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HADRONIC CHARM PRODUCTION IN QCD

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ABSTRACT

We consider how a $c\bar{c}$ pair produced in a hadronic collision may be converted into either a $c\bar{c}$ bound state or a pair of charmed particles. The fact that many other quarks are present leads us to doubt a naive application of duality to the charm sector alone. The possibility of charmed quark combination with other already existing quarks makes straightforward calculations of the charm production cross section in QCD larger than recently expected, although sensitive to the quark mass. If the observations of excess neutrinos in "beam dump" experiments are in fact due to charm, we find that they can be accommodated if the charmed quark mass is toward the lower end of the range of masses usually considered.

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The question of charm production seems shrouded in mystery, not because of lack of information, but because of too much information of an incompatible nature. On the experimental side, there have been many searches for charm in hadronic collisions. However, until recently all the accelerator experiments gave only upper limits for the production cross sections and the numbers were getting quite small indeed. But now there have been seen anomalous neutrino induced events in the "beam dump" experiments at CERN [1-3] that can be quite naturally explained as charm production followed by weak decay, provided that the charm production cross section is large -- about 30 μb per target nucleon using the smallest of the three experimental values at $\sqrt{s}$ = 27 GeV. There are also some unusual cosmic ray events [4] compatible with charm production with the aforementioned cross section and a lifetime of 10^{-12} - 10^{-14} sec.

On the theoretical side there seems to be confusion because there are a number of different calculations giving a rather wide range of possible values for the cross section. However, the field is more settled than first appears. Many of the earlier calculations that gave large cross sections depended on having a large charm content in the nucleon ocean [5], but this is probably considerably less than the value that was first supposed. The corresponding mechanisms for J/ψ production [6] -- charmed quark fusion -- would lead us to expect extra muons in conjunction with the J/ψ, and the non-observation of these muons [7] speaks against any process that requires significant numbers of charmed quarks in the initial state. One is left with a growing credence that it is gluons in the initial state which are responsible for the primary interaction that leads to charm [8-10], at least in proton-proton or protonnucleus collisions. We will concentrate on the gluon-gluon process although for other beams and lower energies the process $q\bar{q} \to c\bar{c}$ where $q = u,d,s$ is also important [9,10] and it has also been suggested that even though the charm content of the proton is small, the hard scattering of gluons on charm quarks or light quarks on charm quarks can contribute noticeable to charm production [11]. This however leaves us in a rather diffident situation, as apparently reliable calculations [9] of gluon induced charm production give cross sections an order of magnitude or so smaller than those mentioned in the first paragraph.

We propose here an elementary reexamination of charm production, including an examination of duality type calculations of bound charm production [12,13], to see if a larger cross section really ought to be expected. The answer is yes, although, along with Jones and Wyld [9], we find that the results are sensitive to the quark mass.

The main point can be seen by examining the first two diagrams of fig. 1. The first thing that must happen in any case is that some interaction must occur among the fundamental constituents of the incoming hadrons which must result in the formation of a charmed quark pair, $c\bar{c}$. We have drawn the diagrams with gluons colliding to give the charmed quark state as this is what we find happens in most cases of interest, although in some cases the hard scattering of other constituents may also be considered. It is assumed that this interaction may be calculated in perturbation theory; the charmed quarks are heavy enough that the coupling constant relevant to their production is small.

After the $c\bar{c}$ pair is formed, we have a final state expressed in terms of a quark basis and whose cross section we can calculate. These quarks must now turn into observable hadrons, and we follow the usual expectation that this will occur with unit probability (aside from the possibility of the $c\bar{c}$ annihilating immediately which we can expect to be small and calculable in perturbation theory). The question is, how will this occur and what final states are possible. In particular, what can happen to the $c\bar{c}$ if its combined mass is below threshold for turning into charmed particles, i.e., if $2m_c \leq m(c\bar{c}) \leq 2m_D$. We should like to point out that a $D\bar{D}$ (or other charmed hadrons) final state is still possible because the c and $\bar{c}$ can well combine with the residual quarks from the initial hadrons [fig. (1a)]. It is not necessary that the $c\bar{c}$ turn into a bound state if $m(c\bar{c}) \leq 2m_D$, although this is certainly also possible.

Hence, the correct formula for the calculation of charmed particle production in proton-nucleon collisions is

$$\sigma_{tot}\ (\text{charm}) = \int_{4m_c^2}^{s} \frac{ds'}{s'}\, \sigma(s';\ gg \to c\bar{c})\ F(s'/s)$$

$$- \sigma_{tot}\ (\text{charm bound states}) \qquad (1)$$

where

$$F(\tau) = \tau \int_{\tau}^{1} \frac{dx}{x}\, f_g(x)\ f_g(\tau/x) \quad . \qquad (2)$$

In the above, $\sqrt{s}$ is the total c.m. energy of the proton nucleon system, $\sqrt{s'} = m(c\bar{c})$ is the c.m. energy of the $c\bar{c}$ pair, $f_g(x)$ is the distribution function for gluons within nucleons normalized so that half the momentum of a nucleon is carried by the gluons, or

$$\int_0^1 x\, f_g(x)\, dx = \frac{1}{16} \quad , \tag{3}$$

and $\sigma(s', gg \to c\bar{c})$ is the QCD cross section for the process and energy indicated. The integral term above gives the total production of $c\bar{c}$ quark pairs [8-10], and we shall emphasize that the lower limit is $4m_c^2$ rather than $4m_D^2$. Numerically, it is the small lower limit that will make the cross section large and sensitive to the quark mass.

The above formula is useful because we believe we can calculate independently the production of charmonium bound states [8,10,14]. The bound states in question are the η_c (2.83), the η_c' (3.45?), the ^3P_j (3.41, 3.51, 3.55), and perhaps the (undiscovered) $^1D_2(\sim 3.8)$. All these states can be directly produced by the "fusion" of two gluons; the bulk of hadronic production of the J/ψ presumably comes from the subsequent decay of the above states [10,14], the main contribution coming from the ^3P_j. If the bound state is directly produced from two gluons in a color singlet state, then

$$\sigma_{tot}(i) = \frac{8\pi^2}{M_i^3}\,(2J_i + 1)\,\Gamma(i \to gg)\,F(\tau_i) \tag{4}$$

where for a bound state $\underline{i}$, J_i is its spin, M_i is its mass, $\tau_i = M_i^2/s$, Γ is the gg width (which can be calculated given the bound wave function coming from some potential model), and F is the same as before.

In what follows we will argue that the production of psi like objects ($c\bar{c}$ bound states) procedes mainly through subprocesses in which color is conserved locally, i.e., via color singlet intermediate states. The alternative to this would be that a color octet $c\bar{c}$ is formed, which must then shed its color by emitting soft gluons. However this process is suppressed. Arguments akin to ones showing that confined states with zero total electric charge will not emit long wavelength photons can be used to show that the amplitude for transitions from a color octet state to a color singlet bound state is proportional to the gluon energy and tends to zero for very soft gluons [15]. We then can expect that when a c and a $\bar{c}$ are formed in a color octet state (or color singlet, but widely separated in rapidity) both quarks will bind individually with other quarks to form charm mesons and baryons. The same argument, of course, does not apply if we start with a color singlet $c\bar{c}$, which can bind together easily. The phenomenological success of this method when applied to J/ψ production [10] gives additional support to this picture. For if we use eq. (4) to calculate the cross section for the ^3P_j states, and then multiply these by the calculated [10] or measured [16] values of the $^3P_j \to J/\psi + \gamma$ branching ratio, the resulting cross sections give the bulk of the observed J/ψ production.

It now remains for us to calculate the charm production resulting from eq. (1). The cross section for $gg \to c\bar{c}$, because of color factors and self coupling of gluons, is not a singlet factor times the $\gamma\gamma \to e^+e^-$ cross section. However, it is by now well known, and is

$$\sigma(s', gg \to c\bar{c}) = \frac{64\pi\alpha_{st}^2}{3s'} \left\{ \left[1 + r + \frac{1}{16} r^2\right] \ln\left(\frac{1+\sqrt{1-r}}{1-\sqrt{1-r}}\right) - \left[\frac{7}{4} + \frac{31}{16} r\right] \sqrt{1-r} \right\} \qquad (5)$$

where $r = \dfrac{4m_c^2}{s'}$.

While the calculation of the bound state cross sections [eq. (4)] is only weakly dependent on α_{st}, the above cross section is directly proportional to α_{st}^2 and so we will quote our results for a range of values. We will calculate with fixed $\alpha_{st} = \alpha_{st}(M_\psi^2) = 0.20$ or 0.40 and we shall also see what happens (not much, as it will turn out) if we allow the coupling constant to vary with s' according to

$$\alpha_{st}(s') = \frac{12\pi}{25}\left(\log\frac{s'}{\Lambda^2}\right)^{-1} \qquad (6)$$

with $\Lambda = 0.5$ GeV for the high value of α_{st} and $\Lambda = 0.07$ GeV for the low value [17]. Also, for definiteness we shall let the gluon distribution take the standard form [8],

$$f_g(x) = \frac{n+1}{16x}(1-x)^n \qquad (7)$$

with n = 5. The integral giving the total $c\bar{c}$ production can now be done straightforwardly.

The bound state cross sections are a small problem because of the η_c and η_c', whose hadronic widths seem like they must be smaller than the potential model value [18]. We shall simply leave them out, as it will fortunately happen that the subtraction of the bound state cross section is not numerically crucial. Table I lists the values we use for the widths and cross sections of the ^3P_j and $^1D_2$. The latter has been included because it has been pointed out [19] that it cannot decay into $D\bar{D}$ and that its mass very likely lies below the 3.87 GeV threshold for decay into $D\bar{D}^*$ or $D^*\bar{D}$. The $^1D_2$ width is taken from Novikov et al. [20]; potential models give varying results around this value. The ^3P_j widths are our calculations [10]. We shall hold these widths fixed; changing the quark mass also requires changing parameters in the potential to give the right ψ' - J/ψ mass splitting, etc., with the end result that these widths are more constant than one might expect.

We shall do the following excercise. Suppose that the "beam dump" experiements really do imply a charm cross section 30 μb at $\sqrt{s}$ = 27 GeV. What charmed quark mass would this imply?

Our charm cross section, eq. (1), at $\sqrt{s}$ = 27 GeV is plotted vs. the charmed quark mass in fig. 2. If we accept the higher values of α_{st}, then a somewhat low but not out of the question value of m_c = 1.15 GeV results.

We follow this with fig. 3, which shows the dependence on energy for α_{st} = 0.4 and m_c = 1.15 GeV, using several different beams. For the antiproton and pion cases, $q\bar{q}$ initiated processes are important at lower energies, and they are handled as in ref. [10].

A few comments seem in order.

(a) Our value of m_c = 1.15 GeV is low, but it is not too different from the value obtained by Novikov et al. [20] from applying duality to e^+e^- → hadrons. Duality here means calculating the free $e^+e^- \to c\bar{c}$ cross section and integrating it from threshold $2m_c$ to charm meson threshold $2m_D$, and saying that this area must be equal to the measured cross section area of the resonances. There are no additional quarks in the e^+e^- case, so we have no reason for not believing this statement of duality. It leads to a condition on the charm quark mass, and the value m_c = 1.25 GeV follows. The only dependence on α_{st} is in some correction terms which are considered. It is also interesting to note that some simple potentials which are designed to give charmonium and upsilonium the same mass splittings also tend to give a low charmed quark mass [21].

(b) We are quite sensitive to the charm quark mass, and this mass is not well pinned down. This is really a problem that has essentially relativistic facets. If charmonium were a non-relativistic system, the masses of the various bound states would differ negligibly from each other, and the charm quark mass would be half the mass of any of them. When we calculate the production of mesons containing still heavier quarks we can predict the cross section more definitively since the bound state systems became more non-relativistic and the mass of the heavy quark can be stated with smaller percentage uncertainty.

(c) While there are certainly smooth connections between charmed meson production and bound state production, duality in the sense discussed above does not apply to the hadronic production of charm. That is, we do not expect that there will be a smooth extrapolation between the $D\bar{D}$ cross section at a given dimension mass and some smeared resonance cross section. The reason is that because of the presence of the hadron's residual quarks, there is not a firm connection between $m(c\bar{c})$ and the mass of the charmed particles that finally appear. In particular, not all of the charmed quark pairs produced in the window $2m_c \leq m(c\bar{c}) \leq 2m_D$ are forced to become $c\bar{c}$ bound states [12]. This points up the danger of applying duality arguments to variables which apply only to a subset of quarks and whose values can be changed or made undeterminable by final state interactions, and should be contrasted with the situation in e^+e^- collisions [20] or with the study of Bloom and Gilman [22].

In conclusion we may repeat that the charm cross section could well be large compared to simple extrapoltions of bound state production data. The new "charm" data, if it is that, stimulates consideration of a coherent model with bound state and charm production fitting neatly together.

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Note added. The Cal. Tech. Stanford experiment at FERMILAB, at $\sqrt{s}$ = 27 GeV, also reports single μ production, compatible with charm production followed by weak decay, with a charm production cross section of about 40 μb. (See B. C. Barish, talk presented at the 19th International Conference on High Energy Physics, Tokyo, August 1978.) One of us (R.S.) would like to thank Frank Merritt and Arie Bodek for enlightening discussions on the status of the experimental data.

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TABLE I

The hadronic (2g) widths of the C = + charmonium bound states, and their production cross section at $\sqrt{s}$ = 27 GeV.

State	Width $\Gamma(i \rightarrow gg)$	$\sigma_{tot}(i)$
$^3P_0$ (3.41)	3.3 MeV	0.17 μb
$^3P_1$ (3.51)	.22 MeV	0.03 μb
$^3P_2$ (3.55)	.88 MeV	0.21 μb
$^1D_2$ (3.8)	.17 MeV	0.02 μb
	Total	0.43 μb

FIGURE CAPTIONS

Fig. 1 Process which can lead to charmed particles on charmed bound states. Figures (1a) and (1b) represent two possible processes for $m(c\bar{c}) < 2m_D$, while (1c) can only occur if $m(c\bar{c}) > 2m_D$.

Fig. 2 Total cross section for charmed particle production in $p\mathcal{N}$ as a function of m_c for $\sqrt{s} = 27$ GeV. α_{st} is either as labeled or given by $\alpha_{st}(s') = (12\pi/25)/\log(s'/\Lambda^2)$, with Λ as labeled.

Fig. 3 Total cross sections per target nucleon for charmed particle production as a function of $\sqrt{s}$ for $m_c = 1.1$ GeV. This figure is calculated for $\Lambda = 0.5$ GeV.

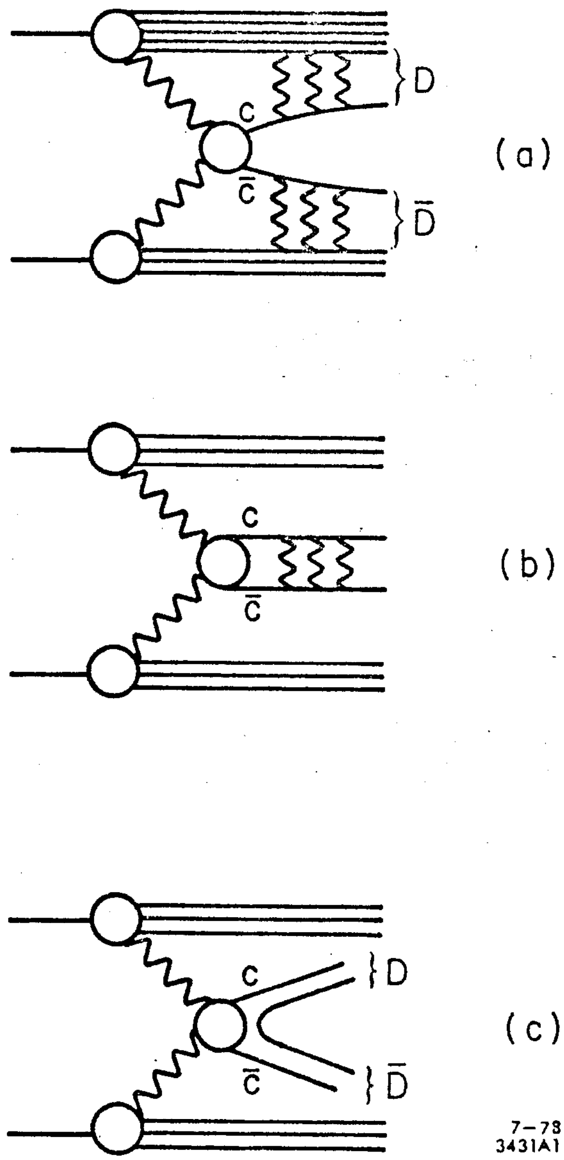
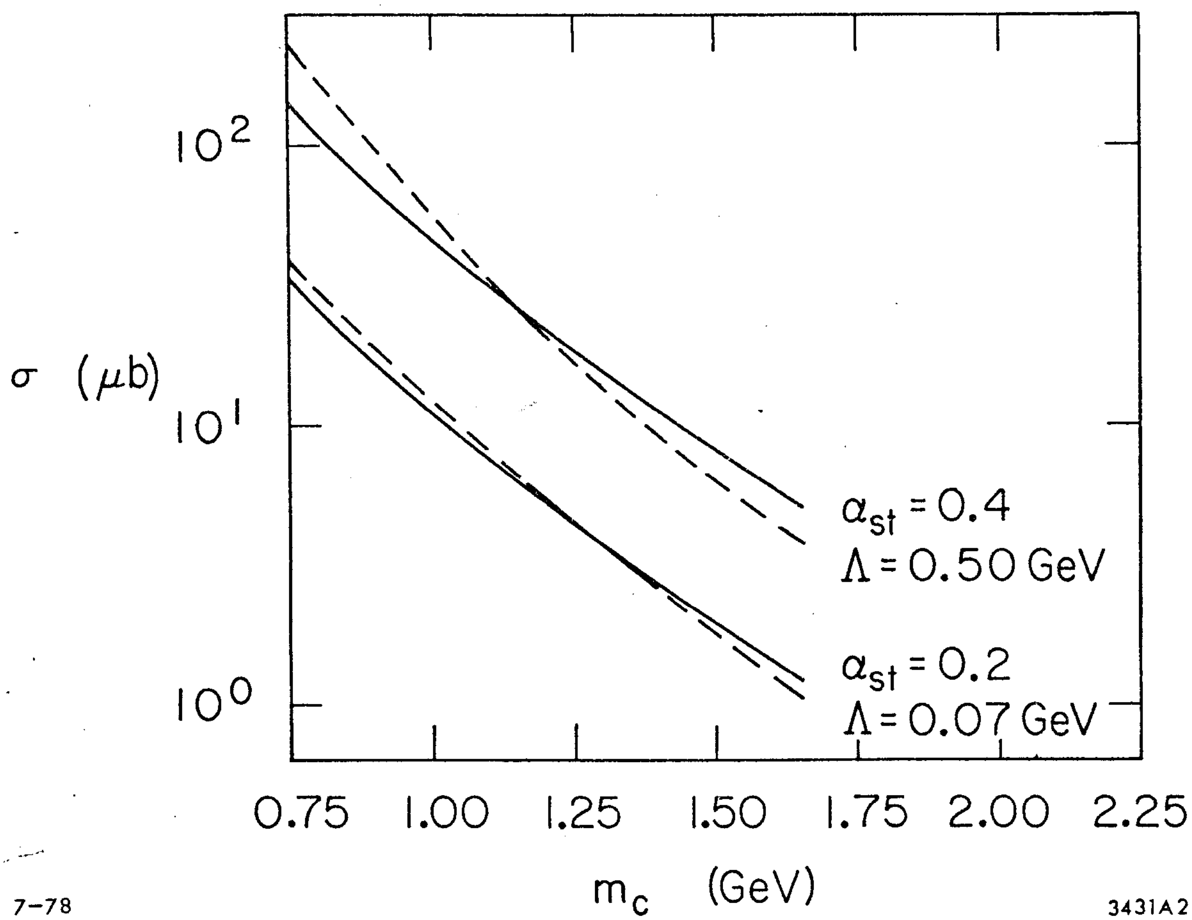
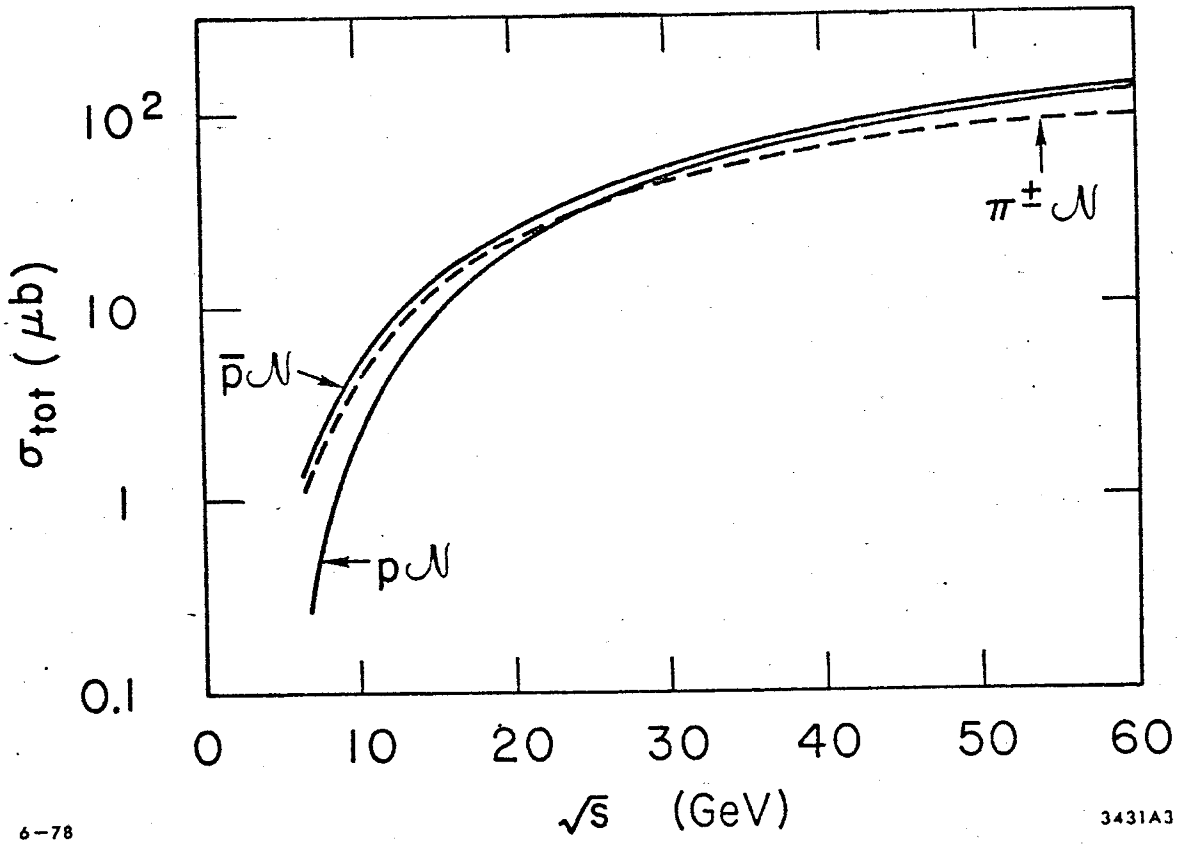


Fig. 1



σ (μb)
10²
10¹
10⁰
α_st = 0.4
Λ = 0.50 GeV
α_st = 0.2
Λ = 0.07 GeV
0.75
1.00
1.25
1.50
1.75
2.00
2.25
m_c (GeV)
7-78
3431A2

Fig. 2



10^2
10
1
0.1
σ_{tot} (μb)
$\bar{p}\mathcal{N}$
$p\mathcal{N}$
$\pi^{\pm}\mathcal{N}$
0
10
20
30
40
50
60
$\sqrt{s}$ (GeV)
6-78
3431A3

Fig. 3