Comments and Addenda

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Limits on the hadronic production of $D(1865)$ charmed mesons

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Our published measurements have shown that lepton pairs account for the bulk of the single prompt muons produced in p-nucleus collisions. We now use our results to set limits on the cross section $\sigma_{D\bar{D}} = \sigma_{D^0\bar{D}^0} + \sigma_{D^+D^-}$, finding with 95% confidence that $\sigma_{D\bar{D}} < 26$ μb at $\sqrt{s} = 19.4$ GeV, and $\sigma_{D\bar{D}} < 59$ μb at $\sqrt{s} = 27.4$ GeV. These limits are at the level of the recently reported cross sections for charmed particles observed in neutrino "beam-dump" experiments, and are 10 times higher than $\sigma_{D\bar{D}}$ expected from a simple extrapolation of the cross section for J/ψ production.

The search for the hadronic production of charmed particles has featured a lengthy series of null results[1-18] followed by recent reports of evidence for a positive signal.[19-23] Figure 1 summarizes the limits and reported rates for $\sigma_{D\bar{D}}$, the total inclusive cross section per nucleon for charmed mesons produced in hadron-nucleus collisions, where $\sigma_{D\bar{D}} = \sigma_{D^0\bar{D}^0} + \sigma_{D^+D^-}$, and D is the charmed meson of mass 1865 MeV/c^2. In obtaining total cross sections from the various experiments, we use $(2.2 \pm 0.6)\%$ as the branching fraction for the decay $D^0 \to K\pi$,[24] and $(10.0 \pm 1.5)\%$ as the total branching fraction for all decays $D \to \mu\nu X$.[25-27] In using results of single μ or ν production to obtain D-meson cross sections, we are assuming that of all charmed particles, D mesons are the dominant source of these leptonic decay products. This assumption is plausible in that the D mesons are the lightest of the charmed particles, and hence should be the most copiously produced, and should have the largest leptonic branching ratio. Limits from searches for $D^0 \to K\pi$ are set assuming $\sigma_{D^0\bar{D}^0} = \sigma_{D^+D^-}$. When not otherwise specified by the authors, we assume the cross section has a linear dependence on target atomic number A and a longitudinal-momentum dependence $(1-x)^4$, where $x = 2p_L/\sqrt{s}$, in analogy to the production of massive muon pairs.[28] The assumption of a linear A dependence reduces

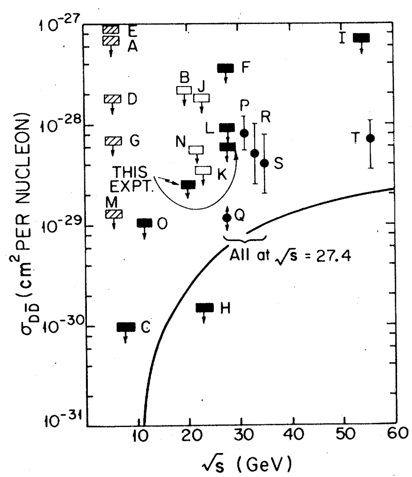

FIG. 1. Total inclusive cross-section limits for $D\bar{D}$ production ($D^0\bar{D}^0$ and D^+D^- combined) by hadrons. Solid symbols are from proton beams, open symbols from neutron beams, and cross hatched symbols from pion beams. Circular symbols represent reports of positive signals, while box symbols represent upper limits. Data point A is from Ref. 1; B, Ref. 2; C, Ref. 3; D, Ref. 4; E, Ref. 6, F, Ref. 8; G, Ref. 10; H, Ref. 11; I, Ref. 12; J, Ref. 13; K, Ref. 14; L, Ref. 15; M, Ref. 16; N, Ref. 17; O, Ref. 18; P, Ref. 19; Q, Ref. 20; R, Ref. 21; S, Ref. 22; T, Ref. 23. The solid curve is an estimate of charmed-particle production based on J/ψ production as described in (3).

the cross sections of Refs. 19 and 21 by a factor of 4, and that of Ref. 20 by 3.5.[29] The strong limit of Ref. 11 is only valid for lifetimes in the range 10^{-13} to 10^{-15} sec, but would be, for example, an order of magnitude higher for lifetimes 10^{-12} or 10^{-16} sec.

In previous publications,[30,31] we have shown that the bulk of hadronically produced prompt muons arise from μ pairs of electromagnetic origin. Now that the D^0 has been discovered,[32] with known branching ratios to leptons,[25-27] and especially in view of recent experiments reporting evidence of prompt neutrinos,[19-21] we examine our previous work for evidence of charm production. In (1) and (2) we compare the measured production rates of μ pairs with those of single, prompt muons, and present the results as new limits on the total cross section for $D\bar{D}$ production. In (3) we give a simple phenomenological argument which indicates $\sigma_{D\bar{D}}$ might be only 2–6 μb in the beam energy range 150–400 GeV.

(1) We compare our rates of inclusive muon production from events containing muon pairs[30] in the p-Be collisions at 150 GeV/c to the total prompt muon signal observed in p-Cu collisions at 400 GeV/c.[33] To make such a comparison, we assume the ratio μ/π from pair sources is the same at 150- and 400-GeV/c beams, and for Be and Cu targets. This is justified to the extent that most muon pairs have low mass,[34] and hence have energy and A dependences similar to those of pions.[28] In the comparison a small excess of prompt muons not of pair origin is observed, shown in Fig. 2. The prompt muon spectrum expected from charmed particle decays is evaluated with a Monte Carlo calculation. We suppose $d\sigma_D/dxdp_T \propto (1-x)^4 p_T \exp(-2.5p_T)$, and take the momentum spectrum for muons from $D \to \mu X$ from Ref. 35. The resulting muon spectrum is normalized to a pion spectrum $\propto (1-x)^5$ with total inclusive cross section of 100 mb at 400 GeV.[36] The curve in Fig. 2 is for the case that $\sigma_{D\bar{D}} = 100$ μb per nucleon, and includes the 10% branching fraction for $D \to \mu X$. The curve includes a factor of 3.5 to account for the linear A dependence of D production in the Cu target compared to $A^{0.7}$ for pion production.[37] The normalization of the curve is roughly linear in the power of the x dependence of D production. That is, the assumption of $(1-x)^5$ instead of $(1-x)^4$ would raise the curve (and hence the limit set below) by 25%. The assumption of $\exp(-2.5p_T)$ for D production corresponds to 800 MeV/c average p_T. A change in the average p_T by 200 MeV/c would induce only a 1% change in the derived limit.

The muon spectrum from D decay is steeper than that of the data in Fig. 2, indicating the data are not necessarily due to charmed particle production. Therefore, we set a limit that $\sigma_{D\bar{D}}$ is no more than 2 standard deviations above the data point at $x = 0.13$, to obtain with 95% confidence, $\sigma_{D\bar{D}} < 59$ μb per nucleon at $\sqrt{s} = 27.4$ GeV. If $\sigma_{D\bar{D}}$ were actually as large as 59 μb, this would require that roughly $\frac{2}{3}$ of all prompt muons with $x > 0.1$ be due to charmed particle decay, and hence unpaired. We view this as extremely unlikely, and point out that in setting the 59-μb limit we have assumed Gaussian errors. In reality, the errors, mainly in normalizations and extrapolations, have much smaller tails.

(2) In a short "beam-dump" experiment with p-Fe collisions at 200 GeV/c, we observed prompt, single muons and muon pairs simultaneously.[31] We found a slight excess of unaccompanied muons over those from muon pairs (see Table I of Ref. 31). This excess is also shown in Fig. 2 of the present paper. As in (1), we compare these single muons to those expected from charmed-particle decay. The spectrum corresponding to $\sigma_{D\bar{D}} = 100$ μb would be 0.87 times that of the curve in Fig. 2, noting that at 200 GeV the inclusive cross section for $(\pi^+ + \pi^-)/2$ is 90 mb,[36] and that the target was Fe instead of Cu. We then derive a 95% confidence limit that $\sigma_{D\bar{D}} < 26$ μb per nucleon at $\sqrt{s} = 19.4$ GeV.

(3) As an estimate of the expected particle production cross section we suppose

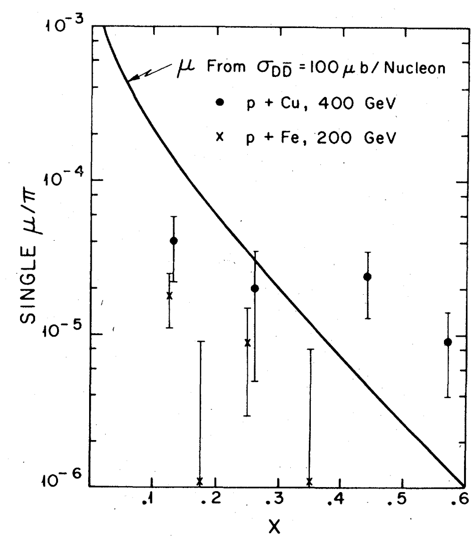

FIG. 2. The number of prompt muons not of pair origin divided by the number of pions as a function of $x = 2p_L/\sqrt{s}$. The solid points are for μ^-/π^- from a comparison of Refs. 30 and 33. The crossed points are for all μ/allπ from Ref. 31. The solid curve is a Monte Carlo estimate of μ^-/π^- in p + Cu collisions at 400 GeV supposing the muons are from D decay with $\sigma_{D\bar{D}} = 100$ μb per nucleon.

$$\sigma_D/\sigma_{J/\psi} \sim \sigma_K/\sigma_\phi \sim \sigma_\pi/\sigma_\rho$$

At 150 GeV/c we have measured $\sigma_\rho \sim 9$ mb, $\sigma_\phi \sim 660$ μb, and $\sigma_{J/\psi} \sim 100$ nb, all per nucleon.[34] We take[36] $\sigma_\pi \sim 90$ mb and $\sigma_K \sim 10$ mb, so that $\sigma_\pi/\sigma_\rho \sim 10$ and $\sigma_K/\sigma_\phi \sim 15$. Allowing a linear dependence on quark mass we might expect $\sigma_D \sim 45\,\sigma_{J/\psi}$. At the energies considered, significant threshold suppressions are present in the production of very massive particles, so we adopt a simple scaling behavior to get $\sigma_D(\sqrt{s}) = 45\,\sigma_{J/\psi}(0.83\sqrt{s})$, noting that $M_{J/\psi}/2M_D = 0.83$. We suppose $\sigma_{J/\psi}$ varies with energy as $B\, d\sigma/dx(x=0)$ and normalize to our measurements of $\sigma_{J/\psi}$ at 150 and 225 GeV/c.[34,38] The resulting estimate of $\sigma_{D\bar{D}}$ is shown as the solid curve in Fig. 1. A similar estimate of $\sigma_{D\bar{D}}$ based on a parametrization of the mass dependence of inclusive particle production has been given by Bourquin and Gaillard.[39]

In summary, our new limits on the hadronic production of charm, shown in Fig. 1, are consistent with, or place only mild constraints on, recently reported cross sections.[19-23] However, our expectations of charmed particle production based on observed J/ψ cross sections are below the reported cross sections, indicating that the binding of $c\bar{c}$ states is effectively weaker than that of ordinary $q\bar{q}$ states.

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