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We study the semi-leptonic decay modes of charmed particles near the charm threshold in e^+e^- annihilation. This provides an indirect test for the charm hypothesis. We present various lepton-kaon correlations which reflect the underlying V or S, T interactions.

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The discovery of narrow resonances$^{(1)}$ indicates the existence of particles with new quantum numbers. This hypothesis is further supported by the recent observation of dimuon events$^{(2)}$ and μ^-e^+ events$^{(3)}$ in neutrino scattering which are widely interpreted as due to the decays of hadrons with new quantum numbers. One of the striking phenomena about the μ^-e^+ events is that all the observed events have accompanying K_s^0 , which would not be so frequently expected from ordinary hadron decays. The observation of K_s^0 in the μ^-e^+ neutrino experiments is however expected in charm models.$^{(4-6)}$ If the structure in $\sigma_{tot}(e^+e^- \to \text{hadron})$ in $4 \leq \sqrt{s} \leq 5$ GeV region reflects $c\bar{c}$ continuum states decaying into charmed particles, many such $\bar{c}q$ $(q = u,d,s)$ composites have already been produced at SPEAR and DESY. The failure to find charmed particles through the dominant non-leptonic modes may be attributed to predominant multi-body decays.

In this note, we advocate the charm search through the semi-leptonic decay modes$^{(7)}$

$$\begin{array}{llr} e^+e^- \longrightarrow c\bar{q} + \text{anything} & \qquad \ell = e,\mu & \\ \qquad\qquad\quad \hookrightarrow \ell^+\nu_\ell \bar{K} + \cdots,\ \ \ell^+\nu_\ell \pi + \cdots & & (1) \end{array}$$

In the same picture, the dimuon and $\mu^-e^+K_s^0$ events occur via

$$\begin{array}{llr} \nu_\mu + N \longrightarrow c\bar{q} + \mu^- + \text{anything} & \qquad \ell = e,\mu & \\ \qquad\qquad\qquad\quad \hookrightarrow \ell^+\nu_\ell \bar{K} + \cdots,\ \ \ell^+\nu_\ell \pi + \cdots & & \\ \qquad\qquad\qquad\quad \hookrightarrow \ell^+\nu_\ell & & (2) \end{array}$$

We note that the same branching ratios are responsible for both processes. We will concentrate on the kinematic region $4 \lesssim \sqrt{s} \lesssim 5$ GeV in e^+e^- annihilation experiments where the ratio $R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$ rises to 5.5 within a short energy interval. Our main <u>assumption</u> is that near the threshold the increase in R (minus about one unit due to charged heavy lepton contribution) comes from charmed meson production (D, D* etc.). The charmed baryon threshold probably lies higher.

Although the crucial test of the charm hypothesis lies in the observation of charmed particles themselves, the semi-leptonic decays of charmed particles will serve as an indirect but attractive test of the various charm models.

The leptons and kaons coming from charm decays are strongly correlated. Their correlation will shed light on the underlying interactions and is the subject of study below. The charm-changing weak currents are given as

$$J_\mu^{\Delta C=1} = \bar{C}_L \gamma_\mu d_L \sin\theta_c + \bar{C}_L \gamma_\mu S_L \cos\theta_c \qquad (\text{GIM model})$$

$$\begin{aligned} J_\mu^{\Delta C=1} = {} & \bar{C}_L \gamma_\mu d_L \sin\theta_c + \bar{C}_L \gamma_\mu S_L \cos\theta_c \\ & + \bar{C}_R \gamma_\mu d_R \cos\theta + \bar{C}_R \gamma_\mu S_R \sin\theta \qquad (\text{vectorlike model}) \end{aligned} \tag{3}$$

where Θ_c is the Cabibbo angle and $\Theta = 0, \pi$ for the DGG$^{(5)}$ and FGM-WZKT$^{(6)}$ vectorlike models respectively. L, R denote left and right handed quarks, respectively.

Cross Section: The cross section $\sigma(e^+e^- \to c\bar{q} + x \to \ell^+\bar{K} + \text{anything})$ for $\ell = e, \mu$ and $\bar{K} = K^-$, $\bar{K}^0$ is the product of production cross section and decay branching ratio. For the GIM and FGM-WZKT models, only the nonstrange charm mesons lead to strangenes $\neq 0$ final states (neglecting $\sin\Theta_c$). If $<\delta R> \sim 2$ is due to the $c\bar{c}$ continuum decaying into charmed mesons states ($c\bar{q}$, $\bar{c}q$ composites) for $4 \lesssim \sqrt{s} \lesssim 5$ GeV, we estimate the production cross section $\sigma(e^+e^- \to c\bar{q} + x)$, summing over u and d quarks, to be $\frac{2}{3} \times 2\sigma(\mu^+\mu^-)$. From the observed 1% dimuon and μ^-e^+ events rates in neutrino reactions, one finds the mean muonic or the electronic branching ratio to be at least 10% and 5% for the GIM and vectorlike models respectively.$^{(8)}$ This ratio interpreted through (2) gives $BR(c\bar{q} \to \mu^+K + \ldots) \sim 10\%$ and 5% for the GIM and FGM-WZKT models respectively. (We have neglected the leptonic decay modes$^{(9)}$ since $\Gamma(D \to \mu\nu)/\Gamma(D \to \mu\nu K) \sim 10^{-3}$ for $m_D \sim 2$ GeV). Thus the cross section is $\sigma(e^+e^- \to \ell^+K^- + x) + \sigma(e^+e^- \to \ell^+\bar{K}^0 + x) \sim 0.14\,\sigma(\mu^+\mu^-)$, $0.07\,\sigma(\mu^+\mu^-)$ for the GIM and FGM-WZKT models respectively. The $|\Delta s| = 1$ and $\Delta s = 0$ pieces of the charm currents are comparable in the DGG model, thus $BR(c\bar{q} \to \mu^+\bar{K} + \ldots) \simeq \simeq \frac{1}{2} BR(c\bar{q} \to \mu^+ + \ldots)$. For this model, one finds $\sigma(e^+e^- \to c\bar{u} + x \to \ell^+K^0 + \text{anything}) + {} + \sigma(e^+e^- \to c\bar{d} + x \to \ell^+\bar{K}^0 + \text{anything}) + \sigma(e^+e^- \to c\bar{s} + x \to \ell^+K^0 + \text{anything}) \sim {} \sim 0.05\sigma(\mu^+\mu^-)$. If the leptons below 650 MeV are not detected, we find that the cross section decreases by 50 - 60% for present lab. energies (see Fig.3). Note that the cross section is still much larger than that of the anomalous μe events.$^{(10)}$ Search for processes (1) (which are being done at DESY and SLAC) would provide an independent information on the branching ratio and test the hypothesis that the same degrees of freedom are being excited in e^+e^- annihilation as in neutrino scattering.$^{(11)}$

Multiplicity: If the lepton and kaon are oppositely charged or form pairs as $\ell^+\bar{K}^o$, ℓ^-K^o in (1), in a charm model they must come from charmed meson decays; the remaining hadrons come from the nonleptonic decays of the charge conjugate charmed mesons. Assuming that the (nonleptonic) decays of charmed mesons have average charge multiplicity equal to (at least) half of the observed number near $R \sim 5.5$ (which is $\langle n_c \rangle_{exp.} \sim 4$), we expect process (1) to contribute to the events $e^+e^- \rightarrow \mu^- + x$ with $\langle n_x^{ch} \rangle \geq 2$. An upper bound for such events with $E_\mu \geq 1$ GeV has been reported by the MP^2 group$^{(12)}$. Noting that the fraction of cross section with $E_\mu \geq 1$ GeV depends very much on the energy of the decaying parents (charmed meson) (see Fig.2), our estimates of the cross section are consistent with the data. In charm models, we also expect that the fraction of events for (1) with non-zero strangeness in the final states to be not too small ($\gtrsim 0.5$), a definite prediction that can be tested.

Next we present the details of the lepton-kaon correlations due to D, D^* decays. Since extra kaons are present, it would be important for the following analysis to select the combination i.e. $\ell^\pm K^\mp$, ℓ^-K^o, $\ell^+\bar{K}^o$ coming from the same charmed meson decay. Noting first that the $|\Delta c| = |\Delta s| = 1$ current in (3) is an isospin singlet in either the GIM or vectorlike models, the more-than-three body decays of D to $\bar{\nu}_\ell$ ℓ K + pions vanish if any one of the pions is soft. Since these multi-pion decays are also limited by phase space, the $D_{\ell 3}$ decays are presumably the most interesting semi-leptonic modes. Further, since D^* will cascade to $D\pi$ if $\Delta = m_{D^*} - m_D > m_\pi$ otherwise $D \rightarrow D\gamma$ will be the dominant decay mode (assuming $m_{D^*} > m_D$), we need concern ourselves only with $D_{\ell 3}$ decays. We shall neglect here the $K^*\ell\bar{\nu}_\ell, \phi\ell\bar{\nu}_\ell$ decay modes of D which are suppressed by phase space and angular momentum barrier.$^{(13)}$ For definiteness we assume $\ell = e$ and $m_D = 2$ GeV. The following is a phenomenological analysis to check whether the interaction is vector (V), scalar (s) or Tensor (T)$^{(14)}$, and apply as well to the π-e correlations in the decay $D \rightarrow \pi\nu e$ and to $F_{\ell 3}$ decays, modulo small corrections due to mass differences.

The Invariant Mass Distribution of eK.

The distribution is independent of the production mechanism and is plotted in Fig.1 for S.V.T. interactions with constant form factors. (As in the case of $K_{\ell 3}$ decay, one can neglect f_- for V interaction). The behavior of $d\Gamma/dM_{eK}$

for pure T can be understood from helicity arguments, and allows an easy check on this possibility. Assuming dipole form factors, we find that the qualitative features of the various correlations discussed in this note are insensitive to the dipole mass M if $M >> (m_D - m_K)$, and we present here only results with constant form factors.

The Electron Energy Spectrum

$d\sigma/dE_e$ is plotted in Fig.2, assuming production of D with definite energy E_D. We note that for pure V, the electron energy spectrum varies slowly with E_D and is thus insensitive to the production cross section,(15) which is a function of E_D, for $E_D \lesssim 2.4$ GeV. We note that the inclusive pion production in e^+e^- annihilation is much suppressed for large $x = 2E_\pi/\sqrt{s}$ or equivalently high energy pions. Assuming the same mechanism for charm mesons production above charm threshold, we infer that the inclusive charmed meson have predominantly low energies. If this is the case, then for pure V the electron energy spectrum is well described by Fig.2 for a wide range of energies ($\sqrt{s} \sim 4$-6 GeV). The average electron energy for $E_e \gtrsim 650$ MeV events is $\langle E_e \rangle \simeq 0.77, 0.88, 0.96$ GeV for $E_D \simeq 2.0, 2.2, 2.4$ GeV respectively.

The Kaon Energy Spectrum $d\sigma/dE_K$ is given in Fig.3.

We note that the spectrum is again insensitive to the energy E_D for pure V, for $E_D \leq 2.4$ GeV. For $E_e \geq 650$ MeV events, the average energy of kaon (from $D_{\ell 3}$ decay) for pure V is $\langle E_K \rangle \simeq 0.79, 0.81, 0.88$ GeV for $E_D \simeq 2.0, 2.2, 2.4$ GeV respectively.

The Ratio of Average Energy of Correlated Kaon and Electron

$\langle E_K \rangle / \langle E_e \rangle$ is in sensitive to the production mechanism and is ~ 1.45 for pure V with constant form factor. For events with $E_e \gtrsim 650$ MeV the ratio is 0.9~1.0 for V, T and 0.8~0.9 for S within the energy range $E_D \sim 2.0 - 2.4$ GeV.

Electron Kaon Angular Correlation

$d\sigma/d\cos\theta_{eK}$ is more energy dependent (Fig.4). For pure V , $d\sigma/d\cos\theta_{eK}$ peaks at large angles. This can be understood by helicity arguments and the Lorentz boost from the rest frame. Pure T interaction can be easily distinguished.

Remarks

We note that except for a D meson decaying nearly at rest, the S and V interactions are difficult to distinguish. This is different from $K_{\ell 3}$ decay where the kaon can be stopped, or decays in flight with a well-known momentum. To distinguish the various interactions it might be best to do the experiments near the charm threshold.

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References and Footnotes

(1) See the Proceedings of the 1975 International Symposium on Lepton and Photon Interactions, Stanford University, for summary of experimental results.

(2) A. Benvenuti et.al.; Phys. Rev. Lett. 34, 419 (1975); ibid 35, 1199 (1975); ibid 35, 1203 (1975); ibid 35, 1249 (1975); B. C. Barish et al., CALT-68-495.

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(7) For general discussion, see M.K. Gaillard, B. W. Lee and J. L. Rosner, Rev.Mod.Phys. 47, 277 (1975).

(8) B. W. Lee Fermi-Lab-Conf. 75/78-THY; V. Barger, R.J.N. Phillips and T. Weiler, SLAC-PUB-1688.

(9) The heavy lepton mode is also small in comparison to the semi-leptonic mode unless the $D_{\ell 2}$ coupling constant $f_D >> f_{K,\pi}$.
I. Karliner, IAS preprint; A. Ali and T. C. Yang (unpublished).

(10) M. L. Perl et al., Phys. Rev. Lett. 35, 1489 (1975)

(11) Search for semi-leptonic decay modes of charm composites in hadronic interactions at Brookhaven gives the bound

$$\frac{\sigma(PN \to \bar{c}q + x)BR(\bar{c}q \to \ell^- K + x)}{\sigma(PN \to J + x)BR(J \to \mu^+\mu^-)} \sim 10^{-3} \text{ (S.C.C. Ting talk given at DESY).}$$

This result means that the production cross section of charmed composites at Brookhaven energy is very small if the semi-leptonic branching ratio is as big as 5-10% or else the branching ratio is small.

(12) M. Cavalli-Sforza et al., Phys. Rev. Lett. 36, 558 (1976)

(13) Kaons from F decays could also affect the eK correlation. All these details will be treated elsewhere.

(14) See R. E. Marshak, Riazuddin and C. P. Ryan. Theory of Weak Interactions in Particle Physics, Chapter V.

(15) This is also noted by T. Walsh using a parton model. We thank G. Kramer for communicating his work on charmed meson pair production cross section in e^+e^- annihilation to us.

Figure Captions

Fig.1 The invariant mass distribution of eK from D_{e3} decay with S,V,T Interactions and constant form factors,all normalized to the same area.

Fig.2 The electron energy spectrum assuming production of D with definite energies $E_D \simeq 2.0$, 2.2 and 2.4 GeV and subsequent D_{e3} decays with constant form factors. All curves are normalized to the same area.

Fig.3 The kaon energy spectrum for the same process as of Fig.2. The dotted line refers to kaon spectrum for events with $E_e \geq 650$ MeV (for the vector interaction).

Fig.4 Electron-kaon angular correlation for the same process as of Fig.2.

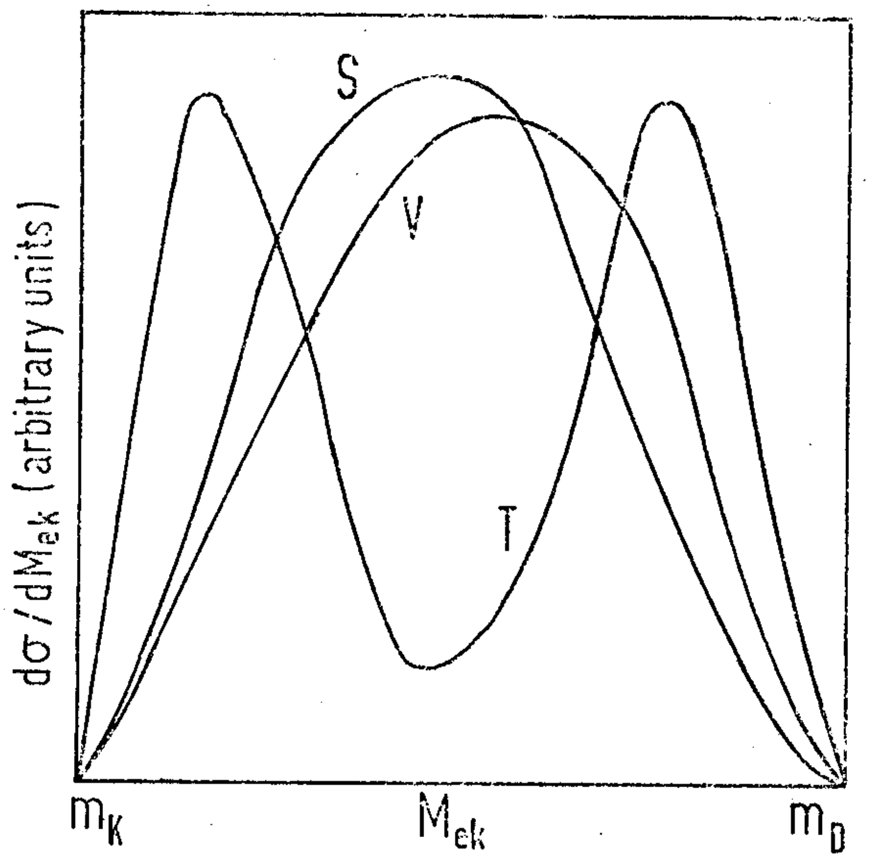
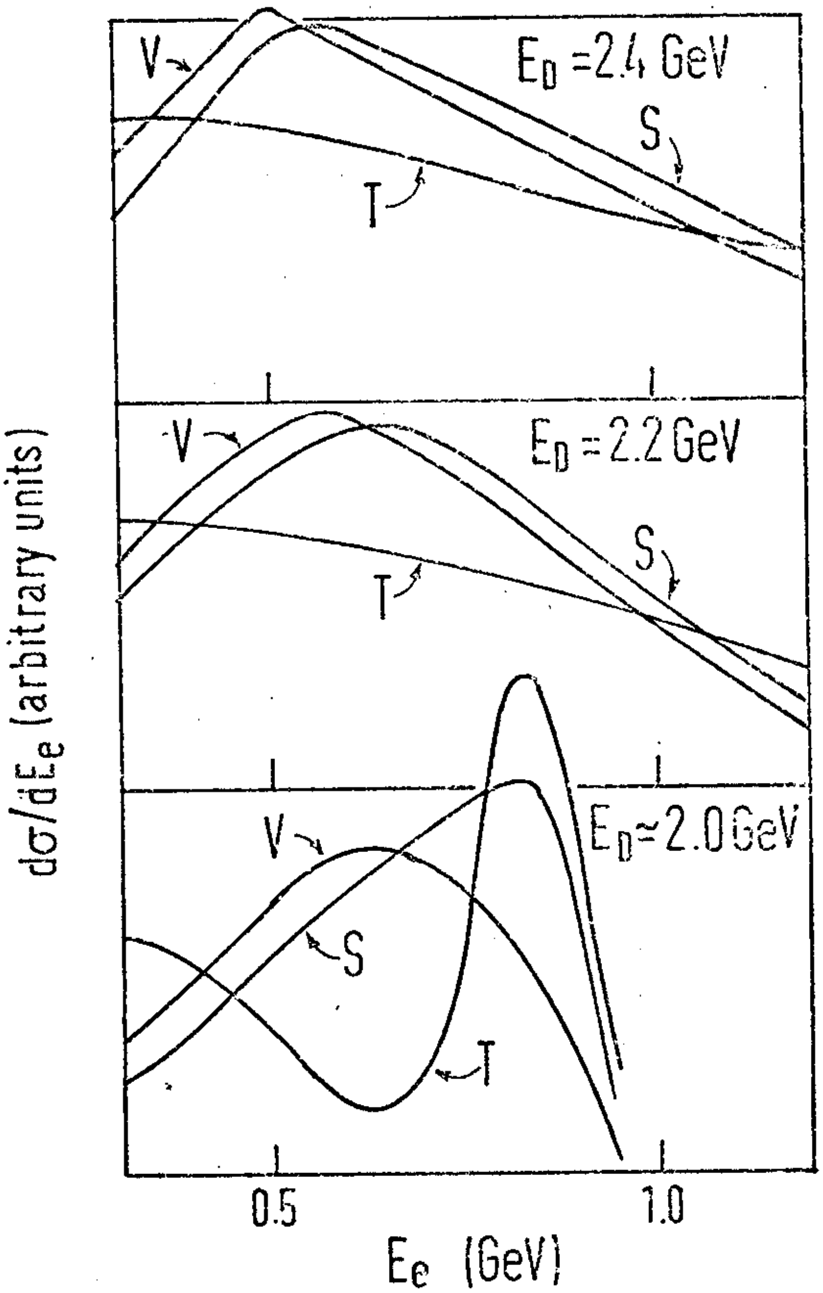
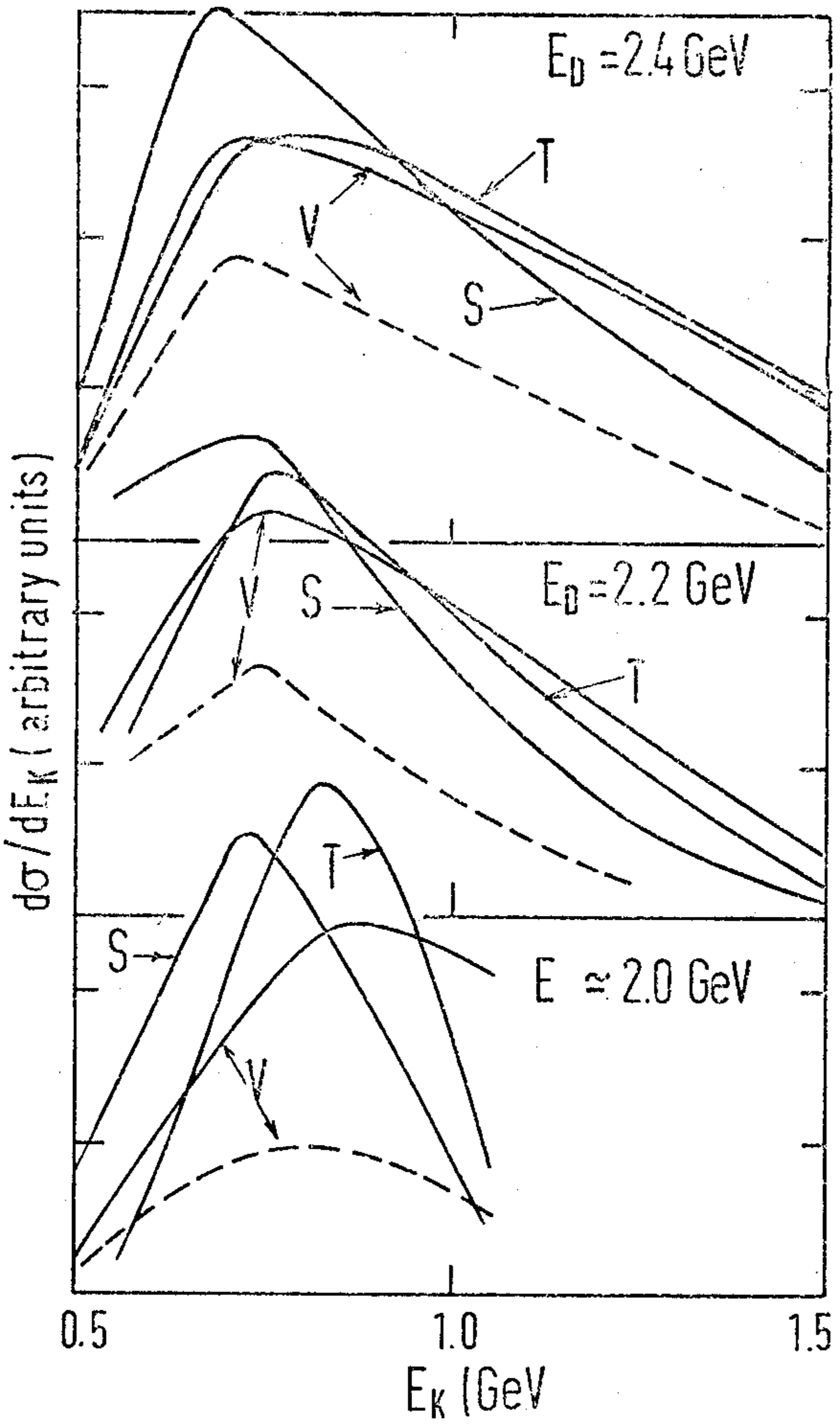


Fig. 1



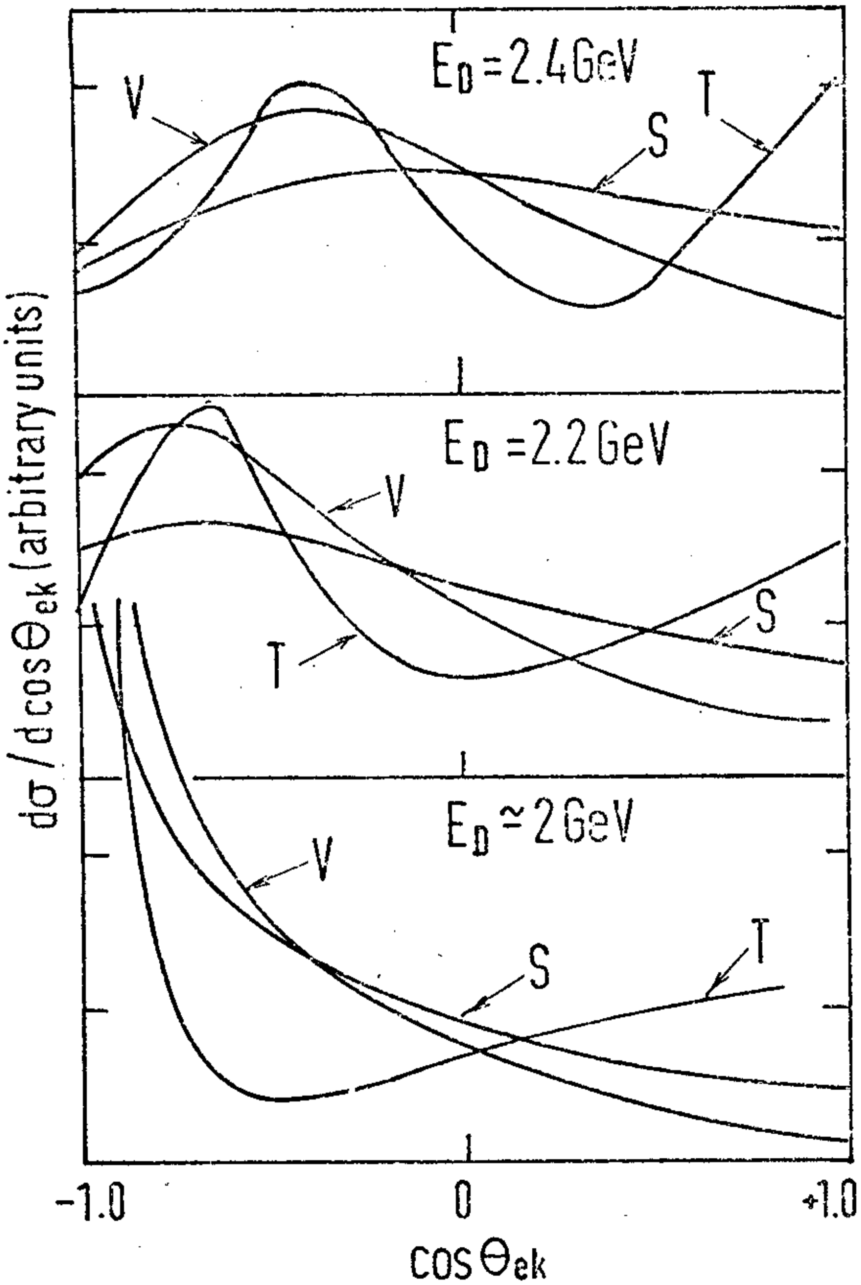
V
S
T
$E_D = 2.4$ GeV
$E_D = 2.2$ GeV
$E_D \simeq 2.0$ GeV
$d\sigma/dE_e$ (arbitrary units)
0.5
1.0
E_e (GeV)

Fig. 2



$E_D = 2.4$ GeV
T
V
S
$E_D = 2.2$ GeV
V
S
T
T
S
$E \approx 2.0$ GeV
V
$d\sigma/dE_K$ (arbitrary units)
0.5
1.0
1.5
E_K (GeV

Fig. 3



E_D = 2.4 GeV
V
S
T
E_D = 2.2 GeV
V
S
T
E_D ≃ 2 GeV
V
S
T
dσ / d cos Θ_ek (arbitrary units)
-1.0
0
+1.0
cos Θ_ek

Fig. 4