SLAC-PUB-2888
March 1982
(T/E)

HEAVY QUARKS IN HADRONIC COLLISIONS*

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ABSTRACT

It is suggested that the presence of $c\bar{c}$-pairs on the 1-2% level in the hadron Fock state decomposition (intrinsic charm) gives a natural description of the ISR data for charm hadron production. The theoretical foundations of the intrinsic charm hypothesis together with its consequences for lepton- and hadron-induced reactions are discussed in some detail. There is no contradiction with the EMC data on F_2^c provided the appropriate threshold dependence is taken into account.

1. INTRODUCTION

Charmed hadron production as observed at the ISR has several remarkable features:

(1) The total cross section for open charm production in pp-collisions at $\sqrt{s}$ = 63 GeV is at the 1 mb level.[1]

(2) Charmed hadrons are abundantly produced in the forward region of phase space. The $pp \to \Lambda_c X$ distribution is roughly flat in x_L;[2]

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*Work supported in part by the Department of Energy contract DE-AC03-76SF00515 and by the Swedish Natural Science Research Council under contract F-PD8207-101.

†On leave of absence from NORDITA, Copenhagen, Denmark.

(Invited talk at the Topical Conference on Forward Collider Physics, Madison, Wisconsin, December 10-12, 1981 and the Europhysics Study Conference: Search for Charm, Beauty and Truth at High Energies, Erice, Italy, November 15-22, 1981.)

$$\frac{d\sigma}{dx_L}\,(pp \to \Lambda_c X) \sim (1-x_L)^{0.4} \quad . \tag{1}$$

Also D^0 and D^+ (which carry no valence quarks in common with the proton) are produced with a flat rapidity distribution; the $pp \to D^0X$ x_L-distribution[3] is consistent with $\sim(1-x_L)^3$. The corresponding strange hadron cross section[4] $d\sigma/dx_L$ $(pp \to K^-X)$ falls much steeper, $(1-x_L)^{6\pm1}$.

(3) The Λ_c can be produced with a diffractive trigger, $pp \to p\Lambda_cX$ with a cross section of the order of 240 ± 120 μb.[5]

In contrast, standard models for charm production based on hard scattering, gluon fusion,[6] predicts smaller cross sections and much more steeply falling longitudinal momentum distributions than observed (the final charm distribution are steeper than the incoming gluons by a factor $(1-x)$ in perturbative calculations). The gluon fusion model is, however, successful in explaining hidden heavy flavor production, $pp \to XX \to \psi\gamma X$, etc.[7,8]

There is, however, another mechanism for heavy quark production, which occurs naturally in QCD. The proton wavefunction at equal time* can be decomposed in terms of Fock state components

$$|uud\rangle,\ |uudg\rangle,\ |uudq\bar{q}\rangle,\ \ldots. \tag{2}$$

including a small contribution for $|uudc\bar{c}\rangle$. The Fock states containing heavy flavors first appear in perturbative theory via vacuum polarization insertions in the gluons exchanged between valence quarks. We will refer to these preexisting Fock components as <u>intrinsic charm</u> states,[9] since they are present in the hadron without regard to external reactions. Since all the intrinsic quarks of a bound state tend to have the same velocity, the charm quarks carry most of the hadron momentum in the Fock state where they are present; i.e., the intrinsic charm quark x-distribution can be as hard as those of the standard valence quarks. A Bag model calculation of the $c\bar{c}$-probability in fact gives $P(|uudc\bar{c}\rangle) \approx 1\%$. Thus, qualitatively the intrinsic charm mechanism can yield cross sections of correct shape and the magnitude observed at the ISR (2% of $\sigma_{tot}(pp)$). Furthermore, it is natural with such states to have large cross sections for the diffractive excitation of preexisting hadron components of the proton (at high energies where kinematic and t_{min} effects are negligible).

There are several reasons why it is important to understand charm production in detail:

(1) If $d\sigma \sim 1/M_Q^2$ (as suggested by the perturbative QCD-vacuum polarization for intrinsic charm), then one expects an appreciable production of b-quarks at the ISR and a non-negligible production of t-quarks at the SPS and Tevatron colliders. The use of a diffractive trigger and the possibility of production at large x will reduce the combinatorial background in the search for t-quark hadrons.

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*In practice the decomposition is made at equal $\tau = t + z$ on the light cone in $A_0 + A_3 = 0$ gauge.

(2) In general, heavy quark production will be useful as a probe of hadron dynamics: in particular, for understanding the basic mechanisms for large x hadron production. The distinctive role of the intrinsic (preexisting) and extrinsic (created by the collision) mechanisms highlights two complementary aspects of QCD. Each contribution has its distinguishing nuclear A-dependence ($A^{2/3}$ versus A), s-dependence and x_L-dependence.

(3) In the case of the intrinsic charm component there are fundamental questions regarding the importance of non-perturbative confining forces on the heavy quark distributions.[10] From the point of view of perturbative theory or operator product expansion, the leading $1/M_c^2$-contribution can be calculated using free quark propagation with up to four interactions in the heavy quark loop.

(4) Because of the heavy mass one expects strong kinematical scale breaking effects in the measured charm distribution.

(5) The presence of intrinsic charm at large x in the nucleon with strong threshold dependence has serious implications for the scale breaking parameterization of perturbative QCD, since the onset of charm masks the effects of QCD-evolution in deep inelastic structure functions.[11]

(6) For the unexpectedly high rate of observed same sign dimuons in ν-reactions[12] the 1% intrinsic charm contributes on a level consistent with the CDHS experiment (all experiments do not agree).

This talk is organized as follows: We first (Sec. 2) review the theoretical expectations for heavy quark production starting with estimates for "soft" production mechanisms and then elaborating more on what is expected from perturbative QCD with regard to open heavy flavor production. Comparisons with experimental data on $c\bar{c}$ are found in Sec. 3. In Sec. 4 a general discussion of higher Fock state decomposition of hadronic states is given and in Sec. 5 we argue for the existence of $|uudc\bar{c}\rangle$ of the 1% level and construct a model for the c(x) distributions. Hadronic production of charm is discussed in Sec. 6. In Sec. 7 our model for c(x) is confronted with data from leptoproduction experiments.

2. "CONVENTIONAL" THEORETICAL EXPECTATIONS FOR HEAVY QUARK PRODUCTION

The production of heavy quarks in hadronic collisions from soft mechanisms is normally expected to be very suppressed. As an example, when considering hadronic production of particles as a tunneling phenomena one finds the probability to produce a qq-pair[13]

$$P(q\bar{q}) \sim \exp\left(-\frac{\pi}{\kappa} m_\perp^2\right) \tag{3}$$

where $m_\perp = \sqrt{p_\perp^2 + m_q^2}$ and κ is the string constant $\approx 0.2\ \text{GeV}^2$. Using $m_u = m_d \approx 0$ MeV, $m_s = 100$ MeV, $m_c = 1500$ MeV and $\langle p_\perp \rangle = 350$ MeV one gets from Eq. (3)

$$u:d:s:c = 1:1:\frac{1}{3}:10^{-10} \tag{4}$$

The reason for the strong suppression of c-quark production is that it is very difficult to localize the energy of a substantial part of a string. Also, in other pictures one obtains a strong suppression. For example, in the statistical model[13] approach the probability for D-meson production is given by

$$P \sim \exp(-2m_D/160 \text{ MeV}) \tag{5}$$

which gives the ratio $\pi:K:D = 1:0.13:3.10^{-5}$.

However, since large masses are involved one expects calculations based on perturbative QCD to be valid. Perturbative QCD gives contributions of order $1/M^2$ in contrast to the $\exp(-\beta M^2)$-behavior for the soft tunneling processes discussed above.

Hadronic production of hidden heavy quark pairs, e.g., ψ, are well described by the hard scattering processes (see Refs 7,8). In the case of open $Q\bar{Q}$ production the following hard scattering processes contribute[6] (see Fig. 1a,b)

$$q\bar{q} \to Q\bar{Q} \tag{6a}$$

$$gg \to Q\bar{Q} \tag{6b}$$

together with the flavor excitation processes[14] (Fig. 1c)

$$qQ(\bar{Q}) \to qQ(\bar{Q}) \tag{7}$$

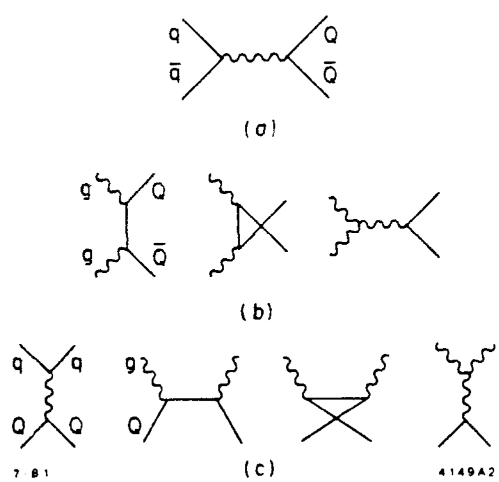

Fig. 1. Lowest order QCD subprocesses for hadron + hadron $\to$ $Q\bar{Q}$ + X.

Predictions from the latter ones depend in detail on the understanding of the charm quark distribution in the proton.

The gluon amalgamation process (6b) is expected to be dominant at very high energies due to the abundance of low-x gluons. The cross section is given by convolution of distribution functions and the subprocess cross section ($\hat{\sigma}$)

$$\sigma(h+h\to Q\bar{Q}X) = \iint\limits_{x_1x_2 > s_{min}/s} dx_1dx_2\ G(x_1)\ G(x_2)\ \hat{\sigma}(s_1, x_2, s) \qquad (8)$$

There are several theoretical uncertainties entering Eq. (8).

i) The lower limit of Eq. (8). The true kinematical threshold, $\sqrt{s_{min}}$, is $2m_D$ but $2m_c$ is presumably more relevant since the charmed hadrons are formed in a fragmentation/recombination process, thereby gaining energy.

ii) The value of m_c. Most authors use m_c = 1.6 GeV. A lower value like m_c = 1.2 GeV, as obtained from potential calculations, would increase the cross section by a factor 4.

iii) Higher order graphs are not yet included.

iv) Higher twist contributions. These are unknown and could be important at such small masses as m_c = 1.6 GeV.

v) Initial state corrections could alter the result by a large factor.[15]

The cross section for $c\bar{c}$ and $b\bar{b}$-production in the FNAL/SPS-ISR energy range from Eq. (8) is given by (see Fig. 2)

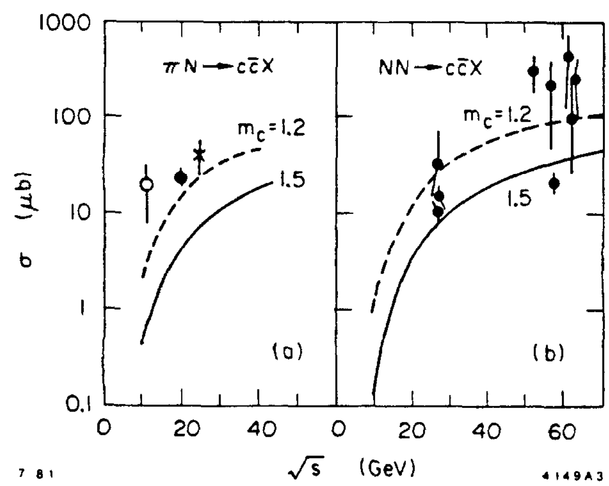

Fig. 2. (a) $\sigma(\pi N \to c\bar{c}X)$ as a function of c.m.s. energy, from Ref. 16.
(b) $\sigma(NN \to c\bar{c}X)$ as a function of c.m.s. energy, from Ref. 16.

$$\sigma(c\bar{c}) = 1\text{-}50\ \mu b$$
$$\sigma(b\bar{b}) = 0.1\text{-}100\ nb \quad (9)$$

The energy dependence is logarithmic which is due to the 1/x-behavior of the gluon distributions. The single particle spectrum for the observed charmed hadrons is expected to be soft, reflecting the incoming gluon distribution.

3. COMPARISON WITH EXPERIMENTAL RESULTS ON OPEN CHARM PRODUCTION

The experimental results on charm production are reviewed in detail in Ref. 1. Here we only briefly mention the most important results. They are:

i) At ISR one observes a large cross section (0.1-0.5 mb) for the reaction $pp \to \Lambda_c^+ X$ (see Fig. 2b). The cross sections for the other channels $pp \to D^+X$, $pp \to D^oX$ are in similar range.

ii) Moreover, the Λ_c^+ seems to be produced diffractively in the forward region of phase space (see Fig. 3a,b). At least one of the experiments has an explicit diffractive trigger.[5] The x_L-distributions of $pp \to D^oX$ is $\sim(1-x)^3$ much more forward than the corresponding strange meson distributions for $pp \to K^-X$ indicating that the charm quark carry a significant fraction of the proton momentum.

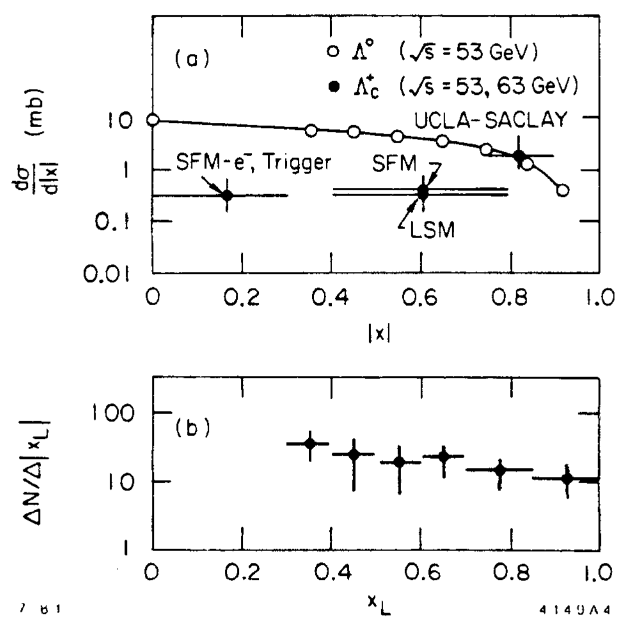

Fig. 3. (a) $d\sigma/d|x|$ for Λ_c^+ at 53 and 63 GeV.[1] The smooth curve is a fit to the Λ^o data points. (b) Unnormalized x_L-distribution for Λ_c^+ from Ref. 2.

iii) The situation for SPS/FNAL experiments is not so clear. One experiment with a diffractive trigger,[17] $\pi^- p \to D\bar{D}X$, observes a forwardly oriented single particle spectrum.

iv) A signal for forwardly produced Λ_b at ISR has also been reported.[18]

The important discrepancy with the hard scattering approach is the x_L-spectrum of Λ_c^+ (see Fig. 3); on general grounds one would expect the Λ_c^+ wave function to favor configurations where the c-quarks have the most momentum (see Fig. 4). On the other hand, the c-quarks produced in a hard scattering process have small x. Hence such c-quarks would most unlikely end up in a fast Λ_c^+. The way to produce fast Λ_c^+ is to have hard c(c)-quarks initially present in the proton, i.e., $|uudc\bar{c}\rangle$ states.[9] In fact, the similarity between $pp \to D^o(c\bar{u})X$ and $pp \to K^+(u\bar{s})X$ momentum distributions suggests that the c- and u-quark distributions are quite similar. We will discuss this intrinsic charm hypothesis in some detail below. Before doing so we briefly mention some recent attempts[19,20] to "improve" on the hard scattering approach.

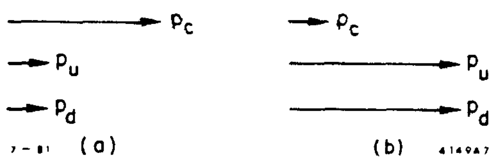

Fig. 4. (a) Typical quark momentum configuration in a Λ_c^+. (b) Typical quark momentum configuration after a hard scattering with a slow c-quark and two fast valence quarks.

i) In Ref. 19 it is hypothesized that a hard c(x)-distribution may arise from a mechanism where the c-quarks gain momentum after the scattering process. We regard such a mechanism as highly unlikely.

ii) In Ref. 20 a diquark process is discussed for producing fast Λ_c^+. This mechanism would, however, not explain the abundant production of fast D^o (which contain no proton valence quarks). This model can be consistent only if the D^o are decay products of charmed baryon resonances. The production of $\bar{\Lambda}_c$ at large x_L in pp-collisions would be decisive.

4. HADRONIC FOCK STATE DECOMPOSITIONS

As mentioned in the introduction, the proton has a general decomposition in terms of color singlet eigenstates of the free Hamiltonian. The existence of higher proton Fock states such as $|uudg\rangle$ has support from hadron spectroscopy: The p-Δ mass splitting (ΔE), which is believed to originate from the one gluon exchange graph, is by cutting the diagram in Fig. 5 related to the probability of having extra gluon states, $(P(|uudg\rangle))$, through the relation

$$\Delta E = \sum_{\substack{\text{gluon}\\ \text{modes}}} P(|uudg\rangle)\,(E_{uud} - E_{uudg}) \tag{10}$$

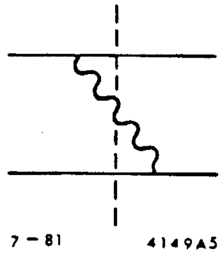

Fig. 5. One gluon exchange diagram responsible for spin-spin splitting of masses and the existence of higher Fock states containing an extra gluon.

The presence of higher Fock states is implicitly present in Ref. 21, where it is shown that rigorous constraints from $\pi \to \mu\nu$ and $\pi \to \gamma\gamma$ decays give a probability <0.25 for having a pion in a pure $q\bar{q}$-state at equal time on the light cone with $A_+ = 0$ gauge for a large class of wavefunctions.

In the next section we explore the consequences of heavy quark pairs $Q\bar{Q}$ in the Fock state decomposition of the bound state wavefunction of ordinary mesons and baryons. Although proton states such as $|uudc\bar{c}\rangle$ and $|uudb\bar{b}\rangle$ are surely rare, the existence of hidden charm and other heavy quarks within the proton bound state will lead to a number of striking phenomenological consequences.

It is important to distinguish two types of contributions to the hadron quark and gluon distributions: Extrinsic and intrinsic. Extrinsic quarks and gluons are generated on a short time scale in association with a large transverse momentum reaction; their distributions can be derived from QCD bremsstrahlung and pair production processes and lead to standard QCD evolution. The intrinsic quarks and gluons exist over a time scale independent of any probe momentum, and are associated with the bound state hadron dynamics. In particular, we expect the presence of intrinsic heavy quarks, $c\bar{c}$, $b\bar{b}$, etc., within the proton state by virtue of gluon exchange and vacuum polarization graphs as illustrated in Fig. 6.

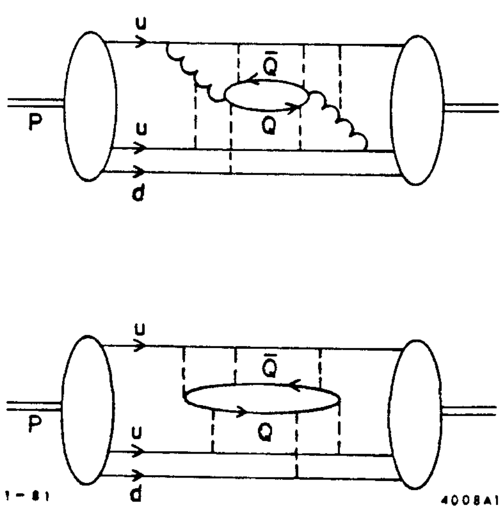

Fig 6. Diagrams which give rise to the intrinsic heavy quarks ($Q\bar{Q}$) within the proton. Curly and dashed lines represent transverse and longitudinal-scalar (instantaneous) gluons, respectively.

The "extrinsic" quarks and gluons correspond to the standard bremsstrahlung and $q\bar{q}$ pair production processes of perturbative QCD. These perturbative contributions yield wavefunctions with minimal power-law fall-off

$$|\psi(k_{\perp i},x_i)|^2 \sim \frac{1}{k_{\perp i}^2} \tag{11}$$

and lead to the logarithmic evolution of the structure functions. In contrast, the intrinsic contributions to the quark distribution are associated with the bound state dynamics and necessarily have a faster fall-off in $k_{\perp i}$ ($\psi \sim 1/k_\perp^2$ or faster).[22] The intrinsic states thus contribute to the initial quark and gluon distributions. A simple illustration of extrinsic and intrinsic $|uudq\bar{q}\rangle$ contributions to the deep inelastic structure functions is shown in Fig. 7a and b. We see that the existence of gluon exchange graphs plus vacuum polarization insertions automatically yield an intrinsic $|uudq\bar{q}\rangle$ Fock state.

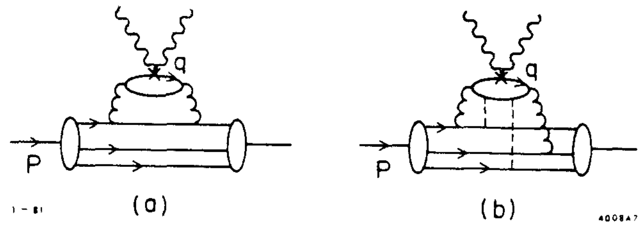

Fig. 7. (a) Example with contribution to the deep inelastic structure functions from an extrinsic quark q. (b) Example with contribution to the deep inelastic structure functions from an intrinsic quark q.

A complete calculation must take into account the binding of the gluon and $q\bar{q}$ constituents inside the hadron (see Fig. 6) so that the analysis is presumably non-perturbative.

We also note that the normalization of the $|uudq\bar{q}\rangle$ state is not necessarily tied to the normalization of the $|uudg\rangle$ components since the latter only refer to transversely polarized gluons; Fig. 7 shows that $q\bar{q}$-pairs also arise from the longitudinal-scalar (instantaneous) part of the vector potential.

5. INTRINSIC HEAVY QUARK STATES

The intrinsic heavy quark states exist on a long time scale. Hence, an estimate of the mixing probability should be possible in the static bag model. Such a study was done by Donoghue and Golowich[23] in the rest frame of the proton. Summing over the lowest states the authors of Ref. 15 obtain the result

$$\begin{aligned} &P(|uudu\bar{u}\rangle):P(|uudd\bar{d}\rangle):P(|uuds\bar{s}\rangle):P(|uudc\bar{c}\rangle) \\ &= 0.20:0.15:0.09:0:0.01 \end{aligned} \qquad (12)$$

which, as far as charm is concerned, is in agreement with the order of magnitude of the charm cross section observed at the ISR. It should also be remarked that the results of Eq. (12) are still consistent with previous bag calculations for the static quantities like magnetic moments and average square radii. (For our purposes it would be desirable to have the calculation of the intrinsic charm content of the proton performed in the infinite momentum frame.)

We now proceed to discuss the c-quark momentum distribution in a $|uudc\bar{c}\rangle$ state. The general form of a Fock state wavefunction is

$$\psi(k_{\perp i},x_i) = \frac{\Gamma(k_{\perp i},x_i)}{M^2 - \sum_{i=1}^{n}\left(\frac{m^2+k_\perp^2}{x}\right)_i} \qquad (13)$$

where Γ is the truncated wavefunction or vertex function. The actual form of Γ must be obtained from the non-perturbative theory, but following Ref. 21 it is reasonable to take Γ as a decreasing function of the off-energy-shell variable

$$\mathscr{E} = M^2 - \sum_{i=1}^{n}\left(\frac{m^2+k_\perp^2}{x}\right)_i \quad . \qquad (14)$$

Independent of the form $\Gamma(\mathscr{E})$, we can read off some general features of the quark distributions:

(1) In the limit of zero binding energy ψ becomes singular and the fractional momentum distributions peak at the values $x_i = m_i/M$. More generally, $\mathscr{E}$ is minimal and the longitudinal momentum distributions are maximal when the constituents with the largest transverse mass $m_\perp = \sqrt{m^2 + k_\perp^2}$ have the largest light-cone fraction x_i. This is equivalent to the statement that constituents in a moving bound state tend to have the same rapidity.

(2) If one considers the proton as a state with virtual fluctuations of $\pi^+ n$, $K^+\Lambda$, $D\Lambda_c$, etc., the most probable configurations are those closest to the energy shell, i.e., $\mathscr{E} \approx 0$. In the case of virtual hidden charm states, the dominant configurations thus have maximal x_c and $x_{\bar{c}}$.

(3) The intrinsic transverse momentum of each quark in a Fock state generally increases with the quark mass. In the case of power law wavefunction $\psi \sim (\mathscr{E})^{-\beta}$ we have $\langle k_\perp^2\rangle \propto m_Q^2$; for an exponential wavefunction $\psi \sim e^{-\beta\mathscr{E}^{1/2}}$, the dependence is $\langle k_\perp^2\rangle \propto m_Q$.

In the limit of large $k_\perp$ one can use the operator product expansion near the light cone (or equivalently gluon exchange diagrams) to prove that, modulo logarithms, the Fock state wavefunctions fall off as inverse powers of $k_\perp^2$.[22] For our purpose, which is to illustrate the characteristic shape of the Fock states containing heavy quarks, we will choose a simple power-law form for the Fock state longitudinal momentum distributions

$$P_{(n)}(x_1 \ldots x_n) = N_n \frac{\delta\left(1 - \sum_{i=1}^{n} x_i\right)}{\left(M^2 - \sum_{i=1}^{n} \frac{\hat{m}_i^2}{x_i}\right)^2} \qquad (15)$$

where the $\hat{m}_i^2$ are identified now as effective transverse masses $\hat{m}_i^2 = m_i^2 + \langle k_\perp^2 \rangle_i$ and the $\langle k_\perp^2 \rangle_i$ are average transverse momenta. With this choice, single-quark distributions have power law fall-offs $(1-x)^2$ and $(1-x)^3$ for mesons and baryons, respectively. (This is the most simple model for the hadronic wavefunction.)

For a $|uudc\bar{c}\rangle$ proton Fock state the momentum distribution is given by

$$P(x_1, \ldots, x_5) = N_5 \frac{\delta\left(1 - \sum_{i=1}^{5} x_i\right)}{\left(m_p^2 - \sum_{i=1}^{5} \frac{\hat{m}_i^2}{x_i}\right)^2} \quad . \tag{16}$$

In the limit of heavy quarks $\hat{m}_4^2 = \hat{m}_5^2 = \hat{m}_6^2 >> m_p^2, \hat{m}_i^2$ $(i = 1,2,3)$ we get

$$P(x_1, \ldots, x_5) = N_5 \frac{x_4^2 x_5^2}{(x_4 + x_5)^2} \delta\left(1 - \sum_{i=1}^{5} x_i\right) \tag{17}$$

where $N_5 = 3600$, P_5 is determined from $\int dx_1 \ldots dx_5 P(x_1, \ldots, x_5) = P_5$, where P_5 is the $|uudc\bar{c}\rangle$ Fock state probability. Integrating over the light quarks (x_1, x_2 and x_3) we get the charmed quark distributions

$$P(x_4, x_5) = \frac{1}{2} N_5 \frac{x_4^2 x_5^2}{(x_4 + x_5)^2} (1 - x_4 - x_5)^2 \quad . \tag{18}$$

By performing one more integration we obtain the charmed quark distribution

$$P(x_5) = \frac{1}{2} N_5 x_5^2 \left[\frac{1}{3} (1 - x_5)\left(1 + 10x_5 + x_5^2\right) - 2x_5(1 - x_5) \log \frac{1}{x_5}\right] \tag{19}$$

which has average $\langle x_5 \rangle = 2/7$ and is shown in Fig. 8. This is to be contrasted with the corresponding light quark distribution derived from Eq. (17) and shown in Fig. 9

$$P(x_1) = 6(1 - x_1)^2 P_5 \quad . \tag{20}$$

A more proper calculation of $c(x)$ can be done by integrating Eq. (16) over 11 variables using, e.g., exponential behavior for Γ. This was done in Ref. 24 using Monte Carlo techniques and the resulting $c(x)$ was found to be somewhat smoother than that of Eq. (19).

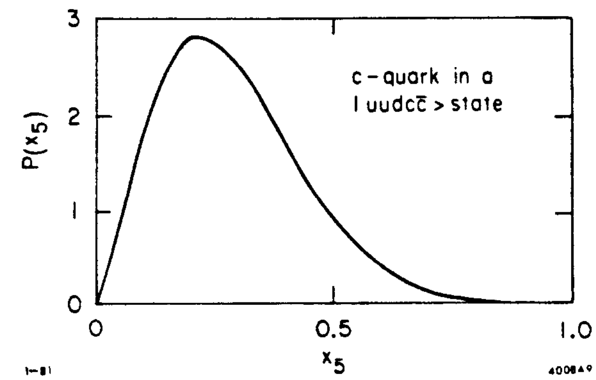

Fig. 8. The x distribution of the charmed quark in a $|uudc\bar{c}\rangle$ state.

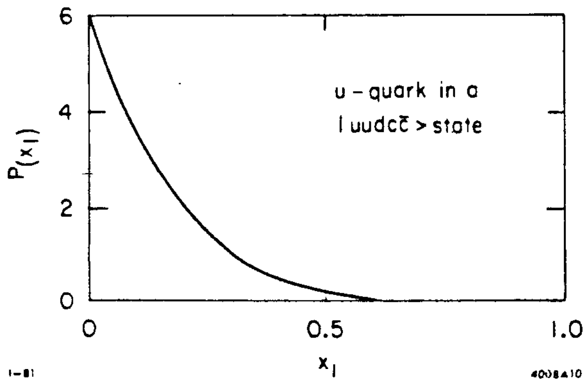

Fig. 9. The x distribution of a light quark in a $|uudcc\rangle$ state.

A more detailed calculation of the perturbative diagrams in Fig. 6 yields an extra power $(1 - x_4 - x_5)$. The controlling factor in the distribution for large x is the energy denominator.

The corresponding c- and u-quark distributions in a $|udc\bar{c}\rangle$ are obtained in the same way. In order to see the contribution of the intrinsic $c\bar{c}$-pairs to the proton structure function, we use the value for $P_5 = 0.01$ from the bag model calculations discussed above. The magnitude of the charm cross section at ISR (0.1-0.5 mb)[1] gives for P_5:

$$P_5 = \frac{\sigma_{\Lambda_c}}{2\sigma_{inel}} \approx \frac{250\ \mu b}{2.30\ mb} = 0.004 \quad . \tag{21}$$

If the production mechanism is <u>inelastic</u> and

$$P_5 = \frac{\sigma_{\Lambda_c}}{2\sigma_{diff}} \approx \frac{250\ \mu b}{2.10\ mb} = 0.01 \tag{22}$$

if it is <u>diffractive</u>. These two possibilities will be discussed in the next section. We conclude that the charm cross section at ISR is compatible with $P_5 = 0.01$.

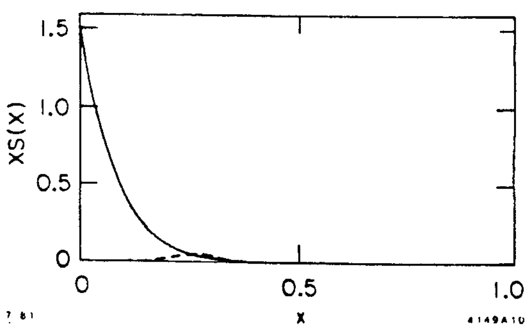

Fig. 10. Comparison of the intrinsic charm sea xc(x) (dashed line) with the total sea at $Q^2 = 5\ GeV^2$ as parameterized by Ref. 25.

The charmed quark distribution $c(x) = P(x_5)$ should be measurable in lepto-production for high enough Q^2 and $W^2 > W^2_{th} = 25\ GeV^2$. Hence to measure c(x) at, e.g., x = 0.5 requires $Q^2 = 25\ GeV^2$ ($x = Q^2/(Q^2 + W^2)$). We emphasize that the intrinsic charm sea c(x) is "rare" but not "wee" as is clear from Fig. 10. A discussion on comparing c(x) with lepto-production data is found in Sec. 6. In order to obtain intrinsic u, d and s-distributions ($|uuduu\rangle$ states, etc.) the wavefunction in Eq. 15 needs a minor modification.

6. HADRONIC PRODUCTION OF CHARM

Hadronic production of multiparticle final states occurs in two different ways, diffractive disassociation and nondiffractive inelastic production. Although at least one experiment of $\Lambda_c^{\pm}$-production has an explicit diffractive trigger,[5] the situation for charm production is far from settled. We will discuss the two production mechanisms below in the light of intrinsic charm.

i) Diffractive production of high M^2-states can be interpreted as a phenomenon of short distance where perturbative QCD should be applicable to some extent. This idea was first considered in Ref. 26 in the context of charm production. Recently these questions have been studied in more detail for high mass diffraction in general in terms of so-called "transparent states."[27-30] The idea is simple and appealing: When the valence quarks of a hadron are close together the net color extension is almost zero and the hadron does not interact with other hadrons. Hence the absorptive cross section is small and the hadron scatters diffractively off the target which then appears to be transparent. This situation is, as pointed out by Ref. 28, very similar to an analogous process in QED: When e^+e^--pairs are produced in very high energy emulsion experiments, they can only be separated by distances smaller than atomic sizes. The e^+e^- has net charge zero — it is not "seen" by surrounding atoms and hence it does not ionize and give rise to visible tracks. In Ref. 30 the knowledge of the pion wavefunction in QCD at short distances is used to derive results for the pion-induced jets emerging from the "transparent" target.

As was discussed in connection with Eq. (13) one expects intrinsic heavy quark states to have large $\langle k_\perp \rangle$ and consequently small transverse dimension. It is therefore tempting to assume that the intrinsic heavy quark states scatter diffractively. With this assumption one obtains in the case of 1% intrinsic charm on a nuclear target[30]

$$\sigma_{\text{charm}}^{\text{diff}} = 0.01 \cdot \sigma_{el} \approx 0.5 \text{ mb} \cdot A^{2/3} \quad . \tag{23}$$

This high value is encouraging as far as production of b- and t-quarks are concerned. A diffractive production mechanism of heavy quarks is also very favorable as far as the combinatorial background is concerned.

For the charm case the Λ_c and D-spectra can be calculated in principle from the strong overlap between the 5-quark and the charmed-hadron state wavefunctions, allowing for decays of excited state, etc. For the purpose of obtaining the x_F-distribution we use a very simple recombination mechanism for the quarks involved in the states. Neglecting its binding energy, the Λ_c spectrum is given by combining the u, d and c-quark in $|uudc\bar{c}\rangle$ to obtain

$$P(x_{\Lambda_c}) = N_5 \int_0^1 \prod_{i=1}^{5} dx_i \, \delta(x_{\Lambda_c} - x_2 - x_3 - x_5) \left(\frac{x_4 x_5}{x_4 + x_5}\right)^2 \delta\left(1 - \sum_{i=1}^{5} x_i\right) \tag{24}$$

(see Fig. 11) with $\langle x_{\Lambda_c}\rangle = 1/7 + 1/7 + 2/7 = 4/7$. The ISR data for $d\sigma/dx\ (pp \to \Lambda_c X)$ is consistent with the prediction that $\langle x_{\Lambda_c}\rangle \approx 0.5$ although the data is even flatter than predicted by Eq. (24). We expect that the low x region for charm production will be filled in by both perturbative and higher Fock state intrinsic contributions. Assume that a hadron interacts strongly only when one of its constituents is very peripheral, $k^2 - m^2 \approx 0$. Since $k^2 - m^2 = x\mathscr{E}$ this implies that the important interacting Fock states have one constituent with $x \simeq 0$.[31] Consequently, the spectator system carry more momentum than in Eq. (24). This effect improves our agreement with the data. The corresponding distribution for $D^-(\bar{c}d)$ is given by

$$P(x_{D^-}) = N_5 \int_0^1 \prod_{i=1}^{5} dx_i\, \delta(x_D - x_3 - x_5) \left(\frac{x_4 x_5}{x_4 + x_5}\right)^2 \delta\left(1 - \sum_{i=1}^{5} x_i\right) \qquad (25)$$

with $\langle x_{D^-}\rangle = 1.7 + 2/7 = 3/7$, and is shown in Fig. 12. The $D^+(c\bar{d})$ distribution would, in principle, be obtained from the $|uudc\bar{c}d\bar{d}\rangle$ Fock state of the proton, where the $d\bar{d}$ could be extrinsic or intrinsic. Assuming that the $\bar{d}$ momentum is small, the D^+ distribution should be close to that of the c-quark shown in Fig. 8. These predictions apply for forward production ($x_F \gtrsim 0.1$), where perturbative contributions and higher Fock state contributions can be neglected. Spectra for pion induced reactions are obtained in the same way.

In addition to charmed mesons and baryons, the J/ψ may also be produced diffractively from the intrinsic charm component of the proton. Compared to the charm production cross section at FNAL energies

$$\sigma(\pi N \to DX) \simeq 20\ \mu b \quad , \qquad (26)$$

J/ψ production data around 200 GeV give[32]

$$\sigma(\pi N \to \psi X) \simeq 100\ nb \quad .$$

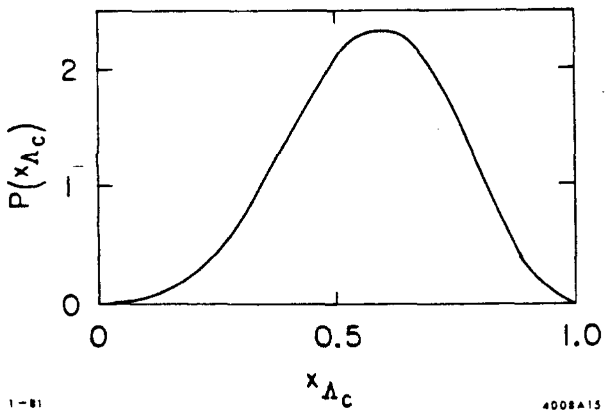

Fig. 11. The x distribution of the Λ_c^+ from the intrinsic charm component of the proton.

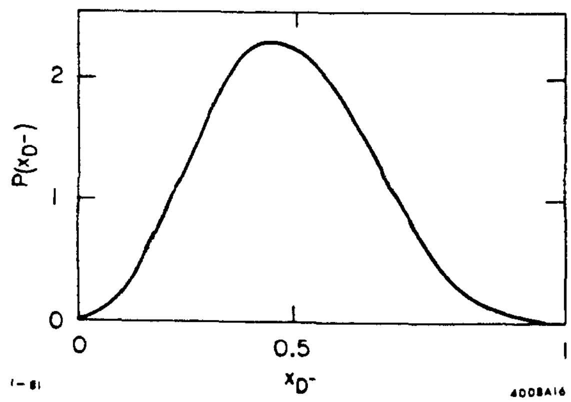

Fig. 12. The x distribution of the D^- from the intrinsic charm component of the proton.

Further, the observed x_F-distribution appears to be more strongly peaked near $x \simeq 0$ compared to what would be expected from the intrinsic charm distribution. Evidently most of the ψ production comes from other central production mechanisms such as gluon and $q\bar{q}$ fusion. In order for the intrinsic charm model to be consistent, there must be a large suppression factor for the ψ production from the intrinsic charm compared to the D production

$$\left.\frac{\sigma(\pi N \to \psi X)}{\sigma(\pi N \to DX)}\right|_{\text{intrinsic charm}} \lesssim 5 \times 10^{-5} \quad . \tag{27}$$

As was shown in Ref. 9, such a suppression factor is obtained using the intrinsic charm wavefunction and taking flavor and color suppression into account.

ii) A simple mechanism for <u>inelastic</u> charm <u>production</u> is gluon exitation of preexisting c-quarks (see Fig. 1c). This process is discussed in Ref. 33.

To study the energy dependence of the "diffraction" mechanism with "intrinsic" heavy quarks we will use the empirical formula for high mass diffraction[34]

$$\frac{d\sigma}{dM^2} = \sigma_0 \frac{1}{M^2} \tag{28}$$

valid for $M^2 \gtrsim 2\ \mathrm{GeV}^2$. The integrated charm cross section is given by

$$\sigma = \sigma_0^c \int_{M_0^2}^{M_1^2} \frac{dM^2}{M^2} = \sigma_0^c \log \frac{(1-x_1)s}{\left(M_{\Lambda_c} + M_D\right)^2} \quad , \tag{29}$$

where in this case M_0^2 is the threshold value for associated production of a pair of hadrons containing charmed quarks. The upper limit M_1^2 is determined from the kinematical relation $M_1^2 = s(1-x_1)$ where x_1 is the lower fractional momentum cut on the recoiling proton. In the ISR $pp \to p_1\Lambda_c X$ experiment[5] one triggers on events with $x_1 \geq 0.8$. If we assume that essentially all the charm cross section $\sigma_c \sim 300\ \mu b$ is due to diffractive production, then we can determine $\sigma_0 = 77\ \mu b$. From this we predict that at SPS and FNAL energies ($s \cong 400$-$600\ \mathrm{GeV}^2$), the total $pp \to$ charm cross section should be of the order of 150 μb. Clearly this prediction is larger than present experimental data at SPS/FNAL with both pion and proton beams.[35] The energy dependence thus seems to be stronger than what is implied by Eq. (29).

Concerning production of heavy quarks on nuclear targets one expects an $A^{2/3}$-dependence from the intrinsic charm model. This is in contrast to the perturbative hard scattering cross section, which should be proportional to A.

As far as the production of b- and t-quarks are concerned, one can argue on general grounds that the probability of a hadron to contain an intrinsic heavy quark pair should fall as

$$P_{Q\bar{Q}} \propto \frac{\alpha_s^2(R^{-2})}{R^2 m_Q^2} \qquad (30)$$

where R is a hadron size parameter. Assuming $\sigma_c \simeq 300$ b, $m_c = 1.5$ GeV, $m_b = 5$ GeV, and $m_t = 20$ GeV and using Eq. (29), one obtains the cross sections for b- and t-quark production as shown in Table I.

Table I. Cross section for b- and t-production at ISR and Tevatron energies from Eqs. (29) and (30). The numbers in parentheses are the conventional perturbative QCD-predictions.

	ISR ($\sqrt{s}$ = 63 GeV)	Tevatron ($\sqrt{s}$ = 2000 GeV)
b	15 μb (0.5)	70 μb (2)
t (m_t = 20 GeV)	0	3 μb (0.1)

7. THE INTRINSIC CHARM AND LEPTOPRODUCTION EXPERIMENTS

An important test of the intrinsic charm content of the proton is the direct measurement of the charm quark distribution in deep inelastic scattering:

$$F_2^c(x,Q^2) = \frac{4}{9}\, x \left[c(x,Q^2) + \bar{c}(x,Q^2)\right] \qquad (31)$$

As is clear from Fig. 10, the intrinsic charm sea is very small compared to the total sea. However, it should be visible in experiments explicitly looking for leptoproduction of charm. This is the case in dimuon production (Fig. 13a)

$$\mu^{\pm}N \to \mu^{\pm}\mu^{\pm}X \qquad (32)$$

where one of the final state muons originates from charm decay.

There are, however, a number of complications:

a) The model dependence of the charm fragmentation function and the associated experimental acceptance corrections.[36]

b) A strong scale-breaking effect associated with a high mass threshold:

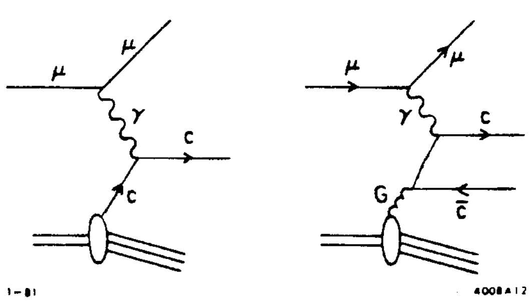

Fig. 13. Lepto-production of charm from the intrinsic charm sea and via the proton-gluon fusion model, respectively.

$$W^2 = (p+q)^2 > W_{th}^2 = (m_D + m_{\Lambda_c})^2 \simeq 17 \text{ GeV}^2 \tag{33}$$

The W^2-threshold enters explicitly in the Bjorken condition. Let x_i^+ be the light cone momentum fractions $x_i^+ = (k_i^o + k_i^3)/(P^o + P^3)$ of the hadronic constituents with $\Sigma x_i^+ = 1$ and $\Sigma k_{\perp i} = 0$. The Bjorken condition for putting the final state on shell (p^--conservation) is then

$$\begin{aligned} \frac{2M_P\nu}{Q^2} = \frac{1}{x_{Bj}} &= \frac{1}{x_c} + \frac{1}{Q^2}\left[\frac{m_{c_\perp}^2}{x_c} + \frac{m_{\bar{c}_\perp}^2}{x_{\bar{c}}} + \sum_{i=u,u,d} \frac{m_{i_\perp}^2}{x_i} - M_P^2\right] \\ &\geq \frac{1}{x_c} + \frac{W_{th}^2 - M_P^2}{Q^2} \end{aligned} \tag{34}$$

Thus, in general, the light cone momentum fraction of the charmed quark is larger than the Bjorken value x_{Bj} with the excess controlled by W_{th}^2/Q^2. Since $c(x,Q^2)$ falls with x, this means that $F_2^c(x_{Bj},Q^2)$ increases with Q^2 for fixed x_{Bj} unless $Q^2 >> 17 \text{ GeV}^2$. The usual rescaling variable

$$\zeta = x_{Bj} + \frac{m_c^2}{Q^2} \tag{35}$$

is incorrect since it ignores the heavy mass of the spectator system.

The EMC-[37] and BFP-data[38] which are binned at fixed x_{Bj} do show significant rise with Q^2. This kinematic effect has to be extrapolated to $Q^2 >> W_{th}^2$ before accurate comparisons with the intrinsic charm distribution can be made. Threshold factors of the form $(1-(W_{th}/W)^2)^n$ may be useful for the parameterization of the data.

c) The c(x)-distribution as measured in deep inelastic scattering at large Q^2 differs from that determined in low momentum transfer hadron-production because of standard QCD-evolution. This tends to further suppress $F_2^c(x,Q^2)$ at large x and Q^2 (see Fig. 14).

The comparison of the intrinsic charm production (see Eq. (19)) with data was done in Ref. 39. The limits on intrinsic charm is $\lesssim 0.5\%$. However, the comparison does not include the threshold suppression from Eq. (34), so that the net result is not inconsistent with the predicted form and 1% normalization of intrinsic charm. A definitive comparison requires a detailed analysis of the scale breaking effects.

A very interesting implication of intrinsic charm for νN and $\bar{\nu}N$ charge current reactions is the production of beauty quarks ($\bar{\nu}c \to \mu^+ b$ and $\nu\bar{c} \to \mu^-\bar{b}$).[9] The subsequent leptonic decay of the b and $\bar{b}$ then leads to same-sign muon pairs (see Fig. 15). The experimentally observed rate of same-sign muon pairs is unexpectedly high, although the different experiments disagree with an order of magnitude.[12] Using the intrinsic charm distribution with present limits on the left handed c-b coupling the c-b process almost agrees with the CDHS data.

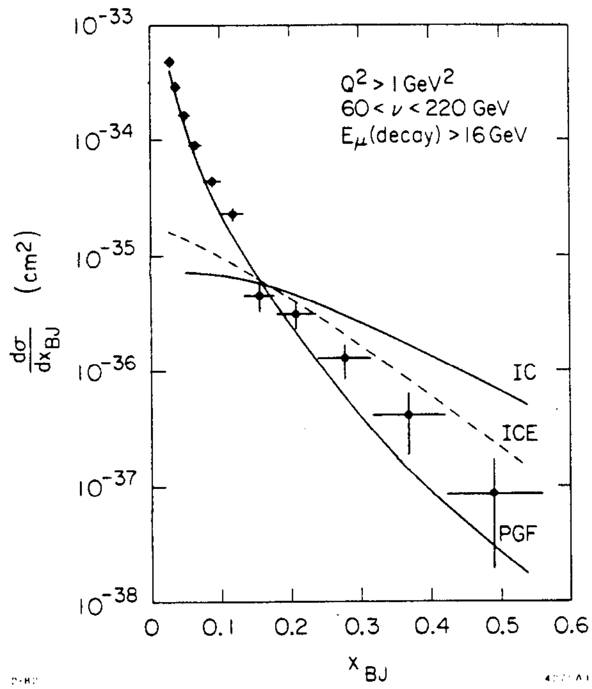

Fig. 14. Variation of $d\sigma/dx_{Bj}$ with x_{Bj} for dimuons in the range $Q^2 > 1$ GeV^2, $60 < \nu < 220$ GeV, decay muon energy >16 GeV. The horizontal bars represent the bin widths. The figure is taken from Ref. 39. The curves are:

PGF: photon-gluon fusion model,
IC: intrinsic charm model,
ICE: intrinsic charm model with maximum Q^2 evolution.

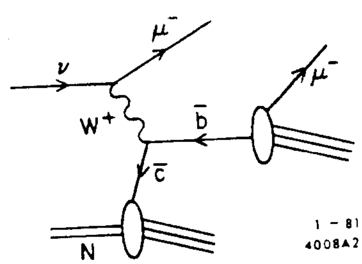

Fig. 15. Same sign dimuon pair production from the intrinsic charm component of nucleons.

8. CONCLUSIONS

There are a number of theoretical and phenomenological issues related to intrinsic charm:

i) Do the Fock states containing heavy quarks have a small transverse dimension? Note that the structure of the energy denominator in Eq. (15) implies that all the quarks in the $|uudc\bar{c}\rangle$ state have larger $k_\perp$ than in the $|uud\rangle$ state.

ii) How much of the strange sea can be attributed to the intrinsic $|uuds\bar{s}\rangle$-Fock state rather than standard evolution? A phenomenological analysis given by R. Phillips[24] gives $P(|uuds\bar{s}\rangle) \approx 0.031$.

iii) What is the correct mechanism for the high energy excitation of the charm component? Note that, in general, gluon (or Pomeron) interactions occur coherently with all the quarks of the nucleon Fock state. In time ordered perturbation theory the charm production can occur before, during, or after the hadronic interaction.

iv) A more detailed calculation on the intrinsic charm wavefunction may be possible in Bag models, lattice calculations or more directly from the QCD equations of motion.[40] The magnitude of the p-Δ hyperfine splitting can give a bound on the intrinsic gluon and $q\bar{q}$ Fock state components.

v) Much more experimental information is needed to unravel the role of the different QCD contribution

a) The x_L-dependence of Σ_c, $\Lambda_{\bar{c}}$, D^0 and D^+. The $\Lambda_{\bar{c}}$ distribution is particularly important since it determines the $\bar{c}(x)$ without complications from valence quark recombination or resonance decays.

b) The physics of intrinsic charm can depend in detail on the nature of the incoming hadron; K, π, p and γ.

c) The threshold dependence, $(1 - s_{th}/s)^n$, of heavy quark production must reflect the nature of the production mechanism.

d) The nuclear A-dependence separates the intrinsic and hard scattering contributions. The A^α-behavior is a function of x; at large x we expect $\alpha = 2/3$.

e) Hidden charm states, χ, ψ, ..., should be seen at some level at large x from the intrinsic charm.

In conclusion, a valence-like charm quark distribution c(x) in the nucleon at the 1% level accounts qualitatively for hadron induced charm production in magnitude, shape and diffractive features at ISR energies. There is no contradiction with the EMC-data on $F_2^c(x)$ provided the appropriate threshold dependence is taken into account.

In any event, the determination of the charm quark distribution is important for understanding the Fock state structure of the hadronic wavefunctions and as a probe of hadron dynamics in the nonperturbative domain.

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