG. 3. (a) Fragmentation function obtained from D^0 and D^*. (b) Comparison of $(s/\beta)d\sigma/dz$ for D^0 with results for D^*.

using the μ-pair cross section at an average center-of-mass energy of 27.3 GeV instead of 29.0 GeV. The errors include contributions from the extrapolation factor, statistics, the acceptance calculation, and a major contribution from the D branching ratios.[12]

The sum of our measurements $R(D+\bar{D}) = R(D^0+\bar{D}^0)+R(D^+ + D^-)$ is 3.0 ± 0.6. This result is slightly below the predicted total charm cross section of $R(c+\bar{c}) = 3.53$,[13] and allows for the presence of a smaller amount of production of charmed baryon and charmed-strange mesons which do not decay through the D^0 or D^+.

This value of $R(D+\bar{D})$ is very close to our measurement[10] of $R(D^*+\bar{D}^*) = 2.7 \pm 0.9$, implying that D^*'s are the dominant source of the D's. The ratio $R(D+\bar{D})/R(D^*+\bar{D}^*) = 1.1 \pm 0.4$, where one would expect 1.0 if all D's had their origin in the production and decay of D^*'s. Simple spin-counting arguments predict a direct D component equal to one third of the direct D^*'s which would result in a prediction of 1.33 for $R(D+\bar{D})/R(D^*+\bar{D}^*)$. Our measurement of this ratio can be further improved by confining the comparison of all three reactions to $z \geq 0.5$, thus avoiding extrapolation uncertainties. This results in a measured D/D^* ratio for $z \geq 0.5$ of $1.0^{+0.3}_{-0.2}$. Our results, therefore, are consistent with no direct D production at all or with direct D production at the level predicted by simple spin counting.

Finally, we have used our inclusive D^0 and D^+ signals to obtain a measurement of the electroweak charge asymmetry of charmed quark production. This has been done in the past[3] for the D^* and Ref. 10 presents our new measurements using that technique. For this analysis, we combine the $K\pi$ and $K\pi\pi$ data with the laboratory-angle restriction of $|\cos\theta| < 0.8$ for the charmed system. We then divide that sample into forward and backward hemispheres for the charmed quark relative to the electron direction. The asymmetry, $A = (F-B)/(F+B)$, is measured by a simultaneous fit with identical background shape and normalization to be -0.08 ± 0.12, after correction[14] to the full solid angle. Systematic errors are estimated to be less than a few per cent. The prediction of the standard model for 29 GeV is -0.095.

This measurement of the charmed quark asymmetry from D production can be combined with our measurement from D^* production[10] of $A = -0.15 \pm 0.09$ to obtain our current best value of $A = -0.12 \pm 0.08$. The error takes into account the small overlap of D^0 events entering both data samples.

This work was supported by the U.S. Department of Energy and the Sloan Foundation. We acknowledge the work of the technical staffs of SLAC and the collaborating institutions whose efforts made the experiment possible.

[(a)]Visitor from Wakayama Medical College, Wakayama, Japan.

[(b)]On leave of absence from Instituto Nazionale di Fisica Nucleare, Pisa, Italy.

[1]J. M. Yelton *et al.*, Phys. Rev. Lett. **49**, 430 (1982).

[2]C. Bebek *et al.*, Phys. Rev. Lett. **49**, 610 (1982); P. Avery *et al.*, Phys. Rev. Lett. **51**, 1139 (1983).

[3]M. Althoff *et al.*, Phys. Lett. **126B**, 493 (1983).

[4]S. Ahlen *et al.*, Phys. Rev. Lett. **51**, 1147 (1983).

[5]D. Bender *et al.*, Phys. Rev. D **30**, 515 (1984).

[6]The jet structure of the events tends to produce asymmetric "decays" ($|\cos\theta^*| \to 1$) for random combinations of tracks because the limited p_t of the average background track is smaller relative to the thrust (D^0) axis than is the average p_t of the products of an actual D^0 decay.

[7]We have checked the effect of the decay-angle cut by using $D^0 \to K^-\pi^+$ combinations observed within a $D^{*+} \to D^0\pi^+$ transition. For this very clean subsample of $D^0 \to K^-\pi^+$ events, the distribution in decay angle is indeed observed to be isotropic.

[8]We use the Lund Monte Carlo program with Feynman-Field fragmentation functions. See, for example, B. Andersson, G. Gustafson, and T. Sjoestrand, Phys. Rep. **97**, 33 (1983).

[9]We use the D branching fractions $B_R(D^0 \to K^-\pi^+) = 0.030 \pm 0.006$ and $B_R(D^+ \to K^-\pi^+\pi^+) = 0.063 \pm 0.011$ from R. Schindler *et al.*, Phys. Rev. D **24**, 78 (1981). These D branching fractions, together with the D^* branching fraction $B_R(D^{*+} \to D^0\pi^*) = 0.44 \pm 0.10$, provide a self-consistent fit to the SPEAR data of M. M. Coles *et al.*, Phys. Rev. D **26**, 2190 (1982).

[10]M. Derrick *et al.*, "Charm Quark Production and Fragmentation in e^+e^- Annihilation at 29 GeV" (to be published).

[11]C. Peterson *et al.*, Phys. Rev. D **27**, 105 (1983), sug gests

$$D(z) = \frac{A}{z}\left(1 - \frac{1}{z} - \frac{\epsilon}{1-z}\right)^{-2},$$

where the parameter ϵ is a function of the charmed quark mass.

[12]The full sample reported here has a smaller number of inclusive D^0's observed per unit integrated luminosity than our result in Ref. 4 on a much smaller sample of 19.6 pb^{-1} which also forms part of this analysis. An ac-

ceptable fit to the earlier data sample is obtained, however, with use of parameters from the total sample. We conclude that the 2σ discrepancy is due to a statistical fluctuation.

[13]An estimate of $R(c+\bar{c})=3.53$ for the number of c or $\bar{c}$ quarks produced relative to μ pairs is made including $\frac{4}{3}$ units from c and $\frac{1}{3}$ from b quarks and assuming all $b \rightarrow c$. A value of $\alpha_s=0.17$ is used for the QCD correction.

[14]The correction factor to full solid angle from $|\cos\theta|<0.8$ is 1.14 and assumes only that the angular distribution is of the form $1+a\cos\theta+\cos^2\theta$.