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Diffractive production of charm from flavor-excitation diagrams

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A perturbative quantum-chromodynamics (QCD) analysis of heavy-quark production in hadron collisions can account for the observed diffractive Λ_c^+ production. The dominant graphs are flavor excitation by gluons ($q\bar{c} \to q\bar{c}$ and $g\bar{c} \to g\bar{c}$) of charm. The essential input is a hard charm x distribution. Estimates are made for the Λ_b^0 cross section.

The order-α_s^2 diagrams for the production of charm quarks in hadron collisions are shown in Fig. 1. For annihilation diagrams where the heavy-quark pair is produced via two momentum transfers carried by light quarks [Fig. 1(a)] or by gluons [Fig. 1(b)], the longitudinal momentum x_L carried by the produced pair is small. These graphs contribute to central production (i.e., at small x_L) of charm and have been extensively studied.[1] The additional diagrams in Fig. 1(c) have been forgotten since early considerations in 1978.[2] In this paper we point out that these neglected graphs can account for diffractive production of heavy flavors, such as the production of Λ_c^+ at large x_L in pp collisions.[3] We begin with a discussion of the properties of the diffractive charm quantum-chromodynamics (QCD) graphs. Subsequently we quantify our remarks with an explicit calculation that reproduces the observed Λ_c^+ distributions and cross section.

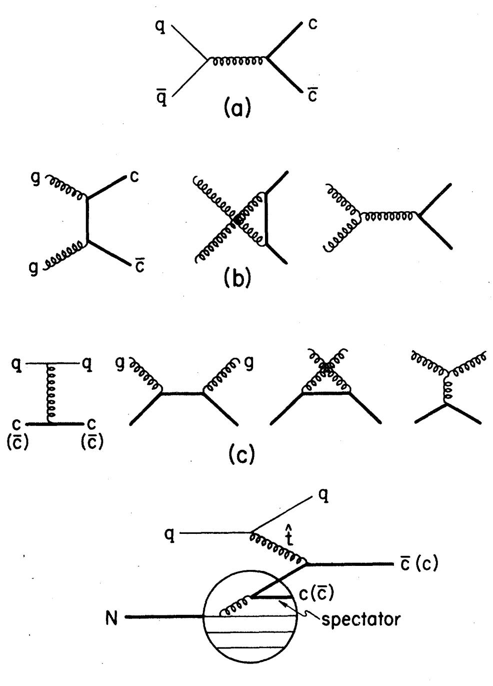

FIG. 1. Order-α_s^2 diagrams for charm production. In part (d) the circle represents a quasiperturbative QCD origin of the $c\bar{c}$ in the incident nucleon.

We hypothesize that the charm or anticharm quarks with which the gluons interact in Fig. 1(c) are not "intrinsic"[4] but are generated by QCD evolution of the structure functions, as illustrated pictorially in Fig. 1(d). That is, we suppose that at low Q^2 the charm content of the proton is virtually nil, but at Q^2 of order $4m_c^2$ one has sufficient resolution to find charm quarks deep inside the proton. This implies a physical cutoff $-\hat{t} \geq \hat{t}_c$ on the momentum transfer $\hat{t}$ of the $qc \to qc$ and $gc \to gc$ subprocesses in Fig. 1(c), whose amplitudes would otherwise be divergent at $\hat{t}=0$: The point is that for $-\hat{t} < \hat{t}_c$ the probe simply does not see any charm quarks. We expect $\hat{t}_c$ to be of order m_c^2. As in any leading-order QCD calculation, the specification of scales is uncertain by factors. For $\hat{t}_c$ in the range m_c^2 to $4m_c^2$, the predicted "diffractive" charm cross section from the flavor-excitation diagrams of Fig. 1(c) is actually larger than that from the annihilation diagrams of Figs. 1(a) and 1(b).

Following the gluon scattering process in Fig. 1(c), the charm quarks will fragment into charmed hadrons. When the $\bar{c}$ is scattered, the spectator charm quark can easily recombine with two parallel moving valence quarks of comparable velocity. It will fragment primarily into a charmed baryon resulting in Λ_c^+ production at large x_L; fusion of the fast spectator charm quark with a slow sea antiquark to form a D meson will occur infrequently. In the other cases the scattered charm quark will lead to production at relatively lower x_L of Λ_c^+ or D.

It is usually thought that a charm distribution generated by QCD evolution would be soft. We argue that this is not necessarily the case. We are talking about the evolution of the charm distribution from low Q^2 up to $Q^2 \sim 4m_c^2$. In this region the evolution will be rapid, because of the large effective coupling. For the same reason the leading-order perturbative evolution equations will not be reliable: Higher-order and higher-twist effects will be crucial in determining the charm distribution. Hence we believe it is not incompatible with the *spirit* of a "quasiperturbative" QCD evolution to suppose that the fractional-momentum distribution $xc(x,Q^2)$ of charm at $Q^2 \sim 4m_c^2$ will actually be quite hard. [Of course, at higher Q^2, after further (perturbative) evolution, $xc(x,Q^2)$ will peak towards low x, but this is not the kinematic region of interest.] If we make this assumption, we are able to expain the data on Λ_c^+ production.

We are also motivated by the following argument used in other contexts.[4,5] If a $c\bar{c}$ pair is produced and remains bound to the rest of the proton for some time, then the charm quarks must travel with roughly the same velocity as the valence quarks. In this configuration most of the momentum of the proton is carried by charm due to its large mass. Now, this argument relies on having a long time scale. However, for Q^2 *less* than $4m_c^2$, the time scales *are* relatively long, so we feel that this argument should have some validity for the early stages of the evolution of the charm distribution. Consequently, we shall assume a charm distribution resembling the broad Bjorken-x distribution of the valence quarks. The difference from the intrinsic-charm picture[4] is that the charm is not present at very low Q^2.

For an explicit evaluation of the flavor-excitation cross section, we assume a QCD-evolved charm distribution of the form

$$xc(x, \langle Q^2 \rangle) = Nx^l(1-x)^k \qquad (1)$$

at an effective value $\langle Q^2 \rangle$ for the processes. The normalization N is fixed such that

$$\int dx\, xc(x) = 0.005 \ , \qquad (2)$$

which is the level of charm found at $Q^2 \simeq 4m_c^2$ in the QCD moment analysis of Buras and Gaemers.[6] This choice for N is not crucial since the normalization of the flavor-excitation cross sections is also very dependent on the resolution cutoff $\hat{t}_c$. The parameters l,k are chosen $\geq \frac{1}{2}$ so that $xc(x)$ resembles the momentum distributions of valence quarks. Since $c(x,Q^2)$ is expected to fall at large fixed x with increasing Q^2, the stringent experimental limits on $c(x,Q^2)$ from charm-muoproduction data at high Q^2 pose no difficulty here.[7,8]

The effective Q^2 scale of the charm distribution enters through the strong coupling constant

$$\alpha_s(Q^2) = 12\pi/[(33-2f)\ln(Q^2/\Lambda^2)] \ ,$$

for which we make the typical choices $f=4$, $\Lambda=0.5$ GeV, and $Q^2=4m_c^2$, with $m_c=1.5$ GeV.

The x_L distribution of charm production in $pp \rightarrow cX$ at $\sqrt{s}=62$ GeV predicted by the diagrams of Fig. 1(c) is shown in Fig. 2, for the choice $l=k=1$ in Eq. (1). Similar results are obtained for other l,k choices that have $l \simeq k \lesssim 3$. The dashed curve is the contribution associated with a spectator c quark (the gluon interaction occurring from $\bar{c}$), which should fragment mainly to Λ_c^+. The dotted curve is the contribution from the c quark that interacts, whose fragments may be Λ_c^+ or D. The solid curve is the sum of these contributions. For a hard charm fragmentation function, as has been advocated,[5] we can directly compare these results with the diffractive Λ_c^+ data, which are plotted in Fig. 2.

The present data can be described by various choices of $l,k \geq \frac{1}{2}$. The parameter k controls how the momentum is shared between the interacting and spectator quarks in the diffractive region. The parameter l controls how much charm is deposited in the central region by the flavor-excitation diagrams. The determination of these parameters will require simultaneous consideration of diffractive and central regions, including the contributions of the flavor-creation diagrams of Fig. 1(b) to the central region.[9]

The total charm cross section from flavor-excitation diagrams is given in Fig. 3 versus the $\hat{t}$ cutoff, for the choice $l=k=1$. For $\hat{t}_c$ in the range m_c^2 to $4m_c^2$ and charm normalization determined by Eq.

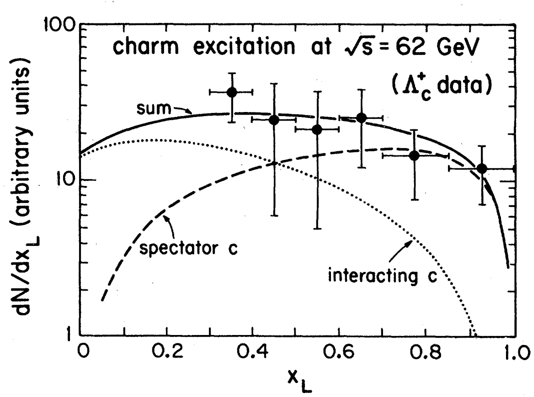

FIG. 2. Longitudinal-momentum distributions for charm excitation in $pp \rightarrow cX$ at $\sqrt{s}=62$ GeV, based on the diagrams of Fig. 1(c) and the charm momentum distribution of Eq. (1) with $l=k=1$ and $\hat{t}_c=m_c^2$. The spectator c contribution is expected to fragment predominantly to Λ_c^+, whereas the interacting c contribution can lead to either Λ_c^+ of D. The Λ_c^+ data points are from Ref. 3.

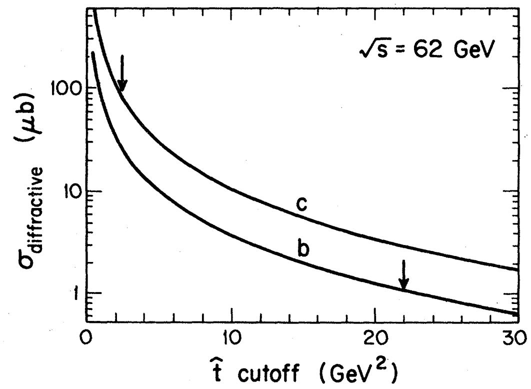

FIG. 3. Total c and b production cross sections from the flavor-excitation diagrams of Fig. 1(c) vs the resolution cutoff on the subprocess momentum transfer $\hat{t}$. The cutoff values $\hat{t}_c = m_c^2$ and $\hat{t}_b = m_b^2$ are denoted by arrows.

(2), the cross section varies from 100 to 10 μb, in agreement with current experimental indications.[10]

The transverse-momentum distribution of the spectator fragments is expected to be comparable to that of light-quark fragments, $\langle p_T \rangle \simeq 0.3$ GeV, though it may be somewhat larger due to the increased mass. The interacting charm quark is produced with $p_T^2 \gtrsim Q^2$, which results in a broadening of the p_T distribution, in qualitative accord with observations.[3]

To predict diffractive b-quark production, we change the heavy-quark mass to $m_b = 4.7$ GeV and change the physical cutoff to

$$\hat{t}_b = \frac{m_b^2}{m_c^2} \hat{t}_c \ , \qquad (3)$$

which reflects the excitation needed to produce a $b\bar{b}$ pair in the company of the usual constituents of the proton. We further assume that the evolved $xb(x, \langle Q^2 \rangle)$ distribution at the appropriate $\langle Q^2 \rangle$ for b production is similar to that used in the charm analysis. The b-production cross section is also shown in Fig. 3 versus the $\hat{t}$ cutoff. We estimate that the Λ_b^0 cross section is at the few-percent level of Λ_c^+ for $\hat{t}_b$ given by Eq. (3).

Although at present our estimates contain quantitative uncertainties, we find that the diffractive production of charm is understandable within the context of perturbative QCD. This explanation requires a hard charm distribution in x at $Q^2 \simeq 4m_c^2$ which cannot be deduced from first principles until the behavior of QCD evolutions at low Q^2 is better understood. Nevertheless, there are testable consequences of this hypothesis of which diffractive charm production is an important example. A detailed description of the calculations and a more complete analysis will be contained in a forthcoming paper.[9]

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