$J/\psi$ Production and Absorption in High Energy Proton-Nucleus Collisions

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Abstract

Measured $J/\psi$ production cross sections for 200 and 450 GeV/c protons incident on a variety of nuclear targets are analyzed within a Glauber framework which takes into account energy loss of the beam proton, the time delay of particle production due to quantum coherence, and absorption of the $J/\psi$ on nucleons. The best representation is obtained for a coherence time of 0.5 fm/c, previously determined by Drell-Yan production in proton-nucleus collisions, and an absorption cross section of 3.6 mb, which is consistent with the value deduced from photoproduction of the $J/\psi$ on nuclear targets.

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Propagation of a highly relativistic particle through a medium is of interest in several areas of physics. High energy proton-nucleus scattering has been studied for many decades by both the nuclear and particle physics communities [1]. Such studies are particularly relevant for the Relativistic Heavy Ion Collider (RHIC), which will collide beams of gold nuclei at an energy of 100 GeV per nucleon, and for the Large Hadron Collider (LHC), which will collide beams of lead nuclei at 1500 GeV per nucleon [2].

In a recent paper [3] we modeled the production of high mass, Drell-Yan, pairs of leptons as measured in collisions of 800 GeV/c protons incident on a variety of nuclear targets by the Fermilab collaboration E772 [4]. Our modeling was done on the basis of hadronic degrees of freedom. We took into account the energy loss of the beam proton as it traversed the nucleus as well as the Landau-Pomeranchuk-Migdal effect [5]. The latter basically acknowledges that there is a time ordering in the appearance of produced particles; the hard particles (Drell-Yan pairs) appear before the soft particles (typically pions). This is a quantum mechanical effect, essentially the uncertainty principle. By fitting to the atomic mass number dependence of the Drell-Yan cross section at high Feynman $x$ we were able to infer a value for the proper coherence or formation time of 0.4±0.1 fm/c. This value is about what should be expected a priori. In the center of mass frame of the colliding nucleons at the energies of interest a typical pion is produced with an energy of $E_\pi \approx 500$ MeV. By the uncertainty principle this takes a time of order $\hbar c/E_\pi \approx 0.4$ fm/c.

A related process is the production of $J/\psi$ in high energy proton-nucleus collisions which we shall address in this paper. This is also a relatively hard process and so both energy loss of the beam proton and the Landau-Pomeranchuk-Migdal effect must be taken into account. However, there is an additional effect which plays a role, and that is the occasional absorption or breakup of the $J/\psi$ in encounters with target nucleons. (The inelastic interaction of one of the leptons in Drell-Yan production with target nucleons is ignorably small.) The absorption cross section, $\sigma_{\text{abs}}$, has been estimated in a straightforward Glauber analysis without energy loss and with an infinite coherence/formation time to be about 6-7 mb [6]. This has formed the basis for many analyses of $J/\psi$ suppression in heavy ion collisions. Any anomalous suppression may be an indication of the formation of quark-gluon plasma [2, 7], hence the importance of obtaining the most accurate value of $\sigma_{\text{abs}}$ possible. This cross section has also been inferred from photoproduction experiments of $J/\psi$ on nuclei from which a value much less than that has been obtained [8]. This has been a puzzle. One attempt to resolve this apparent discrepancy consists of modeling the produced $J/\psi$ state as a pre-resonant color dipole state with two octet charges [9]; however, the results are only semi-quantitative.

For a basic description of high energy proton-nucleus scattering we prefer to work with hadronic variables rather than partonic ones. We 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. [10], and to Drell-Yan production in 800 GeV proton-nucleus collisions in ref. [3]. In order to compute the production cross section of $J/\psi$ in proton-nucleus collisions we need a parametrization of it in the more elementary nucleon-nucleon collisions. For this we call upon the parametrization of a compilation of data by Lourenço [11].

\[ B\sigma_{NN \rightarrow J/\psi}(x_F > 0) = 37 \left(1 - m_{J/\psi}/\sqrt{s}\right)^{12} \text{nb} \]  

(1)
Figure 1: Branching ratio into muons times cross section to produce $J/\psi$ with $x_F \geq 0$ in proton-nucleus collisions at 200 GeV/c. The data is from NA38 [11]. The dashed line is $A$ times the nucleon-nucleon production cross section. The solid curve represents full energy loss with zero coherence/formation time, while the banded region represents partial energy loss with a coherence/formation time within the limits set by Drell-Yan production. (Computations were done for C, Al, Cu, W and U and the points connected by straight lines to guide the eye.)

Here $B$ is the branching ratio into dimuons and $x_F$ is the ratio of the momentum carried by $J/\psi$ to the beam momentum in the center of mass frame ($-1 < x_F < 1$). Due to the degradation in momentum of the proton as it traverses the nucleus it is important to know the $x_F$ dependence of the production. The Fermilab experiment E789 has measured this dependence at 800 GeV/c [12] to be proportional to $(1 - |x_F|)^5$. Assuming that this holds at lower energy too we use the joint $\sqrt{s}$ and $x_F$ functional dependence and magnitude:

$$\frac{d\sigma_{NN\rightarrow J/\psi}}{dx_F} = 6\sigma_{NN\rightarrow J/\psi}(x_F > 0)(1 - |x_F|)^5.$$  \hspace{1cm} (2)

The cross section in proton-nucleus collisions can now be computed in LEXUS with no ambiguity.

Figures 1 and 2 show the results of our calculation in comparison to data taken by NA38 [11]. The dashed curves are $A$ times the nucleon-nucleon production cross section; they obviously overestimate the data. The solid curves show the result of LEXUS with full energy degradation of the beam proton without account taken of the Landau-Pomeranchuk-Migdal effect; they obviously underestimate the data. The hatched regions represent the inclusion of the latter effect with a proper formation/coherence time $\tau_0$ in the range of 0.3 to 0.5 fm/c consistent with Drell-Yan production [3]. The time delay is implemented as follows [3]: The energy available for the production of $J/\psi$ is that which the proton had $n$ collisions prior; that is, the previous $n$ collisions are ignored for the purpose of determining the proton’s energy. This is an approximate
Figure 2: Same as figure 1 but for a beam momentum of 450 GeV/c.

treatment of the Landau-Pomeranchuk-Migdal effect. The $n$ is related to the beam energy and to the coherence time $\tau_0$ in the center of mass frame of the colliding nucleons. The proper coherence time is essentially the same as the proper formation time of a pion since most pions are produced with rapidities near zero in that frame. The first proton-nucleon collision is the most important, so boosting this time into the rest frame of the target nucleus and converting it to a path length (proton moves essentially at the speed of light) gives

$$\gamma_{\text{cm}} c \tau_0 \approx \sqrt{\gamma_{\text{lab}}/2} c \tau_0.$$  

This path length may then be equated with $n$ times the mean free path $l = 1/\sigma_{\text{tot}}^{\text{NN}}$. Using a total cross section of 40 mb, a nuclear matter density of 0.155 nucleons/fm$^3$, and $0.3 < \tau_0 < 0.5$ fm/c we obtain $2 < n < 3$ at 200 GeV/c and $3 < n < 5$ at 450 GeV/c. As may be seen from the figures, the data is overestimated, indicating the necessity for nuclear absorption.

We now introduce a $J/\psi$ absorption cross section on nucleons and compute its effect within LEXUS in the canonical way \[\text{[6]}\]. When the $J/\psi$ is created there will in general be a nonzero number of nucleons blocking its exit from the nucleus. Knowing where the $J/\psi$ is created allows one to calculate how many nucleons lie in its path, and hence, to compute the probability that it will be dissociated into open charm. We choose a value of $\tau_0$ allowed by Drell-Yan measurements, mentioned above, and then vary $\sigma_{\text{abs}}$, assuming that it is energy independent. The lowest value of chi-squared for the 200 and 450 GeV/c data set taken together is obtained with $\tau_0 = 0.5$ fm/c and $\sigma_{\text{abs}} = 3.6$ mb. The results are shown in figures 3 and 4. The fitted values all lie within one standard deviation of the data points. This is quite a satisfactory representation of the data. It means that both Drell-Yan and $J/\psi$ production in high energy proton-nucleus collisions can be understood in terms of a conventional hadronic analysis when account is taken of the energy loss of the beam proton, the Landau-Pomeranchuk-Migdal effect, and nuclear absorption of the $J/\psi$ in the final state. It also means that the absorption cross section for $J/\psi$ inferred from high energy proton-nucleus collisions is consistent with the value
Figure 3: Same data as in figure 1. The solid curve is the best fit of the model which includes beam energy loss with a coherence time of 0.5 fm/c (n=3 at this energy) and a $J/\psi$ absorption cross section of 3.6 mb.

inferred from photoproduction experiments on nuclei.

It will be very instructive to repeat this analysis in the language of partonic variables.

Figure 4: Same data as in figure 2. The solid curve is the best fit of the model which includes beam energy loss with a coherence time of 0.5 fm/c (n=5 at this energy) and a $J/\psi$ absorption cross section of 3.6 mb.
Actually, the analysis with parton energy loss alone was reported by Gavin and Milana [13] with satisfactory results obtained for Drell-Yan and $J/\psi$ if the partons lose about 1.5 GeV/fm. Nuclear shadowing [14] needs to be taken into account too. The relationship among all these effects is not well-understood, nor is the relationship between these effects in partonic and hadronic variables. Finally, the implications for nucleus-nucleus collisions [2] will undoubtedly be important; they are under investigation.

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