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Upper limit on D production in proton-nucleon interactions

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The null results from measurements of the polarization of prompt muons produced by 400-GeV protons indicate an upper limit $B_\mu\sigma_{D^0} + B_\mu\sigma_{D^+} < 10^{-31}$ cm^2 may be placed upon the production cross section for D particles, where B_μ is the branching ratio for its three-body decay into a meson, neutrino, and muon. Recent measurements suggest $B_\mu \approx 0.07$ which indicates $\sigma_D < 7\times 10^{-31}$ cm^2.

The D^0 and D^+ mesons with masses near 1.87 GeV have been produced via e^+e^- annihilation at SLAC.[1,2] However, despite many attempts[3-11] these particles have not been observed in hadronic interactions. Some of these experiments[3,4,7] were designed to be more sensitive to the production of particles with masses above 2 GeV and consequently have a limited effectiveness in placing an upper limit on D production. One charmed-particle search[6] did not attempt to place a limit on the total cross section since only one production channel, $n + \text{nucleon} \to J + C + \overline{C}$, was investigated. A limit of 2.6×10^{-30} cm^2 was set on the cross section times hadronic branching ratio for $\pi^+ p \to \overline{D}^0 C_1^{++}$ by an experiment using 10-GeV pions on a bubble chamber.[9] An experiment which used 15-GeV π^+ on a bubble chamber[5] set a limit on the D cross section times the branching ratio B to $K+\pi$: $\sigma_D B < 3\times 10^{-31}$ cm^2, while a more recent experiment[10] using 10.5-GeV π^- on a solid target set a limit $\sigma_{\overline{D}^0} B < 2\times 10^{-31}$ cm^2. A search using emulsions as a target for 300-GeV protons[8] has set a limit $\sigma_D < 1.5\times 10^{-30}$ cm^2.

Previously reported measurements of the polarization of prompt muons[12,13] may be used to place an upper limit on the cross section for the production of D particles in proton-nucleon interactions times their branching ratio to a meson, neutrino, and muon. This is a much different approach to the investigation of charmed-particle production than the techniques used in Refs. 3–10 and hence is sensitive to D production in a different way. It may be noted that an upper limit may be placed on $\sigma_D B_\mu$ by measuring the flux of prompt muons.[11] Measurement of the polarization of these muons allowed an increase in sensitivity to D production of nearly an order of magnitude beyond this since it was determined that about 90% of prompt muons could not be produced by D decay.

For a decay mediated by a $V-A$ current, relativistic leptons will have left-handed helicity while antileptons will be right-handed. Thus for $D^+ \to \overline{K}^0 \mu^+ \nu_\mu$ the neutrino will be produced left-handed and the muon will be right-handed. The helicity of the muon is not completely constrained as its velocity is not the speed of light. However, examination of the Dalitz plot as a function of T_μ reveals that the decay configurations are heavily weighted towards those in which the muon has a kinetic energy much larger than its rest mass and therefore the great majority of muons emitted by this decay mode will have a velocity near c and a polarization near $+1$ in the direction of flight. Detailed calculation shows that the expected polarization of muons from $D \to K\mu\nu$ is 0.89 in the rest frame of the D. Under most kinematic conditions the net polarization of muons with any given energy in the lab will be nearly the same as in the rest frame of the D.

Since negative muons make only a small contribution to the polarization which was measured, the experiment is not sensitive to the production of D^- and $\overline{D}^0$ mesons whose decays are expected to produce negative muons. Calculation of an upper limit on $B_\mu\sigma_{D^0} + B_\mu\sigma_{D^+}$ may be done on the basis of the polarization measurements and a few reasonable assumptions. The D^+ and D^0 were assumed to decay via a $V-A$ current to $K\mu\nu$. Although the production spectra of D particles is not known it seems likely that the x and p_t dependence of D production may be roughly similar to that of the J/ψ. For the purpose of this calculation I have assumed a form:

$$\frac{d^2\sigma_D}{dx\,dp_t} = A\exp(-ap_t)\exp(-b|x|) \quad (p_t \text{ in GeV}/c)$$

with central values $b = 10$, $a = 1.75$ in the center-of-momentum frame of the two colliding nucleons—a form which fits J/ψ production.[14-16]

The production and decay characteristics given in the previous paragraph define the shape of the muon spectrum generated by D decay. If the true production spectrum is substantially different from that given above, the muon spectrum will be altered. The final result is nearly independent of the true x spectrum. Changing "b" by 5 units causes only about a 10% variation in the limit on

TABLE I. Upper limit which may be calculated for $B_\mu\sigma_{D^0}+B_\mu\sigma_{D^+}$ as a function of a, where $d^2\sigma_D/dxdp_t \propto \exp(-ap_t)\exp(-10|x|)$.

a [(GeV/c)$^{-1}$]	Upper limit (nb)
1.0	20
1.25	30
1.5	67
1.75	100
2.0	165
2.25	280

D production. However, the result is quite heavily dependent upon the exponent used for the transverse momentum spectrum. Table I lists the limit for D production based upon various values for the parameter a. Changing this parameter by 0.5 (GeV/c)$^{-1}$ causes about a factor-of-3 difference in the limit. Uncertainty concerning the true x spectrum and other contributions[17] affecting the sensitivity of the experiment are negligible compared with this factor.

Having calculated the shape of the muon spectrum generated by D decay one can now place constraints on the magnitude of various points within this spectrum—thereby placing limits on the rate of D production. While muons created by D decay will have a longitudinal polarization near +0.89, those created by electromagnetic processes (which conserve parity) must have zero longitudinal polarization. A longitudinal polarization of $P=-0.01\pm0.14$ for 185-GeV prompt muons produced in the forward direction and $P=-0.06\pm0.16$ for 54-GeV prompt muons with p_t near 1.9 GeV/c has been observed. These muons were produced by the interaction of 400-GeV protons with copper targets as discussed in Refs. 12 and 13. In addition to these measurements at Fermilab, results have been published for a prompt-muon polarization measurement made at Brookhaven.[18] It was found that the longitudinal polarization of prompt muons produced with transverse momenta near 1.95 GeV/c was $P=-0.15\pm0.18$.

Many measurements have indicated that the bulk of prompt muons are created electromagnetically[12,13,18-20] with a spectrum similar to that of mesons.[21,22] Let μ_D/μ_p be the ratio of the number of muons produced by D decay to the number of prompt muons. A measurement of μ_D/μ_p at high transverse momentum places a more severe restriction on the production of muons by D decay than a measurement made in the forward direction since prompt muons have a steeper dependence upon p_t than muons produced by D decay. The polarization measurement for muons with p_t near 1.9 GeV/c at Fermilab (confirmed at BNL) indicates an upper limit of 10% may be placed upon the fraction of prompt muons which come from D decay in that kinematic region. In the kinematic region of the measurement at Fermilab (for muon energies near 54 GeV and p_t 1.9 GeV/c) the spectrum of electromagnetically produced muon pairs is described by[19]

$$\frac{d^2\sigma_p}{dxdp_t}=13\exp(-10.4x)\exp(-3.5p_t)\times10^{-29}\ \text{cm}^2\,.$$

A Monte Carlo calculation based upon the previously defined spectrum for muons from D decay and this spectrum for electromagnetically produced dimuons indicates that 10% of the positive prompt-muon flux in that kinematic region would come from D decay if

$$\frac{B_\mu d^2(\sigma_{D^0}+\sigma_{D^+})}{dxdp_t}=2.4\exp(-1.75p_t)\times\exp(-10|x|)\times10^{-31}\ \text{cm}^2\,.$$

Integrating over $-1<x<1$ and $0<p_t<\sqrt{s}/2$ gives

$$B_\mu(\sigma_{D^0}+\sigma_{D^+})=10^{-31}\ \text{cm}^2$$

as the upper limit for D production times the branching ratio to a meson, muon, and neutrino.

A recently published measurement of the semileptonic branching ratio of D particles[23] gives $B_\mu\approx0.07$. Assuming that $\sigma_{D^0}=\sigma_{D^+}$, for $a=1.75$, this gives the result $\sigma_D<7\times10^{-31}$ cm^2.

[1] G. Goldhaber *et al.*, Phys. Rev. Lett. 37, 255 (1976).
[2] I. Peruzzi *et al.*, Phys. Rev. Lett. 37, 569 (1976).
[3] E. J. Blesser *et al.*, Phys. Rev. Lett. 35, 76 (1975).
[4] J. J. Aubert *et al.*, Phys. Rev. Lett. 35, 416 (1975).
[5] V. Hagopian *et al.*, Phys. Rev. Lett. 36, 296 (1976).
[6] M. Binkley *et al.*, Phys. Rev. Lett. 37, 578 (1976).
[7] D. Bintinger *et al.*, Phys. Rev. Lett. 37, 732 (1976).
[8] G. Coremans-Bertrand *et al.*, Phys. Lett. 65B, 480 (1976).
[9] M. C. Goddard *et al.*, Phys. Rev. D 16, 2730 (1977).
[10] R. Cester *et al.*, Phys. Rev. Lett. 40, 139 (1978).
[11] A. M. Jonckheere *et al.*, Phys. Rev. D 16, 2073 (1977). This experiment was sensitive to the production of $D\bar{D}$ if both particle decays produced a muon. It placed a limit $\sigma_D<10^{-29}$ cm^2. No polarization information was obtained.
[12] L. B. Leipuner *et al.*, Phys. Rev. Lett. 36, 1011 (1976).
[13] M. J. Lauterbach *et al.*, Phys. Rev. Lett. 37, 1436 (1976). Final analysis of the data has slightly changed the numbers quoted for polarization in Refs. 12 and

13.

[14]T. O'Halloran, in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California*, edited by W. T. Kirk (SLAC, Stanford, 1976), p. 189.

[15]G. J. Blanar *et al.*, Phys. Rev. Lett. 35, 346 (1976).

[16]H. D. Snyder *et al.*, Phys. Rev. Lett. 36, 1415 (1976). The authors of this paper point out that much of the ψ data can be fitted using a transverse-momentum dependence of $\exp(-1.6p_t)$.

[17]For example, muons produced by $D \to K\mu\nu$ will have a slightly larger polarization than those produced by $D \to K^*\mu\nu$ and it is not clear which mode will make a larger contribution, although the sum of these two branching ratios appears to be near 0.15. The experiment is also sensitive to muons produced by $D \to \pi\mu\nu$, though this branching ratio is small.

[18]D. M. Grannan *et al.*, Phys. Lett. 69B, 125 (1977).

[19]H. Kasha *et al.*, Phys. Rev. Lett. 36, 1007 (1976).

[20]K. J. Anderson *et al.*, Phys. Rev. Lett. 37, 803 (1976).

[21]J. P. Boymond *et al.*, Phys. Rev. Lett. 33, 112 (1974); L. M. Lederman, Phys. Rep. 26C, 149 (1976). Measurements made by these groups show that the transverse momentum dependence for prompt muon production is about the same as—or perhaps slightly less steep—than that of pion production.

[22]M. Bourquin and J. M. Gaillard, Phys. Lett. 59B, 191 (1975). This paper indicates that the transverse-momentum dependence for lepton production from ($\rho^0 + \omega^0 + \psi$) is the same as for the "continuum contribution" and equal to about $\exp(-3.8p_t)$. The use of $\exp(-3.5p_t)$ in the present work is somewhat conservative in order to avoid any overestimate of the sensitivity of the measurement.

[23]J. M. Feller, *et al.*, Phys. Rev. Lett. 40, 274 (1978).