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D^* and D MESON PRODUCTION IN e^+e^- ANNIHILATION AT 29 GeV *

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ABSTRACT

Recent results on D^* and D meson production at 29 GeV are presented from the DELCO, HRS, and MARK II collaborations at PEP.

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I. Introduction

Recent results are reported on D^* and D meson production at a center-of-mass energy of 29 GeV from data taken at PEP by the DELCO (Caltech-SLAC-Stanford), HRS (Argonne-Indiana-LBL-Michigan-Purdue-SLAC), and MARK II (Harvard-LBL-SLAC) collaborations. D^* production cross sections and fragmentation functions are presented for all three experiments. In addition, the HRS collaboration presents measurements of the D^* charge asymmetry and the inclusive production cross sections for neutral and charged D mesons.

The approximate integrated luminosity for the data samples reported here are given in Table I. Each detector logged 100 to 110 pb^{-1} in the 1982-83 run period. The present results are therefore based on an analysis of only a portion of the available data.

Table I. Integrated luminosities reported in this paper.

Detector	Year		
	1980-81	1981-82	1982-83
DELCO	---	20 pb^{-1}	70 pb^{-1}
HRS	---	20	60
MARK II	15 pb^{-1}	20	---

II. D^* Production

The D^* results are based on the fully visible decay chain:

The numbers of observed events are given in Table II. Analysis efforts on decay modes other than reaction (1) are in progress but are not reported here.

All three experiments identify the D^* events by observing a peak in the mass difference, $\Delta = M(K^- \pi_1^+ \pi_2^+) - M(K^- \pi_2^+)$, where $M(K^- \pi_2^+)$ is restricted to lie in a band centered on the D^0 mass. Because the $D^* \rightarrow D^0 \pi$ decay has a Q value of only a few MeV, the resolution for Δ is much better than that for the separate $(K\pi)$ and $(K\pi\pi)$ mass combinations. Moreover, the first pion (π_1) is kinematically constrained to travel with nearly the same lab velocity as the D^* , such that its lab momentum, $p_{\pi_1} = (m_{\pi}/m_{D^*})p_{D^*}$ is nearly always smaller

than p_{π_2} .

Table II. Numbers of events used in the D^* study. All events listed stem from the decay chain $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^- \pi^+$ (together with the charge conjugate reaction).

Detector	Z_{D^*} Range ^(a)	Total Events ^(b)	Bkgd. Events ^(b)	$e^+e^- \rightarrow D^{*+} X$ Signal
DELCO (TOF)	0.15 - 0.4	18	4	14
DELCO ($\check{C}$ tags)	0.3 - 1.0	58	14	44
HRS	0.2 - 0.4	32	18	14
	0.4 - 1.0	59	3	56
MARK II	0.4 - 1.0	29	4	25

(a) $Z_{D^*} = 2E_{D^*}/E_{CM}$.

(b) Uncorrected for acceptance and efficiencies.

The distribution in Δ for the MARK II collaboration ¹⁾ is shown in Fig. 1. No positive tagging of kaons is required, although time-of-flight consistency within 2σ (where $\sigma \approx 360$ psec) is demanded for all tracks whether assigned a kaon or pion mass. Whenever the neutral ($K\pi$) combination also satisfies the D^0 cut ($1.76 < M(K\pi) < 1.96$ GeV/c²), the value of Δ is computed. A clear peak is seen in Fig. 1 for $Z_{D^*} > 0.4$, but no significant signal is apparent for $Z_{D^*} < 0.4$.

The DELCO results ²⁾, shown in Fig. 2, are based on two different particle tagging schemes. One sample is required to have a Cerenkov tag on either a kaon or a pion, where the threshold is set near 2.6 $\check{G}$ GeV/c. This method is efficient for finding D^* mesons in the range $0.3 < Z_{D^*} < 1.0$. A second sample is found by requiring a time-of-flight tag on the kaon track. This procedure identifies kaons below ~ 1.5 GeV/c and is efficient for finding D^* mesons in the range $0.15 < Z_{D^*} < 0.4$. Events are then entered into the Δ plot provided that the ($K\pi$) system satisfies a broad D^0 cut ($1.66 < M(K\pi) < 2.20$ GeV/c²) and that the opening angle between the K and π tracks satisfies a momentum-dependent cut designed to remove background from the three-body decays, $D^0 \rightarrow K^- \pi^+ \pi^0$. The DELCO detector observes significant signals above background in both data samples, where the background is estimated by the shaded histograms resulting from wrong-sign ($K\pi\pi$) and ($K\pi$) mass combinations.

The D^* signal seen by the HRS collaboration ³⁾ is shown in Figs. 3-5.

Figure 3 is a scatter plot of $M(K\pi_2)$ versus Δ for all correct-sign mass combinations having $Z_{D^*} > 0.2$. A clear concentration of events is seen in the neighborhood of $M(K\pi) = 1865 \text{ GeV}/c^2$ and $\Delta = 145 \text{ MeV}/c^2$. Projections of Fig. 3 are shown in Fig. 4 corresponding to the slices $1810 < M(K\pi) < 1920 \text{ MeV}/c^2$ and $143 < \Delta < 148 \text{ MeV}/c^2$. In Fig. 5, the Δ plot is further divided into four regions of Z_{D^*} . The D^* signal is practically free of background for $Z_{D^*} > 0.4$. Although combinatorial backgrounds grow rapidly as Z_{D^*} decreases, a clear signal is still seen in the HRS for $0.2 < Z_{D^*} < 0.4$.

The D^* signal in the HRS is observed with simpler selections and with less combinatorial background than the other two detectors. This is made possible by the superior momentum and mass resolutions of the HRS (see Table III). It should also be noted that this signal is seen without invoking particle identification from either the time-of-flight system or the Čerenkov counter system.

Table III. Comparison of resolutions for DELCO, HRS, and MARK II.

Detector	B (Tesla)	Tracking		$\sigma_M \text{ (MeV}/c^2\text{) at } D^0$
		Radius (m)	$(\sigma_p/p)^2$ (Charged Trks)	
DELCO	0.33	0.49	$(0.02 \text{ p})^2 + (0.06)^2$	150
HRS	1.62	1.90	$(0.001 \text{ p})^2 + (0.004)^2$	17
MARK II	0.23	1.43	$(0.01 \text{ p})^2 + (0.015)^2$	75

The normalized D^* fragmentation function,

$$D(Z_{D^*}) = \frac{1}{\sigma} \frac{d\sigma}{dZ},$$

is plotted in Fig. 6 for all three experiments. All three experiments observe the hard component for $Z_{D^*} > 0.5$, as first seen by the MARK II group¹⁾. The DELCO and HRS experiments also find significant D^* production for $Z_{D^*} < 0.4$. Soft D^* production is in fact expected from b-quark decays assuming that the $b \rightarrow c$ sequence occurs most of the time. Moreover, the presence of D^* mesons created via $e^+e^- \rightarrow c\bar{c}g$ or $c\bar{c}\gamma$ tends to shift some entries to lower energy fractions because the denominator used is $E_{CM}/2$ rather than the true (but unmeasured) energy of the parent charmed quark. Although the statistical accuracy of the data may not yet warrant detailed phenomenological interpretation, it is clear that a significant increase in the observed numbers of events can be anticipated over the next few years, and that more

sophisticated interpretations will be needed.

In Table IV are listed the measured values of the inclusive cross section,

$$\sigma(D^*) = \sigma(e^+e^- \rightarrow D^{*+}X) + \sigma(e^+e^- \rightarrow D^{*-}X) ,$$

and the ratio,

$$R_D^* = \frac{\sigma(D^{*+}) + \sigma(D^{*-}) + \sigma(D^{*0}) + \sigma(\overline{D^{*0}})}{\sigma(\mu^+\mu^-)} ,$$

where the neutral D^* production cross section is assumed by isospin arguments to be equal to that of the charged D^* . In extracting the cross sections, all three experiments use the same values for the D^* and D branching ratios ⁴). The present uncertainties in these branching ratios are approximately 20% and are unfortunately larger than the statistical uncertainties of the D^* signal. If all c-quark and b-quark production resulted in D^* production, the maximum expected value for R_D^* would be

$$(R_D^*)_{\max} = 2 \left(\frac{4}{3} + \frac{1}{3} \right) \left(1 + \frac{\alpha_s}{\pi} \right) = 3.5 ,$$

which may be compared to the weighted average of the three experiments,

$\overline{R}_D^* = 2.4 \pm 0.5$. This result suggests, at the two standard deviation level, that D^* production does not saturate the c-quark and b-quark production.

Table IV. Inclusive cross sections for charged D^* meson production in e^+e^- annihilation at 29 GeV.

Detector	$\sigma(D^{*+} + D^{*-})(a)$ (nb)	R_D^*
DELCO	0.15 ± 0.04	2.7 ± 0.7
HRS	0.105 ± 0.04	1.9 ± 0.7
MARK II	0.25 ± 0.13	4.7 ± 2.4

- (a) The observed reaction and decay chain is: $e^+e^- \rightarrow D^{*+}X$, $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$ (plus charge conjugate). All three experiments use the branching ratios from Reference 4; $BR(D^{*+} \rightarrow D^0\pi^+) = 0.44 \pm 0.10$ and $BR(D^0 \rightarrow K^-\pi^+) = 0.030 \pm 0.006$.

III. Measurement of Charge Asymmetry in D^* Production

The HRS collaboration has made a preliminary measurement of the D^* charge asymmetry,³⁾ shown in Fig. 7. The events in the plot are required to

have $Z_{D^*} > 0.4$ and $|\cos \theta| < 0.7$, where θ measures the angle between the e^- and D^{*+} (or between the e^+ and D^{*-}). The curve shows a fit to the form $(1 + a \cos \theta + \cos^2 \theta)$, yielding an asymmetry of $A = -0.25 \pm 0.18$. This result may be compared to the expected value at 29 GeV in the Standard Model, $A = -0.09$. The quoted uncertainty is entirely statistical; overall detector asymmetry has been determined to be less than 0.01.

A significant improvement in this measurement may be anticipated within the next year as more events are accumulated and as additional decay modes are included in the study. The excellent resolution of the HRS should prove important in keeping backgrounds and attendant systematic effects at a minimum.

IV. Inclusive Measurement of D Meson Production

The HRS collaboration also has made an inclusive measurement of neutral and charged D meson production in the region $Z_D > 0.4$. The inclusive mass plots for $(K^- \pi^+)$ and $(K^- \pi^+ \pi^+)$, together with their charge conjugate combinations, are presented in Fig. 8. No prior selection of D^* candidates is made for these events. The data shown are based on the sample from the 1981-82 run (20 pb^{-1}). For comparison, a similar plot for $(K\pi)$ masses is also shown from the MARK II detector ¹⁾. The power of excellent mass resolution for this kind of study is quite evident. Cross sections for inclusive D meson production are given in Table V.

Table V. Inclusive cross sections for neutral and charged D meson production in e^+e^- annihilation at 29 GeV as observed by the HRS.

Decay Modes	$D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^+ \pi^-$		$D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^- \rightarrow K^+ \pi^- \pi^-$
Range of Z_D	> 0.4	> 0.5	> 0.5
Nc. of Events	114 ± 25	77 ± 15	52 ± 16
Branching Fraction (Reference 4)	0.030 ± 0.006		0.063 ± 0.015
Cross Section Observed with Z_D Range (nb)	0.30 ± 0.11	0.20 ± 0.07	0.088 ± 0.037
Cross Section Extrapolated to All Z_D (nb)	0.36 ± 0.13		0.15 ± 0.06

A few cross section ratios of interest are obtained from the HRS data:

$$R_{D^0/D^{*+}} = \frac{\sigma(D^0 + \bar{D}^0)}{\sigma(D^{*+} + D^{*-}) + \sigma(D^{*0} + \bar{D}^{*0})} = 1.7 \pm 0.7 ,$$

$$R_{D^0/D^+} = \frac{\sigma(D^0 + \bar{D}^0)}{\sigma(D^+ + D^-)} = 2.3 \pm 1.2 ,$$

$$R_D = \frac{\sigma(D^0 + \bar{D}^0) + \sigma(D^+ + D^-)}{\sigma(\mu^+ \mu^-)} = 4.6 \pm 1.4 .$$

If all D^0 mesons originate from D^{*+} parents, the ratio $R_{D^0/D^{*+}}$ would be expected to be 0.7 ± 0.1 from the known D^{*+} branching fractions. Thus the HRS data indicate (at the 1 to 1.5 standard deviation level) the existence of sources of D^0 meson production, in addition to D^{*+} decay. On the other hand, the combined D meson cross sections are sufficient to saturate the expected c-quark plus b-quark cross sections ($R_{c+b} = 3.5$).

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Fig. 1 D^0 meson signal seen by the Mark II collaboration. Two regions of D^0 energy fractions are shown, where $Z = 2E_A/E_{CH}$.

Fig. 2 D^0 meson signal seen by the DELCO collaboration (a) using a Cerenkov-tagged sample of events, and (b) using a time-of-flight tagged sample of events.

Fig. 3 D^+ meson signal seen by the HRS collaboration. No particle tagging is used. The pion used in the $(K\pi)$ combination is the more energetic pion from the $(K\pi\pi)$ combination.

Fig. 4 Projection of the HRS data from Figure 3, where (a) $1810 < M(K\pi) < 1920$ MeV/c^2 and (b) $143 < \Delta < 148$ MeV/c^2 , where $\Delta = M(K\pi\pi) - M(K\pi)$.

Fig. 5 HRS data from Fig. 4(a) sliced into four zones of D^0 energy fraction.

Fig. 6 D^0 meson fragmentation function for the DELCO, HRS, and MARK II experiments, where $D(z)$ is the normalized function, $\frac{1}{\sigma} \frac{d\sigma}{dz}$.

Fig. 7 Production angular distribution of charged D^* mesons as observed in the HRS. The angle θ is between the e^- and D^{*+} (or the charge conjugate particles).

Fig. 8 Measurement by the HRS collaboration of inclusive D^0 mesons (upper plot) and inclusive D^+ and D^- mesons (lower plot). The MARK II collaboration search for inclusive D^0 mesons is shown for comparison.