Suppression factors in charmed-particle production*

V. Barger
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

R. J. N. Phillips
Rutherford Laboratory, Chilton, Oxon, England
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Quantitative estimates are presented for the production of particles with nonzero charm number, based on the close dynamical similarity with associated production of strange particles, and using the idea that symmetry breaking comes mostly through trajectory displacements. We find that cross sections may be realized at the level of 1 nb for two-body reactions and 60 nb for inclusive reactions in the triple-Regge region. Crucial elements in the calculations are the negative intercepts of the charmed Regge trajectories, and kinematic suppression through the $t_{\min}$ cutoff.

I. INTRODUCTION

The discovery of the new ψ particles[1] has given further stimulus to the search for charmed particles,[2] for which persuasive theoretical arguments already existed. If the $\psi(3100)$ meson is the $c\bar{c}$ counterpart of the $\lambda\bar{\lambda}$ state $\phi(1019)$, it establishes the mass scale for charmed particles.[3] Since the crucial test is the observation of particles with nonzero charm number, and experimental searches are now underway, it is important to have some estimates of the production cross sections that may be expected.

In this paper we present quantitative estimates of charmed-particle production, based on the close similarity with associated production of strange particles, simply extrapolating ideas that have proved successful in describing the latter. We deduce the relative suppression of charmed versus strange particle production, in terms of the displacement between the Regge trajectories of charm and strangeness exchange. The results are sensitive to input parameters, but even the most optimistic assumptions give very small cross sections. In quasi-two-body processes, charm production is suppressed by factors 10^3 or more compared to strangeness production at the same energy; compared to peak strangeness production the suppression is 10^6 or more. For inclusive charm production, in the triple-Regge scaling region, suppression is typically 10^{-4} or more.

Key factors in our calculations are the high threshold energy of charm production, the negative intercepts of the charmed trajectories, kinematic suppression through the $t_{\min}$ cutoff, and the residue dependence of dual Regge models. The similarity between λ and c quark contributions in SU(4) quark-model wave functions is an important simplifying feature.

In the following sections we present estimates of charm production by exclusive two-body scattering, by inclusive processes, and by the two-body decay of high-mass noncharmed systems produced by Reggeon exchange.

Near the completion of our work, we learned of estimates by Field and Quigg,[4] who exploit similar ideas and reach qualitatively similar conclusions; our more optimistic D^* trajectory is chosen to equal theirs.

II. TWO-BODY ASSOCIATED CHARM PRODUCTION

There is a direct correspondence in SU(4) symmetry between hadrons that contain one strange quark λ, and these that contain one charmed quark c, as illustrated by the quark-model wave functions given in Table I. (For charmed-particle notation we follow Gaillard *et al.*, Ref. 3.) Hence in the SU(4) symmetry limit the amplitudes are pairwise equal for reactions such as the following, as illustrated in Fig. 1(a):

K^* exchange	D^* exchange
$\pi^- p \to K^0\Lambda^0$	$\pi^- p \to D^- C_0^+$
$\pi^+ p \to K^+\Sigma^+$	$\pi^+ p \to \bar{D}^0 C_1^{++}$
$\bar{p}p \to \bar{\Lambda}\Lambda$	$\bar{p}p \to \bar{C}_0{}^- C_0^+$
$\gamma p \to K^0\Lambda^0$	$\gamma p \to D^- C_0^+$.

The large mass splitting between charmed and noncharmed states implies substantial SU(4) symmetry breaking. Experience with SU(3) indicates that symmetry breaking is due principally to trajectory displacements: We adopt the same attitude toward SU(4). To relate SU(4) couplings of different trajectories, we take as a prototype the s dependence and t dependence of the typical dual amplitude

TABLE I. Quark-model wave functions.

Charmed particle	Quark content	Strange particle	Quark content
C_1^{++}	$c\mathcal{P}\mathcal{P}$	Σ^+	$\lambda\mathcal{P}\mathcal{P}$
C_1^+	$c(\mathcal{P}\mathcal{N}+\mathcal{N}\mathcal{P})/\sqrt{2}$	Σ^0	$\lambda(\mathcal{P}\mathcal{N}+\mathcal{N}\mathcal{P})/\sqrt{2}$
C_1^0	$c\mathcal{N}\mathcal{N}$	Σ^-	$\lambda\mathcal{N}\mathcal{N}$
C_0^+	$c(\mathcal{P}\mathcal{N}-\mathcal{N}\mathcal{P})/\sqrt{2}$	Λ^0	$\lambda(\mathcal{P}\mathcal{N}-\mathcal{N}\mathcal{P})/\sqrt{2}$
D^+	$c\bar{\mathcal{N}}$	$\bar{K}^0$	$\lambda\bar{\mathcal{N}}$
D^0	$c\bar{\mathcal{P}}$	K^-	$\lambda\bar{\mathcal{P}}$

$$A(s,t)=\beta\,\Gamma(1-\alpha_t)\Gamma(\tfrac{3}{2}-\alpha_s)/\Gamma(\tfrac{3}{2}-\alpha_t-\alpha_s) \qquad (1a)$$

$$\simeq\beta\Gamma(1-\alpha_t)(-\alpha_s's)^{\alpha_t} \text{ for large } s \qquad (1b)$$

and take exact SU(4) coefficients β. Here α_s' is the slope of the s-channel Regge baryon trajectory, which we fix at the observed value of $\alpha'=0.9\text{ GeV}^{-2}$. The effect of these assumptions is that the coupling constants of t-channel particles (defined by residues at the poles in t) obey exact SU(4) symmetry within a factor α_t'.

We thus predict for any of the above pairs of related two-body reactions, at large s,

$$\frac{d\sigma/dt(\text{associated charm production})}{d\sigma/dt(\text{associated strangeness production})} = \left[\frac{\Gamma(1-\alpha_{D^*}(t))}{\Gamma(1-\alpha_{K^*}(t))}\right]^2(\alpha_s's)^{-2\Delta\alpha(t)}, \qquad (2a)$$

where

$$\Delta\alpha(t)=\alpha_{K^*}(t)-\alpha_{D^*}(t)\,. \qquad (2b)$$

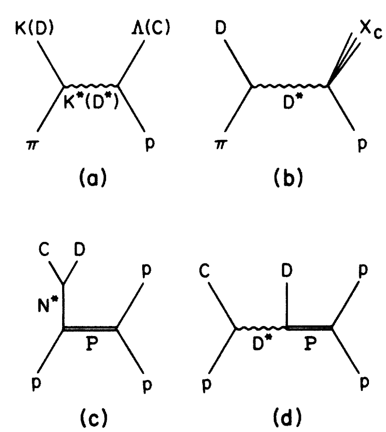

FIG. 1. Mechanisms for associated production of strangeness and charm. (a) Two-body exclusive; (b) charmed-particle inclusive; (c) charmed-particle decay of noncharmed system; (d) charm-exchange mechanism dual to (c).

For the K^* trajectory we take the usual linear form, and we likewise assume a linear D^* trajectory:

$$\alpha_{K^*}(t)=1+0.9(t-m_{K^*}^2)=0.3+0.9t\,, \qquad (3)$$

$$\alpha_{D^*}(t)=1+\alpha_{D^*}'(t-m_{D^*}^2)\,. \qquad (4)$$

From quadratic SU(4) mass formulas[3] the expected D^* mass is about 2.2 GeV; the main uncertainty in α_{D^*} is the slope. We consider the following two extreme possibilities:

(a) Universal slope: $\alpha_{D^*}'=0.9$,

$$\alpha_{D^*}(t)=-3.3+0.9t\,. \qquad (5a)$$

(b) Shallow slope $\alpha_{D^*}'=0.33$ conjectured[4] from nonparallel ρ, K^*, ϕ trajectories:

$$\alpha_{D^*}(t)=-0.60+0.33t\,. \qquad (5b)$$

One further important factor is the threshold effect, which is incorporated in the integrated cross sectión through the formula

$$\sigma=\frac{1}{k^2s}\int_{t_{\min}}^{t_{\max}}|A|^2dt\,. \qquad (6)$$

This approach adequately describes[5] $\pi^-p\to K^0\Lambda^0$ data from threshold up as shown in Fig. 2. The corresponding predictions for $\pi^-p\to D^-C_0^+$, using the same residue β, are also illustrated in Fig. 2; we consider both linear and quadratic mass formulas[3] for C_0, with the masses

$$m_D=2.2\text{ GeV}\,, \qquad (7a)$$

$$m_{C_0}=2.9\text{ GeV (quadratic)}, \qquad (7b)$$

$$m_{C_0}=4.6\text{ GeV (linear)}\,. \qquad (7c)$$

The striking features of these associated charm-production predictions are the following:

(i) strong suppression at all energies relative to strangeness production, through Eq. (2a);

(ii) substantial further suppression from the $t_{\min}$ cutoff, even far above threshold (e.g., costing a factor of about 2 in σ at $s=1000$);

(iii) for the most optimistic of our estimates, σ rises to 0.5 nb.

All other two-body charm-exchange cross sections suffer similar strong suppressions, since D^* is the leading charmed trajectory and the various SU(4) Clebsch-Gordan coefficients are of order unity. Baryon exchanges are especially unfavored. Charmed $F^\pm$ production proceeds by D^* exchange, with kaon beams. $S^{+,0}, A^{+,0}$ baryons can also be made by kaons, with charmed baryon exchange. The baryons T^0, X_u^{++}, X_d^+, and X_s^+ cannot be made with less than three particles in the final state, and also require charmed baryon exchange. (For notation see Gaillard *et al.*[3])

For comparisons using the more optimistic high-

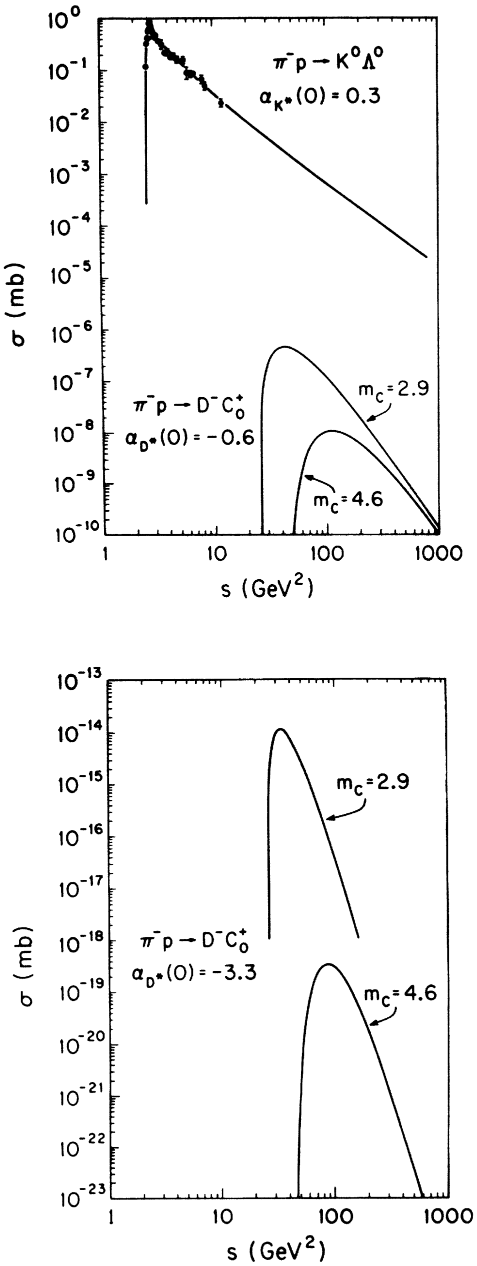

FIG. 2. Cross sections for two-body associated production of strangeness and charm. Predictions of $\sigma(\pi^- p \to D^- C_0^+)$ are shown for two choices of the D^* trajectory and for two choices of the C_0 mass. The normalization is determined by the fit to $\sigma(\pi^- p \to K^0 \Lambda)$, data points from CERN-HERA Report No. 72-1 (unpublished).

lying charmed trajectories, the Γ functions in Eqs. (1b) and (2a) make little difference and can be omitted. The integration in Eq. (6) is then trivial, and we get a simple formula for the net suppression,

$$\frac{\sigma_1(\text{charm})}{\sigma_2(\text{strangeness})} = \frac{\alpha_2'}{\alpha_1'}(0.9s)^{2\alpha_1(t^1_{\min}) - 2\alpha_2(t^2_{\min})} \ldots, \tag{8}$$

where indices 1 and 2 label the charm-exchange and strangeness-exchange cases (the terms involving $t_{\max}$ are negligible except right at threshold, and have been dropped). As further illustrations, Fig. 3 shows this suppression factor for the following pairs of channels.

(a) $\bar{p}p \to \bar{D}D, \bar{K}K$. The low $\bar{D}D$ threshold offers an enhancement, but this is offset by the need for baryon exchange with larger $\Delta\alpha$. For this illustration we take

$$\alpha_\Lambda(t) = -0.62 + 0.90t, \tag{9a}$$

$$\alpha_{C_0}(t) = -2.27 + 0.33t, \tag{9b}$$

using the quadratic mass formula for C_0 with an optimistic slope.

(b) $\bar{p}p \to \bar{C}_0 C_0, \bar{\Lambda}\Lambda$. Here we use Eqs. (3), (5b), and (7b).

III. INCLUSIVE CHARMED-PARTICLE PRODUCTION

One might hope to realize bigger cross sections in inclusive reactions such as $\pi^- p \to D^- X_c^+$, where the charmed particle is produced in association with many different recoiling systems X_c of mass M (see Fig. 1b). A specific estimate is possible in the triple-Regge region ($s \gg M^2 \gg 1$), where

$$\frac{d\sigma}{dt\,dx} = f(t)\left(\frac{s}{s_0}\frac{M_0^2}{M^2}\right)^{2\alpha(t)-1}. \tag{10}$$

Here $x \simeq 1 - M^2/s$ is the usual Feynman variable. In the usual dual models $f(t)$ is roughly constant

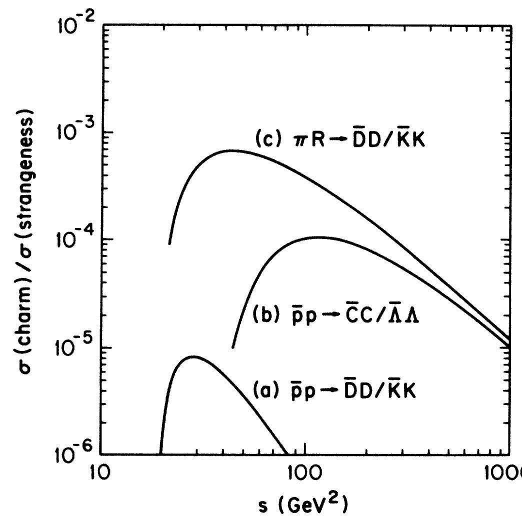

FIG. 3. Suppression factors σ(charm)/σ(strangeness) calculated from Eq. (8) for the following cases: (a) $\bar{p}p \to \bar{D}D/\bar{K}K$; (b) $\bar{p}p \to \bar{C}C/\bar{\Lambda}\Lambda$; (c) $\pi R \to \bar{D}D/\bar{K}K$ where R is a Reggeon. See text for details.

and the energy scales are set by the trajectory slopes: $s_0 = M_0^2 = \alpha_s')^{-1} = 1.1\ \mathrm{GeV}^2$. If so, s_0 and M_0^2 vanish from the expression.

We can now try the same approach as before, breaking SU(4) through the trajectories $\alpha(t)$ only, to relate charm and strangeness production. However, an inconsistency then appears; this symmetry-breaking prescription does not give equivalent results in the exclusive and inclusive formulas, if M_0^2 is taken to be universal. To see this, we extrapolate the triple-Regge formula in the usual duality spirit down to the two-particle threshold: $M \to M_{\text{th}}$ ($= m_\Lambda, m_C$ in the strangeness and charm production cases). The exclusive formula defines the t dependence and the relative charm suppression by Eqs. (1)–(2); to reproduce these results in the exclusive limit of the triple-Regge formula, we must choose

$$s_0 = 1/\alpha_s' ,$$
$$M_0 = M_{\text{th}} , \tag{11}$$
$$f(t) = f_0[\Gamma(1 - \alpha(t))]^2 ,$$

where f_0 is a constant.

We take Eqs. (10)–(11) to define our inclusive cross sections, with SU(4) symmetry breaking through $\alpha(t)$ and M_{th} only. The cross section $d\sigma/dx$ is calculated by integrating over t up to $t_{\min}$, that scales with x:

$$t_{\min} = m_\pi^2(1-x) - m_D^2(1-x)/x . \tag{12}$$

As in the exclusive case, the charm-production cross section is suppressed both by the low D^* trajectory and by the kinematic $t_{\min}$ cutoff; the relative importance of these effects depends on x. This suppression is partly offset by the fact that high-M^2 production is more favored for a low D^* trajectory. Note also the explicit dependence on M_{th}. Figure 4 shows estimates of the cross section $E^* d\sigma/dp_L^* \approx x\, d\sigma/x$ for the reaction $\pi^- p \to D^- X_c$, based on $pp \to \Lambda X$ data[6] (assuming that $\pi p \to KX$ is closely comparable). These calculations omit the Γ-function factor in Eq. (11) and use the value $f_0 = 31\ \mathrm{nb/GeV}^2$, determined by the fit to $pp \to \Lambda X$ data.

Though strictly derived for x near 1, the triple-Regge results may provide a reasonable estimate through the range $0.5 \leqslant x \leqslant 1$. Integrating over this range and using the optimistic D^* trajectory of Eq. (5b), we find cross sections of order 60 nb and 3 nb for C_0 masses of 2.9 and 4.6 GeV, respectively.

IV. CHARM PRODUCTION VIA DECAY OF NONCHARMED SYSTEM

An alternative suggested mechanism,[3] that seems at first sight to avoid the suppression from charmed

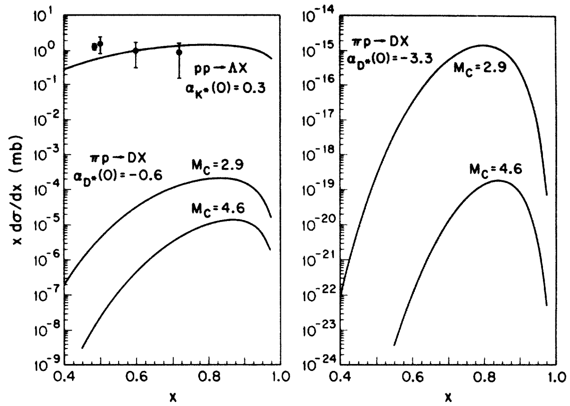

FIG. 4. Inclusive cross sections $E^* d\sigma/dp_L^* \approx x d\sigma/dx$ for the process $\pi^- p \to D^- X$, calculated in the scaling region from Eqs. (10)–(12), for two choices of the D^* trajectory and two choices of the C_0 threshold mass. The normalization is fixed by the fit to $pp \to \Lambda X$ data from Ref. 6, assumed to be closely comparable to $\pi p \to KX$.

Reggeon exchange, is the production of high-mass noncharmed systems that can subsequently decay into two charmed particles, as illustrated in Fig. 1(c) for $pp \to \bar{D}Cp$ (with a diffractive production mechanism). However, duality arguments equate this amplitude to the charm-exchange mechanism in Fig. 1(d), that contains the Regge-exchange factor $(s_{CD})^{\alpha_{D^*}}$ and hence has roughly the same suppression as two-body charm-exchange mechanisms.

To consider the above example more carefully, note that the Pomeron exchange mechanism at high energies favors small momentum transfer, so we can approximate the $Pp \to \bar{D}C$ kinematics by treating P as a zero-mass particle. Since the pion mass is also negligible, the suppression of $Pp \to \bar{D}^0 C_0^+$ versus $K^+\Lambda^0$ is just the same as the suppression of $\pi^- p \to D^- C_0^+$ versus $K^0\Lambda^0$, estimated in Sec. 2, at any common value of $s = s_{CD}$.

As another illustration, consider $\pi N \to D\bar{D}N$ where $D\bar{D}$ comes from a system formed by exchanging a Reggeon R. Here R is presumably not the Pomeron, if the Gribov-Morrison rule holds, but otherwise the general outlines of Figs. 1(c) and 1(d) still apply and D^* is still the relevant charm-exchange trajectory. Hence we can estimate the suppression of $\pi N \to D\bar{D}N$ versus $K\bar{K}N$ by applying Eq. (8) to $\pi R \to D\bar{D}, K\bar{K}$ scattering. The result is shown in Fig. 3, with the optimistic D^* trajectory of Eq. (5b): Here note that s refers to $s_{D\bar{D}}, s_{K\bar{K}}$, the squared mass of the produced system.

A similar suppression argument seems to apply to the decay of high-mass $c\bar{c}$ systems, that can be diffractively photoproduced. Two-body DD modes are dual to D^* exchange, and therefore suppressed relative to $\psi\psi$ modes that can be dual to Pomeron exchange. However, this argument cannot be used near threshold, where $D\bar{D}$ may be the only open allowed channel.

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