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Brief Reports

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Production of heavy quarks: A nonperturbative approach

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We identify a way of producing heavy quarks overlooked by perturbative QCD. It successfully accommodates the data on photoproduction and hadroproduction of heavy quarks. Rates at higher energies are expected to be significantly in excess of those predicted by perturbative QCD.

Perturbative quantum chromodynamics (QCD) has been used with mixed degrees of success to calculate the production of final states containing heavy quarks in photon, lepton, and hadron collisions.[1] The main challenge that perturbative QCD has been unable to meet concerns the copious inelastic production of charmed particles or ψ's by photons and leptons. The elastic production, where the $c\bar{c}$ pair materializes as a ψ or $D\bar{D}$ carrying the photon energy, is well understood in terms of the leading gluon-fusion process $\gamma g \rightarrow c\bar{c}$. It is the Bethe-Heitler process of QCD. Inelastically produced charm quarks, on the other hand, share the photon energy with a gluon, e.g., $\gamma g \rightarrow (c\bar{c})g$. Inelastic production is therefore a higher-order process in α_s, implying a reduced cross section (about 20% of the elastic) and a broadened transverse-momentum distribution due to the $(c\bar{c})$ recoil against the gluon. Both these predictions are at variance with experiment. Already for photon energies of order 50 GeV the inelastic production is equal to (for ψ's) or in excess of (for charmed-particle pairs) the elastic.[2] We reopen here the question of whether a nonperturbative production mechanism could be a source of charmed particles. We identify such a mechanism and show it accommodates the photoproduction cross section for charmed, and strange, as well as nonstrange, quarks. Photoproduction is then converted into hadroproduction by photon-gluon substitution. We thus successfully obtain the rate and threshold dependence of charm production by hadrons. If correct, this description of heavy-quark production has the very important prediction that rates for high-energy photoproduction or leptoproduction of heavy quarks significantly exceed those predicted by perturbative QCD.

We firstly wish to draw attention to a very simple way to calculate charm photoproduction and hadroproduction cross sections. We will basically extend the additive quark model to include photons and gluons. In photoproduction, we consider the initial photon fragmenting into a quark and antiquark. One of these fragments then scatters from the target (Fig. 1). In hadroproduction, one hadron emits a gluon, which fragments into a quark and antiquark. Thus charm photoproduction and hadroproduction are related by straightforward photon-gluon substitution. We note that parts of this picture have been used before.[3,4]

Our intentions are modest. We do not set out to calculate details of final states, or give a complete model. We are attempting to give a consistent overall picture of heavy-quark cross sections, and from our results we infer that the dominant production mechanisms may indeed be soft, nonperturbative processes, and not low-order perturbation theory.

The diagram for photoproduction is shown in Fig. 1.

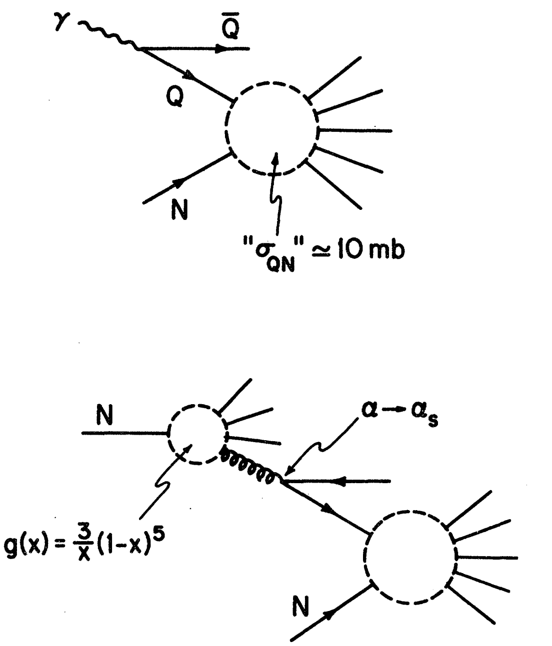

FIG. 1. Schematic representation of our proposal for calculating heavy-quark production by photon and hadron beams.

The fractional momentum distribution of a quark in a photon is obtained from QED:

$$q_\gamma(x) = 3e_q^2 \frac{\alpha}{2\pi} \ln\frac{s}{s_0}[x^2+(1-x)^2] \ , \qquad (1)$$

where e_q is the quark charge, s is the center-of-mass energy squared, and s_0 sets the scale. We choose $s_0 = 1$ GeV^2; it could of course depend on flavor. We choose $\sigma_{qN} = 7$ mb for $q = u,d$, and for heavier quarks $q = s,c$ we take

$$\sigma_{qN} = (m_u/m_q)^2 \sigma_{uN} \ , \qquad (2)$$

with $m_{u,d} = 0.25$ GeV, $m_s = 0.5$ GeV, and $m_c = 1.5$ GeV so that $\sigma_{sN} = 2$ mb and $\sigma_{cN} = 0.2$ mb. Obviously, these numbers can be juggled. For light quarks, Eq. (1) just represents the equivalent-photon (or better, equivalent-electron) result for $\gamma N \to qX$ scattering. The argument of the logarithm is a transverse-momentum cutoff and this leads to a logarithmic dependence of the cross section.[3] For heavy quarks, the photon's heavy-quark content depends on the Q^2 with which it is probed. Therefore, the argument of the logarithm is now $Q^2 \simeq 4m_c^2$. However, in the kinematic range we consider, replacing Q^2 by s leads, within the precision expected from our estimates, to the same results for the magnitude as well as the energy dependence of the cross section.[3] Equation (1), therefore, represents an analytic interpolation able to handle light and heavy quarks and interpolates between the two limits. The photoproduction cross section for a particular flavor is then given by

$$\sigma_{\gamma N} = e_q^2 \frac{3\alpha}{\pi} \ln\frac{s}{s_0} \int_\tau^1 [x^2+(1-x)^2 dx\, \sigma_{qN}$$

$$= e_q^2 \frac{\alpha}{\pi}(1-\tau)(2-\tau+2\tau^2) \ln\frac{s}{s_0} \sigma_{qN} \ . \qquad (3)$$

We choose $\tau = (m_N + 2m_q)^2/s$ in order to incorporate the correct threshold behavior; at high energies the exact definition is unimportant as $\tau \to 0$. At $E_\gamma = 170$ GeV, for example, we find

$$\sigma(\gamma N \to u,d) = 104 \ \mu\text{b} \ ,$$
$$\sigma(\gamma N \to s) = 5 \ \mu\text{b} \ ,$$
$$\sigma(\gamma N \to c) = 2 \ \mu\text{b} \ , \qquad (4)$$
$$\sigma(\gamma N \to \text{all}) = 111 \ \mu\text{b} \ ,$$

which is certainly reasonable. In Fig. 2 we show the energy dependence of the charm-production cross section.

It is important to point out that σ_{qN} represents the cross section for the scattering of an off-mass-shell quark from the nucleon. Therefore, the smaller value compared to the standard 10-mb value of the additive quark model is not surprising. Heavier quarks are more off-shell, i.e., shorter-lived fluctuations, motivating the $1/m_q^2$ suppression of the interaction cross section typical of a fermion propagator in Eq. (2).

It is clear that precise evaluation of the cross sec-

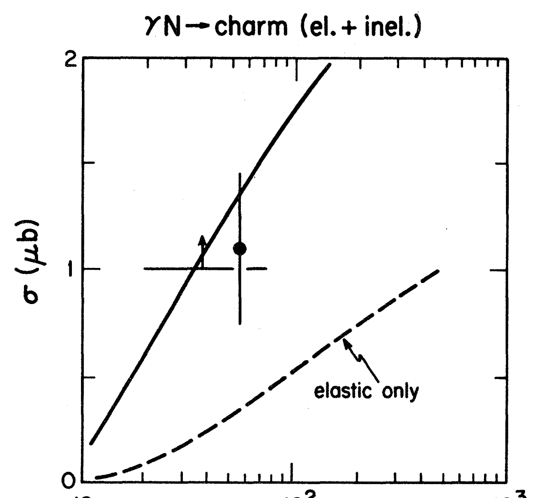

FIG. 2. Our calculation for the total (elastic + inelastic) charm-photoproduction cross section is compared to data and to a perturbative QCD calculation interpolating the elastic photoproduction data (see Ref. 2 for details).

tion implied by this new mechanism is impossible. Ambiguities result for (i) the argument and the scale of the logarithm in Eq. (1), (ii) the off-shell and threshold behaviors of the quark-nucleon cross section, and (iii) the quark mass; e.g., a change in the argument from $\ln(s/s_0)$ to $\ln(4m_c^2/s_0)$ leads to a change by a factor 2 (this change still leaves a substantial cross section, and can be compensated for by a change of s_0).

However, we have not set out to compute the quark cross section, but rather to demonstrate that soft production mechanisms are capable of accounting for the difference between the data and the standard perturbative calculation on charm photoproduction. At this point it is important to note that the evidence[2] that the latter cannot account for the data goes beyond the evidence presented in Fig. 2.

For charm hadroproduction we use photon-gluon substitution, following an idea of Fritzsch and Streng,[4] though we count colors differently. The diagram is shown in Fig. 1. The fractional momentum distribution of a quark in a gluon is

$$q_q(x) = \frac{1}{2}\frac{\alpha_s}{2\pi}\ln\frac{s}{s_0}[x^2+(1-x)^2] \ . \tag{5}$$

The gluon-nucleon cross section is then related to the photon-nucleon cross section by

$$\sigma_{gN} = \left[\frac{1}{6e_q^2}\right]\frac{\alpha_s}{\alpha}\sigma_{\gamma N} \ , \tag{6}$$

and then the nucleon-nucleon cross section is

$$\sigma_{NN} = \frac{\alpha_s}{3\alpha e_q^2}\int_\tau^1 dx\, G(x)\sigma_{\gamma N} \ , \tag{7}$$

where we choose $xG(x)=3(1-x)^5$ for the gluon density and again $\tau=(m_N+2m_q)^2/s$. We use

$$\alpha_s = 12\pi/25\ln(m_q^2/\Lambda^2)$$

with $\Lambda=0.1$ GeV. The resulting charm cross section is shown in Fig. 3.

Although these simple ideas are successful, they are clearly incomplete. The structure of the final state cannot be calculated in detail. If correct, however, they predict rates for photoproduction, leptoproduction (the virtual photon can be treated in the same way), and hadroproduction in excess of those predicted by perturbative QCD calculations, which are not valid in the high-energy regime anyway.[2,5]

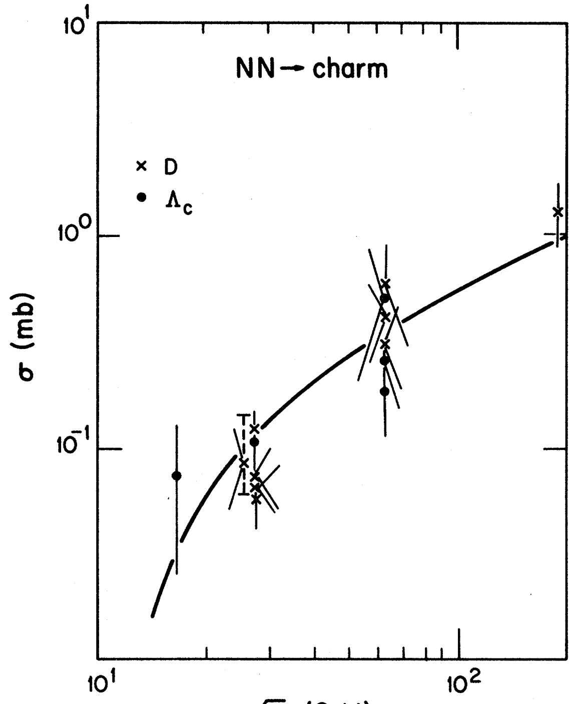

FIG. 3. Photon-gluon substitution turns the photoproduction calculation of Fig. 2 into a prediction for hadroproduction of charm (for detailed references to the data, see Ref. 2).

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[1]R. J. N. Phillips, in *High Energy Physics—1980,* Proceedings of the XXth International Conference, Madison, Wisconsin, edited by L. Durand and L. G. Pondrom (AIP, New York, 1981), p. 1470.

[2]For a detailed discussion, see F. Halzen, rapporteur's talk at the XXIst International Conference on High Energy Physics, Paris, 1982 (unpublished).

[3]F. Halzen and D. M. Scott, Phys. Lett. 72B, 404 (1978). The kinematics and related ambiguities of Eq. (1) applied to heavy quarks are discussed in this reference. For a detailed discussion of how Eq. (1) applies to light quarks, see, e.g., M. S. Chen and P. Zerwas, Phys. Rev. D 12, 187 (1975).

[4]H. Fritzsch and K. H. Streng, Phys. Lett. 78B, 447 (1978).

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