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HEAVY QUARK PRODUCTION PROCESSES IN QCD*

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ABSTRACT

We discuss two novel QCD effects which enhance the production of heavy quarks and supersymmetric hadrons beyond that conventionally expected from gluon fusion.

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1. Introduction

One of the few anomalies in the generally successful comparison of quantum chromodynamic predictions with experiment is charm hadroproduction. None of the main features observed for charm production—the magnitude of the cross section, its energy or x_L dependence, its diffractive nature or dependence on nuclear target number—appear to conform to the properties expected[1] from the basic QCD fusion subprocesses $gg \to c\bar{c}$ and $q\bar{q} \to c\bar{c}$.

The understanding of the correct mechanisms for charm production is important not only for testing QCD, but also for providing a reliable extrapolation to the production of heavier quark states, supersymmetric hadrons, and other states containing heavy $SU(3)$-colored constituents. Reliable estimates of the heavy quark background to new rare processes, the background to Drell-Yan processes, possibilities for secondary beams of c, b, and t quark hadrons, and radiation shielding considerations for new high energy, high luminosity accelerators such as the SSC depend on a clear understanding of heavy quark production processes at high energies and large x_L. The possibility of using kaon or hyperon beams to enhance heavy quark production also needs to be explored. From the theoretical point of view, a basic understanding of charm production in QCD should lead to new insights into mechanisms for quark and gluon jet hadronization, the interaction of quarks in nuclear matter, and features of hadron wavefunctions involving heavy quark constituents.

An extensive review of the measurements of charm production in hadron collisions has now been published so the discussion here will be relatively brief.[2,3] The first experiments at the ISR indicated that the total charm production cross section is of the order of 1 mb at $\sqrt{s} = 53$ to 63 GeV. Compatibility with the latest D branching ratios and the measured e/π ratio (extrapolated from data in the central rapidity region) implies[2] a somewhat smaller cross section: $\sigma(D\bar{D}+X) \leq 500\mu b$ and $\sigma(\Lambda_c\bar{D}+X) \leq 100\ \mu b$ at $\sqrt{s} = 62$ GeV, rates considerably larger than that expected from the fusion mechanism. A recent analysis[4] of so-called "long-flying" cascades in cosmic ray data at lab energies above 40 TeV ($\sqrt{s} \gtrsim 300$ GeV) suggests heavy quark production cross sections of order 4 ± 1 mb/nucleon.

The ISR data implies nearly flat production of charm hadrons at large x_L, particularly Λ_c production[5] : $d\sigma/dx_L\ (pp \to \Lambda_c X) \sim (1-x_L)^{0.40\pm0.25}$, including sizeable contributions from the diffractive process $pp \to p\Lambda_c X$. At SPS-FNAL energies ($19 < \sqrt{s} < 26\ GeV$) charm production cross sections are apparently an order of magnitude smaller, but still indicate relatively fast forward charm hadron production; the LEBC-EHS hydrogen bubble chamber experiment[6] (pp collisions at $E_{\rm lab} = 360$ GeV), which has relatively flat acceptance in x_L finds $dN/dx_L \sim (1-x_L)^{1.8\pm0.8}$ for the production of $D^+(c\bar{d})$, $D^-(\bar{c}d)$, $D^0(c\bar{u})$, and $\overline{D}^0(\bar{c}u)$ independent of whether the D or $\overline{D}$ carries a valence quark of the proton or not. The corresponding strange-particle production cross section is much steeper (see Fig. 1). Although statistically weak, the LEBC results suggest strongly that the charm quark momentum distributions probed in proton collisions are much harder than those for strange quarks. This disparity is clearly difficult to explain in terms of the $gg \to c\bar{c}$ fusion mechanism. The E613[7] and E595[8] Beam Dump experiments at FNAL report a steeper distribution $(1-x)^{5\pm1}$ for D's produced in tungsten and iron targets, but this result could be compatible with the LEBC experiment if the nuclear target dependence is strongly dependent on x_L, which is generally the case for soft hadron production.[9] The only explicit A-dependent measurement, the Michigan Beam Dump experiment[10] (400 GeV $p\ Be$, pW collisions), indeed indicates an average $\sim A^{.72}$ dependence, averaged over its acceptance, compared to A^1 expected for the perturbative fusion process.

Another intriguing anomaly in charm hadroproduction is seen in the WA-42 experiment[11] at the SPS, which reports copious production of the $A^+(csu)$ charmed strange baryon in 135 GeV Σ^- collisions on a beryllium target. The A^+ is observed in the $\Lambda K^-\pi^+\pi^+$ channel with a hard distribution $(1-x_L)^{1.7\pm0.7}$ for $x_L > 0.6$. The corresponding cross section times branching ratio (taking the above form for all x_L), for forward x_L is 4.7 μb/nucleon assuming A^1 dependence. If the branching ratio for the measured channel is 3% to 5% this implies

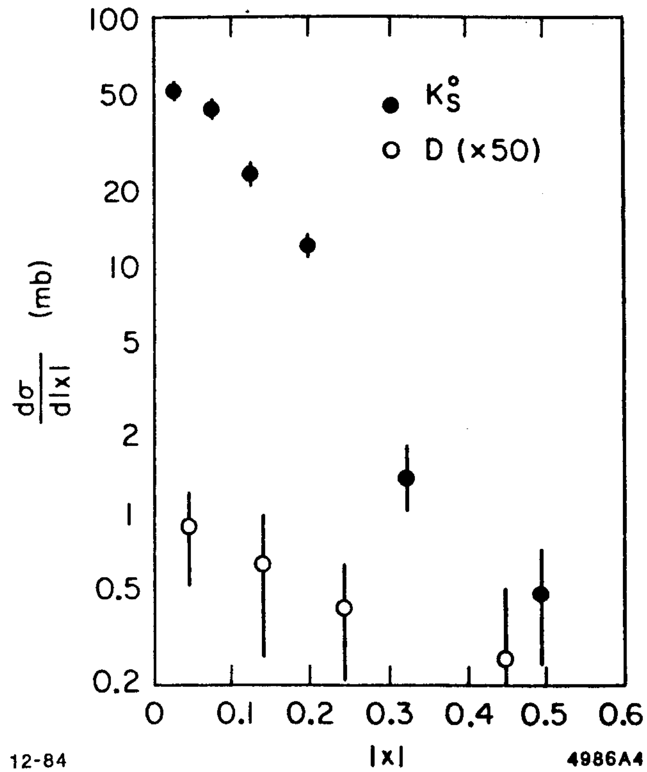

Fig. 1. Comparison of kaon and D meson production in pp collisions. From S. Reucroft, Ref. 5.

a total cross section in the 100 to 150 μb range, compared to cross sections of order 30 μb for $pp \to \Lambda_c X$ measured at higher energies in the LEBC experiment. Even larger cross section would be expected for charmed-strange (csd) baryons which carry two valence quarks of the $\Sigma^-(sdd)$. The experimental results suggest the possibility of systematically enhanced production of heavy quark states by hyperon and strange particle beams.

Since the momentum of a charmed hadron tends to follow the momentum of the produced charmed quark (the Bjorken-Suzuki effect), the hadroproduction data indicates that charm quarks have large momentum fraction in the nucleon more characteristic of a valence quark than a sea quark distribution. This question can be settled directly by measurements of deep inelastic scattering of leptons on the charm constituents of the nucleon at $Q^2 \gg 4m_c^2$. The available high Q^2 data from the EMC collaboration[12] (see Fig. 2), as extracted from $\mu N \to \mu\mu X$ data, indeed does seem to indicate an anomalously large $c(x, Q^2)$ distribution at large Q^2 and $x_{Bj} \sim 0.4$ compared to that expected for the photon-gluon fusion diagrams or equivalently, from QCD evolution. Although the data has low statistics and thus could be misleading, it clearly suggests the existence of mechanisms for charm production other than the standard photon-gluon fusion subprocess. In this talk we will discuss two interrelated effects which are in the direction to enhance charm production at large x_L and are surely present in QCD at some level. Much more theoretical and experimental work will be required to verify whether these effects can account for the observed features of heavy quark hadroproduction.

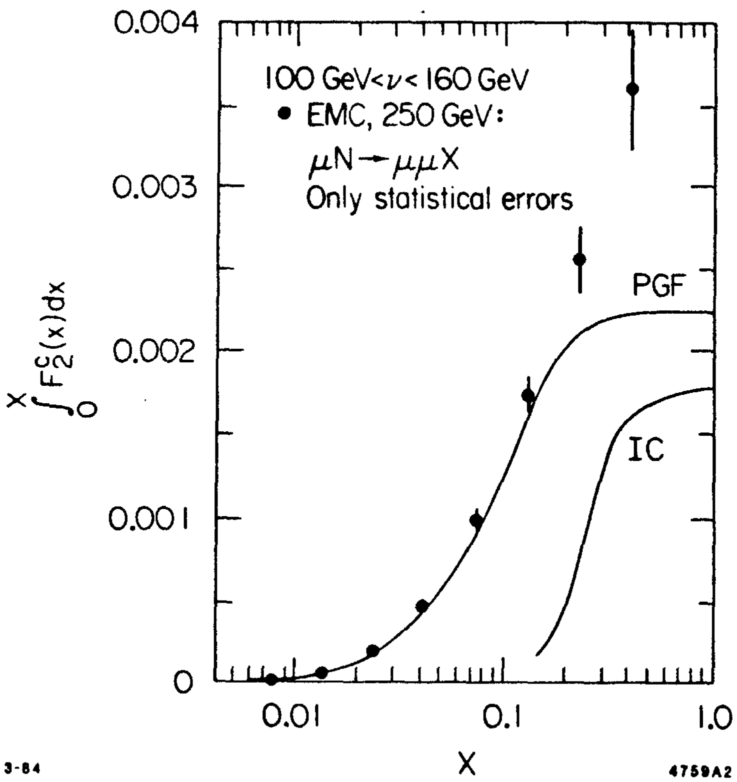

Fig. 2. EMC data[12] for the integrated charm quark x_{Bj} distribution in the nucleon deduced from $\mu N \rightarrow \mu\mu X$. The photon-gluon fusion (PGF) model predicts that the integrated momentum distribution saturates at $x_{Bj} = 0.1$ whereas the data indicates a substantial contribution beyond $x_{Bj} = 0.4$. The intrinsic charm (IC) prediction is from Ref. 15.

2. Intrinsic Heavy Quark Fock States

In a relativistic quantum field theory, a bound state cannot be described in terms of a fixed number of constituents at a given time since Fock states beyond the minimal valence component are always generated from exchange forces. For example, at fixed time on the light-cone $\tau = t + z$, the probability of non-valence states in a state of mass M is given by $\langle p| \partial V_{\rm eff}/\partial M^2 |p\rangle$ where $V_{\rm eff}$ is the effective potential constructed from the light-cone Hamiltonian truncated onto the valence Fock state sector.[13] Thus, positronium in QED at equal time on the light-cone contains a spectrum of Fock states $|e^+e^-\rangle$, $|e^+e^-\gamma\rangle$, $|e^+e^-e^+e^-\rangle$, $|e^+e^-\mu^+\mu^-\rangle$, etc. generated from (non-instantaneous) photon exchange, vacuum polarization, light-by-light insertions, etc. At equal τ the constituents $i = 1, \ldots n$ in each Fock state ψ_n are on their mass shells: $k_i^2 = m_i^2$, $k^0 > 0$, satisfy 3-momentum conservation: $\sum_{i=1}^n \vec{k}_{\perp i} = \vec{p}_\perp = 0$, $\sum_{i=1}^n x_i = 1$ ($x_i \equiv k_i^+/P^+, 0 < x_i < 1$), but are off the light-cone energy shell: $\epsilon_n \equiv M^2 - \sum_i [(k_\perp^2 + m^2)/x]_i < 0$. The structure function and momentum distributions of the constituents at resolution scale Q can be computed directly from the light-cone wavefunctions summed over all Fock states:

$$G_{a/p}(x, Q) = \frac{dN}{dx} = \sum_n \int^{k_\perp^2 < Q^2} [d^2k_\perp]\,[dx] \sum_{i=a} \delta(x_i - x)\; |\psi_n(x_i, \vec{k}_{\perp i})|^2 \,. \quad (2.1)$$

Thus, in the case of positronium, a finite fraction of its momentum $(\mathcal{O}(1/m_\mu^2))$ is carried by muon constituents [at resolution scales $Q^2 \gtrsim \mathcal{O}(m_\mu^2)$]. The mass shift of an atom due to virtual muon pairs is given by the Serber-Uehling vacuum polarization result $\Delta M(1S) = 4\alpha(Z\alpha)^4 m_e^3/15\pi m_\mu^2$. The momentum distributions of the intrinsic heavy constituents are controlled in large measure by the light-cone energy denominator

$$\frac{dN}{d^2k_\perp dx} \sim \left[\frac{\Gamma(x)}{M^2 - \sum_{i=1}^n \left(\frac{k_\perp^2 + m^2}{x}\right)_i}\right]^2 \quad (2.2)$$

which tends to peak at $x_i \propto \sqrt{m_i^2 + k_{\perp i}^2}$, i.e. equal rapidity or relative velocity of the constituents. This effect has been worked out in detail by K.

Hornbostel[14] who finds that the momentum distribution of a muon in the positronium $|e^+e^-\mu^+\mu^-\rangle$ Fock state indeed tends to significantly broaden to large x as the binding energy is increased so that momentum can be readily transferred from the valence (e^+e^-) to heavy $(\mu^+\mu^-)$ constituents. The contribution of heavy pair vacuum polarization to the photon wavefunction renormalization corresponds to the standard sea or "extrinsic" contribution induced by QCD evolution.

It is thus natural to look at the role of intrinsic heavy quark Fock states in the nucleon bound state wavefunction in QCD.[15] To leading order in $1/m_Q^2$ the intrinsic contributions correspond to twist six terms in the effective QCD Lagrangian[16] :

$$\begin{aligned} \mathcal{L}_{QCD}^{eff} &= -\frac{1}{4} F_{\mu\nu a} F^{\mu\nu a} - \frac{g^2 \frac{N_C}{2}}{60\pi^2 m_Q^2} D_\alpha F_{\mu\nu a} D^\alpha F^{\mu\nu a} \\ &+ C \frac{g^3}{\pi^2 m_Q^2} F_\mu^{a\nu} F_\nu^{b\tau} F_\tau^{c\mu} f_{abc} + O\left(\frac{1}{m_Q^4}\right) \quad . \end{aligned} \tag{2.3}$$

For QED $e^2(\partial_\alpha F_{\mu\nu})^2/60\,\pi^2 m_\ell^2$ gives the standard $(\alpha/15\pi\ q^2/m_\ell^2)$ Serber-Uehling vacuum polarization contribution to the mass shift of an atom due to heavy lepton pairs. In QCD the corresponding $\alpha_s(D_\alpha F_{\mu\nu})^2/m_Q^2$ term yields a heavy quark pair contribution to the proton state with from two to six gluon attachments to the nucleon constituents. Note that as in the atomic case, the running coupling constant $\alpha_s(k^2)$ is evaluated at the soft momentum scale of the bound state, not at the heavy particle mass scale. Since the coupling constant is large and the number of contributing graphs is large, it is not unreasonable that the momentum carried by a charm quark pair in the nucleon is of the order of 1/2%, as indicated by the EMC data.[12]

In addition to causing a shift in the nucleon mass, the dimension-six contributions of the effective Lagrangian imply the existence of Fock states in the nucleon containing an extra $Q\bar{Q}$ pair. Eventually lattice gauge theory or the light-cone equation of state will provide a full QCD solution for hadronic wavefunctions. At this point we can deduce[15,16] the following semiquantitative properties for intrinsic states such as $|u\,u\,d\,Q\bar{Q}\rangle$:

1. The probability of such states in the nucleon is nonzero and scales as m_Q^{-2}.
2. The maximal wavefunction configurations tend to have minimum off-shell energy, corresponding to constituents of equal velocity or rapidity, *i.e.*,

$$x_i \equiv \frac{(k^0 + k^z)_i}{p^0 + p^z} \quad \propto \quad \sqrt{(k_\perp^2 + m^2)_i}\ . \tag{2.4}$$

   Thus the heavy quarks tend to have the largest momentum fraction in the proton wavefunction, just opposite to the usual configuration assumed for sea quarks. A simple model[15] for the $|q\,q\,q\,Q\bar{Q}\rangle$ state which incorporates counting rule behavior at $x_i \sim 1$ and inverse power behavior in ϵ_n predicts a valence-like momentum distribution for the heavy quarks in the nucleon. As seen in Fig. 2, the EMC data for the charm structure function is consistent with this prediction.
3. The transverse momenta of the heavy quarks are roughly equal and opposite and of order m_Q, whereas the light quarks tend to have soft momenta as set by the hadron wavefunction.
4. The effects are strongly dependent on the features of the valence wavefunction: the intrinsic heavy quark probability is thus presumably larger in baryons than in mesons, non-additive in nucleon number (A^α, $\alpha > 1$) in heavy nuclei, and sensitive to the presence of strange quarks.
5. In deep-inelastic scattering on an intrinsic charm quark the heavy quark spectator will be found predominately in the target fragmentation region.

The presence of intrinsic charm quarks in the nucleon also has implications for other hard scattering processes involving incident charmed quarks.[15,16] In general, the charm quark in the nucleon will reflect both extrinsic and intrinsic $(1/m_c^2)$ contributions. Using QCD factorization this implies significant intrinsic charm contributions to hard scattering processes such as $c + g \to c + X$ at $p_T^2 \gg 4m_c^2$, with the intrinsic contribution dominating the large x domain.

The characteristic signal for such contributions is a $\bar{c}$ spectator jet in the beam fragmentation region. These hard-scattering results can also be applied to b-quark and t-quark production processes, with the intrinsic contribution scaling as $1/m_{Q^2}$ for $p_T^2 \gg 4m_Q^2$ at production energies well above threshold. Similarly, if supersymmetric particles of mass $\tilde{m}$ exist, they contribute to intrinsic SUSY Fock states[16] in the nucleon at order $1/\tilde{m}^2$. The intrinsic $\tilde{q}(x)$ or $\tilde{g}(x)$ distribution is again predicted to dominate at large x. Hard scattering processes such as $\tilde{q} + \bar{q} \to \tilde{\gamma} + \gamma$ can produce purely electromagnetic monojet events. Note that the associated supersymmetric $\tilde{\bar{q}}$ or $\tilde{g}$ partner appears in the beam fragmentation region.

3. Estimates of the Total Charm Production Cross Section

The presence of a hard-valence-like charm distribution in the nucleon can, at least qualitatively, explain some of the anomalous features of the charm hadroproduction data discussed in the introduction.[15] The fact that the c and $\bar{c}$ and similarly D and $\overline{D}$ distributions are harder than the corresponding strange particle distributions can be attributed to the fact that the skewing of quark distributions to large x only really becomes effective for quarks heavier than the average momentum scale in the nucleon. One can explain the nearly flat Λ_c cross section if there is recombination of the charm quarks with the u and d spectator quarks of the nucleon. However, recombination cannot explain the similar distributions observed in the LEBC experiment for D and $\overline{D}$, unless it is the heavy quarks that carry most of the momentum. Thus diffractive excitation of the intrinsic heavy quark Fock states may well be the source of the relatively large diffractive cross section $pp \to \Lambda_c \overline{D} X$ indicated by ISR measurements.[15]

Calculation of the cross sections for charmed hadron production are highly model dependent. However a quite detailed model recently proposed by Khodjamirian and Oganessian[17] based on excitation of intrinsic charm in the nucleon appears to give a good account of the magnitude, x_L and energy dependence of the FNAL, SPS, and ISR data.

A crucial question is the extrapolation of the intrinsic heavy quark contribution to b and t quarks. The fusion cross section scales as $1/m_Q^2$. As shown in Ref. 18, the intrinsic contribution actually scales as $1/m_Q^4$ at high energies since the probe momentum must be sufficiently large ($|t| > m_Q^2$) in order to unveil the intrinsic $1/m_Q^2$ scaling Fock states. This is contrary to the expectations stated in Refs. (15)-(17). Thus it seems unlikely that the intrinsic contribution will be more important than the fusion process $gg \to Q\overline{Q}$ for t-quark hadroproduction.

In a related approach Roy and Desai[19] have proposed that charm pairs can evolve from the hadronization of scattered quarks due to the intrinsic charm component of ordinary hadrons. The model is used to predict central region charm production, same-sign dileptons in neutrino deep inelastic reactions, and charm hadrons in the fragmentation of high E_T jets at the SPS collider.[20] The total cross section calculations however do not take into account the suppression noted above and in Ref. 18 for soft processes.

4. Distortion Due to Pre-binding Effects in Heavy Quark Production

Although the fusion subprocess $gg \to Q\overline{Q}$ is evidently the dominant mechanism for t quark production in high energy pp collisions, it is not clear that the application of QCD perturbation theory (i.e. Born approximation) to the total production cross section integrated over all momentum transfer is justified. As an example of the types of complications possible, consider the cross section for the photoproduction of a heavy lepton pair in the Coulomb field of a nucleus in QED. For large Z the cross section is strongly distorted at small lepton velocities $v_\pm \ll Z\alpha$ by multiple soft Coulomb interactions[21] :

$$d\sigma(\gamma Z \to \ell\bar{\ell}X) = d\sigma_0 \frac{\zeta_+\zeta_-}{(e^{\zeta_+}-1)(1-e^{-\zeta_-})} . \tag{4.1}$$

Here $d\sigma_0$ is the Bethe-Heitler cross section computed in Born approximation, and

$$\varsigma^{+} = \frac{2\pi Z\alpha}{v^{+}} \qquad \varsigma^{-} = \frac{2\pi Z\alpha}{v^{-}} . \tag{4.2}$$

These results are strictly valid for $\varsigma^{+} \ll 1$ but ς^{-} can be unrestricted. The effect of the correction factor is to distort the cross section toward small negative-lepton velocity (relative to the target rest frame). As $v^{-} \Rightarrow 0$, the enhancement is so strong that even the threshold phase-space factor in σ_0 is cancelled. Conversely, the cross section is exponentially damped when the positive lepton has low velocity.

An analogous effect evidently will also occur in QCD.[22] For example in charm photoproduction $\gamma p \to c\bar{c}X$, we expect the Born cross section based on photon-gluon fusion $\gamma g \to c\bar{c}$ to be strongly distorted toward charm production in the target fragmentation region; e.g. the charm quark rapidity will be skewed toward that of the spectator qq system of the nucleon where it can bind to form color singlets. As a simple model we will estimate this preconfining effect by replacing $\pi Z\alpha \to \frac{4}{3}\pi\alpha_s(q^2)$ in the QED distortion factor, Eq. (4.1). We will also choose q^2 to be the relative momentum of the c-quark and the spectator system and limit $|\alpha_s| \leq 4$. Clearly this gives only a very uncertain estimate of physics controlled by QCD non-perturbative effects. As shown in Fig. 3, the behavior predicted by this model indicates significant increases in the magnitude of the heavy quark production cross sections and significant skewing of the heavy particle momentum distribution towards large x_L. We are presently continuing to study the predictions of this model, including the effects of recombination with the incident valence quarks and the influence of strange quarks in the beam.

It thus seems likely that the distortion of the fusion Born approximation cross section due to prebinding attractive forces in QCD will be significant for the production of heavy quarks at collider energies, enhancing the production of the Λ_t, etc. in the forward region. Unlike the case of soft final-state interaction corrections to hard scattering processes, the corrections discussed here coherently enhance the production process and are not limited by unitarity to be of

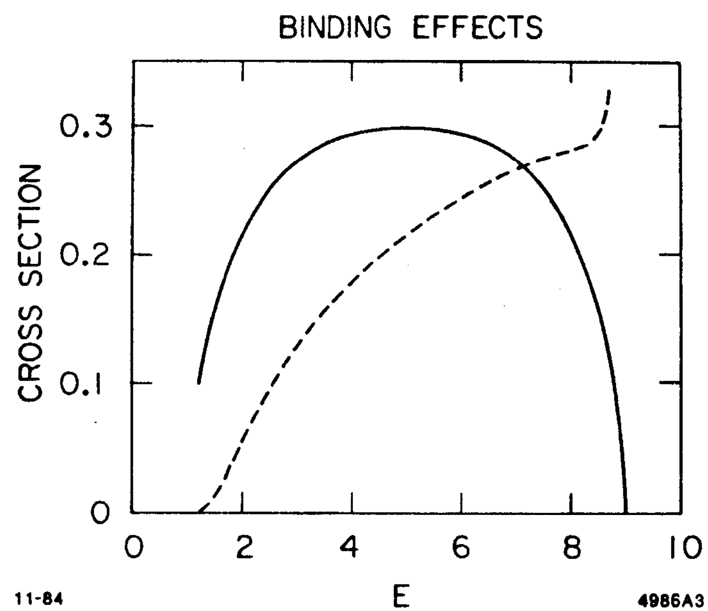

Fig. 3. The Bethe-Heitler cross section $\gamma Z \to \ell^{+}\ell^{-}Z$ in Born approximation as a function of the positive lepton energy. The dotted curve shows the modified spectrum due to multiple scattering using Eq. (4.1) with $Z\alpha \to 4/3\,\alpha_s(Q^2)$. We have used $\alpha_s(Q^2) = 4\pi/\beta_0 \ell n(1 + Q^2/\Lambda^2)$, $|\alpha_s| < 4$, where $\Lambda = 200$ MeV and Q^2 is the 3-momentum squared of the lepton relative to the target.

$O(1)$.[‡1] If there are strange quarks in the incident-hadron, then the distortion is likely to be magnified, since a strange quark tends to be more non-relativistic than u and d quarks in a hadron and thus more effective in "capturing" other quarks. This possibility could explain the relatively copious production of the $A^+(csu)$ in the Σ^- fragmentation region, and suggests an important role of hyperon and strange meson beams for charm and heavy particle production experiments.

The nominal scaling behavior for the total heavy quark production cross section based on the $gg \to Q\overline{Q}$ process is

$$\sigma_{Q\overline{Q}}(\sqrt{s}) = \frac{m_c^2}{m_Q^2}\,\sigma_{c\bar{c}}\left(\sqrt{s}' = \frac{m_c}{m_Q}\sqrt{s}\right) \; . \qquad (4.3)$$

The prebinding distortion factor is not expected to significantly modify this behavior.

Assuming that most of the observed charm cross section is non-intrinsic we may use Eq. (4.3) to extrapolate to the heavier quarks. For production well above threshold ($s \gg 4m_Q^2$), the $\frac{1}{2}\,mb$ charm cross section seen at the ISR implies $\sigma_{b\bar{b}} \sim 50\,\mu b$ at the $SP\overline{P}S$ collider ($\sqrt{s} = 540$ GeV) and $\sigma_{t\bar{t}} \sim \frac{1}{2}\,\mu b$ at the SSC ($\sqrt{s} = 40$ GeV).

At lower energies we can extrapolate the $\sim 20\,\mu b$ charm cross section at SPS/FNAL energies ($\sqrt{s} \cong 20$ GeV) using

$$\frac{m_c = 1.8\ GeV}{\sqrt{s} = 20\ GeV} \cong \frac{m_b = 5\ GeV}{\sqrt{s} = 63\ GeV} \cong \frac{m_t = 40\ GeV}{\sqrt{s} = 540\ GeV} \qquad (4.4)$$

to obtain $\sigma_{b\bar{b}}(\sqrt{s} = 63\ GeV) \sim 2\mu b$ at the ISR and $\sigma_{t\bar{t}}(\sqrt{s} = 540\ GeV) \sim 20\ \mu b$ at the $SP\overline{P}S$ collider. We predict a sizeable fraction of these events to be diffractive in nature, producing high-x_L $b\bar{b}$ or $t\bar{t}$ heavy quark systems.[‡2] This extrapolation also predicts

$$\sigma_{Q\overline{Q}}(m_Q = 1\ TeV,\ \sqrt{s} = 40\ TeV) \sim 10^{-3}\ \mu b\ . \qquad (4.5)$$

Similar extrapolations are of interest for hyperon beams. Extrapolating from the WA42 experiment at $\sqrt{s} = 16$ GeV discussed in the introduction we predict

$$B\sigma(\Sigma^- N \to \Sigma^0(bsu)X) \sim 1\ \mu b \qquad (4.6)$$

for Σ^- beams at $p_{\mathrm{Lab}} = 1200$ MeV, $\sqrt{s} \sim 50$ GeV, assuming that the branching ratio for the $\Sigma^0(bsu)$ decay channel is similar to that for the $\Lambda K^-\pi^+\pi^+$ channel in which $A^+(csu)$ is seen by WA42.

5. Conclusions

We have identified two novel effects in QCD, each of which acts to enhance the production of heavy quark and supersymmetric particles beyond what is conventionally expected from gluon fusion. Both effects are present in QED, but are compounded in QCD because of the increased number of diagrams and the much larger coupling constant. The intrinsic charm quark distribution in the nucleon could account for the observed enhancements of the charm structure function at large x and features of the charm production data but this mechanism is relatively suppressed for heavier systems. Prebinding distortion of the fusion cross section is, however, likely to be significant for the production at low p_T of all particles containing heavy colored constituents. At this stage the QCD calculations are highly model dependent although they agree with the general properties which can be inferred from the operator product expansion in the heavy quark mass. Much more theoretical analysis of these effects is clearly needed.

It is also clear that much more experimental work is necessary to extend and confirm the reported anomalous heavy quark signals. The intrinsic charm

‡1 We wish to thank A. Mueller for helpful discussions on this point.

‡2 We estimate that, excluding acceptance cuts but including a branching ratio of $\sim 1/12$, the 120/nb total luminosity first run at the $SP\overline{P}S$ collider should have produced of order 100 hadroproduced $t\bar{t}$ with $t \to b\mu\nu$.

distribution in the nucleon can be best measured in deep inelastic electron and muon scattering well above the charm threshold at large Q^2 and $x_{Bj} \gtrsim 0.4$. It is clearly very important to extend existing measurements in this region, and to determine the associated s-dependence, A-dependence and charm jet correlations. We note that prebinding enhancement of the fusion process will be maximum in diffractive channels where both the Q and $\overline{Q}$ can bind with the target fragments into color singlets. Correspondingly, the enhancement of the photon-gluon fusion subprocess implies an increased signal for charm pair photoproduction in the target fragmentation region. The possibility of enhanced charm and beauty quark production in hyperon and kaon beams is also implied and is one of the most important areas of investigation for future fixed target experiments. In addition, in virtually every hadroproduction channel there is a severe lack of information on charm pair correlations, the A-dependence as a function of energy and x_L, and the constraints of e/π and lepton pair rates over the whole kinematic range. In understanding the nature of heavy quark production, critical information will be provided by the correlation between the hadrons containing the heavy Q versus $\overline{Q}$. Both intrinsic charm and the prebinding distribution mechanism suggest that both heavy quark systems will be produced toward large x_L in the same direction. A comparison of such correlations for diffractive and non-diffractive $Q\overline{Q}$ production would be especially useful.

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20. The UA1 collaboration (G. Arnison *et al.*, CERN-EP/84-86 (1984)) reports a surprising large number (0.65 ± 0.33) of charged $D^{*\pm}$ with $z > 0.1$ per jet ($\langle P_T \rangle = 28$ GeV) in $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV.

21. See, e.g. A. I. Akhiezer and V. B. Berestesky, *Quantum Electrodynamics*, Moscow (1953).

22. S. J. Brodsky and J. F. Gunion, to be published.