On $J/\psi$ Production in Nuclear Collisions

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Abstract

Data on $J/\psi$ production in inelastic proton–proton, proton–nucleus and nucleus–nucleus interactions at 158 A·GeV are analyzed and it is shown that the ratio of mean multiplicities of $J/\psi$ mesons and pions is the same for all these collisions. This observation is difficult to understand within current models of $J/\psi$ production in nuclear collisions based on the assumption of hard QCD production of charm quarks.

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1 Introduction

According to the factorization theorem of perturbative QCD\cite{1} inclusive cross section of a hard process should increase proportionally to $A$ in p+A interactions and proportionally to $A^2$ in A+A collisions. Models describing $J/\psi$ production are built on the basis of this prediction (for review see\cite{2}). They treat creation of a $c\bar{c}$ pairs as a hard process and they further assume that the initial number of $J/\psi$ mesons is proportional to the number of charm pairs. Therefore in the absence of medium effects the $J/\psi$ cross section is expected to increase as $A(A^2)$ for p+A (A+A) collisions.

Experimental results on $J/\psi$ production in p+A interactions contradict this naive expectation showing an increase of the cross section proportional to $A^{0.9}$. This reduction of the $A$–dependence is usually explained as being predominantly due to final state interactions of the $J/\psi$ meson (or its premeson state) with nucleons\cite{3}. However models based on this picture and parameters fitted to the p+A data in general overpredict recent results on $J/\psi$ production in central Pb+Pb collisions at 158 A·GeV (for review see\cite{4}). This reduction of $J/\psi$ production in the latter data is usually interpreted as due to interactions of $J/\psi$ (pre)mesons with surrounding high density matter (ultimately the Quark Gluon Plasma)\cite{5}.

In high energy A+A collisions (from central S+S to central Pb+Pb) the multiplicity of pions and strange hadrons increase proportionally to the number of colliding nucleons (participant nucleons)\cite{6}. These data and their interpretation in terms of a statistical QGP model\cite{7} suggested the question whether a similar dependence may be observed for charm and consequently for $J/\psi$ production. A simple estimation of the centrality dependence of the $J/\psi$ to pion ratio in Pb+Pb collisions indicates that this hypothesis may be in fact correct\cite{8}.

The aim of this paper is to review available experimental results to obtain information concerning the $A$–dependence of $J/\psi$ yield. In particular we study the $A$–dependence of the $J/\psi$ to pion ratio using results on proton–proton and nucleus–nucleus interactions (Sections 2 and 3) and proton–nucleus interactions (Section 4). We summarize also results on the $A$–dependence of the open charm yield in p+A interactions (Section 5).
2 \( J/\psi \) Multiplicity in p+p Interactions

In p+p interactions the \( J/\psi \) cross section was measured at five different collision energies, \( \sqrt{s} = 6.8 \) GeV [8], 8.7 GeV [9], 19.4 GeV [10], 24.3 GeV [11] and 52 GeV [12]. Most of the data are measured for \( x_F > 0 \) and they are not corrected for the branching ratio to the measured decay channel.

The mean multiplicity of \( J/\psi \) mesons in full momentum space, \( \langle J/\psi \rangle \), is obtained in the following way. The \( x_F \) distribution of \( J/\psi \) is assumed to be symmetric with respect to reflection at \( x_F = 0 \). The most recent values of the branching ratios \( J/\psi \rightarrow \mu^+\mu^- (B_{\mu\mu} = 0.0601) \) and \( J/\psi \rightarrow e^+e^- (B_{ee} = 0.0602) \) were used [13]. The cross sections of \( J/\psi \) production were further divided by the cross sections for inelastic p+p interactions at the corresponding collision energy. The latter cross sections were calculated according to the parametrization of the experimental data given in [13]. The resulting values of \( \langle J/\psi \rangle \) are given in Table 1.

For comparison with the data on nucleus–nucleus collisions at the SPS the mean \( J/\psi \) multiplicity for p+p interactions at 158 GeV (\( \sqrt{s} = 17.3 \) GeV) is needed. In this energy range the energy dependence of the integrated cross section for \( J/\psi \) production can be conveniently parametrized by [14]:

\[
\sigma^{J/\psi} = \sigma_0 \left(1 - \frac{m_{J/\psi}}{\sqrt{s}}\right)^a,
\]

where \( a = 12 \) and \( \sigma_0 \) are parameters fitted to the data, \( \sigma^{J/\psi} \) and \( m_{J/\psi} \) are \( J/\psi \) cross section and mass, respectively. This parametrization predicts a decrease of the \( J/\psi \) yield by about 25% when going from \( \sqrt{s} = 19.4 \) GeV to \( \sqrt{s} = 17.3 \) GeV. Thus we can estimate \( \langle J/\psi \rangle \) to be \( (2.9 \pm 0.5) \cdot 10^{-6} \) at \( \sqrt{s} = 17.3 \) GeV using the measured value of \( \langle J/\psi \rangle = (3.8 \pm 0.3) \cdot 10^{-6} \) at \( \sqrt{s} = 19.4 \) GeV (see Table I). The result of the above interpolation, shown by the open circle in Fig. 1, agrees with the value estimated in Ref. [14] for p+p interactions at 150 GeV using data available at this energy [10] and an additional assumption concerning an unpublished ratio of cross sections.

The mean multiplicity of negatively charged hadrons (more than 90% are \( \pi^- \)-mesons) in nucleon–nucleon (N+N) interactions at 158 GeV is \( \langle h^- \rangle = 3.01 \pm 0.06 \) [15]. This mean multiplicity was calculated as \( \langle h^- \rangle = \langle \langle h^- \rangle_{pp} + 2\langle h^- \rangle_{pn} + \langle h^- \rangle_{nn} \rangle / 4 \), where \( \langle h^- \rangle_{pp}, \langle h^- \rangle_{pn} \) and \( \langle h^- \rangle_{nn} \) are mean multiplicities of negatively charged hadrons for p+p, p+n and n+n interactions at 158 A-GeV, respectively [15].

Taking the value of \( \langle J/\psi \rangle \) calculated above we obtain \( \langle J/\psi \rangle / \langle h^- \rangle = (0.96 \pm 0.17) \cdot 10^{-6} \) for N+N interactions at \( \sqrt{s} = 17.3 \) GeV. This ratio is further used for the comparison with nucleus–nucleus data.
\section*{3 \dots Production in Nucleus–Nucleus Collisions}

The production of $J/\psi$ in nucleus–nucleus collisions was measured by the NA38 Collaboration for O+Cu, O+U and S+U interactions at 200 A·GeV \cite{16} and by the NA50 Collaboration for Pb+Pb interactions at 158 A·GeV \cite{17, 18}. The procedure which allows to calculate the $\langle J/\psi \rangle / \langle h^- \rangle$ ratio from the published data is described below using as an example the Pb+Pb results.

The measured $J/\psi$ cross section in minimum bias Pb+Pb collisions is:

$$B_{\mu\mu}\sigma_{\text{acc}}^{J/\psi} = 21.9 \pm 0.2 \pm 1.6 \, \mu b,$$

This cross section refers to the NA50 acceptance $0 < y_{cm} < 1$ and $-0.5 < \cos \theta_{CS} < 0.5$, where $y_{cm}$ is the $J/\psi$ rapidity calculated in the c.m. system and $\theta_{CS}$ is the Collins–Soper angle \cite{19}. In order to get an estimate of the total $J/\psi$ cross section we assume that the $J/\psi$ production for $y_{cm} > 1$ can be neglected and that the distribution in $\cos \theta_{CS}$ is uniform \cite{14}. This leads to a correction factor for the acceptance equal to 4. Based on the h+p results at 200 GeV \cite{10} one can estimate that neglecting $J/\psi$ yield at $y_{cm} > 1$ may lead to an underestimation of the $J/\psi$ multiplicity by less than 30%. A similar conclusion is reached when the $J/\psi$ rapidity distribution in Pb+Pb collisions is assumed to be similar to the rapidity distribution of the $\phi$ mesons measured by the NA49 Collaboration \cite{20}.

In addition, the cross section presented by NA50 is corrected here for the branching ratio $J/\psi \rightarrow \mu^+ + \mu^-$ ($B_{\mu\mu} = 0.0601$) \cite{13}. The cross section for $J/\psi$ production resulting from the above procedure is:

$$\sigma^{J/\psi} = 1.46 \pm 0.12 \, \text{mb},$$

where systematic uncertainty of our extrapolation procedure is not included in the quoted error. The $J/\psi$ multiplicity can be calculated as

$$\langle J/\psi \rangle = \frac{\sigma^{J/\psi}}{\sigma} = (2.07 \pm 0.17) \cdot 10^{-4},$$

where $\sigma$ is the total cross section of inelastic Pb+Pb collisions calculated to be 7040 mb using a parametrization of the measured data given in Ref. \cite{21}.

The results of the NA35 and NA49 Collaborations \cite{6} indicate that the ratio of $\langle h^- \rangle$ to the mean number of participant nucleons, $\langle N_P \rangle$, is the same for central S+S and Pb+Pb collisions 158 A·GeV and equal to $\langle h^- \rangle / \langle N_P \rangle = 1.93 \pm 0.14$. We assume therefore the same value of the ratio for inelastic Pb+Pb collisions. Using the mean number of participant nucleons for the latter collisions calculated within the Fritiof model \cite{22} ($\langle N_P \rangle = 102$) we get $\langle h^- \rangle = 197 \pm 14$. This leads to $\langle J/\psi \rangle / \langle h^- \rangle = (1.05 \pm 0.11) \cdot 10^{-6}$ for inelastic Pb+Pb collisions at 158 A·GeV.

A similar procedure is used to calculate the $\langle J/\psi \rangle / \langle h^- \rangle$ ratio for O+Cu, O+U and S+U interactions. There are however two difference. The $J/\psi$ cross sections for oxygen and sulphur induced reactions are measured at 200 A·GeV \cite{16}. Therefore for the comparison with the results at 158 A·GeV the measured values are scaled down by 25\% according to the energy dependence of the $J/\psi$ multiplicity established for p+p interactions (see Section 2). Due to projectile–target asymmetry the $x_F$ distribution of $J/\psi$ is expected to be not symmetric with respect to reflection at $x_F = 0$. The correction for this effect is neglected.
The ratios obtained for nucleus–nucleus collisions and the corresponding ratio for N+N interactions at the 158 A·GeV are shown in Fig. 2 as a function of $\langle N_p \rangle$. It is surprising that the ratio $\langle J/\psi \rangle / \langle h^- \rangle$ is similar for nucleon–nucleon and nucleus–nucleus interactions. One should however keep in mind that the ratios for nucleus–nucleus collisions may be underestimated by up to 30%. We repeat that this uncertainty is due to limited acceptance of the $J/\psi$ measurement for nucleus–nucleus collisions. This systematic error can be reduced when the results on the rapidity or $x_F$ distributions are published.

Finally we note that the ratio $\langle \text{hard process} \rangle / \langle h^- \rangle$ is expected to increase by a factor of about 3 when going from N+N to Pb+Pb interactions, where $\langle \text{hard process} \rangle$ denotes here a mean multiplicity of any process for which the cross section in A+A collisions increases as $A^2$. 
4 $J/\psi$ Production in p+A Interactions

The inclusive cross section for $J/\psi$ production in p+A interactions is measured in the region $x_F > 0$ and it is usually parametrized as [4]:

$$\sigma^{J/\psi} = \sigma_0(J/\psi) \cdot A^{\alpha(J/\psi)},$$

where $\sigma_0(J/\psi)$ and $\alpha(J/\psi)$ are parameters fitted to the experimental data. A strong dependence of $\alpha(J/\psi)$ on $x_F$ was recently measured by the E866 Collaboration [23] at 800 GeV. The $x_F$ distribution of $J/\psi$ decreases by a factor of about 10 from $x_F = 0$ to $x_F = 0.4$ [24]. The results were obtained by various experiments [10, 25, 26, 27] in the collision energy range 200–800 GeV and they were compiled in [4]. The $\alpha(J/\psi)$ values are shown in Fig. 3 as a function of $\sqrt{s}$ (filled circles).

In order to compare the $A$–dependence of $J/\psi$ and $h^-$ production the parameter $\alpha$ was fitted here to data [15] on the total multiplicity of negatively charged hadrons produced in p+A interactions at 200 GeV and 360 GeV. In the fit the multiplicity of proton–nucleon (p+N) interactions at the corresponding energy was included. This multiplicity was calculated as $\langle h^- \rangle = (\langle h^- \rangle_{pp} + \langle h^- \rangle_{pn})/2$ [15]. Finally the $\alpha$ parameter fitted to the multiplicity data was added to the $\alpha$ parameter obtained by the fit to the inelastic cross section results ($\alpha = 0.72 \pm 0.01$) [28]. The obtained values of $\alpha(h^-)$ ($\alpha(h^-) = 0.88 \pm 0.01$ at 200 GeV and $\alpha(h^-) = 0.90 \pm 0.02$ at 360 GeV) are shown in Fig. 4 (open circles). The values of $\alpha(h^-)$ are similar to the values of $\alpha(J/\psi)$. There is no evidence for any significant energy dependence both for $\alpha(h^-)$ and $\alpha(J/\psi)$. Similar values of the $\alpha$ parameter for $h^-$ and $J/\psi$ production imply that the ratio $\langle J/\psi(x_F > 0) \rangle/\langle h^- \rangle$ is approximately independent of $A$ for p+A interactions at high energy. We note that the difference in the $\alpha$ parameter of 0.02 (typical for the values shown in Fig. 3) results in 10% change in the multiplicity ratio between p+N and p+Pb interactions. This can be compared to about 70% increase of the ratio $\langle \text{hard process} \rangle/\langle h^- \rangle$ expected when going from p+N to p+Pb interactions, where $\langle \text{hard process} \rangle$ denotes here a mean multiplicity of any process for which the cross section in p+A interactions increases as $A$ ($\alpha = 1$).

The measurements of $J/\psi$ production in the backward hemisphere ($x_F < 0$) are poor. However, the experimental data [23] seems to indicate that $\alpha(J/\psi)$ for $x_F < 0$ is similar to $\alpha(J/\psi)$ for $x_F > 0$ (we note that this is not the case for pion production). This suggests that our conclusion concerning the similar $A$–dependence of $h^-$ and $J/\psi$ production, based on the $J/\psi$ data from the forward hemisphere only, may remain unchanged when the $J/\psi$ results in full phase space become available.
5 Conclusions

The main result of this paper is that the ratio of mean multiplicities of $J/\psi$ mesons and pions is similar for inelastic proton–proton, proton–nucleus and nucleus–nucleus interactions at 158 $A\cdot$GeV. In our opinion this experimental observation justifies a question whether the generally accepted picture of $J/\psi$ creation based on the factorization theorem of the perturbative QCD and subsequent suppression of the $J/\psi$ yield by the interactions with the surrounding medium is valid. In this picture the observed scaling behaviour of the data, $\langle J/\psi \rangle / \langle h^- \rangle \approx const(A)$, can be treated only as due to accidental cancelation of several large effects.

It is obvious that the mechanism of $J/\psi$ production can not be understood without data on open charm creation. Published data on $D$ and $\bar{D}$ production in p+A interactions are insufficient. The results on the $A$–dependence are summarized in Fig. 4, where $\alpha(D, \bar{D})$ is shown as a function of $x_F$ for interactions at 400 GeV [29] and 800 GeV [30]. It is clear that these data do not allow to distinguish between $\alpha \approx 1$, as usually assumed for charm production on the basis of perturbative QCD, and $\alpha \approx 0.9$, the value obtained for pion and $J/\psi$ production. Data on open charm production in nucleus–nucleus collisions do not exist. It is therefore crucial for our understanding of the mechanism of charm creation and $J/\psi$ production to measure open charm yields in nucleus–nucleus collisions.

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Table 1 The results on mean multiplicity of $J/\psi$ mesons produced in p+p interactions.

| $\sqrt{s}$ [GeV] | $\langle J/\psi \rangle \cdot 10^6$ | Reference |
|------------------|---------------------------------|-----------|
| 6.8              | 0.021 ± 0.006                   | 8         |
| 8.7              | 0.075 ± 0.037                   | 9         |
| 19.4             | 3.8 ± 0.3                       | 10        |
| 24.3             | 4.6 ± 0.8                       | 12        |
| 52.0             | 19.7 ± 8.7                      | 11        |
Figure 1: The multiplicity of $J/\psi$ mesons produced in $p+p$ interactions as a function of the collision energy. The filled circles indicated measured data. The open circle shows the estimated multiplicity at $\sqrt{s} = 17.3$ GeV.
Figure 2: The ratio of the mean multiplicities of $J/\psi$ mesons and negatively charged hadrons for inelastic nucleon–nucleon (square) and inelastic O+Cu, O+U, S+U and Pb+Pb (circles) interactions at 158 A-GeV plotted as a function of the mean number of participant nucleons. For clarity the N+N point is shifted from $\langle N_p \rangle = 2$ to $\langle N_p \rangle = 5$. The dashed line indicates the mean value of the ratio.
Figure 3: Comparison between $\alpha(J/\psi)$ (filled circles) and $\alpha(h^-)$ (open circles) for p+A interactions in the energy range 200–800 GeV. The dotted line shows the value $\alpha = 1$ characteristic for the $A$–dependence of total charm cross section obtained in models based on the perturbative QCD. The dashed line indicates the value $\alpha = 0.9$ measured for pion production in full phase space.
Figure 4: Dependence of $\alpha(D, \overline{D})$ on $x_F$ for p+A interactions [29, 30] (filled symbols) and $\pi$+A interactions [31, 32, 33, 34] (open symbols) at 250–800 GeV. Circles indicate results obtained by reconstruction of $D$ and $\overline{D}$ decays. Squares indicate data obtained by the analysis of prompt single leptons or neutrinos. The results for which the $\langle x_F \rangle$ is not given are plotted at the lower edge of the acceptance region. The dotted line shows the value $\alpha = 1$ characteristic for the $A$–dependence of total charm cross section obtained in models based on the perturbative QCD. The dashed line indicates the value $\alpha = 0.9$ measured for pion production in full phase space.