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CHARM PRODUCTION YIELD FROM TARGET NUCLEI FILTERING INTRINSIC PROJECTILE CHARM

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Abstract

Estimating the process of filtering an intrinsic projectile charm component by a target nucleus as proposed earlier, we obtain upper limits for the cross sections of open charm and J/Ψ . Comparing with experiment, we conclude that this filtering mechanism is not sufficient to explain the observed A^{α}–dependence at large final state momenta.

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1 Nuclear Filter Mechanism for Projectile Charm

The results from various experiments on open ($D\bar{D}$) and hidden (J/Ψ) charm production in hadron–nucleus collisions show some remarkable features [1] – [10]. Going from protons towards heavier target nuclei, the production cross section per nucleon is reduced, especially in the large x_F domain. The inclusive J/Ψ production cross section is usually parametrized in the form

$$\frac{d\sigma}{dx_F}(hA \to J/\Psi\, X) = \frac{d\sigma}{dx_F}(hN \to J/\Psi\, X) \cdot A^{\alpha} \tag{1}$$

and similarly for the $D\bar{D}$ production. The data reveal clearly that the value of α decreases from $\alpha \simeq 1$ at low x_F to $\alpha \simeq 0.75$ at $x_F = 0.8$. This trend cannot be understood within the perturbative QCD calculation, since the last gives always an A^1 dependence. In contrast to this observation, the experimental results on Drell–Yan muon pairs show a clear A^1–dependence [11] as is expected from perturbative QCD. Assuming the perturbative nature of the production mechanism also for the J/Ψ , final state interaction effects have been studied, but they seem unable to explain the observed trend of the data as well [12,13].

One might argue that a perturbative calculation is not applicable at high x_F values. In this case, some model is required to explain the observed behavior of charm production cross sections. Recently, Brodsky and Hoyer proposed the possibility of charm particles to originate from the intrinsic projectile charm component [14]. They expanded the projectile hadron state vector, say for a pion, in terms of those of constituents as

$$|\pi\rangle = \alpha_0|q\bar{q}\rangle + \alpha_g|q\bar{q}g\rangle + \sum_{f=u,d,s,c,b} \alpha_f|q\bar{q}f\bar{f}\rangle + \cdots \tag{2}$$

which shows that the incident pion has some amplitude α_c to contain a virtual $c\bar{c}$–pair. Due to its mass, the pair has a small space–time extension ($r \sim 1/2m_c$). In a high energy collision, the larger parent hadron surrounding the virtual pair may be stripped off by the target nucleus, turning it into a real pair. In other words, the target nucleus acts as a filter of the projectile charm content. Since this effect is expected to be proportional to the geometrical transverse area of the target nucleus, the resulting cross section is related to the hadron-nucleon cross section as $\sigma(hA \to c\bar{c}) = \sigma(hN \to c\bar{c}) \cdot A^{\frac{2}{3}}$. The mechanism works most effectively as long as the relative phases of the expansion amplitudes (2) do not vary significantly during the interaction, restricting its applicability to short interaction times and charm pairs carrying a large momentum fraction.

The suggested mechanism seems to be qualitatively consistent with the observed $A^{\frac{2}{3}}$–dependence of the cross section for large x_F values. Combining with perturbative charm production (A^1), dominating at low x_F, we may expect that a complete picture is obtained that can account for the trend of the data.

The purpose of this letter is to study whether this remains true when turning the idea in a more quantitative form.

2 Charm Production Estimation

– *Momentum validity range.*

The condition of the expansion (2) to be 'frozen' during the interaction with the nucleus requires the lifetime of the virtual pair, $\tau_c \approx \hbar/2m_c$, to be larger than the time of interaction with the target nucleus. The interaction time is estimated using the pion mean free path in nuclear matter, λ_π, to be $t_{\text{in}} \approx \lambda_\pi/\gamma c$ (in the $c\bar{c}$ frame). With the pion inelastic cross section, $\sigma^{in}_{\pi N} \approx 30$ mb, we estimate $\lambda_\pi = (\sigma^{in}_{\pi N} \cdot \rho)^{-1} \approx 2$ fm. The condition $\tau_c \geq t_{\text{in}}$ leads to $\gamma \geq 30$. Accordingly, the minimum momenta needed for this mechanism to be effective is $p^\pi_{\text{min}} = 4$ GeV/c for pions. This does not restrict the applicability of the proposed intrisic charm filtering mechanism (ICF) to the existing experimental data. The same is true for proton projectiles. Here we restrict ourselves to consider pions only.

– *Intrinsic charm component.*

In order to get a rough upper limit on the probability of finding intrinsic projectile charm,

we use the approximate expansion $|\pi\rangle \approx \alpha_g|q\bar{q}g\rangle + \sum_{f=u,d,s,c} \alpha_f|q\bar{q}f\bar{f}\rangle$ for the pion projectile. From the uncertainty principle, the probability of finding a pair with given flavour scales inversely with its mass, $|\alpha_1/\alpha_2|^2 = m_2/m_1$. Using the completeness relation $\sum_i |\alpha_i|^2 = 1$ and the schematic values $m_g = m_{u\bar{u}} = m_{d\bar{d}} = m_\pi, m_{s\bar{s}} = m_\phi, m_{c\bar{c}} = m_{J/\Psi}$ gives an upper limit of $|\alpha_c|^2 \leq 1.4\%$.

A different estimation of the upper limit for $|\alpha_c|^2$ can be obtained from the high momentum component, corresponding to the $c\bar{c}$ mass, of the measured proton form factor. This gives a upper limit of the same order.

A more careful analysis has been performed by the EMC collaboration [15], leading an upper limit of $|\alpha_c|^2 \leq 0.59\%$. We will use this value in the following.

– *Liberating the intrinsic $c\bar{c}$–pair.*

Since the $c\bar{c}$–pair is virtual and very heavy, its spatial extension during the collision is very small compared to the rest of the projectile hadron. As stated before, one therefore expects the target nucleus to be (almost) transparent to the $c\bar{c}$–pair while it will absorb the larger parent hadron.

To put this idea in more quantitative terms, we treat the $c\bar{c}$–pair (c) and the rest of the projectile hadron (h) as a coupled system (c – h). Since the time of interaction in question is very short (≤ 0.1 fm/c), we can neglect the intrinsic dynamics of each of the components. The coupling is taken in first order as a harmonic oscillator, characterized by the system size $\langle r^2_{c-h}\rangle^{\frac{1}{2}}$. The system is in its ground state before scattering. A transition to any excited state caused by the interaction with the target is interpreted as the liberation of the intrinsic charm pair from its parent hadron.

Using the absorption model from [13] to evaluate the time evolution of the system while interacting with the nuclear gluonic fields, we can compute the probability of c – h to survive, i.e. to remain in its ground state. A numerical calculation with appropriate parameter values describing an intrinsic pion charm component leads to a value of $P^{c-h}_{\text{sur}} \approx 0.2$, averaged over the target nucleus volume ($A \sim 200$).

This result states that the charm liberating probability is $P_{\rm lib} = 1 - P_{\rm sur}^{c-h} = 0.8$ and increases further to $P_{\rm lib} = 1$ in the case of no interaction between the components c,h. So it confirms the qualitative image that the parent hadron is almost certainly stripped off by the target nucleus, liberating the intrinsic c$\bar{\rm c}$–pair.

– ***Production rate for open charm.***

So far, we have an estimate of the probability to liberate the projectile intrinsic c$\bar{\rm c}$–pair in a collision by absorbing the parent hadron. From the point where it is set free, it may interact with the residual nucleon before it is distributed into final states.

For open charm states, we do not need to account for further nuclear interactions downstreams since they merely alter the probability of obtaining different open charm states, while we are interested in the total number of D$\bar{\rm D}$'s only. Since the contribution of bound charm states in the expansion of the liberated charm pair is marginal (see below) and we are interested in an upper limit only, we simply assume the charm pair to turn entirely into D$\bar{\rm D}$ final states, $P_{c\bar{c}\to DD} = 1$.

The probability of the incoming pion to produce a D$\bar{\rm D}$ pair via this ICF mechanism is obtained by multiplying the estimates of the different parts of the mechanism. Using the values for the upper limits we obtained before leads the overall upper limit for the probability of open charm production

$$P_{DD}^{\rm ICF} = |\alpha_c|^2 \cdot (1 - P_{\rm sur}^{c-h}) \cdot P_{c\bar{c}\to D\bar{D}} = 4.7 \cdot 10^{-3}\,. \qquad (3)$$

We turn this into a production cross section using the geometrical transverse area of the target nucleus, $S = \pi r_0^2 A^{\frac{2}{3}}$, and writing the nucleus cross section as $\sigma(hA) = \pi r_0^2 P^{\rm ICF} A^{\frac{2}{3}} = \sigma_0^{\rm ICF} A^{\frac{2}{3}}$. This leads to the result for the open charm the cross section

$$\sigma_0^{\rm ICF}(D\bar{D}) = 180\,{\rm nb} \qquad (4)$$

which is our upper limit on the open charm production expected from the ICF, integrated over the momentum range where this mechanism is effective.

Note that, in order to get an upper limit, the pion intrinsic charm can be simply assumed to be liberated entirely, without having uncertainties in estimating the detailed mechanism. Then the cross section of a pion to yield a charm final state can be estimated from the measured inelastic pion cross section to be $\sigma^{\rm ICF} = \sigma_{\pi N}^{in} \cdot |\alpha_c|^2$ which gives the same value as (4) [16].

– ***Production rate for J/Ψ .***

For a J/Ψ as final state, we remind that the interaction of the almost pointlike c$\bar{\rm c}$–pair with the nucleus is small since it is an almost pointlike particle. Let us write the probability for the c$\bar{\rm c}$–pair turning into a physical J/Ψ as

$$P_{c\bar{c}\to J/\Psi} = |\langle J/\Psi\,|c\bar{c}\rangle|^2 \cdot r(A) \qquad (5)$$

where the first factor is the probability of finding the physical J/Ψ state in the initial (liberated) charm pair, and r is a target–A dependent reduction factor due to absorption of the state in the residual nuclear volume, turning the J/Ψ into higher excited states.

For simplicity, let us take the c$\bar{\rm c}$–pair wave function as a gaussian with a width corresponding to the c$\bar{\rm c}$ separation at the instant it becomes a real pair, $r_{c\bar{c}} \sim \hbar c/2m_c$. The J/Ψ wave function is described by a gaussian as well, the width corresponding to the physical size $\langle r_{J/\Psi}^2\rangle^{\frac{1}{2}} = 0.45$ fm. In this case, we obtain the projection to be $|\langle J/\Psi\,|c\bar{c}\rangle|^2 = 2.2\%$. Using the beforementioned absorption model, the reduction of J/Ψ 's is calculated to be $r \approx 0.9$ ($A \sim 200$), confirming that the c$\bar{\rm c}$–pair set free in one point is hardly affected by the remaining nuclear matter it has to transverse.

The probability to obtain a J/Ψ from the liberated charm pair is so found to be $P_{c\bar{c}\to J/\Psi} = 2\%$.

The upper limit for the probability to find a J/Ψ in the final state from the incident pion via ICF is

$$P^{\rm ICF}_{J/\Psi} = |\alpha_c|^2 \cdot (1 - P^{c-h}_{\rm sur}) \cdot P_{c\bar{c}\to J/\Psi} = 9.4 \cdot 10^{-5}\,. \qquad (6)$$

Proceeding as before, we obtain an upper limit for the x-integrated J/Ψ production cross section,

$$\sigma_0^{\rm ICF}(J/\Psi) = 3.6\,{\rm nb}. \qquad (7)$$

3 Comparison with experiment

To compare the quantitative estimate with experiment, we need to specify what fraction of the measured cross section is due to the ICF–mechanism. For this, we refer to the detailed analysis of NA3 [8] that measured the differential cross section, determining the fraction of J/Ψ 's produced by 'conventional' perturbative mechanism (hard scattering process, $\sim A^{0.97}$) and of nonperturbative ('diffractive') component ($\sim A^{0.77}$). The fraction of the 'diffractive' component was determined to be $\sigma_d/(\sigma_h+\sigma_d) = 0.18 \pm 0.03$ for all pion energies in the range of 150 – 280 GeV/c. Therefore, a candidate for the nonperturbative mechanism as ICF must account for 18% of the total cross sections. Since the differentiation J/Ψ – D$\bar{\rm D}$ only occurs in the final state, this fraction should be the same for the case of open charm production. This argument is supported by experimental results that show the same x_F-dependence of α for both final states [3,5].

The NA27 experiment, using a π^-–beam at 360 GeV/c, determined the open charm cross section to be $\sigma(D\bar{D}) = (15.8 \pm 2.7)\mu$b [2]. Other experiments agree with this result (for an overview, see [5]). The diffractive part of the cross section, for which a nonperturbative mechanism has to account, is $\sigma(D\bar{D}) = (2.8 \pm 0.5)\mu$b. This is the value to be compared with the upper limit on open charm supplied by ICF, $\sigma(D\bar{D}) = 0.18\mu$b, which differs from the one extracted from experiment by an order of magnitude.

For the J/Ψ , the total production cross section has been measured by NA3 with the result $\sigma(\pi N \to J/\Psi\, X) = (99 \pm 11.6)$ nb, in agreement with other experimental results [9]. Towards higher beam energies, the cross section is increased [10], but we restrict ourselves to the momentum range where the contribution of the diffractive component was determined by NA3. This result leaves for the nonperturbative component a fraction of $\sigma(\pi N \to J/\Psi\, X) = (17.8 \pm 2.1)$ nb. The upper limit on this cross section via the ICF–mechanism is $\sigma^{\rm ICF}(\pi N \to J/\Psi\, X) = 3.6$ nb. Again, the ICF value is substantiallly lower than the experimental one.

In this note, we estimated quantitatively the contribution of intrinsic components of the projectile hadron to the charm production according to the ICF mechanism. Accepting the EMC experimental upper limit of measured intensity of intrinsic charm component, we conclude that the mechanism fails to explain the observed magnitude of the charm production cross section. The upper limit to the production yield via the ICF mechanism is estimated to be by an order of magnitude less than the measured diffractive charm production cross section, indicating that this mechanism cannot represent the latter one entirely. Consequently, it cannot reproduce the A^α–dependence in the high x_F–range as well. It might still produce some small effects detectable experimentally, but it leaves open the question for the nature of the diffractive production mechanism for the charm particles.

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