Photon-Gluon-Fusion Analysis of Charm Photoproduction

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(Received 21 June 1990)

Results on the photoproduction of 10000 fully reconstructed charmed particles from the 10^8 recorded triggers of Fermilab experiment E691 have been analyzed in the photon-gluon-fusion model. We find that the total cross section, its rise with energy, and the p_T^2 and x_F distributions can be explained by a high mass for the charm quark ($m_c = 1.74^{+0.13}_{-0.18}$ GeV/c^2) and a soft gluon distribution [$G(x) \sim (1-x)^{n_g}$, where $n_g = 7.1 \pm 2.2$].

PACS numbers: 13.60.Le, 12.38.Qk, 13.60.Rj

Predictions of perturbative QCD at fixed-target energies can be used to extract information on the structure of hadrons. In particular, the quark structure functions have been measured in deep-inelastic scattering experiments with lepton probes. These experiments are not directly sensitive to the gluon structure function $G(x)$, which enters only as a correction in deep-inelastic lepton scattering. However, other processes such as hadroproduction and photoproduction of heavy quarks and prompt-photon production are directly sensitive to $G(x)$. In an earlier paper we described the measurement of the total photoproduced charm cross section, its dependence on energy, and the p_T^2 and x_F distributions of charmed mesons.[1] In this paper we describe the extraction of the gluon structure function per nucleon in beryllium and the charm-quark mass from these measurements, using the photon-gluon-fusion (PGF) model.[2]

Photoproduction of heavy quarks as described by PGF (see Fig. 1) is uniquely suited for the measurement because only one structure function, $G(x)$, is involved. Furthermore, in leading order α_s and $G(x)$ enter linearly in the differential cross section. However, the appropriateness of this process is mainly because measurement of a *single* outgoing parton is sufficient to determine the entire kinematics. The uncertainties that remain include the intrinsic k_T^2 of the initial-state partons and the fragmentation of the outgoing heavy quark. The uncertainty in intrinsic k_T^2 is minimal because only one initial-state particle has this k_T^2, which in turn is shared by the two outgoing heavy quarks (reducing the effect on each). The uncertainty due to k_T^2 can be further minimized by restricting analysis to the region of high p_T^2 where perturbative QCD predictions are, in any case, on firmer ground. Thus the only remaining uncertainty is the heavy-quark fragmentation, which is reasonably well understood from e^+e^- production. In a recent publication[3] it was shown that the next-to-leading-order correc-

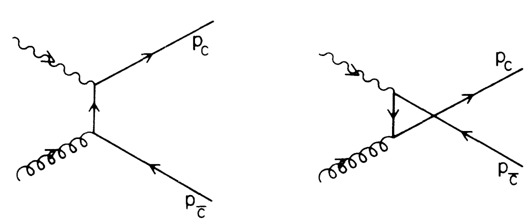

FIG. 1. The Feynman diagrams that contribute to photon-gluon-fusion production of charm at the tree level.

tions for heavy-quark photoproduction are indeed small as compared to those in heavy-quark hadroproduction, Drell-Yan, and prompt-photon production. Specifically, the total cross-section estimate is increased by only 32% relative to the leading-order calculation and the shape of the differential distributions are essentially unaffected.

Our charm-production experiment E691 collected data using the tagged-photon spectrometer at Fermilab and has already been described elsewhere.[4] In summary, the photons ranged in energy from 80 to 230 GeV ($\langle E_\gamma \rangle = 145$ GeV), and were incident on a beryllium target followed by a high-resolution silicon-microstrip vertex detector and a spectrometer.[4] This analysis is of the total cross section and differential distributions in p_T^2 and x_F, described in a previous publication,[1] for the high-statistics modes $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, and $D^+ \to K^-\pi^+\pi^+$. (Charge-conjugate states are included implicitly throughout this paper.)

As can be seen from Fig. 1, the kinematics in the parton frame is given entirely by the photon energy E_γ and by the fraction x of the nucleon's momentum that is carried by the gluon. The parton-level cross section $\hat{\sigma}(\hat{s})$ rises roughly logarithmically with the square of the energy in the photon-gluon collision, $\hat{s}$. The total cross section is given by

$$\sigma_{c\bar{c}}(E_\gamma) = \int_{x_{\min}}^{1} dx\, \hat{\sigma}_{c\bar{c}}(xs) \frac{G(x)}{x}, \qquad (1)$$

where s is the square of the center-of-mass energy in the photon-nucleon collision. The total cross section $\sigma_{c\bar{c}}$ is most sensitive to m_c, the charm-quark mass. The minimum x that is probed by a given photon energy is given by

$$x_{\min} \approx m_{\text{thresh}}^2 / 2 m_N E_\gamma, \qquad (2)$$

where m_N is the nucleon mass. As the photon energy is increased, more and more of the gluon distribution is probed by going to lower x. Thus, the rise in cross section is a measure of the shape of the gluon structure function and is sensitive to the power n_g in the assumed shape:

$$G(x) = (1-x)^{n_g}, \qquad (3)$$

where $G(x)$ is the momentum density of gluons in a nucleon. Although this shape (motivated by counting rules) is expected to be valid only at large x, we simply follow the convention of using this form for all x. In fact, what our data are most sensitive to is the slope of $G(x)$ in the range $x = 0.04$–0.08. A scaling distribution is assumed at least in part because the available range of Q^2, the argument of α_s, is narrow (≈ 16–25 GeV^2) since the mass of the produced $c\bar{c}$ pair peaks sharply near threshold.

The parton-level differential cross section can be written as

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi e_q^2}{\hat{s}^2} \alpha \alpha_s \left(-2 + \frac{(\rho+1)}{t_1 t_2} - \frac{\rho^2/4}{t_1^2 t_2^2} \right), \qquad (4)$$

where e_q is the charge of the charm quark and ρ, t_1, and t_2 are defined by

$$\rho = 4 m_c^2 / \hat{s}, \qquad (5)$$

$$t_1 = (m_c^2 - \hat{t})/\hat{s} = (1 - \hat{\beta}_c \cos\hat{\theta})/2, \qquad (6)$$

$$t_1 + t_2 = 1, \qquad (7)$$

where $\hat{\beta}_c$ is the speed of the charmed quark in the partonic center-of-mass frame, and $\hat{s}$ and $\hat{t}$ are the familiar Mandelstam variables in the partonic center-of-mass frame. It is clear from Eq. (4) that the cross section peaks as $t_1 \to 0$ and $t_1 \to 1$. The range of t_1 is limited to

$$(1-\beta_c)/2 < t_1 < (1+\beta_c)/2, \qquad (8)$$

where the limits correspond to $\cos\hat{\theta} = \pm 1$. A lighter charm quark allows t_1 to approach its limits of ± 1 which leads to more forward-backward peaking of the quarks and hence a softer p_T^2 distribution. The x_F distribution in the range measured is not very sensitive to either m_c or n_g, but is sensitive to the fragmentation scheme used. Because of the limited range of Q^2, α_s is effectively a constant. Thus the cross section is insensitive to a choice of the argument of α_s which we assume to be $\hat{s}$ (the only scale in the process).

Recently, Ellis and Nason[3] calculated the next-to-leading-order (NLO) corrections to the total and differential cross sections. It is clear from that work that the differential cross sections are virtually unchanged in shape from the leading-order (LO) case, so we use the simpler leading-order results to fit our differential cross sections. The NLO total cross section, however, is 32% larger than the LO result at our energies and hence we use the NLO result to fit our total cross section. Our $\sigma_{c\bar{c}} = 0.58 \pm 0.01 \pm 0.06$ μb, at a mean photon energy of 145 GeV, when fitted by the NLO results yields a charm-quark mass of $1.6^{+0.3}_{-0.1}$ GeV/c^2. The errors include the theoretical errors due to the renormalization scale and the gluon distribution as mentioned in Ref. 2. The gluon distribution used in Ref. 2 is not strictly a scaling distribution of the form (3), but is well approximated by that form with $n_g = 7.4$. As described earlier[1] the total cross section is derived assuming an A dependence of the form $A^{0.93}$, but is consistent with A^1 within systematic errors.

Fixing m_c to 1.74 GeV/c^2 (our final combined fit value below), we next fitted the slope of the cross section versus energy to find n_g and obtain $n_g = 8.8^{+2.3}_{-2.3}$. A nice feature of this result is that it arises from the slope of the *total* cross section and hence is independent of uncertainties arising from fragmentation and the intrinsic k_T^2 of partons. As the PGF-model prediction does not have an appreciable curvature in the region studied, there is no further information contained in higher-order moments.

We view fragmentation as having three kinds of uncertainties:

(1) The fragmentation scheme could have the c and $\bar{c}$

quarks fragmenting independently of each other.

(2) Even in the case of string fragmentation, the $c\bar{c}$ pair can hadronize independent of the target or with one string between the charm quark and the target diquark and another between the anticharm quark and the target quark.

(3) There are errors on the parameters of the charm fragmentation function as measured by e^+e^- experiments.

The first two of these can be viewed as uncertainties in the dressing of the charm quark.

The errors in the fragmentation-function parameters[5] are propagated through our analysis and do not contribute significantly to any of the errors on our measurements. In our Monte Carlo simulation (which used the Lund Monte Carlo program[6] for fragmentation) we varied the fraction of remnant nucleon momentum in the diquark and found almost no effect on our final results and consequently this error is ignored. Allowing the $c\bar{c}$ pair to hadronize independently results in a charged-particle and baryon multiplicity in the forward acceptance of our detector which is less than $\frac{1}{2}$ of that observed and hence we disallow this possibility. Finally, since there is evidence that string fragmentation describes data better than independent fragmentation[7] (in our case $\chi^2_{\text{string}}=3.9$ vs $\chi^2_{\text{ind}}=4.8$) we have chosen string fragmentation in this analysis (see Fig. 2). As is to be expected from the above discussion, the x_F distribution shape is relatively insensitive to the PGF-model parameters, for which it yields $m_c=1.8^{+0.2}_{-0.6}$ GeV/c^2 and $n_g=5^{+2}_{-5}$.

Fortunately, in this process there is only one parton in the initial state and hence the intrinsic k_T^2 (of the gluons) is only half as important as in most other processes.

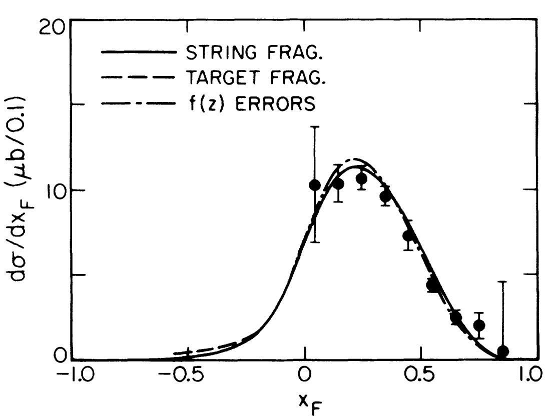

FIG. 2. The x_F dependence of the cross section on Be for production of charm events ($d\sigma_{c\bar{c}}/dx_F$). The curves are for string fragmentation (solid), for the case where the diquark carries a fixed fraction of the remnant nucleon momentum (dashed), and for the fragmentation-function parameters changed by 1 standard deviation (dot-dashed). The string fragmentation scheme is used as the "central value," with the other schemes providing measures of systematic errors.

Also, this k_T^2 is then shared by the two heavy quarks, further reducing the effect on the p_T^2 distribution of a single charmed particle. Results from measurements of the Drell-Yan process[8] are inconclusive about the magnitude of the *intrinsic* k_T^2 because of higher-order contributions. However, a fairly conservative conclusion would be that the intrinsic p_T^2 of the lepton pair is in the range 0.4–0.8 GeV$^2/c^2$. Depending on the degree of kinematic correlation in the charm-quark pair, this amounts to a p_T^2 of 0.05–0.2 GeV$^2/c^2$ for the single charm quark. We make the overly conservative assumption that the extra p_T^2 to be added to charmed mesons due to this effect is 0.15 ± 0.15 GeV$^2/c^2$, i.e., it can be as large as 0.30 GeV$^2/c^2$. Since this smearing affects mainly the low-p_T^2 region and since perturbative QCD is considered more reliable at higher p_T^2, we have analyzed the p_T^2 distribution of charm mesons with a cut at $p_T^2=2$ GeV$^2/c^2$. A fit yields $m_c=1.8^{+0.2}_{-0.4}$ GeV/c^2 and $n_g=5^{+5}_{-1}$ (see Fig. 3). The asymmetric errors are explained by the nonlinear dependence of the p_T^2 distribution on m_c and n_g.

We have also explored the effect of a spin-0 gluon on the differential cross section. The shape is not very sen-

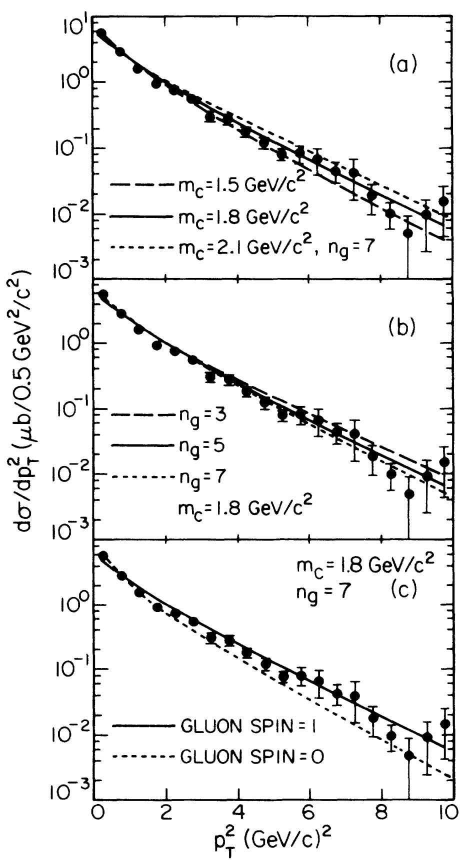

FIG. 3. The p_T^2 dependence of the cross section on Be for production of charm events ($d\sigma_{c\bar{c}}/dp_T^2$). The curves are for different values of m_c, the charm-quark mass, and of n_g, the power of $1-x$ in the gluon structure function. Also shown is the prediction for a spin-0 gluon.

sitive to the spin because Eq. (4) changes to

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi e_q^2}{\hat{s}^2}\alpha\alpha_s\left[\frac{\rho^2/4}{t_1^2 t_2^2} - \frac{\rho - \frac{1}{2}}{t_1 t_2}\right]. \tag{9}$$

Fitting the p_T^2 distribution indicates a weak preference for a spin-1 gluon.

Finally, the four fits mentioned above and listed in Table I are combined in a single fit which minimizes the sum of the individual χ^2. Figure 4 illustrates the 1σ allowed ranges of the parameters from the four separate fits. The combined fit yields $m_c = 1.74^{+0.13}_{-0.18}$ GeV/c^2 and $n_g = 7.1 \pm 2.2$. It is clear from Fig. 4 that these final values are within the 1σ ranges of the four individual fits. The errors are mainly systematic, with the intrinsic k_T^2 of the gluons being the dominant effect. The systematic error includes the change in the parameters when the entire p_T^2 distribution is included in the fit.

In conclusion, the results of fits to $\sigma_{c\bar{c}}$, its rise with energy, the x_F distribution, and the p_T^2 distribution are tabulated in Table I. Also listed are the results of a combined fit. The most reliable result is the combined fit including data only for the region $p_T^2 > 2$ GeV^2/c^2 which yields $m_c = 1.74^{+0.13}_{-0.18}$ GeV/c^2 and $n_g = 7.1 \pm 2.2$ at $Q^2 = 20$ GeV^2. As mentioned earlier, it would be more accurate to say that we have measured the ratio $[dG(x)/dx]/G(x)$ for gluons in beryllium at $x = 0.06$ to be -7.6 ± 2.3; we quote the result for n_g because it is conventional to do so. Thus we have determined the mass of the charm quark and contributed additional information on the shape of the gluon distribution.[9] The value of m_c should be useful in describing other processes involving similar perturbative QCD calculations, e.g., in neutrino- and hadro-induced charm production provided next-to-leading-order calculations are used.

We would like to acknowledge useful discussions with E. L. Berger and R. K. Ellis. We gratefully acknowledge the assistance of the staff of Fermilab and of all the participating institutions. This research was supported by the U.S. Department of Energy, by the Natural Sciences and Engineering Research Council of Canada through the Institute of Particle Physics, by the National Research Council of Canada, and by the Brazilian Conselho Nacional de Desenvolvimento Científico e Technológico. Fermi National Accelerator Laboratory is operated by the Universities Research Association, Inc. under contract with the U.S. Department of Energy.

TABLE I. Results of fits with the photon-gluon-fusion model of charm production. The result of a fit with a $p_T^2 > 2$ GeV^2/c^2 cut is considered the most reliable in perturbative QCD and also has smaller uncertainties due to the intrinsic k_T^2 of gluons.

Fit quantity	m_c (GeV/c^2)	n_g
$d\sigma/dp_T^2$,		
$2 < p_T^2 < 10$ GeV^2/c^2	$1.8^{+0.2}_{-0.4}$	5^{+5}_{-1}
$d\sigma/dx_F$	$1.8^{+0.2}_{-0.6}$	5^{+2}_{-5}
$\sigma_{c\bar{c}}$ vs E_γ	1.74 (fixed)	8.8 ± 2.3
$\sigma_{c\bar{c}}$	$1.6^{+0.3}_{-0.1}$	~7 (see Ref. 2)
Combined fit,		
$2 < p_T^2 < 10$ GeV^2/c^2	$1.74^{+0.13}_{-0.18}$	7.1 ± 2.2

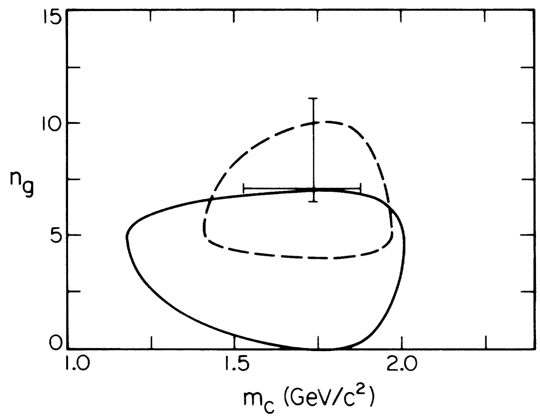

FIG. 4. The 1σ limits for m_c and n_g from the four fits described in the text. The horizontal line is for the total-cross-section measurement (n_g fixed at its combined-fit value of 7.1 ± 2.2) and the vertical line is for the rise of the total cross section with energy (m_c fixed at its combined-fit value of $1.74^{+0.13}_{-0.18}$ GeV/c^2). The dashed curve is for the p_T^2 fit and the solid curve is for the x_F fit. The combined-fit result is at the intersection of the two lines.

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