Charm Production in e^+e^- Annihilation

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The cross sections for charm production in continuum e^+e^- annihilation near 10 GeV and near 30 GeV are presented. With the latest values for the D-meson decay branching ratios, about 70% of the charm quarks end up in the D^0 or $D^\pm$ mesons. There is no evidence for a charm deficit. The relative production of the vector and pseudoscalar mesons is in accord with the expectations of spin counting. Measurements of the D^* decay angular distribution show that the vector mesons are primarily produced with equal populations in all helicity states, although there is some evidence for D^* alignment for the highest D^* momenta in the 10 GeV data.

1. Introduction

The total cross section for the e^+e^- annihilation to hadrons through the one-photon exchange graph is:

$$\sigma_T = \frac{4\pi\alpha^2}{3s} \cdot R \left(1 + \frac{\alpha_s}{\pi} + \dots\right),$$

where R is given by the color factor of three times the sum of the squares of the quark charges or $11/3$ for PEP and PETRA data near $\sqrt{s} = 30$ GeV, and $10/3$ for ARGUS and CLEO data in the continuum below $b\bar{b}$ threshold. The first-order QCD correction is about 5%. At the higher PETRA energies, the electroweak effects increase the cross section to a significant extent. Typical values[1] for R such as 3.96 ± 0.09 from MAC and $4.13 \pm 0.08 \pm 0.14$ from JADE are in accord with these simple expectations.

The charm sector is unique in that the individual cross sections for the $e^+e^- \rightarrow c\bar{c}$ reaction can be measured by identifying the mesons and baryons that contain the charm quark: all of the charm quarks finally give a D^0 , $D^\pm$, $D_s^\pm$ meson or Λ_c baryon. The additional production of $c\bar{c}$ pairs in the fragmentation chain is expected to be very small, unlike the case of the light quarks u , d , s , so that the total cross section for $e^+e^- \rightarrow c\bar{c}$ can be measured. This is, in principle, also true for $b\bar{b}$ production, but the smaller production cross section, the tiny decay branching ratios into identifiable final states, and the lack of any

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absolute B mesons decay branching ratios, has so far precluded any such measurements.

2. Experimental Details

The D^0 , D^+ , and D^{*+} mesons are directly observed in the spectrometers via the decay modes: $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, and $D^{*+} \rightarrow D^0 \pi_b^+ + K^- \pi^+ \pi_b^+$. Near 10 GeV both the ARGUS and CLEO collaborations have observed production of the neutral and charged mesons.[2] At 29 GeV, only the HRS[3] has sufficient resolution to see these decays. Figure 1 shows the $K\pi$ and $K\pi\pi$ effective masses measured in the HRS for $Z > 0.45$ and with an helicity angle selection $|\cos \theta_\pi^*| < 0.7$ for the $D^0 \rightarrow K^- \pi^+$ decay and $|\cos \theta_p^*| > 0.3$ for the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay. The angle θ_p^* is the angle between the normal to the $K\pi\pi$ decay plane with respect to its line of flight. The mass peaks are clear.

Fig. 1. Effective mass distribution
(a) $K^- \pi^+$, (b) $K^- \pi^+ \pi^+$.

Fig. 2. Distribution in the mass
difference δ .

The vector meson $D^{*+}(2010)$ has been observed by all of the e^+e^- detectors since the low Q value of 5.8 MeV in the $D^{*+} \rightarrow D^0 \pi^+$ decay leads to a well measured peak in the distribution of the $D^{*+} - D^0$ mass difference δ . However, it is only with the resolution of the HRS that a measurement of the D^{*+} production over the

full Z range is possible for the 30 GeV data. Figure 2 shows the D^{*+} - D mass difference, δ , for $K^-\pi^+$ pairs in the range $1.81 < M_{K^-\pi^+} < 1.92$ GeV.

3. Production Cross Section

To measure the production cross sections, the relevant decay branching ratios must be known. Even for the simplest decay $D^0 \rightarrow K^-\pi^+$ this has turned out to be difficult, with published values varying by more than a factor of two. In this paper, I use the latest MarkIII[4] values of $BR(D^0 \rightarrow K^-\pi^+) = 4.2 \pm 0.56\%$ and $BR(D^+ \rightarrow K^-\pi^+\pi^+) = 9.1 \pm 1.4\%$ in calculating the cross sections. This $D^0 \rightarrow K^-\pi^+$ BR agrees well with the HRS measurement[5] of $4.5 \pm 0.08 \pm 0.5\%$.

Since the D^0 and D^+ mesons are only measured for $Z > 0.45$, the shape of the D^{*+} fragmentation function for the full Z range was used to extrapolate the D measurements to threshold. The resulting cross sections and R values are given in Table I. A value for $BR(D^{*+} \rightarrow D^0\pi^+)$ of 0.57 ± 0.056 was used.[6]

Table I

Total cross sections and R values for charm meson production in e^+e^- annihilation at $\sqrt{s} = 29$ GeV.

	$\sigma(\text{nb})$	R
$D^{*+} + D^{*0}$	0.232 ± 0.041	1.99 ± 0.35
$D^0 + D^0$	0.205 ± 0.031	1.76 ± 0.27
$D^+ + D^-$	0.075 ± 0.014	0.64 ± 0.12
total $D^\pm, D^0$	0.280 ± 0.040	2.40 ± 0.35

Figure 3 compares the $D^{*+}(2010)$ fragmentation function[1] at 10 GeV and near 30 GeV in terms of the light cone variable, $x^+ = \frac{(P+E)_{\text{meson}}}{(P+E)_{\text{max.}}}$. All of the data have been corrected using the above branching ratios.

4. Comparison with Expectation

The expected R value for charm production is 3.60. This is the sum of $(2 \cdot \frac{4}{3} (1 + \frac{\alpha_s}{\pi}))$ for the $e^+e^- \rightarrow c\bar{c}$ reaction, plus the $b \rightarrow c$ contribution. The latter is $(2 \cdot \frac{1}{3} (1 + \frac{\alpha_s}{\pi})(1.15))$: the 1.15 factor comes in because, on average, each b quark decay is estimated to give 1.15 c quarks since the $b \rightarrow c w$ followed by the $w \rightarrow s\bar{c}$ decay yields a pair of charm quarks. The measurements of the charm multiplicity in b decay[2] are $0.95 \pm 0.30 \pm 0.10$ from ARGUS and $0.90 \pm 0.25 \pm 0.10$ from CLEO, smaller than, but not in disagreement with, the 1.15 expected.

Fig. 3. Comparison of the fragmentation distribution for D^* production at (a) 10 GeV, (b) 30 GeV.

Comparing the R value of 3.60 with 2.40 ± 0.35 measured says that $67 \pm 10\%$ of charm quarks end up in D mesons. The value measured by CLEO at 10.55 GeV is $71 \pm 6 \pm 10\%$.

Now the contribution of the D_S^+ and Λ_c baryon must be added. Unfortunately, absolute decay branching ratios for these particles are not known and, in addition, the Λ_c has not been observed in the 30 GeV energy region. The conventional wisdom is that the $u:d:s$ ratio should be 1:1:1/3 and that the baryon-meson ratio is about 8%. With these assumptions, the D mesons should account for 70% of the charm, in agreement with the observations. There is no evidence for a charm deficit.

The vector-to-vector plus pseudoscalar ratio expressed as $D^*/(D^* + D)$ is 0.83 ± 0.17 from the HRS data and $0.85 \pm 0.11 \pm 0.17$ from the CLEO data, in agreement with 0.75 expected from spin counting.

5. Search for Vector-Meson Alignment

Since the D^* is a vector particle ($J^P = 1^-$), it could be produced aligned. To measure the alignment, the angular distribution of the decay $D^{*+} \rightarrow D^0 \pi^+$ is analyzed. The coordinate system used has the z axis in the direction of the D^* momentum and the y axis is along the production plane normal of the D^* . The azimuthal angle (ϕ) is chosen to be zero in the production plane. The polar angle (θ) is the helicity angle of the D^* .

For a $J^P = 1^-$ particle, the decay angular distributions in $\cos \theta$ and ϕ are given by:

$$\omega(\cos \theta) = \frac{3}{4}[(1 - \rho_{00}) + 3(\rho_{00} - 1) \cos^2 \theta] ,$$

$$\omega(\phi) = \frac{1}{2\pi}[(1 + 2\rho_{1-1}) - 4\rho_{1-1} \cos^2 \phi] ,$$

where the ρ 's are the density matrix elements. The alignment parameter $\eta = \frac{1}{2}(\rho_{00} - 1)$ measures the relative amount of quark helicity flip to non-flip[8] in the quark-meson transition.

The allowed range of η is $-\frac{1}{2} < \eta < 1$. If f and $1-f$ are the fraction of quarks giving a pseudoscalar or a vector meson, then statistical arguments give

$$\eta = \frac{1}{2} \left(\frac{1-2f}{2-f} \right) = \frac{1}{4} [1 - 3(V/P)] .$$

If $f = \frac{1}{2}$, $V/P = 3$, and if $f = 1$, $V/P = 1$, so a measurement of η gives the V/P ratio, within the context of these ideas.

A value of $\rho_{00} = 1/3$ corresponds to an equal population of all helicity states. At 29 GeV, the HRS collaboration[9] reported $\rho_{00} = 0.37 \pm 0.04$, $\rho_{1-1} = 0.04 \pm 0.03$, $\text{Re} \rho_{10} = 0.00 \pm 0.01$ and $\eta = 0.06 \pm 0.06$. This value of η gives $V/V+P = 0.80 \pm 0.05$, a more precise result than that given by the cross section ratios.

Fig. 4. Distribution in α . The dashed line shows the result of Suzuki.

A suggestion of a finite alignment has been reported for ρ^0 production in ν and $\bar{\nu}$ interactions[10]. At this conference, the CLEO collaboration[11] presented a beautiful new study of D^* alignment and report a finite η value of $0.06 \pm 0.02 \pm 0.02$. Figure 4 shows these results, together with similar data, from ARGUS[12]. For a distribution in $\cos \theta$ given by $\frac{3}{6 + 2\alpha} (1 + \alpha \cos^2 \theta)$, then α is related to ρ_{00} and η by the expressions $\alpha = \frac{3\rho_{00}-1}{1-\rho_{00}} = \frac{3\eta}{1-\eta}$. Both 10 GeV experiments show a significant increase in α to about 0.5 ($\eta \sim 0.14$) for high momentum D^* 's. By comparison, the data does not support the simple suggestion of Suzuki[13] that the heavy quark Q emits a colinear gluon that splits into a $q\bar{q}$ pair and the heavy meson results from the $Q\bar{q}$ combination. The predicted x^+ variation of α for this model is shown by the dashed line. I note finally that the observation of a finite alignment at high x^+ would rule out the stochastic branching models for heavy quark fragmentation.

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