Coherence time effects on J/ψ production and suppression in relativistic heavy ion collisions

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Using a coherence time extracted from high precision proton-nucleus Drell-Yan measurements and a nuclear absorption cross section extracted from pA charmonium production experiments, we study J/ψ production and absorption in nucleus-nucleus collisions. We find that coherence time effects are large enough to affect the measured J/ψ–to–Drell-Yan ratio. The S+U data at 200A GeV/c measured by NA38 are reproduced quantitatively without the introduction of any new parameters. However, when compared with recent NA50 measurements for Pb+Pb at 158A GeV/c, the data is not reproduced in trend or in magnitude.

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Ultrarelativistic heavy ion collisions offer the tantalizing possibility of forming and studying a new form of matter predicted by QCD: the quark-gluon plasma. A vigorous experimental program has existed at the CERN SPS for more than 10 years. RHIC now signals the dawn of a new era in heavy ion physics at Brookhaven National Laboratory. Several experimental signals have been put forward as candidates for QCD plasma signatures [1]. Of those, the most famous is probably that of J/ψ suppression in nucleus-nucleus collisions. The theoretical and experimental activity that have followed this seminal suggestion have been considerable as the disappearance of the J/ψ can directly be linked to deconfinement and Debye screening in the plasma [2]. The interested reader will find a recent snapshot of the state of this field in Ref. [3].

Before an experimentally observed J/ψ suppression pattern is interpreted as an unambiguous signal of the existence of a quark-gluon plasma, it is imperative to rule out all competing explanations of purely hadronic origin. Moreover, the hadronic scenarios considered should incorporate elements of physics that are known to be relevant at the energy scale under consideration. It is one such line of thought that we follow in this paper. We study charmonium production in relativistic heavy ion collisions along with the appropriate background, Drell-Yan pair production. Our paper is organized as follows. First we recall the main features of a model that is successful in explaining high precision Drell-Yan data measured in proton-nucleus collisions. Those data enable one to extract a formation time characteristic of the emission of soft hadrons, essentially pions. Next we recall the application of this model to the production of J/ψ in pA collisions. From those measurements we have extracted a cross section for J/ψ absorption on the nucleon. With this formulation we make parameter-free calculations for nucleus-nucleus collisions and compare them with experimental data.

In almost all considerations involving heavy ion collisions at any energy, the issues of dynamics and elementary processes remain intimately connected and inseparable. In view of this, a successful modeling of nuclear collisions is a necessary prerequisite to a deeper exploration of the fine points of the nuclear dynamics. To simulate the heavy ion collision we prefer to work with hadronic variables rather than partonic ones, and make a straightforward linear extrapolation from proton-proton scattering. This extrapolation, referred to as LEXUS, was detailed and applied to nucleus-nucleus collisions at beam energies of several hundred GeV per nucleon in Ref. [4]. Briefly, the inclusive distribution in rapidity y of the beam proton in an elementary proton-nucleon collision is parametrized rather well by

$$W_1(y)=\lambda\frac{\cosh y}{\sinh y_0}+(1-\lambda)\,\delta(y_0-y), \tag{1}$$

where y_0 is the beam rapidity in the laboratory frame. The parameter λ has the value 0.6 independent of beam energy, at least in the range in which it has been measured, which is 12–400 GeV [5]. It may be interpreted as the fraction of all collisions which are neither diffractive nor elastic. As a nucleon cascades through the nucleus its energy is degraded. An underlying assumption in this model is that of straight line trajectories. In the case of a nucleus-nucleus collision, one obtains the single-particle rapidity distribution of the mth projectile nucleon after a collision with the nth target nucleon through the solution of an evolution equation [4]:

$$W^P_{m,n}(y)=\int dy_P\,dy_T\,W^P_{m,n-1}(y_P)W^P_{m-1,n}(y_0-y_T)\times Q(y-y_T,y_P-y_T,y-y_P). \tag{2}$$

In the above, the kernel is

$$Q(s,t,u)=\lambda\frac{\cosh s}{\sinh t}+(1-\lambda)\,\delta(u), \tag{3}$$

originating from Eq. (1). Equation (2) is a Boltzmann-type equation that is solved numerically. This rapidity distribution

TABLE I. The S+U processes are measured by NA38 [8] in collisions at 200*A* GeV/*c* and the Pb+Pb processes are measured by NA50 [19] in collisions at 158*A* GeV/*c*. The entries in columns labeled with different values of *n* represent calculated values. The J/ψ cross sections are obtained using a J/ψ-nucleon absorption cross section of $\sigma_{\rm abs}=3.6$ mb.

	Process	$\sigma^{\rm tot}_{\rm expt}$	$n=\infty$	$n=3$	$n=2$
S+U					
	Drell-Yan	$310\pm10\pm25$ nb	449 nb	328 nb	272 nb
	J/ψ	$7.78\pm0.04\pm0.62$ μb	12.2 μb	8.38 μb	6.83 μb
Pb+Pb					
	Drell-Yan	$1.49\pm0.01\pm0.11$ μb	1.97 μb	1.22 μb	0.95 μb
	J/ψ	$21.9\pm0.02\pm1.6$ μb	44.5 μb	26.1 μb	19.8 μb

then gets folded with impact parameter over the density distributions of the projectile and target nuclei, using a method described in detail in Ref. [4].

Recently we have extracted the quantum coherence time needed to reproduce Drell-Yan pair production data in pA collisions. This can also be formulated in terms of the Landau-Pomeranchuk-Migdal effect [6]. We briefly recall the procedure followed. We began by computing the Drell-Yan yield at leading-order (LO) with the GRV94 structure functions [7] with a fixed K factor. Those structure functions reflect a flavor-asymmetric Dirac sea. Adopting a K factor of 2.1, we compared the results to pp and pd Drell-Yan data at 450 GeV/c [8] taking into account the experimental acceptance and angular cuts. We found good agreement for the measured values of the cross sections [9].

Turning then to the case of proton-nucleus collisions as measured by the E772 Collaboration [10], we deduced [11] that the formation (or coherence) time needed to fit the measured $\sigma^{DY}_{pA}/\sigma^{DY}_{pD}$ ratios at different values of x_F is $\tau_0=0.4\pm0.1$ fm/c, in the frame of the colliding nucleons. Practically, this coherence time has to do with the particle production process and can be related to an initial state energy loss for some of the Drell-Yan producing collisions [12] as follows. In LEXUS, we assumed that the energy available to produce a Drell-Yan pair was that which the proton had after n previous collisions. In order to reproduce the 800 GeV/c E772 data, we needed $n=5\pm1$. The n collisions correspond to a path length of $n/\sigma^{\rm tot}_{NN}\rho$ in the target nucleus rest frame, where $\sigma^{\rm tot}_{NN}$ is a total cross section of 40 mb, and ρ is a nuclear matter density of 0.155 nucleons/fm^3. Lorentz transforming to the nucleon-nucleon center of mass, one obtains the value of the proper coherence time quoted above. In this language, a traditional Glauber-type model (with no energy loss) would have $n=\infty$. Fixing τ_0, the range in n appropriate for the energies being considered in this work (nucleon momenta of 158 GeV/c and 200 GeV/c) is found to be $2\leqslant n\leqslant3$. Note that n is a parameter that depends only on the incident energy.

We then investigated J/ψ production in pA collisions [13,14] taking into account the necessary experimental cuts. The additional input needed there was the cross section for producing J/ψ in elementary nucleon-nucleon interactions. We used the Schuler parametrization [15], also used by Lourenço [14]:

$$B\sigma_{NN\to J/\psi}(x_F>0)=37(1-m_{J/\psi}/\sqrt{s})^{12}\ \text{nb}. \tag{4}$$

Here, $\sqrt{s}$ in the center-of-mass energy of the nucleon pair and B is the branching ratio into a muon pair. Using the functional x_F dependence of the differential cross section as measured by E789 [16], one can write a normalized differential cross section to use as an input in LEXUS:

$$\frac{d\sigma_{NN\to J/\psi}}{dx_F}=6\sigma_{NN\to J/\psi}(x_F>0)(1-|x_F|)^5. \tag{5}$$

From our analysis [13], we have extracted a J/ψ absorption cross section in nuclear matter of 3.6 mb. It is worthwhile to note that this value is in numerical agreement with the same quantity deduced from experiments of J/ψ photoproduction on nuclei [17]. It is smaller than that used in other phenomenological heavy ion applications [18]. The parameters in this model are thus completely determined by proton-nucleus data.

We now turn to recent experiments on the production of the J/ψ in S+U [8] collisions at 200*A* GeV/c and in Pb+Pb [19] collisions at 158*A* GeV/c, at the CERN SPS. Because the J/ψ is measured through its decay into dimuons, the production cross section has traditionally been divided by the natural background in the appropriate invariant mass region: that of Drell-Yan pairs. However, since the absolute cross section measurements are now available, we will first verify the predictions of our model there. Including isospin and the appropriate respective detector acceptance, the results for absolute cross sections are shown in Table I.

Consider the system S+U at 200*A* GeV/c. The coherence time arguments made earlier in this paper suggest that the values $n=2$ and $n=3$ should bracket the experimental data. We observe that indeed this is so, both for the measured Drell-Yan and J/ψ absolute cross sections. One can go further and plot $B\sigma^{J/\psi}/\sigma^{DY}$ against collision centrality. One needs a model to map the impact parameter bins that enter as input in our dynamical model into bins of measured transverse energy. The experimental collaboration has in fact provided the impact parameter range that corresponds to a measured J/ψ–Drell-Yan ratio [8]. Comparison to the experimental data is shown in Fig. 1. One can see that our results are consistent with the data within experimental uncertainties. Again, we emphasize that no new parameters

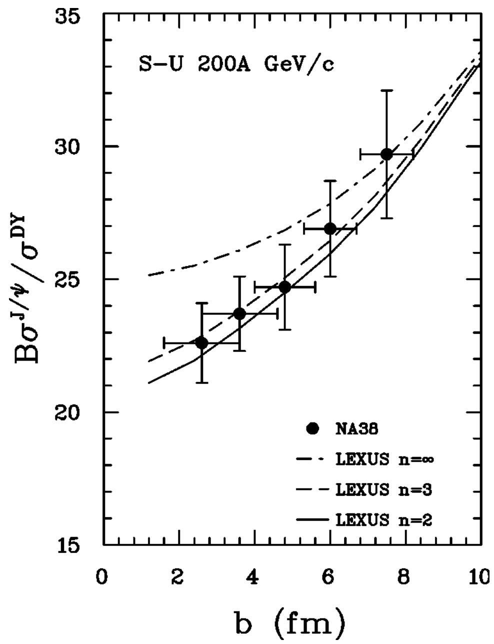

FIG. 1. Ratio of J/ψ to Drell-Yan production cross sections. B is the branching ratio into a muon pair. The data are from Ref. [8].

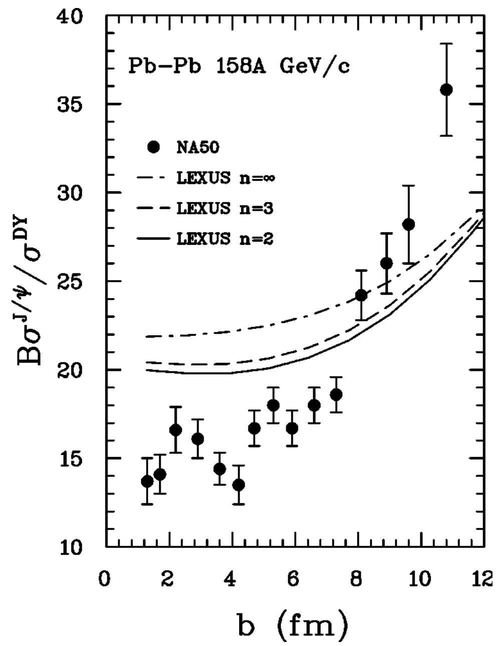

FIG. 2. Same as Fig. 1, except that this is for the heavier system. The data are from Ref. [20].

were introduced. It is also worthwhile to note that the numerator and denominator of the plotted ratio have been calculated from ''first principles,'' the meaning of which is clear in the context of this paper: LO Drell-Yan calculations and a parametrization of the differential J/ψ production in nucleon-nucleon collisions. The absolute cross sections calculated with no energy loss (or infinite coherence time) fail to reproduce the experimental results. This is also the case for their ratio.

We now turn to experimental results obtained by the NA50 Collaboration with Pb projectiles and targets. From Table I we see that the measured Drell-Yan cross section exceeds our larger ($n=3$) value by about one standard deviation. The experimental J/ψ value falls within the predicted range. Plotting the J/ψ–to–Drell-Yan ratio against the impact parameters determined by the experimental collaboration [20] one obtains Fig. 2. Application of this model with its parameters determined solely from pA physics does not yield a satisfactory representation of this experimental data. The latter is not reproduced in trend nor is it in magnitude. Note, however, that the poor quality of this fit is entirely comparable with those obtained with other hadronic approaches [21]. Also shown in this figure is the effect of the coherence time on this ratio. It appears that this effect is not as spectacular here as it partially cancels in the numerator and denominator. The flattening and slight increase of the ratio, as one goes to smaller impact parameters, can be attributed to the J/ψ cross section growing slightly faster than the Drell-Yan. Here also, the calculated absolute cross sections with no energy loss far exceed the experimental values. Note in passing that the use of MRS A′ structure functions [22] does not alter the conclusions reached in this work.

We also considered possible nuclear structure effects on the ratio shown in Fig. 2. It is known that parton distribution functions that have a flavor-asymmetric Dirac sea, like the one we use in this work, will yield different Drell-Yan cross sections depending on whether one has $p+p$, $p+n$, $n+n$ or $n+p$ collisions. In our treatment the isospin content of the nucleus is assumed to be uniformly distributed according to the overall charge of the colliding partners. Experimentally, Pb is known to have a neutron skin [23] of 0.19 ± 0.09 fm. This value is in fact too small to have an effect on the calculations shown here. Finally, it seems useful to point out that in Fig. 2 the Pb data do not seem to converge to the vacuum ratio as one moves towards more peripheral collisions, unlike the measurements of S-induced reactions. This aspect is also present in other hadron-based approaches [24].

We have investigated nucleus-nucleus collisions with a model that incorporates the coherence time associated with the emission of soft quanta in hadronic interactions. This approach translates into lost energy for the formation of hard radiation, such as high-mass Drell-Yan pairs and J/ψ. We have obtained results in quantitative agreement with experimental data for the reaction S on U at 200A GeV/c. The ratio of J/ψ to Drell-Yan cross sections as a function of collision centrality, as well as the total absolute cross sections are reproduced by our model. Therefore, we can understand Drell-Yan and J/ψ formation in pA and S+U collisions in terms of the same physics. This model fails to reproduce measurements done in connection with the heavier Pb+Pb system.

Several points still need to be clarified. It will be very instructive to repeat this analysis in partonic variables including nuclear shadowing [25]. A systematic exploration of the freedom allowed by the most recent high-precision pA measurements [26] is called for and is underway. Nevertheless, if the Pb+Pb data stand the test of time, it does not seem possible to escape the conclusion that J/ψ suppression is caused by high energy density. Whether it is due to absorption on hadronic co-movers [27] or quark-gluon plasma remains an open and exciting question.

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