Production and leptonic decay modes of charmed mesons*

R. Michael Barnett
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 21 July 1975; revised manuscript received 22 September 1975)

Charmed-meson production in hadronic collisions is estimated in a general peripheral model. The shape of the spectra of leptons from charmed-meson decay modes is shown, and bounds are given on branching ratios to those decay modes. A possible source of leptons in hadronic collisions is suggested.

With the discovery[1-3] of narrow resonances at 3.1 and 3.7 GeV and a wide resonance[4] at 4.1 GeV, and with the advent of theories with charmed quarks,[5-8] the search for charmed mesons (containing one charmed quark) was begun.[9] It is therefore of interest to know the relative production of charmed mesons to pions in pp scattering. Given the cross section for charmed-meson production, a calculation of the spectra of muons and electrons from charm decay will be shown to place bounds on various leptonic and semileptonic decay modes.

The cross section for charmed-meson production can be estimated in a general peripheral model.[10] This model is a simple internal exchange parameterization (see Fig. 1) which accounts for energy masses and thresholds. It describes well the relative production of π, K, ρ, and ψ mesons[11] from very small to very large transverse momentum $p_\perp$. For charm production the model includes the effect of the associated production of a second charmed particle.

From Fig. 1 the single-particle spectrum in the central plateau region can be expressed as

$$E\frac{d\sigma}{d^3p}=\frac{1}{s}\int d^4p'\int d^4k'\delta^4(p'+k'+p)\beta_L{}^2(t_L)\beta_R{}^2(t_R)A_L(s_L',t_L)A_R(s_R',t_R)g^2\,,$$

where the β's are propagators, the A's are off-shell absorptive parts from the inclusively summed particles, and $t_L=p'^2$ and $t_R=k'^2$. Further details can be found in Refs. 10 and 11.

The results for the production of charmed mesons of mass = 1.9 GeV are shown in Fig. 2. This result is expected to be accurate to at least a factor of 2 and is insensitive to small changes in mass. The large mass is the main cause of the suppression relative to pion production at small $p_\perp$ (although threshold and exchange effects also contribute), and thus at large $p_\perp$ the suppression is much weaker.

These results can be compared with those obtained by other approaches such as Ref. 12 where 2 or 3 orders of magnitude more charmed mesons are predicted at small $p_\perp$. However, the thermodynamic model of Hagedorn[13] with spectra given by $\exp[-(p_\perp^2+m^2)^{1/2}/160\text{ MeV}]$ predicts a charmed-meson-to-pion ratio that is remarkably similar to that of the peripheral model (though lacking its energy dependence) over the whole range of $p_\perp$ except for being smaller by a factor of 3 (at $E_{1ab}=300$ GeV). The two models have similar pion spectra except at very large $p_\perp$ (where the general peripheral model fits the observed spectrum[14]).

It follows from these results that it will be difficult to see evidence of charmed mesons at small $p_\perp$ (where almost all events occur) in pp scattering.

Given the single-particle spectrum for charmed-meson production, the spectra of muons and electrons from the decay of the charmed mesons can be calculated. In the "conventional" four-quark model,[5-7] the decays $K\mu\nu$, $Ke\nu$, $K\mu\nu$+pions, and $Ke\nu$+pions are expected to have significant branching ratios. In other models[8,15] the decays $\mu\nu$ +pions and $e\nu$+pions occur with probabilities approximately equal to those above. In these models

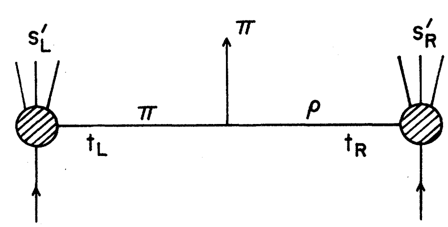

FIG. 1. The general peripheral model mechanism for production of a particle (here a pion) with momentum p by exchange of particles such as ρ and π (in $pp\to\pi$ + anything).

the decay into $\mu\nu$ is not suppressed by $\tan^2\theta_{\rm Cabibbo}$; for pseudoscalar charmed mesons the decay mode $e\nu$ is greatly suppressed relative to $\mu\nu$ as it is for the K meson. However, Altarelli *et al.*[16] have suggested that vector charmed mesons may be lighter than the pseudoscalars. The vectors have no suppression of $e\nu$ relative to $\mu\nu$.

The calculation of the μ spectrum resulting from the decay into $\mu\nu$ of charmed mesons with a given $p_\perp$ distribution can be done analytically[17] and by use of a Monte Carlo program. For decays into three or more particles, the resulting μ and e spectra were calculated with the Monte Carlo program. Experimentally,[18,19] it has been observed that the $p_\perp$ distribution of both muons and electrons is very close to that of pions multiplied by a factor of about 10^{-4} for $p_\perp$ between 1.5 and 5.5 GeV/c and for $E_{\rm lab}$ between 300 and 1500 GeV. Pions from the decay of charmed mesons are a small fraction of those produced directly and are not considered here.

Since the spectrum falls quickly as a function of $p_\perp$ and since the products have in general only a fraction of the momenta of the parent, the spectra of the products lie significantly below that of the parent at large $p_\perp$. The magnitude of the ratio of parent and product spectra depends strongly on two factors: (1) the number of decay products, and (2) the steepness of the parent spectrum. The decay factor $D(p_\perp)\equiv\rho_{\rm lepton}(p_\perp)/\rho_{\rm charm}(p_\perp)$, where $\rho \equiv E(d\sigma/d^3p)$, can be used then to calculate the ratio of leptons to pions as a function of $p_\perp$:

$$\frac{\rho_{\rm lepton}(p_\perp)}{\rho_{\rm pion}(p_\perp)}=\frac{\rho_{\rm charm}(p_\perp)}{\rho_{\rm pion}(p_\perp)}\,D(p_\perp)R_B\,,$$

where the charmed-meson-to-pion ratio was found in the general peripheral model and R_B is the branching ratio to any given mode with the lepton.

The observed rates for muons and electrons are approximately equal, so that pseudoscalar charmed-meson decay into $\mu\nu$ and $e\nu$ cannot be the source of the observed leptons, and we therefore find for pseudoscalars $R_B(\mu\nu)<0.3\%$. If further data should indicate an excess of muons over electrons, that might suggest that pseudoscalars make a small contribution in this mode. If the hypothesis of Altarelli *et al.*[16] is assumed, we find that if $R_B(\mu\nu)\approx 0.5\%$ for vector charmed mesons (0.5% is good to a factor of about 2) the results shown in Fig. 3 are obtained. Those authors suggest larger branching ratios to $\mu\nu$ which are not consistent with our results.

For the $K\mu\nu$, $Ke\nu$, $\pi\mu\nu$, and $\pi e\nu$ decay modes[20] (where interchanging μ and e has little effect on the resulting spectra) one finds two reasons why these muons and electrons are probably not the observed leptons: (1) As exemplified in Fig. 4 (at $E_{\rm lab}=300$ GeV), the ratio of spectra shows a tendency toward peaking at most energies which is not evident in the data, and (2) the shapes of the ratios of spectra change as a function of energy, so that even if the μ/π ratio were flat at one energy, it would not be at another energy. The peaking

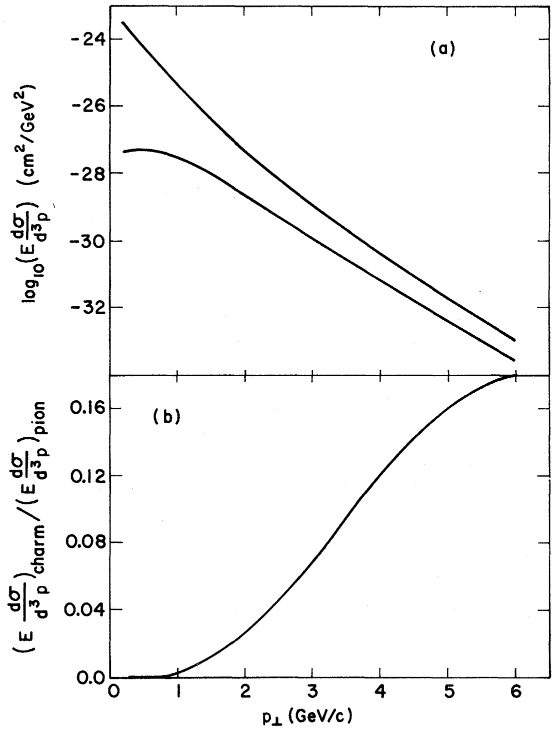

FIG. 2. (a) The single-particle inclusive spectra of pions (top curve) and charmed mesons predicted by the model for $E_{\rm lab}=300$ GeV. (b) The predicted ratio of the charmed meson to pion inclusive spectra for $E_{\rm lab}=300$ GeV; at $E_{\rm lab}=1500$ GeV this ratio is increased everywhere by a factor of about 1.5.

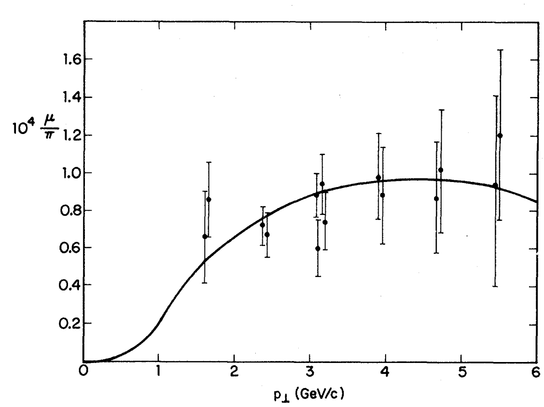

FIG. 3. The ratio of μ to π inclusive spectra at $E_{\rm lab}=300$ GeV for μ from the decay of vector charmed mesons to $\mu\nu$; the data are from Ref. 18.

occurs because products of parents at large $p_\perp$ have a much lower $p_\perp$ and products of parents at very low $p_\perp$ gain energy from the decay of the heavy parent; as a result there is a range of $p_\perp$ which is most favored for the products. The second effect is a reflection on the change with energy of the steepness of the charmed-meson spectrum (similar to the pion spectrum). This change occurs because at fixed small $p_\perp$ the spectra (like the cross sections) rise very slowly with energy, whereas at fixed large $p_\perp$ the spectra rise rapidly consistent with scaling of the form $p_\perp^{-n} f(2p_\perp/\sqrt{s})$.

The bounds on branching ratios to three-particle decays so that these leptons would not have been observed experimentally are found to be about 1% for $\pi\mu\nu$ and $\pi e\nu$ and about 3% for $K\mu\nu$ and $Ke\nu$. These results are quite insensitive to the form factor chosen for the charmed-meson decay as long as an otherwise random distribution of product energies and directions is chosen. The theoretical expectations for the branching ratios could be greater or less than these bounds depending on details of the models.

The lepton spectra for four-or-more-particle decays tend to peak at lower $p_\perp$, where there are few or no data, so that it is difficult to put bounds on these decay modes. However, if the sum of those modes were to contribute 10^{-4} leptons relative to pions for $p_\perp$ from 0.5 to 1.0 GeV/c (as at higher $p_\perp$), a branching ratio of almost 20% to the sum of those modes would be necessary.

If one accepts the hypothesis of Altarelli *et al.*,[16]

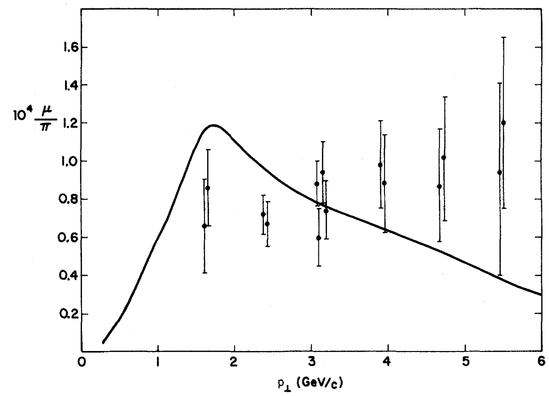

FIG. 4. The ratio of μ to π inclusive spectra at $E_{\rm lab} = 300$ GeV for μ from the decay of charmed mesons to $\pi\mu\nu$; the data are from Ref. 18.

then perhaps the above decay modes also contribute to Fig. 3 in the region just above $p_\perp \approx 0.5$ GeV/c. Should experiment show that this lepton-pion ratio does not decrease sharply for $p_\perp$ below 0.5 GeV/c or at low energies, then the charmed-meson origin of the observed leptons could be positively ruled out.

The author would like to thank his colleagues at Harvard including A. De Rújula, S. Glashow, H. Quinn, C. Rubbia, A. Sessoms, and L. Sulak, and also D. Silverman at the University of California, Irvine, for helpful discussions.

---

*Work supported in part by the National Science Foundation under Grant No. MPS73-05038 A01.

[1]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974); Nucl. Phys. B89, 1 (1975).

[2]J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974).

[3]G. S. Abrams *et al.*, Phys. Rev. Lett. 33, 1453 (1974).

[4]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 764 (1975).

[5]S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[6]M. Gaillard, B. W. Lee, and J. Rosner, Rev. Mod. Phys. 47, 277 (1975).

[7]T. Appelquist and D. Politzer, Phys. Rev. Lett. 34, 43 (1975); Phys. Rev. D 12, 1404 (1975); A. De Rújula and S. L. Glashow, Phys. Rev. Lett. 34, 46 (1975); T. Appelquist *et al.*, *ibid.* 34, 365 (1975); C. G. Callan *et al.*, *ibid.* 34, 52 (1975); E. Eichten *et al.*, *ibid.* 34, 369 (1975); S. Borchardt *et al.*, *ibid.* 34, 38 (1975); S. Okubo *et al.*, *ibid.* 34, 236 (1975).

[8]M. Barnett, Phys. Rev. Lett 34, 41 (1975); Phys. Rev. D 11, 3246 (1975); H. Harari, Phys. Lett. 57B, 265 (1975); F. Wilczek, Princeton report, 1975 (unpublished).

[9]See, for example, A. M. Boyarski *et al.*, Phys. Rev. Lett. 35, 195 (1975).

[10]M. Barnett and D. Silverman, Phys. Rev. D 10, 1510 (1974).

[11]M. Barnett and D. Silverman, Phys. Rev. D 12, 2037 (1975); and University of California at Irvine report, 1975 (unpublished).

[12]See the addendum to Ref. 6 where the authors use a method of G. Farrar and J. Rosner, Phys. Rev. D 10, 2226 (1974).

[13]R. Hagedorn, CERN Yellow Report No. 71/12, 1971 (unpublished).

[14]J. W. Cronin *et al.*, Phys. Rev. Lett. 31, 1426 (1973).

[15]A. De Rújula, H. Georgi, and S. Glashow, Phys. Rev. Lett. 35, 69 (1975).

[16]G. Altarelli, N. Cabibbo, and L. Maiani, Phys. Rev. Lett. 35, 635 (1975).

[17]M. Barnett and D. Silverman, Phys. Rev. D 8, 4151 (1973).

[18]J. P. Boymond *et al.*, Phys. Rev. Lett. 33, 112 (1974).

[19]F. W. Büsser *et al.*, Phys. Lett. 53B, 212 (1974).

[20]The possibility that these decay modes contribute to the observed lepton spectra has been discussed by L. Lederman, unpublished paper abstracted from a talk given at the Informal Conference on Theoretical Physics, Rutherford Labs, 1975 (unpublished).