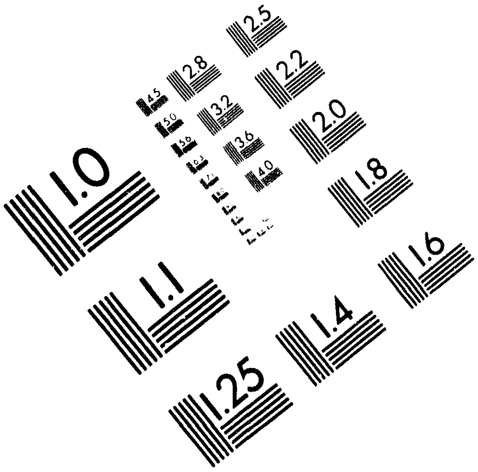

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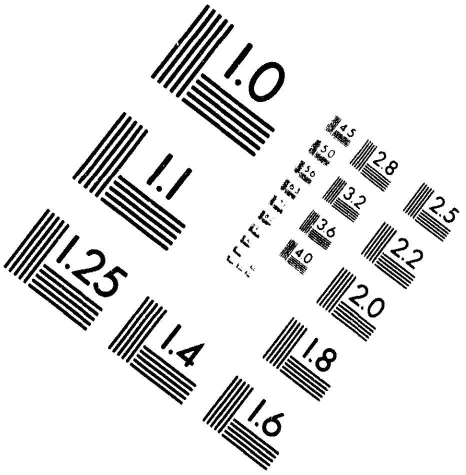

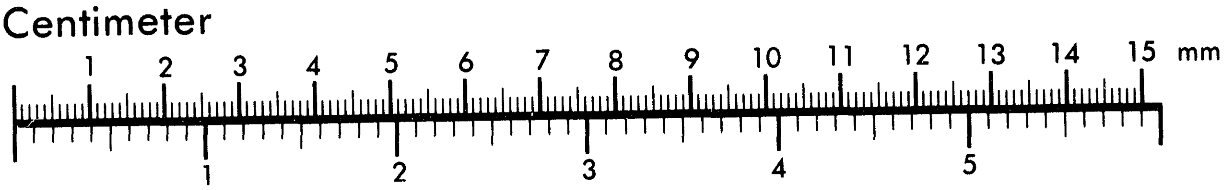

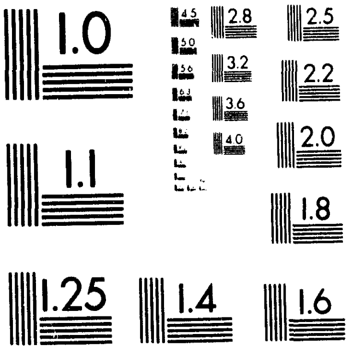

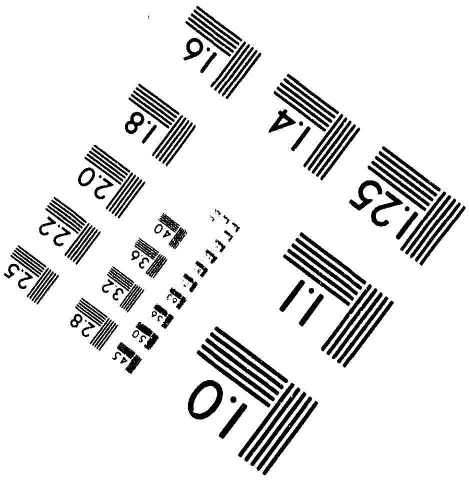

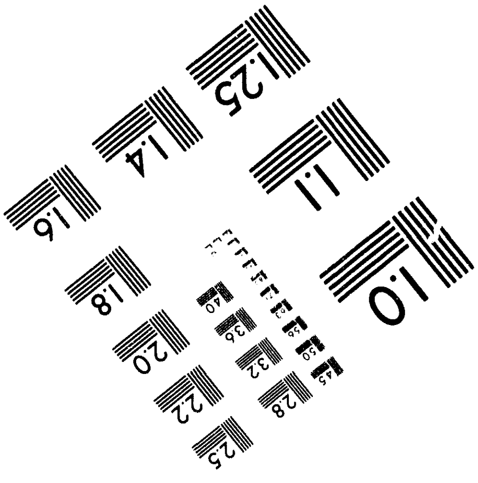

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SUMMARY OF THE WORKING GROUP ON TESTS OF QCD[*]

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Abstract

The working group discussed several topics related to charm production that can provide important input for our understanding of QCD. It was recognized that studies of both open and hidden charm in a high-statistics experiment will be essential in order to understand the production mechanisms. Nuclear effects were also discussed and a connection was made to similar effects observed in other reactions.

1 INTRODUCTION

It has been recognized for some time that charm production is a very important tool for studying QCD. The reason for that is obvious. The charm quark is the lightest of the heavy quarks, heavy enough for perturbative methods to be meaningful and on the other hand light enough that it is readily accessible in fixed-target experiments in large numbers. Charmonium and open-charm states have been studied in hadron–hadron and hadron–nucleus interactions, in real and virtual photon–nucleon processes on free and bound nuclei, in neutrino interactions, and in electron–positron collisions. The wealth of data has lead to significant progress in understanding the fundamental processes that are responsible for charm production and the strong interaction that is behind them. It is equally evident that much more can be learned from an improved study of charm production with much higher statistics. The working group discussed several topics in which the considered high-statistics charm experiment could have an impact in our understanding of QCD. This paper summarizes the subjects that were discussed and a few additional relevant topics. More information can be found in the contributions of the members of the working group and in the references.

In QCD, charm hadroproduction is understood as a hard scattering process between the elementary constituents of the participating hadrons, quarks and gluons, followed by fragmentation and hadronization of the produced charm quarks. The hard process provides the opportunity to test perturbative QCD mechanisms, while the hadronization allows studies of longer-range aspects of the strong interaction. Once the production mechanism is well understood, the process can then provide a measurement of the parton distributions of the

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interacting hadrons. This is of particular interest since the process is dominated, at present energies, by gluon interactions and therefore can provide direct information on the gluon distribution, which is poorly constrained by other types of experiments.

2 TOTAL CHARM HADROPRODUCTION CROSS SECTION

The QCD prediction for the charm hadroproduction cross section is given by an expression of the form

$$\sigma = \sum_{ij} \int \mathrm{d}x_1 \mathrm{d}x_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}(x_1 x_2 s, \mu^2) \quad (1)$$

where $f_i(x_1, \mu)$, $f_j(x_2, \mu)$ are the distributions of the partons i, j participating in the interaction, in the beam and target, respectively, evaluated at some appropriate scale μ, x_1 and x_2 are the momentum fractions carried by the partons, and $\hat{\sigma}$ is the elementary cross section between the partons. Here, s is the hadron–hadron center-of-mass energy, while $x_1 x_2 s$ is the CMS energy for the parton–parton subprocess, which to leading order can be gluon–gluon fusion ($gg \to c\bar{c}$) or quark-antiquark annihilation ($q\bar{q} \to c\bar{c}$). The cross section $\hat{\sigma}$ can be calculated in perturbative QCD, while the parton distribution functions are taken from measurements in other experiments, usually deep inelastic lepton scattering.

Earlier calculations, to leading order in QCD, underestimated the observed cross section, unless a very light (1.2 GeV) charm quark mass was used (see Ref. [1] for a review). Recent, next-to-leading order, calculations reproduce the data both in magnitude and in shape (energy dependence), using a mass of 1.5 GeV; however, the theoretical uncertainties are still substantial. The situation was summarized in the plenary talk by Ridolfi[2].

Recent results from E769[3], at 250 GeV beam energy, provide a much more accurate measurement of the cross section than has been available until now. A precise measurement at 800 GeV can be used as an even more stringent test of the QCD calculations, using the lower-energy data to constrain the absolute normalization, since the shape is less sensitive to uncertainties such as the charm quark mass and the renormalization scale. It may therefore help to discriminate between different sets of parton distributions, especially different gluon densities.

3 HADROPRODUCTION OF OPEN-CHARM STATES

Additional tests of QCD are possible by studying the differential distributions $\mathrm{d}\sigma/\mathrm{d}x_F$ and $\mathrm{d}\sigma/\mathrm{d}p_T^2$ in semi-inclusive production of various charm states, as well as correlations in associated charm–anticharm production. A detailed comparison of theoretical predictions with experimental data was presented by Ridolfi[2]. In general, the distributions agree qualitatively with the theoretical calculations, except that a "leading-particle effect" is seen by several experiments[4][5][6] in D-meson production by pion beams: the distribution of the D that shares a valence quark with the incoming beam pion (D^- for a π^- beam) is harder in x_F. This asymmetry between leading and non-leading particles is not predicted by the perturbative QCD mechanism $gg \to c\bar{c}$, where the c and the $\bar{c}$ have equal probabilities to be produced at high x_F. It can be understood as a "color-drag" effect, where a valence quark from the beam recombines with the produced c or $\bar{c}$ and pulls it along the beam direction. Fragmentation models that include the effect, such as the PYTHIA Monte Carlo, can reproduce the observed asymmetry.

Alternatively, the asymmetry can be explained in terms of an intrinsic-charm component in the beam[7]: a π^- fluctuating into a $|d\bar{u}c\bar{c}\rangle$ state can break up into a D^- or a D^0 ($|d\bar{c}\rangle$ or $|\bar{u}c\rangle$) carrying a substantial fraction of the beam momentum, while no such mechanism exists for the charge-conjugate states D^+ and $\bar{D}^0$. A similar picture arises in the context of the valon model[8] with a significant component of c and $\bar{c}$ quarks in the sea. The upcoming results from the full data sample of the high-statistics experiment E791[6] will allow a detailed comparison of the asymmetry as a function of x_F and p_T with the theoretical predictions of these models. In particular, the intrinsic-charm model predicts that the asymmetry will be predominantly at low p_T, where the heavy and valence quarks are aligned. It will be extremely interesting to search for a similar asymmetry in a future experiment with a proton beam, not only for D production, but also for Λ_c and $\bar{\Lambda}_c$, for which a similar effect would be expected.

An intrincic-charm component in the proton wavefunction would give rise to diffractive production of charm in proton–nucleon interactions. A search for such diffractive production by E653[9] produced an upper limit of 1.8% of the total cross section for D^+ production in p–Si interactions. This does not rule out the intrinsic-charm model of Ref. [7], which predicts a value of about 1.1%. This number should be well within reach of the future charm experiment, if diffractive events can be identified efficiently.

3.1 Fragmentation in Perturbative QCD

The hadronization of a produced charm quark into a bound state is in general a non-perturbative process, due to the small masses of the light quark-antiquark pairs produced in the fragmentation. Several phenomenological models exist that attempt to describe the process. However, it has been recently realized that fragmentation of heavy quarks or gluons into bound states containing two heavy quarks, such as η_c, J/ψ, χ_c, and (the yet unobserved) B_c, can be substantial and in the kinematic region of large p_T, perhaps the dominant mechanism. Because of the large masses involved, this processes should be calculable in PQCD. In fact, there has been a significant amount of work in the last two years in calculating fragmentation functions into heavy-heavy quark systems. This has been motivated in part by the apparent excess of J/ψ production at the Tevatron[10], compared to the expectations from the lowest-order production mechanism.

In this workshop, Cheung presented a model[11], in which the derived expressions for the perturbative fragmentation functions are treated as phenomenological functions with two free parameters that can be fitted to describe the non-perturbative fragmentation of a heavy quark to a heavy-light system. The free parameters are the mass ratio $r = m_{\rm light}/m_{\rm meson}$ of the light quark to the meson, and an overall normalization. The model makes specific predictions about the relative production of different spin states. In the limit $r \longrightarrow 0$, the treatment is similar to the methods of the Heavy Quark Effective Theory.

As an example, the fragmentation fuctions $c \longrightarrow D$ and $c \longrightarrow D^*$ were presented. The observables $P_V = D^*/(D + D^*)$ (the ratio of vector mesons to total), $\langle z \rangle$ (average fractional energy carried by a meson), and $\alpha = (2L - T)/L$ (the spin asymmetry parameter) as a function of z, were calculated and compared with data. Good agreement was obtained with $r = 0.167$ ($m_{\rm light} = 0.3$ GeV) for P_V and $\langle z \rangle$, less good for $\alpha(z)$. The model can be further tested with more data, especially on production rates of P-wave states, and more precise measurements of the spin asymmetry parameter.

4 HADROPRODUCTION OF CHARMONIUM STATES

Even though production of charmonium states is not the main purpose of the experiment considered here, the possibility of a dimuon trigger presents the opportunity to accumulate a very substantial sample of hidden-charm states decaying into two muons. With reasonable assumptions on trigger and reconstruction efficiencies, an experiment with 10^8 fully reconstructed charm decays should also expect to have between 0.5 and 1 million $J/\psi \longrightarrow \mu^+\mu^-$ events[12]. Furthermore, the open geometry of this experiment will also allow it to see charmonium states decaying to additional particles, such as photons and pions, also with high statistics. The importance of charmonium production in testing perturbative QCD processes was stressed by several speakers in the working group.

4.1 Production of χ_c States

Production of the different 1P charmonium states offers a good tool for discriminating among different perturbative production mechanisms. In the color-evaporation model[13], the fundamental hard process, either gluon–gluon fusion or quark–antiquark annihilation, involves a color-octet intermediate state (a single gluon) which decays into a $c\bar{c}$ pair; the color is "evaporated" from the final state through emission of soft gluons that are neglected in the calculation (see Fig. 1, left). The prediction for the relative rates of the three spin states, χ_{c0}, χ_{c1}, and χ_{c2} is simply given by $2J + 1$ (1:3:5). In the color-singlet model[14], on the other hand, the intermediate state is a colorless object, as two gluons couple directly to $c\bar{c}$, or a quark and an antiquark annihilate into two gluons (Fig. 1, right). The predicted relative rates are 3:0:4 for the gluon-fusion subprocess and 0:4:1 for the annihilation subprocess.

During the workshop, Spiegel presented[15] preliminary results from E672 on production of χ_{c1} and χ_{c2} by a 515-GeV π^- beam, detected in the decay channel $\chi_c \longrightarrow \gamma J/\psi$. The ratio of χ_{c1} to χ_{c2} production cross section was 0.6 ± 0.2, consistent with, but more accurate than, earlier results with similar beams. This is what would be expected from the color-evaporation model, either from gluon fusion or quark annihilation. However, the result can

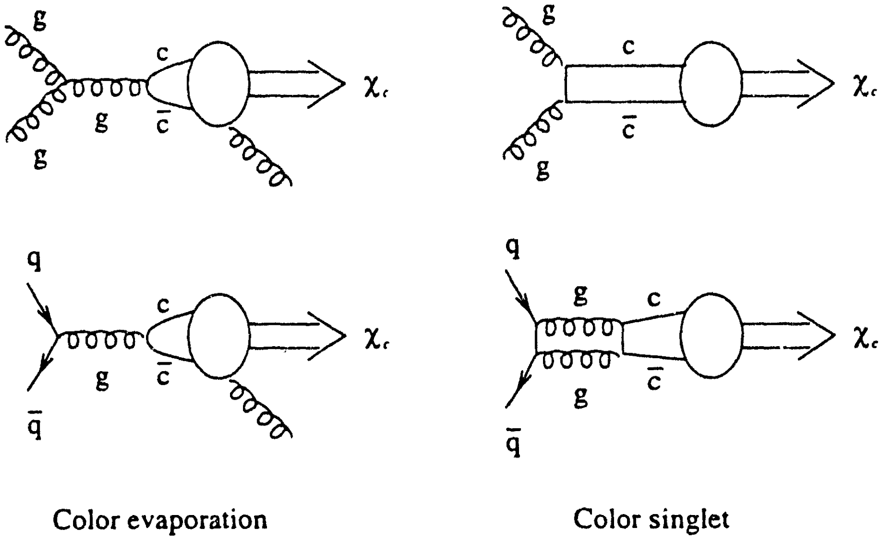

Figure 1: Diagrams for χ_c production in perturbative QCD, in the color-evaporation model (left) and the color-singlet model (right). The top graphs are for gluon-gluon fusion, the bottom ones for quark-antiquark annihilation.

also be understood in the color-singlet model, with the contributions from the two diagrams combining to produce the same ratio.

On the other hand, results from E705[16] with a 300-GeV p beam give a ratio consistent with zero, which seems to exclude the evaporation model and to favor the color-singlet model, dominated by the fusion diagram. However, the evaporation model is ruled out by only 2σ. In addition, it is not clear why both graphs should contribute in the pion experiment, while the gluon-fusion graph dominates in the lower-energy proton experiment. Furthermore, this particular mechanism predicts very little direct J/ψ production, while the experiments see a substantial direct J/ψ component, about 90 nb/nucleon with protons[15]. Clearly, the issue is still far from settled.

A high-statistics charm experiment that combines muon identification and good photon detection will undoubtedly provide important new information, at an energy more than twice that of previous experiments. In addition, higher statistics should allow studies of angular correlations, which can further help discriminate among different mechanisms.

1.2 J/ψ and ψ' Production

As mentioned in the previous section, in addition to the directly produced J/ψ and ψ' states, a substantial fraction of the observed rates is due to the radiative decays of the χ_c states. The fraction of directly produced J/ψ's can provide additional tests of the production mechanism. In the workshop, it was shown by Tang[17] that measurement of the polarization of the produced states provides such a test.

The polarization λ of the J/ψ is determined by the angular distribution of its decay muons in the J/ψ rest frame. This has the form, in the Gottfried-Jackson frame,

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \lambda \cos^2\theta, \tag{2}$$

where θ is the angle between the μ^+ and the projectile direction.

The polarization of the J/ψ was calculated[17], both for the direct component and the contributions from χ_{c1} and χ_{c2} radiative decays (the contribution from χ_{c0} is negligible). Direct production gives $\lambda \simeq 0.25$, while the two χ_c states produce $\lambda \simeq -0.15$ and 0.85, respectively. The result was also shown as a function of x_F and was compared with data from πN interactions. Discrepancies were found between the calculated and the measured values. These discrepancies could not be removed by adjusting the individual subprocess normalizations (K factors) according to the observed cross sections of direct and radiative J/ψ's. It was further argued that the polarization of ψ' should be the same as that of the direct J/ψ. However, the measured value is $\lambda_{\psi'} = 0.02 \pm 0.14$, significantly lower than the expected 0.25. From this discussion, it appears likely that higher-twist contributions, such as those due to an intrinsic charm component in the beam, may be important in the production of the ψ and χ states. More precise data on the production rates and polarizations would be helpful in deciding the merit of the different theoretical arguments.

5 NUCLEAR DEPENDENCE OF CHARM PRODUCTION

One of the outstanding puzzles of charm hadroproduction is the observation of a significant reduction in the per-nucleon production cross section for J/ψ and ψ' on heavy targets[18][19], while no nuclear dependence was seen by several experiments on open-charm production[20][21], consistent with a hard scattering process. If the A-dependence of the cross section is parameterized as A^α, then $\alpha = 1$ implies no nuclear effects, while $\alpha < 1$ ($\alpha > 1$) means nuclear suppression (enhancement). A hard, pointlike process is characterized by $\alpha \simeq 1$, while typical hadronic total cross sections show a dependence close to $\alpha \simeq 2/3$, implying that the interaction takes place mostly on the surface of the nucleus. The two ψ states show a similar nuclear dependence, $\alpha \simeq 0.9$. Understanding the origin of the nuclear effects is very important, not only in order to dissentangle the aspects of charm production that are due to the hard process, rather than a medium influence, but also for the additional information they provide on the strong interaction. In particular, studies of nuclear effects provide the opportunity to investigate longer-range aspects of QCD, using relatively well understood short-range processes.

A tempting explanation for the depletion seen in the ψ cross section in nuclear targets would be a suppression of the gluon sea in a bound, compared to a free, nucleon. Indeed, the ψ data correspond to smaller values of x_2 (see Eq. (1)) than the open-charm production data, obtained at lower beam energies (results from E789[21] with 800-GeV protons were at small x_F and therefore also at larger x_2 than the ψ data). This would imply a nuclear "shadowing" effect for the gluon sea significantly larger than the corresponding effect for the quark-antiquark sea, as seen in Drell-Yan production. However, this explanation probably fails considering the fact that the effect does not appear to scale with x_2, when the results are compared with ones at lower energies[22]. Instead, the effect scales with x_F and is larger at higher x_F.

An alternative explanation is higher-twist terms, due to intrinsic charm, present in the beam, dissociating diffractively in the presence of a nucleus[23]. Since diffraction occurs primarily on the surface, it is characterized by an exponent $\alpha \simeq 2/3$, and the diffractive component reduces the A-dependence of the total cross section from $\alpha = 1$ to a smaller number. In addition, the intrinsic charm component becomes more significant at high x_F, due to the high mass of the charm quark. However, E789 sees no need for such a component in their J/ψ differential cross section as a function of x_F, which can be described in terms of gluon-fusion and quark-annihilation processes exclusively. This can be used to set very stringent upper limits in the contribution from intrinsic charm[18], which not consistent with this model.

In this workshop, Kopeliovich presented a calculation based on final-state interactions of the $c\bar{c}$ state propagating through the nucleus[24]. Naively, this appears to be an unlikely explanation: the ψ' has a radius 4 times larger than J/ψ and the rescattering effects should be more important. Also, one might expect less suppression of the cross section at high x_F, since the faster $c\bar{c}$ pair remains longer, due to time dilation, in its presumably small-sized, color-singlet state, before it evolves into a full-size vector meson and therefore has fewer interactions propagating through nuclear matter, according to the ideas of color transparency. Nevertheless, a detailed calculation of the space-time evolution of the state reveals a much more complicated picture.

In this approach, the effect is closely related to nuclear effects seen in other processes, such as photoproduction of vector mesons and deep inelastic scattering at low x, which can be described as fluctuation of the virtual photon into a $q\bar{q}$ pair, followed by propagation of the pair through the nucleus. Rather than assume a monotonic increase of the quark-antiquark separation with time, the strength of the final state interactions is calculated quantum-mechanically, by expanding the matrix element in a series of all the appropriate intermediate states, including off-diagonal elements (a detailed presentation can be found in a recent review on color transparency presented by Nikolaev[25] and in references therein). The interplay of coherence and formation lengths can lead to an increase or decrease of the cross section, depending on energy and mass scale (corresponding to shadowing and antishadowing in inelastic scattering). The overlap of the initial and final states is also affected by the nodal structure of the first radially excited state, in this case ψ'. The calculation reproduces the observed x_F dependence of the nuclear suppression of the charmonium states fairly well and it also provides a unified description of a large number of similar effects in other processes.

In this model, the similarity in the nuclear dependences of the J/ψ and ψ' hadroproduction cross sections is accidental and is only approximate (in photoproduction, a significant variation is predicted with Q^2). Furthermore, a similar x_F dependence is expected[24] for the nuclear effects in hadroproduction of open charm; however, the overall level of $\alpha(x_F)$ is shifted upwards, so that $\alpha(0) \simeq 1$. This is consistent with all measurements, where no nuclear suppression is seen in the central region. The additional suppression in the production of the charmonium states is due to the total absorption of these states in nuclear matter, while no such channel is available for open charm. This of course can be tested in an experiment with enough statistics at high x_F, if at least two targets with different A are used. Indeed, it is imperative to study any possible nuclear effects in charm production at high x_F where no such data exist, before results from production on heavy targets can be interpreted properly.

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