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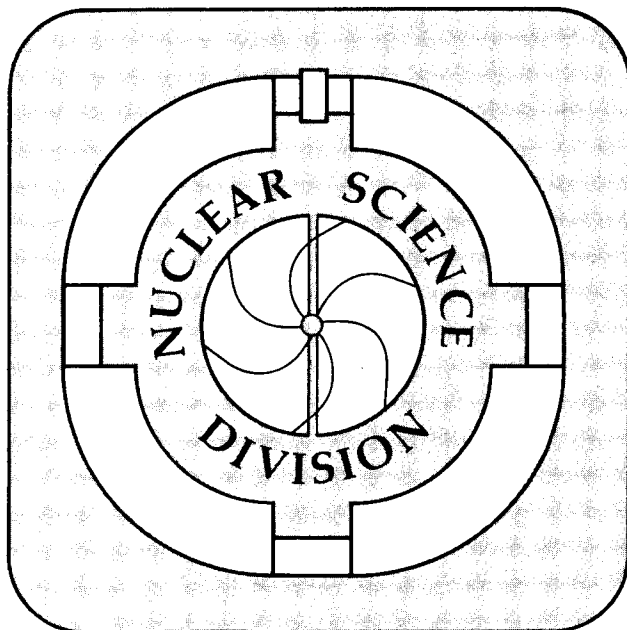
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NUCLEAR SCIENCE DIVISION

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Subnuclear shadowing effect on the J/ψ production *

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Abstract

A model for the J/ψ production in hadron-nucleus and nucleus-nucleus collisions is presented. It takes account of the finite-energy constraint along with the requirement of unitarity. Two extreme regimes are found for which the J/ψ - production cross section have a different behaviour with the nuclear mass numbers. The regime for low values of A is responsible for the deviations from linearity observed in hA collisions, while the large AB regime explains the strong suppression observed in high-E_T nucleus - nucleus events. The phenomenological implications of the model are discussed.

1 Introduction

The search for the Quark-Gluon Plasma (QGP) is one of the greatest challenges with which today's high energy physicist are faced. From the theoretical point of view, the most difficult problem consists in specifying how this new state of matter can be recognized, in other words, finding reliable signatures of the QGP formation. Matsui and Satz suggested in 1986 [1] that the high density of colour charges in the QGP would prevent charmed and anticharmed pairs of quarks from creating a bound state. This effect is known as colour screening. The failure in forming $c\bar{c}$ bound states would be translated into a reduction in the number of J/ψ particles in the final state. Shortly after this signature was proposed, the NA38 Collaboration reported that a significant decrease of the ratio of the resonant $\mu^+\mu^-$ production cross section in the region of the J/ψ mass to the continuum of Drell - Yan $\mu^+\mu^-$ production in nucleus A - nucleus B collisions ($R = \sigma^{AB \to \psi}/\sigma^{AB \to (\mu^+\mu^-)_{DY}}$) was observed in events with a large transverse energy (i.e., central collisions)[2]. Nonetheless, before we ca assume that what NA38 has found is a signal of QGP formation, we must investigate all other possible sources of this phenomenon.

A necessary step to understand the J/ψ suppression in nucleus - nucleus collisions is the investigation of the J/ψ production in hadron - nucleus collisions. It was known before NA38 data came out, that the hadron - nucleus J/ψ production cross section is not linear with the atomic mass number of the nucleus (A)[4]. Besides, it is reasonable that J/ψ particles have to be created by a hard parton - parton fusion process in order to generate the large J/ψ mass. This was in contradiction to the common belief that all hard processes should be linear with A as a consequence of the factorization property. A first explanation of this phenomenon was outlined by the NA3 Collaboration in terms of J/ψ absorption within the nuclei via inelastic J/ψ - nucleon collision. This interpretation cannot explain why the J/ψ suppression in hadron-nucleus collisions becomes stronger as x_F approaches 1. This fact has lead the NA3 Collaboration to assume that a fraction of the J/ψ 's is produced by another mechanism different from parton-parton fusion. They called this mechanism diffractive and found that in order to fit the data, the cross-section has to be proportional to A^β , with $\beta = 0.77 \pm 0.01$ for incident pions and $\beta = 0.71 \pm 0.01$ for incident protons. The relative contribution of this diffractive component to the total cross-section was estimated to be 0.18 ± 0.03 for incident pions at all energies and 0.29 ± 0.06 for incident protons at $200\,GeV/c$; both results have been obtained after integrating over $x_F > 0$. In ref. [3] we extracted the value of the absorptive J/ψ - nucleon cross section ($\sigma_{abs}^{\psi N}$) necessary to obtain the behaviour observed in pA collisions and we used it to interpret the NA38 data, but we couldn't get the right suppression for the different E_T bins. We pointed out that the

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contribution from another component of the J/ψ production that behaves with A as $A^{0.71}$ has to contribute as much as 50% to obtain results in accordance with the data. On the other hand, it is difficult to justify, on physical grounds, the large value of $\sigma_{abs}^{\psi N}$ (4 mb) obtained [4].

Other interesting works have been published which try to explain the phenomenon of the J/ψ suppression as a consequence of the inelastic interactions of some of the produced $c\bar{c}$ pairs with secondary hadrons [5,6] or comoving partons [7]. Similar problems are present in these cases when the values of the corresponding absorption cross sections and of the secondary particles or comoving partons have to be justified. Besides, one should expect o wrong x_F dependence of the J/ψ production, since it is natural to assume that fast $c\bar{c}$ pairs, that would lead to large-x_F J/ψ particles, are less likely to find secondary hadrons or comoving partons in their way.

A model constructed to explain the J/ψ production in nuclear collisions must take several things into account. The dependence of $\sigma^{hA \to J/\psi}$ on A has been commonly parametrized with a function of the form A^α, being $0 < \alpha < 1$; nevertheless, a much better fit is obtained with a monotonically decreasing quadratic function of the form $\sigma^{hA \to J/\psi} = kA - k'A^2$ [8], with k and k' positive. Since this expression gives negative values for the cross section when A is large enough, we are forced to admit that it may only be an approximation to a positive definite function valid only when $k'A/k$ is small. On the other hand, NA3 and NA38 data suggest that the behaviour of the J/ψ production cross section has another limiting case. This occurs when the number of participating hadrons is large due to the centrality of the collision, giving a dependence of $\sigma^{hA \to J/\psi}$ ($\sigma^{AB \to J/\psi}$) on the nuclear size of the form $A^{2/3}$ ($(AB)^{2/3}$). This new regime becomes more evident for events containing a large-x_F J/ψ particle. Therefore, a goal of the model should consist in reproducing these two distinct behaviours. It must also explain the x_F and Q_T dependence of the J/ψ production as well as the dependence on the energy of the collision.

The purpose of this letter is to present a model that has all the features mentioned above and whose basic ingredients are unitarity and energy constraints. I gave the name of subnuclear shadowing to the effect since all the treatment is similar to that employed in the study of nuclear shadowing [9]. Nevertheless, it should not be confused with the shadowing effect discussed by Brodsky et al. [10] which refers to the modifications of the parton structure functions due to nuclear interactions.

Next section is dedicated to the exposition of the model and it is followed by section 3 in which its phenomenology is discussed. Finally, the letter ends with a section containing the conclusions and some remarks.

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2 The Model

Most of the previous works on this subject have disregarded all possible energy constraints on the J/ψ production. This is due to the small value of the J/ψ mass (M_ψ) compared with the usual values of the collision energies. Nevertheless, we have to take into account that typical parton structure functions have a pole at $x = 0$. This makes it difficult for a parton from the projectile to combine with another one from the target to form a system with energy above the J/ψ mass threshold. Simple models can be formulated to test this assertion. For instance, let us assume that the structure functions of quarks and antiquarks are proportional to $1/\sqrt{x}$, and those for the remaining diquarks are proportional to $(1-x)^{3/2}$. Even though these assumptions are unrealistic and have been taken in this way for convenience, we can have indications of how kinematical constraints work. With this simple minded model, we obtain that for proton-proton collisions at $\sqrt{s} = 20\,GeV$ the ratio of the probability of finding a $q\bar{q}$ pair with center of mass energy larger than $3.6\,GeV$ to the same probability with a threshold of $3\,GeV$ decreases significantly with the centrality of the collision. In fact this ratio gives 0.13 when the protons are assumed to be composed of valence quarks only, and 0.08 when an extra $q\bar{q}$ pair from each proton sea take part in the interaction (central collisions). More realistic models should give us an even greater decrease of the above ratio since parton structure functions in a hard process present steeper poles at the origin ($1/x$). On the other hand, it is clear from NA38 data that the strongest suppression is observed in kinematical regions where finite-energy effects are important, i.e. around the tail of the E_T distribution.

Unitarity is another property that must be fulfilled by the model. If we study a particular hard process in a hA collision experiment, we have to consider that factorization seems to imply that the cross-section has to be proportional to A. Nevertheless, unitarity makes this linear relation to break down under certain conditions which are favoured by the presence of kinematical constraints.

Let us remind ourselves that a high energy nucleus-nucleus collision is commonly assumed to be a consequence of an independent superposition of nucleon-nucleon interactions. A good treatment of the problem is given by the optical approximation to the Glauber-Gribov model which ensures unitarity in a natural way [9]. In this context, the nucleus-nucleus inelastic cross-section is given by:

$$\sigma_{AB} = \int d^2\vec{b}\,[1 - (1 - \sigma_{NN}T_{AB}(\vec{b}))^{AB}] \quad , \tag{1}$$

where $\vec{b}$ is the relative position of the nuclei on the impact parameter plane, σ_{NN} is the nucleon-nucleon inelastic cross-section, and $T_{AB}(\vec{b})$is the profile function defined as:

$$T_{AB}(\vec{b}) = \int d^2\vec{s}\, T_A(\vec{s}) T_B(\vec{b} - \vec{s}) \qquad ; \qquad (2)$$

$$T_A(\vec{b}) = \int dz\, \rho_A(\vec{b}, z) \qquad . \qquad (3)$$

Here ρ_A represents the nucleon-probability density inside the nucleus.

Expression (1) can be expanded in terms of contributions from all possible configurations, each characterized by the number of participating nucleons from each nucleus and the number of nucleon-nucleon inelastic interactions. The corresponding expression for pA collisions is obtained by substituting $T_A(\vec{b})$ for $T_{AB}(\vec{b})$ in (1) and A for AB in the exponent. This model can be applied to the study of cross-sections characterized by a certain criterion (generally called criterion C) which is defined by saying that a nucleus-nucleus collision satisfies the criterion if at least one nucleon-nucleon subcollision satisfies it. One such a criterion might be the occurrence of a given hard process. The cross-sections of these events are obtained from (1) substituting the cross-sections of nucleon-nucleon collisions satisfying the criterion, σ_C, for σ_{NN}.

Two major assumptions have been made: The independent superposition of nucleon-nucleon collisions and the absence of energy constraints. Expression (1) has been obtained disregarding any possible variation of σ_{NN} due to the existence of multiple nucleon-nucleon collisions. In this case, this shouldn't matter very much since any possible thresholds for inelastic collisions are way too small compared with typical collision energies.

It is also clear from eq. (1) that linearity with AB is attained when $\sigma_{NN} T_{AB}(\vec{b}) \ll 1$. Besides, a behaviour of the type $(AB)^{2/3}$ ($A^{2/3}$ in pA) should be observed when $(1 - \sigma_{NN} T_{AB}(\vec{b}))^{AB} \ll 1$ which corresponds to the behaviour of a surface term. This last condition is fulfilled when $\sigma_{NN} T_{AB}(\vec{b})$ and/or AB are large.

In order to formulate our model we have to take into account that hard interactions take place at the parton level. We have to consider also the energy constraints mentioned above. Parallel to the Glauber-Gribov model, we can assume that J/ψ production in hadron-nucleus and nucleus-nucleus collisions is due to an independent superposition of parton-parton interactions, namely $q\bar{q} \rightarrow c\bar{c}$ and $gg \rightarrow c\bar{c}$. This is very different from what happens in soft hadronic collisions, in which case the interaction region is comparable to the hadronic sizes and factorization can not be applied. So, let us think of a hadron in hadron-hadron collision (a-b collision), as composed of n_q quarks, $n_{\bar{q}} = n_q - 3B$ (B being the baryon number) antiquarks and n_g gluons. If we neglect fluctuations of parton-parton $\rightarrow J/\psi$ cross-sections ($\sigma_{q\bar{q}}$ and σ_{gg}) due to the structure function and take them as effective values, we can write the following expression for the $ab \rightarrow J/\psi$ cross-section:

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$$\sigma^{ab \to J/\psi} = \sum_{n_q^a} \sum_{n_q^b} \sum_{n_g^a} \sum_{n_g^b} P(n_q^a, n_g^a) P(n_q^b, n_g^b) \sigma_{ab}^{n_q^a, n_g^a, n_q^b, n_g^b} \qquad . \tag{4}$$

Here $P(n_q, n_g)$ is the probability of having those values for the parton composition of the hadron, and $\sigma_{ab}^{n_q^a, n_g^a, n_q^b, n_g^b}$ is given by:

$$
\begin{aligned}
\sigma_{ab}^{n_q^a, n_g^a, n_q^b, n_g^b} &= \int d^2\vec{b}\,[1 - (1 - \sigma_{q\bar{q}} t_{ab}^{(q)}(\vec{b}))^{n_q^a n_q^b}] + \int d^2\vec{b}\,[1 - (1 - \sigma_{q\bar{q}} t_{ab}^{(q)}(\vec{b}))^{n_{\bar{q}}^a n_q^b}] + \\
&+ \int d^2\vec{b}\,[1 - (1 - \sigma_{gg} t_{ab}^{(g)}(\vec{b}))^{n_g^a n_g^b}] \qquad .
\end{aligned}
\tag{5}
$$

Here $t_{ab}^{(q)}(\vec{b})$ ($t_{ab}^{(g)}(\vec{b})$) is defined as $T_{AB}(\vec{b})$ of equation (1), using now the quark (gluon) probability density inside the hadron; in this respect, I have neglected differences between valence quarks, sea quarks and sea antiquarks. These parton profile functions have to incorporate the kinematical constraints of the system which are expected to be important due to the large J/ψ mass, so they have to be interpreted as the convolution of the parton-probability densities on the impact parameter plane, and have to be normalized to the probability that a pair of partons have the energy required to produce the desired final state. In order to understand the meaning of eq.'s (4) and (5) let's study the case when $\sigma_{q\bar{q}} t_{ab}^{(q)}(\vec{b}) \ll 1$ and $\sigma_{gg} t_{ab}^{(g)}(\vec{b}) \ll 1$ by neglecting higher order terms in the expansion of $\sigma^{ab \to J/\psi}$ in powers of these two quantities:

$$
\begin{aligned}
\sigma^{ab \to J/\psi} &\simeq \sigma_{q\bar{q}} < n_q^a n_{\bar{q}}^b + n_{\bar{q}}^a n_q^b > -\frac{1}{2}\tau_{q\bar{q}}^2 \sigma_{q\bar{q}}^2 < n_q^a n_{\bar{q}}^b(n_q^a n_{\bar{q}}^b - 1) + n_{\bar{q}}^a n_q^b(n_{\bar{q}}^a n_q^b - 1) > + \\
&+ \sigma_{gg} < n_g^a n_g^b > -\frac{1}{2}\tau_{gg}^2 \sigma_{gg}^2 < n_g^a n_g^b(n_g^a n_g^b - 1) > \qquad .
\end{aligned}
\tag{6}
$$

Here $< ... >$ means average over all parton configurations and

$$\tau_{q\bar{q}}^2 = \int d^2\vec{b}\,[t_{ab}^{(q)}(\vec{b})]^2 \quad , \quad \tau_{gg}^2 = \int d^2\vec{b}\,[t_{ab}^{(g)}(\vec{b})]^2 \qquad . \tag{7}$$

These coefficients have dimensions of $(area)^{-1}$, and it is obvious from (6) that its inverse has to be the characteristic overlapping area between two hadrons in a $ab \to J/\psi$ event weighted with the probability of finding a pair of partons with energy enough to produce a J/ψ (s_{ov}). This s_{ov} can be related to the single and double J/ψ production (σ_ψ, $\sigma_{\psi\psi}$) to the lowest order in these two quantities in a simple manner:

$$\frac{s_{ov}}{s_h} \simeq \sqrt{\frac{\sigma_{\psi\psi}}{< n_q^a n_{\bar{q}}^b + n_{\bar{q}}^a n_q^b + n_g^a n_g^b - 1 > \sigma_\psi}} \qquad , \tag{8}$$

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where s_h is the transverse hadron area. All this suggest that the quadratic terms in eq. (6) have a clear interpretation as screening corrections. This correction would be completely negligible if there were no energy constraints, since in that case s_{ov} would be the real overlapping area with dimension of the order of s_h, making $\tau_{pp}^2 \sigma_{pp} \rightarrow 0$ (subindices pp stand for both $q\bar{q}$ and gg).

When we move from hadron-hadron collisions to nucleus-nucleus (hadron-nucleus) we have to change two things. First of all, we have to replace $t_{ab}(\vec{b})$ by $t_{AB}(\vec{b})$ $(t_A(\vec{b}))$ obtained from the parton-probability density inside the nucleus, which has to be the convolution of the parton-probability densities in a nucleon with the nucleon-probability density in the nucleus. Second, the number of participating partons will be proportional to AB (A). The expression for the corresponding cross-section is:

$$
\sigma^{AB \rightarrow J/\psi} = \sum_{n_q^a} \sum_{n_q^b} \sum_{n_g^a} \sum_{n_g^b} P(n_q^a, n_g^a) P(n_q^b, n_g^b) \times
$$

$$
\times \{ \int d^2\vec{b}[1 - (1 - \sigma_{q\bar{q}} t_{AB}^{(q)}(\vec{b}))^{AB n_q^a n_q^b}] + \int d^2\vec{b}[1 - (1 - \sigma_{q\bar{q}} t_{AB}^{(q)}(\vec{b}))^{AB n_q^a n_q^b}] +
$$

$$
+ \int d^2\vec{b}[1 - (1 - \sigma_{q\bar{q}} t_{AB}^{(g)}(\vec{b}))^{AB n_g^a n_g^b}] \} \qquad . \tag{9}
$$

To see the implications of the above expression, let's consider the case of hadron-nucleus collisions. Expanding $\sigma^{hA \rightarrow J/\psi}$ we obtain:

$$
\sigma^{hA \rightarrow J/\psi} \simeq kA - k'A^2 \qquad , \tag{10}
$$

with k and k' positive constants, which are linear and quadratic, respectively, in the parton - parton cross-sections. Corrections to equation (10) would come both from higher order terms in (6) and non-zero order terms in the expansion of the corresponding τ^2's as a function of A. This approximation is valid when $k'A/k$ is small. Obviously, the quantity k'/k^2 has to be of the order of magnitude of $\tau_{pp}^2 \sim 1/s_{ov}$.

In the opposite case, in which the number of participating partons is vary large making $(1 - \sigma_{q\bar{q}} t_{AB}^{(q)}(\vec{b}))^{AB n_p^a n_p^b} \ll 1$, expression (9) tends to be proportional to the nucleus-nucleus overlapping area and will depend on AB as $(AB)^{2/3}$. This situation would correspond to very central events.

In the formulation of the model, only self shadowing of the J/ψ production has been taken into account. In other words, I neglected shadowing effects due to other parton-parton processes like Drell-Yan pair creation. This is justified by the fact that all other processes either have a very small cross section compared with the J/ψ production cross-section, or the mass region of the process is too small to have any significant effect on the energy constraints. Nevertheless, we can not completely rule out the possibility of having contributions to the J/ψ suppression from those kind of

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sources. This would mean that additional terms would contribute to the value of k', bing those terms linear in both the new parton-parton process cross-section and in the parton-parton→ J/ψ cross-section. It is important to note that these additional contributions should become more important under extreme kinematical conditions such as in high E_T events.

3 Phenomenology

The model presented in the former section doesn't provide us with an easy method for computing the J/ψ production cross-section in nuclear collisions. In fact, few things can be said of the different quantities entering eq.'s (4) and (5) except that they have to be compatible with all known experimental and theoretical constraints. Nevertheless, the model can help us to understand many features of the experimental data and can give relevant qualitative predictions. It is also worth noting that the large AB behaviour is more general than the model itself, since it can be extracted from arguments based on unitarity alone. This behaviour appears in very extreme cases for which we can say that the target acts, roughly, as a black disc.

The low A limit characterized by eq. (10) is useful to study the case of $hA \to J/\psi$ collisions. In ref. [8] data on J/ψ production in $\pi^- A$ and $\bar{p}A$ collisions at 125 GeV/c were collected, and a quadratic fit to the dependence of the $\pi^- A \to J/\psi$ cross section on A was done on purely empirical grounds. For $k = 63.17 \pm 2.0$ and $k' = 0.11 \pm 0.01$ (in nbarns) an impressively good fit to the 5 points available was obtained, as is shown in fig. 1. In order to test the coherence of these two quantities, we need to have an estimate of the value of s_{ov}/s_h. In [11], measurements of the double J/ψ production cross section in proton-nucleus collisions at 400 GeV/c have been presented which allow us to extract an order of magnitude of 10^{-2} for s_{ov}/s_h. This estimate is compatible with the values of k and k' taking into account differences due to the different values of the collision energies and missing factors attached to the geometry of the system.

Let us now recall that k'/k^2 increases with decreasing s_{ov}, which means that it should be larger when the energy threshold is pushed to higher values. This have a clear implication. Deviations from linearity should be more pronounced when we look at events in which a large-x_F J/ψ has been detected. This effect is also favored by the fact that no variation of the hard parton-parton cross-sections with x_F is expected since they mainly depend on Q_T. Conversely, a high Q_T trigger should make the second term in (10) negligible compared with the first one. This is so because k'/k^2 is linear with the parton-parton cross-sections which decreases with Q_T as $1/Q_T^2$. Both these effects are in agreement with what has been experimentally observed [4]. Finely, we should expect that the dependence of the J/ψ -production cross-section in hA

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collisions on A will present a smaller deviation from linearity when the energy of the collision is increased.

Another interesting point consist in discussing the way in which this model can be applied to study the production of heavier particles. One may think that the corresponding value for k'/k^2 should decrease due to the lower value of the related parton-parton cross-section, however, kinematical constraints become more important. For instance, in the case of Υ production in hA collision studied by the E772 Collaboration [12], the value of the mass is of the order of $10\,GeV$ while the proton-nucleon center of mass energy in the E772 experiment is $39\,GeV$. Furthermore, shadowing of the Υ production due to other hard processes like $c\bar{c}$ pair creation become relevant. As suggested by the comment at the end of section 2, k' for the Υ case has to contain a contribution linear with parton-parton$\rightarrow c\bar{c}$ cross-section, making k'/k^2 for Υ production even larger than for J/ψ production.

One still may wonder why Drell - Yan cross sections are linear with A. In principle it can be said that in the region of the J/ψ mass, parton - parton Drell - Yan cross sections are orders of magnitude smaller than the corresponding values for J/ψ production, and the quadratic term in (10) can be dropped. But still, there is another reason. Drell - Yan $\mu^+\mu^-$ pair production is an electromagnetic process and its long range character prevent us from applying the same arguments that lead to the Glauber - Gribov model, since a clear statement about the interaction area cannot be made.

The low-A limit discussed above can not be applied to the case of J/ψ production in nucleus-nucleus collisions. In fact, if eq. (10) is employed to compute $S^{32}Pb^{207} \rightarrow J/\psi$ cross-section with the assumption the same order of magnitude for k and k', we see that $(k'AB)/k \sim 10$, which makes no sense. Furthermore, when a high E_T cut is used, everything approximately works as though we are dealing with a large effective value for the nuclear mass numbers, $AB^{eff\cdot}(E_T)$. This makes the system move towards the $(AB)^{2/3}$ regime. We can now understand why the J/ψ suppression observed in nucleus-nucleus collisions seemed to be incompatible with the effect observed in hA collisions.

A consequence of the large AB limit is that the suppression of J/ψ production is bounded. A clear signal of QGP formation would be that J/ψ production cross-sections in central nucleus-nucleus collisions vary as $(AB^{eff\cdot}(E_T))^\alpha$, if $\alpha < 2/3$. This could only be observed in the tail of the E_T distribution and in events containing a large-x_F J/ψ particle in the final state. This model doesn't completely rule out other mechanisms for the J/ψ suppression, as those mentioned in the introduction, which may have a small but significant contribution. So, some open charm enhancement can accompany the J/ψ suppression, but much less than needed to account for all missing J/ψ 's, especially in the large-x_F region.

4 Summary and conclusions

The model which has been presented seems to be an useful tool to interpret the experimental results concerning J/ψ production in nuclear collisions. It is inspired in the fact that energy constraints must play an important part in events of this type, and take care of the requirement of unitarity.

The results can be classified according to two regimes. The low-A regime is applied to the case of hA collisions and gives the right functional form for the A-dependence of the cross-section. The phenomenological results qualitatively agree with the known data; nevertheless, more experimental analysis would be desirable. For instance, the variation of k'/k^2 with the energy of the collision would constitute a test of the model.

The large AB regime is appropriate to study the nucleus-nucleus collisions case. The model implies that present experimental data on J/ψ suppression in central collisions can be understood with no need of the assumption that a QGP has been formed. A test of of its major results, namely, the $(AB)^{2/3}$ limit and the absence of a large open charm enhancement, would be very interesting. In connection with this, it is important to remember that a large-x_F cut is necessary. It is in this kinematical region that the $(AB)^{2/3}$ limit can be reached. This cut would also make contributions from other mechanisms , such as those mentioned in the introduction, less significant; this means that open charm production correlated with the J/ψ suppression shouldn't be observed.

Acknowledgments

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Figure captions

- **Figure 1.** $\pi^- A \to J/\psi$ Cross section data compared with the quadratic fit mentioned in the text (continuous line) and with a fit of the form A^α (broken line), ref. [8].

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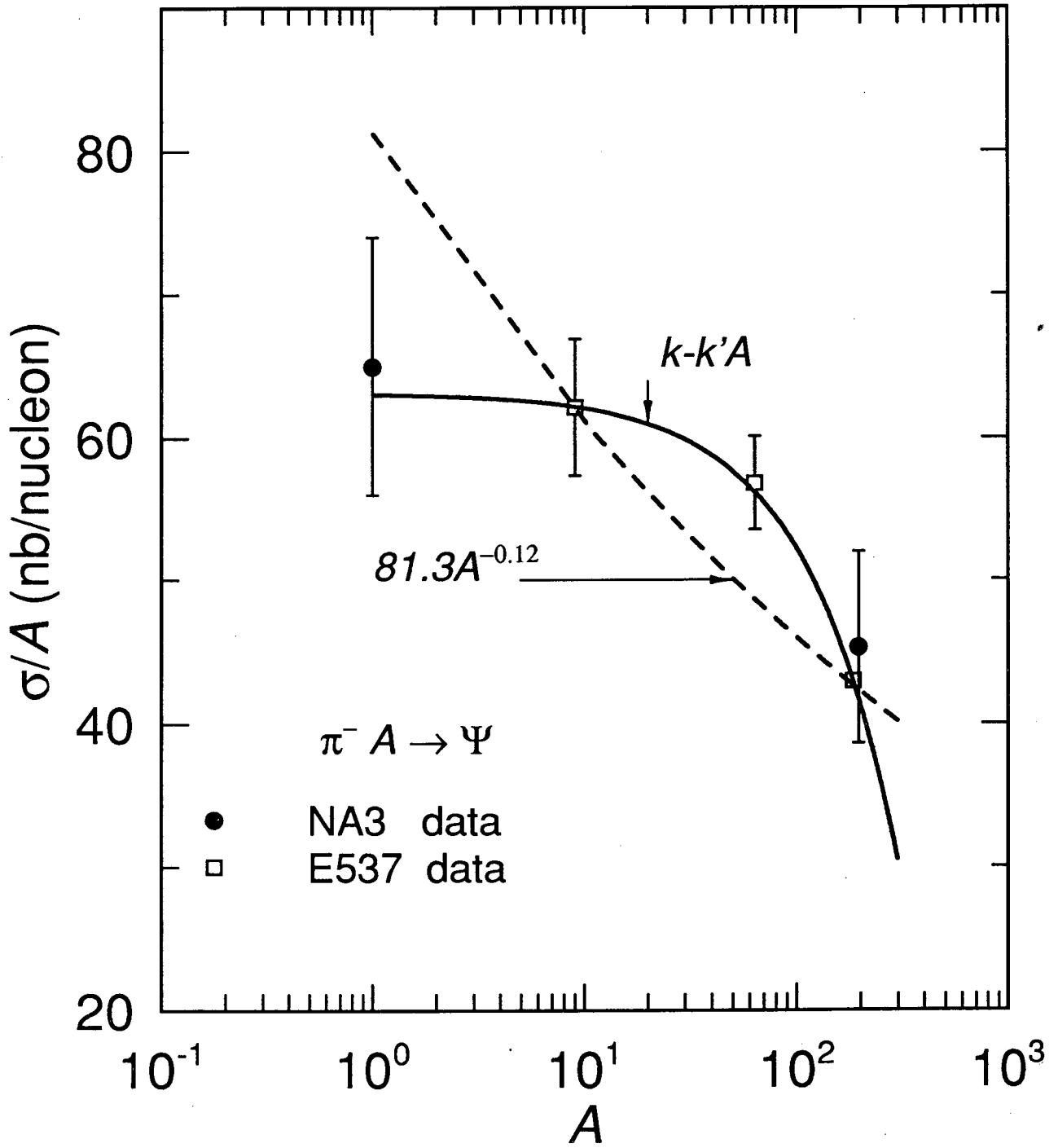
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