INCLUSIVE PRODUCTION OF D AND K MESONS IN e^+e^- ANNIHILATION ☆

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We present measurements of the cross section for inclusive D and K meson production in e^+e^- annihilation in the center of mass energy range 3.6 to 5.8 GeV. D production accounts for most of the increase in the total cross section for hadron production in e^+e^- annihilation at energies above 4 GeV.

Production of charmed particles is generally believed to account for most of the increase in the ratio

$$R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)\,,$$

observed [1] in e^+e^- annihilation in the 4 GeV region. D mesons, the lowest lying charmed states, are expected to constitute the largest fraction of these charmed particles. Since charmed mesons decay predominantly into final states with a kaon, the increase in the kaons inclusive production should be comparable to the D meson production. Measurements of D production in e^+e^- collisions at center-of-mass energies 3.772 GeV ($\equiv \psi''$) [2], 4.03 GeV and 4.41 GeV [3], and at 7 GeV [4], as well as measurements of inclusive $K^\pm$ and K^0_s production in the energy intervals 3.6 to 5.2 GeV [5] and 3.6 to 7.6 GeV [6] have been previously reported and the expected increase of K production has been observed. In this letter we report a new set of measurements of the inclusive kaon production in e^+e^- annihilation, and, for the first time, measurements of the inclusive D meson production in the center-of-mass energy interval 3.6 to 5.8 GeV.

The data used in this analysis were collected with the SLAC–LBL magnetic detector facility at the e^+e^- storage ring SPEAR at SLAC. The data sample consists of events with three or more charged particles detected in the final state. The center-of-mass energy range covered is 3.6 to 5.8 GeV and the total integrated luminosity is approximately 8 pb^{-1}. The apparatus, trigger requirements, event selection criteria, and the time-of-flight system (TOF) have been described elsewhere [7,8]. We will give here a short description of the most relevant aspects of our analysis.

The D^0 and D^+ mesons were identified as peaks in the invariant mass distribution of $K^-\pi^+$ and $K^-\pi^+\pi^+$ combinations, respectively. (To avoid unwieldy notation, a reference to a D meson state always implies the

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sum of that state and its charge conjugate state.) These two decay modes were chosen because they have the highest acceptance in our apparatus and the highest signal-to-background ratio. For this part of the analysis we used the TOF weight technique [3]. Briefly, each particle in an event is assigned a weight proportional to the probability that it is a π, K, or p. These weights are determined from the measured momentum and TOF over a 1.5 to 2.0 m flight path using a gaussian time distribution with a 0.35 ns standard deviation. The π, K, and p weights are normalized so that their sum is unity for each track. All possible combinations of tracks and particle hypotheses are made with each combination weighted by the joint probability that the tracks satisfy the particular particle hypotheses assigned to them. The mass recoiling against the D was required to be larger than 1.8 GeV/c^2 in order to reduce the background due to uncorrelated combinations. As the energy increases the identification of the D becomes progressively more difficult. This is because the D mass is no longer on the tail of the Kπ or K$\pi\pi$ invariant mass distribution and the cut of 1.8 GeV/c^2 does not reduce the background. In addition, the D momentum, and, as a consequence, the K and π momenta are higher and the TOF identification is less effective.

The invariant mass distributions for $K^{\mp}\pi^{\pm}$ and $K^{\mp}\pi^{\pm}\pi^{\pm}$ for several center-of-mass energy intervals are shown in fig. 1. The numbers of observed D's were obtained by fitting these distributions to the sum of a gaussian of fixed mass and width and a smooth background.

Neutral kaons were identified [6] through their decay $K_s^0 \to \pi^+\pi^-$. Each event was projected on the xy plane, i.e., the plane normal to the beams, and for every charge-zero two-particle combination with an opening angle in this plane greater than 10° and smaller than 170° a vertex was determined. In general, the trajectories intersect at two points. Only the intersection closer to the origin (intersection of the e^+e^- beams) was considered. The projected distance of this intersection from the origin was required to (a) be greater than 0.4 cm and smaller than 16 cm, i.e., just inside the first chamber, and (b) be greater than zero by at least five standard deviations. The consistency of the vertex was checked using the z coordinate. If the two tracks were separated by more than 15 cm along the z direction they were rejected. Furthermore,

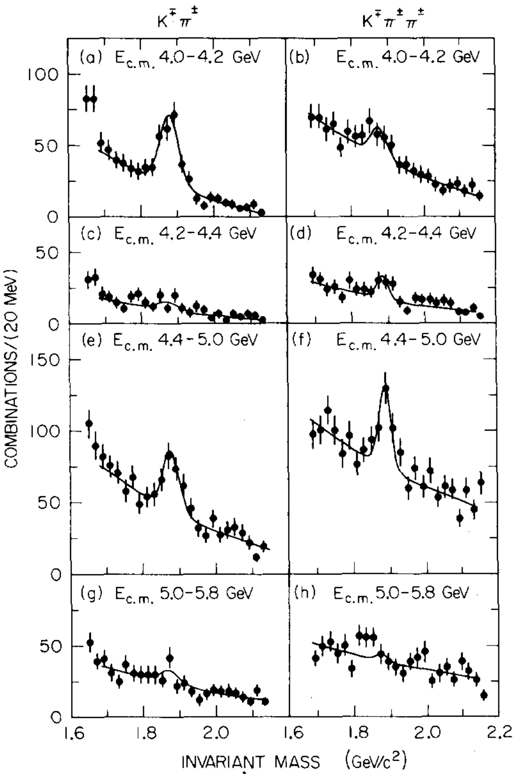

Fig. 1. Invariant mass spectra of weighted $K^{\pm}\pi^{\mp}$ and $K^{\pm}\pi^{\mp}\pi^{\mp}$ combinations for several center-of-mass energy regions. The fits are explained in the text.

the angle between the total momentum vector of the two tracks and the line of flight of the K_s^0 (as defined by the origin and the three-dimensional coordinates of the vertex) was required to be within four standard deviations of zero and, in any case, smaller than 60°. For the pairs that survived these cuts we required that their invariant mass be in the range 0.47 to 0.52 GeV/c^2.

Charged kaons were identified from the measured TOF and momentum using the weight technique. Our TOF resolution allows for unambiguous (i.e. $>3\sigma$) K–π separation for momenta up to 0.65 GeV/c and for 1σ K–π separation for momenta up to 1.2 GeV/c. We corrected for ambiguities due to the limited resolution of the TOF system for momenta up to 1 GeV/c in the following way [9]: we computed the 3 × 3 matrix of π, K, and p identification probabilities as a function of momentum. The inverse of this matrix was then used to obtain the number of produced kaons from the number observed. For momenta above 1 GeV/c

the sensitivity of this method, as applied to kaons, deteriorates rapidly. To evaluate the number of kaons with momenta greater than 1 GeV/c we extrapolated their momentum distribution using an exponential function whose parameters were obtained by fitting the kaon momentum spectrum below 1 GeV/c. We have checked that this correction is consistent with the fraction of K_S^0 (for which the acceptance for momenta greater than 0.4 GeV/c shows very little momentum dependence) with momenta above 1 GeV/c for each corresponding center-of-mass energy. We have also corrected for decay-in-flight of the charged K's.

In order to obtain cross sections from such "weighted" D and K mesons we estimated our detection efficiency by means of a Monte-Carlo simulation of our apparatus which incorporated all the known experimental effects: geometrical acceptance, momentum and TOF resolution, trigger criteria, and cuts used in the analysis. To determine the D meson efficiency we used at each energy a production mechanism which reproduced best the observed D meson momentum distribution. At 4.16 and 4.3 GeV we used a production model of $D^*\bar{D}^*$; at higher energies we used a mixture of $D\bar{D}\pi\pi$ and $D^*\bar{D}^*\pi$.

The kaon detection efficiency was estimated [6] as the product of two terms $\epsilon = \epsilon_K(P_K) \cdot \epsilon_T(P_K, E_{cm})$, where ϵ_K is the efficiency for detecting a kaon of momentum P_K, and ϵ_T is the probability for an event with an observed kaon to trigger and to satisfy our event selection criteria for a hadronic final state. ϵ_T depends on the dynamics and the multiplicity of final states containing a kaon. In the Monte-Carlo simulation used to determine ϵ_T we adjusted the parameters of the production model in such a way that the detected kaon momentum spectrum, the average charged particle multiplicity, and the average charged particle momentum agree with the data for the various c.m. energies under study [‡1].

The number of observed D's, our efficiency estimate, the luminosity at each energy interval, and the measured [2] branching ratios for $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ allow us to determine the cross section for inclusive D meson production. These results together with [‡2] $R_D = (\sigma_{D^0+\bar{D}^0} + \sigma_{D^++D^-})/2\sigma_{\mu^+\mu^-}$ are shown in table 1. We observe a clear D signal in the intervals 4.0–4.2 GeV, and 4.4–5.0 GeV; no significant signal is observed in the region 4.2–4.4 GeV, a region where R also shows a dip [10]. In the region 5.0–5.8 GeV, even though no significant D signal is observed, our efficiency is quite small and our results are not inconsistent with a sizable D meson production. The quantity R_D, shown in fig. 2a, follows the overall shape of R. Within our errors, R_D together with the contribution due to pair production of the heavy lepton τ can account for all of the increase in R observed [1] for c.m. energies greater than 4.0 GeV.

The results of the kaon study are summarized in table 2. The number of observed kaons and the cross section for inclusive kaon production for a series of center-of-mass energy intervals are given. Figs. 2b and 2c are plots of the quantities $R_{K^\pm} = (\sigma_{K^+} + \sigma_{K^-})/\sigma_{\mu^+\mu^-}$ and $R_{K^0} = 2\sigma_{K_S^0}/\sigma_{\mu^+\mu^-}$, where the factor 2 in the R_{K^0} accounts for the undetected K_L^0. $R_{K^\pm}$ and R_{K^0} show an energy dependence similar to the energy dependence

‡1 Because of the relatively low center-of-mass energies the differences between an isotropic phase space model, such as the one used in ref. [6], and a model incorporating jet production, as in ref. [9], are negligible.

‡2 $\sigma_{D^0+\bar{D}^0}$ refers to the cross section for inclusive D^0 or $\bar{D}^0$ production, i.e., $\sigma_{D^0+\bar{D}^0} = \sigma(e^+e^- \to D^0X) + \sigma(e^+e^- \to \bar{D}^0X)$. The same applies, mutatis mutandis, to $\sigma_{D^++D^-}$ and $\sigma_{K^++K^-}$.

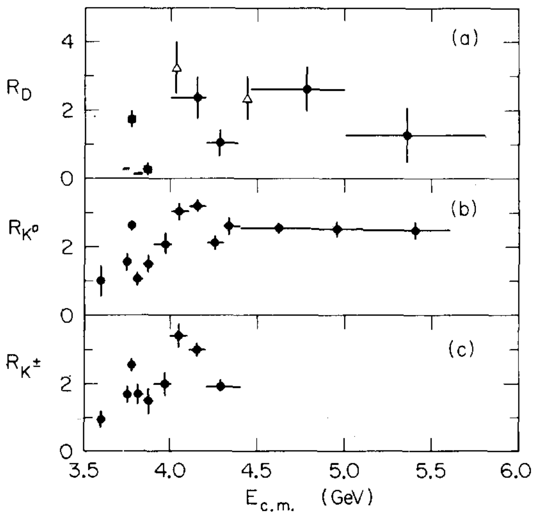

Fig. 2. Plots of (a) the ratio [11] $R_D = (\sigma_{D^0+\bar{D}^0} + \sigma_{D^++D^-})/2\sigma_{\mu^+\mu^-}$, (b) the ratio $R_{K^0} = 2\sigma_{K_S^0}/\sigma_{\mu^+\mu^-}$, (c) the ratio $R_{K^\pm} = (\sigma_{K^+} + \sigma_{K^-})/\sigma_{\mu^+\mu^-}$ as a function of center-of-mass energy. The triangles are from ref. [3] and the squares from ref. [2].

Table 1
Energy, mean energy, integrated luminosity, observed number of D's, cross section for D^0 and D^+ inclusive production, and R_D for several center-of-mass energy intervals.

c.m. energy (GeV)	Mean c.m. energy (GeV)	Integrated luminosity (nb^{-1})	Observed number of D^0 and $\bar{D}^0$	Observed number of D^+ and D^-	$\sigma_{D^0+\bar{D}^0}$ (nb)	$\sigma_{D^++D^-}$ (nb)	R_D a)
3.73–3.76 b)	3.74	180	<2.8 c)	<2.7 c)	<1.7 c)	<1.9 c)	<0.29 c)
3.76–3.79 b)	3.775	1220	130 ± 13	85 ± 11	11.5 ± 2.5	9.1 ± 2.0	1.69 ± 0.27
3.79–3.84 b)	3.81	238	<1.4 c)	<1.4 c)	<0.7 c)	<0.8 c)	<0.13 c)
3.84–3.89	3.87	236	5 ± 3	2 ± 2	2.1 ± 1.4	1.1 ± 1.1	0.28 ± 0.16
4.0–4.2 d)	4.15	1680	153 ± 20	65 ± 21	16.5 ± 5.0	6.2 ± 2.5	2.33 ± 0.57
4.2–4.4	4.28	854	15 ± 9	30 ± 12	3.5 ± 2.1	6.0 ± 2.9	1.03 ± 0.40
4.4–5.0 e)	4.68	2376	108 ± 28	117 ± 30	10.9 ± 3.8	10.1 ± 3.5	2.64 ± 0.65
5.0–5.8	5.36	1115	26 ± 19	11 ± 11	5.6 ± 4.4	2.0 ± 2.0	1.26 ± 0.83
4.028 f)	4.028	1365	182 ± 18	82 ± 14	24.2 ± 7.0	9.6 ± 2.9	3.16 ± 0.73
4.414 f)	4.414	1752	92 ± 18	67 ± 19	12.6 ± 4.2	7.8 ± 3.0	2.29 ± 0.60
6.0–7.8 g)	6.96	22.5 × 10^3	173 ± 31	90 ± 31	3.2 ± 0.9	1.7 ± 0.7	1.34 ± 0.33

a) $R_D = [\sigma_{D^0+\bar{D}^0} + \sigma_{D^++D^-}]/2\sigma_{\mu^+\mu^-}$; see ref. [11]. b) From ref. [2]. c) 90% confidence level.
d) 50% of these data was taken at 4.16 GeV. e) Less than 10% of these data was taken in the vicinity of the $\psi(4.4)$ resonance.
f) From ref. [3], using branching ratios of ref. [2]. g) From ref. [4].

of R_D, as expected for the production and subsequent decay of charmed mesons.

If we make the assumption that the ψ'' decays entirely into $D\bar{D}$ pairs, our measurement of the kaon production near and at the ψ'' together with the total cross section measurements of ref. [11] allow us to estimate the number of charged and neutral kaons per D decay – a result that has been previously reported [12]. For the energy region 3.75–3.79 one third of the total hadronic cross section is due to the ψ''[2],

Table 2
Energy, mean energy, integrated luminosity, observed number of kaons, and cross section for inclusive kaon production for several center-of-mass energy intervals.

c.m. energy (GeV)	Mean c.m. energy (GeV)	Integrated luminosity (nb^{-1})	Number of observed K^0_S	Number of observed a) K^+ and K^-	$\sigma_{K^0_S}$ (nb)	$\sigma_{K^+} + \sigma_{K^-}$ (nb)
3.6	3.600	48	17 ± 8	130 ± 32	3.3 ± 1.5	6.3 ± 1.5
3.73–3.76	3.743	215	118 ± 19	916 ± 136	4.7 ± 0.8	10.6 ± 1.6
3.76–3.79	3.775	1263	1138 ± 58	8082 ± 526	7.7 ± 0.4	15.6 ± 1.0
3.79–3.84	3.811	341	123 ± 20	1522 ± 265	3.1 ± 0.5	10.4 ± 1.8
3.84–3.90	3.869	258	128 ± 19	976 ± 156	4.2 ± 0.6	8.6 ± 1.3
3.90–4.00	3.956	188	126 ± 18	896 ± 160	5.6 ± 0.8	10.8 ± 1.9
4.00–4.10	4.040	383	360 ± 29	3102 ± 292	7.8 ± 0.6	18.0 ± 1.7
4.10–4.20	4.152	1297	1234 ± 58	9006 ± 566	7.8 ± 0.4	15.1 ± 1.0
4.20–4.40	4.286	854	606 ± 40	3561 ± 242	5.5 ± 0.3	9.2 ± 0.6
4.40–4.80	4.619	1830	1181 ± 59	– b)	5.0 ± 0.2	– b)
4.80–5.20	4.948	856	487 ± 38	– b)	4.3 ± 0.3	– b)
5.20–5.60	5.394	667	321 ± 33	– b)	3.6 ± 0.4	– b)

a) Number of events corrected for TOF losses.
b) Above 4.4 GeV the high momentum of the $K^\pm$ makes identification unreliable.

while for the regions 3.73–3.76 and 3.79–3.84 the contribution of the ψ'' to the total cross section is only 10%. We find that there are 1.03 ± 0.27 neutral kaons and 0.83 ± 0.24 charged kaons per ψ'' event. These imply that we have 0.52 ± 0.14 neutral kaons and 0.42 ± 0.12 charged kaons per D decay. For the non-resonant part of the cross section we find that there are 0.26 ± 0.08 neutral kaons and 0.32 ± 0.10 charged kaons per event.

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