J/ψ production in nuclear collisions

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Data on J/ψ 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/ψ mesons and pions is the same for all of these collisions. This observation is difficult to understand within current models of J/ψ production in nuclear collisions. [S0556-2813(99)06110-5]

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I. INTRODUCTION

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

Experimental results on J/ψ 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/ψ meson (or its premeson state) with nucleons [3]. However models based on this picture and parameters fitted to the $p+A$ data in general overpredict recent results on J/ψ production in central Pb+Pb collisions at 158*A* GeV (for review see [4]). This reduction of J/ψ production in the latter data is usually interpreted as due to interactions of J/ψ (pre)mesons with surrounding high density matter (ultimately the quark gluon plasma) [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) [6]. These data and their interpretation in terms of a statistical QGP model [7] suggested the question as to whether a similar dependence may be observed for charm and consequently for J/ψ production. A simple estimation of the centrality dependence of the J/ψ to pion ratio in Pb+Pb collisions indicates that this hypothesis may be in fact correct [7].

The aim of this paper is to review available experimental results to obtain information concerning the A dependence of the J/ψ yield. In particular we study the A dependence of the J/ψ to pion ratio using results on proton-proton and nucleus-nucleus interactions (Secs. II and III) and proton-nucleus interactions (Sec. IV). We summarize also results on the A dependence of the open charm yield in $p+A$ interactions (Sec. V).

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II. J/ψ MULTIPLICITY IN $p+p$ INTERACTIONS

In $p+p$ interactions the J/ψ 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 [12], and 52 GeV [11]. 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/ψ mesons in full momentum space $\langle J/\psi\rangle$ is obtained in the following way. The x_F distribution of J/ψ 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 the J/ψ 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 Ref. [13]. The resulting values of $\langle J/\psi\rangle$ are given in Table I.

For comparison with the data on nucleus-nucleus collisions at 158*A* GeV the mean J/ψ multiplicity for $p+p$ interactions at this energy ($\sqrt{s}=17.3$ GeV) is needed. In this energy range the energy dependence of the integrated cross section for J/ψ 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 σ_0 are parameters fitted to the data; $\sigma^{J/\psi}$ and $m_{J/\psi}$ are J/ψ cross section and mass, respectively. This parametrization predicts a decrease of the J/ψ yield by about 25% when going from $\sqrt{s}=19.4$ GeV to $\sqrt{s}=17.3$ GeV.

TABLE I. The results on mean multiplicity of J/ψ mesons produced in $p+p$ interactions.

$\sqrt{s}$ [GeV]	$\langle J/\psi\rangle 10^6$	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	[11]
52.0	19.7 ± 8.7	[12]

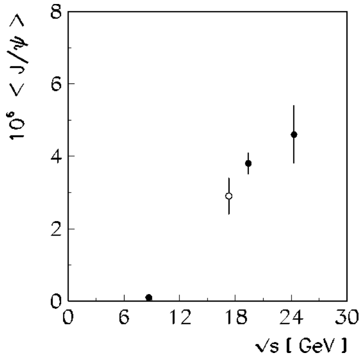

FIG. 1. The multiplicity of J/ψ mesons produced in $p+p$ interactions as a function of the collision energy. The filled circles indicate measured data. The open circle shows the estimated multiplicity at $\sqrt{s}=17.3\,\mathrm{GeV}$.

Thus we can estimate $\langle J/\psi \rangle$ to be $(2.9\pm0.5)\times10^{-6}$ at $\sqrt{s}=17.3\,\mathrm{GeV}$ using the measured value of $\langle J/\psi \rangle=(3.8\pm0.3)\times10^{-6}$ at $\sqrt{s}=19.4\,\mathrm{GeV}$ (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 π^- mesons) in nucleon-nucleon ($N+N$) interactions at 158 GeV is $\langle h^- \rangle = 3.01\pm0.06$ [15]. This mean multiplicity was calculated as $\langle h^- \rangle = (\langle h^- \rangle_{pp} + 2\langle h^- \rangle_{pn} + \langle h^- \rangle_{nn})/4$, 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 GeV, respectively [15].

Taking the value of $\langle J/\psi \rangle$ calculated above we obtain $\langle J/\psi \rangle / \langle h^- \rangle = (0.96\pm0.17)\times10^{-6}$ for $N+N$ interactions at $\sqrt{s}=17.3\,\mathrm{GeV}$. This ratio is further used for the comparison with nucleus-nucleus data.

III. J/ψ PRODUCTION IN NUCLEUS-NUCLEUS COLLISIONS

The production of J/ψ in nucleus-nucleus collisions was measured by the NA38 Collaboration for O+Cu, O+U, and S+U interactions at 200A GeV [16] and by the NA50 Collaboration for Pb+Pb interactions at 158A GeV [17]. The procedure that allows us 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/ψ cross section in minimum bias Pb+Pb collisions is

$$B_{\mu\mu}\sigma_{acc}^{J/\psi} = 21.9\pm0.2\pm1.6 \ \ \mu\mathrm{b}.$$

This cross section refers to the NA50 acceptance $0<y_{\mathrm{c.m.}}<1$ and $-0.5<\cos\theta_{\mathrm{CS}}<0.5$, where $y_{\mathrm{c.m.}}$ is the J/ψ rapidity calculated in the c.m. system and θ_{CS} is the Collins-Soper angle [18]. In order to get an estimate of the total J/ψ cross section we assume that the J/ψ production for $y_{\mathrm{c.m.}}>1$ can be neglected and that the distribution in $\cos\theta_{\mathrm{CS}}$ is uniform [10]. This leads to a correction factor for the acceptance equal to 4. Based on the $h+p$ results at 200 GeV [10] one can estimate that neglecting the J/ψ yield at $y_{\mathrm{c.m.}}>1$ may lead to an underestimation of the J/ψ multiplicity by less than 30%. A similar conclusion is reached when the J/ψ rapidity distribution in Pb+Pb collisions is assumed to be similar to the rapidity distribution of the ϕ mesons measured by the NA49 Collaboration [19]. In addition, the cross section presented by NA50 is corrected here for the branching ratio $J/\psi \to \mu^+ + \mu^-$ ($B_{\mu\mu}=0.0601$) [13]. The cross section for J/ψ production resulting from the above procedure is

$$\sigma^{J/\psi} = 1.46\pm0.12 \ \ \mathrm{mb},$$

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

$$\langle J/\psi \rangle = \frac{\sigma^{J/\psi}}{\sigma} = (2.07\pm0.17)\times10^{-4},$$

where σ 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. [20].

The results of the NA35 and NA49 Collaborations [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 158A GeV and equal to $\langle h^- \rangle / \langle N_P \rangle = 1.93\pm0.14$. 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 [21] ($\langle N_P \rangle = 102$) we get $\langle h^- \rangle = 197\pm14$. This leads to $\langle J/\psi \rangle / \langle h^- \rangle = (1.05\pm0.11)\times10^{-6}$ for inelastic Pb+Pb collisions at 158A 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 differences. The J/ψ cross sections for oxygen and sulphur induced reactions are measured at 200A GeV [16]. Therefore for the comparison with the results at 158A GeV the measured values are scaled down by 25% according to the energy dependence of the J/ψ multiplicity established for $p+p$ interactions (see Sec. II). Due to projectile-target asymmetry the x_F distribution of J/ψ is not expected to be symmetric with respect to reflection at $x_F=0$. The correction for this effect is negelected.

The ratios obtained for nucleus-nucleus collisions and the corresponding ratio for $N+N$ interactions at the 158A 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/ψ measurement for nucleus-nucleus collisions. This systematic error can be reduced when the results on the rapidity or x_F distributions are published.

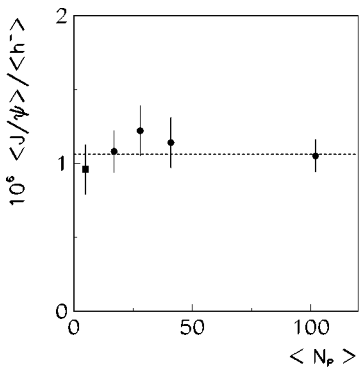

FIG. 2. The ratio of the mean multiplicities of J/ψ mesons and negatively charged hadrons for inelastic nucleon-nucleon (square) and inelastic O+Cu, O+U, S+U, and Pb+Pb (circles) interactions at 158*A* GeV plotted as a function of the mean number of participant nucleons. For clarity the $N+N$ point is shifted from $\langle N_P \rangle = 2$ to $\langle N_P \rangle = 5$. The dashed line indicates the mean value of the ratio.

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 $\langle$hard process$\rangle$ denotes here a mean multiplicity of any process for which the cross section in $A+A$ collisions increases as A^2.

IV. J/ψ PRODUCTION IN $p+A$ INTERACTIONS

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

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

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 [22] at 800 GeV. The x_F distribution of J/ψ decreases by a factor of about 10 from $x_F = 0$ to $x_F = 0.4$ [23]. Thus the A dependence of the integrated J/ψ cross section in the region $x_F > 0$ is dominated by the dependence measured close to $x_F = 0$. The values of $\alpha(J/\psi)$ obtained from x_F integrated data ($x_F \geqslant 0$) or from the data close to $x_F = 0$ range from 0.89 to 0.94. The results were obtained by various experiments [10,24–26] in the collision energy range 200–800 GeV and they were compiled in Ref. [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/ψ and h^- production parameter α 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 α parameter fitted to the multiplicity data was added to the α parameter obtained by the fit to the inelastic cross section results ($\alpha = 0.72 \pm 0.01$) [27]. 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. 3 (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 α parameter for h^- and J/ψ production imply that the ratio $\langle J/\psi \rangle (x_f > 0) / \langle h^- \rangle$ is approximately independent of A for $p+A$ interactions at high energy. We note that the difference in the α parameter of 0.02 (typical for the values shown in Fig. 3) results in a 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 $\langle$hard process$\rangle$ denotes here a mean multiplicity of any process for which the cross section in $p+A$ interactions increases as A ($\alpha = 1$).

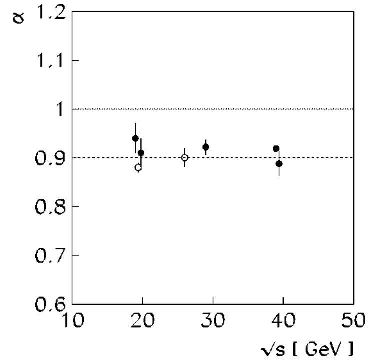

FIG. 3. Comparison between $\alpha(J/\psi)$ (filled circles) and $\alpha(h^-)$ (open circles) for $p+A$ interactions in the energy range 200–800 GeV. The dotted line shows the value $\alpha = 1$ characteristic for the A dependence of total charm cross section obtained in models based on the perturbative QCD. The dashed line indicates the value $\alpha = 0.9$ measured for pion production in full phase space.

The measurements of the J/ψ production in the backward hemisphere ($x_F < 0$) are poor. However, the experimental

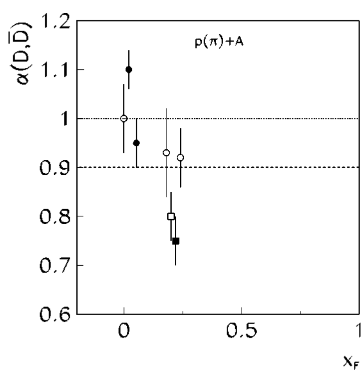

FIG. 4. Dependence of $\alpha(D,\bar{D})$ on x_F for $p+A$ interactions [30,31] (filled symbols) and $\pi+A$ interactions [32–35] (open symbols) at 250–800 GeV. Circles indicate results obtained by reconstruction of D and $\bar{D}$ decays. Squares indicate data obtained by the analysis of prompt single 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.

data [22] 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/ψ production, based on the J/ψ data from the forward hemisphere only, may remain unchanged when the J/ψ results in full phase space become available.

V. CONCLUSIONS

The main result of this paper is that the ratio of mean multiplicities of J/ψ mesons and pions is similar for inelastic proton-proton, proton-nucleus, and nucleus-nucleus interactions at 158*A* GeV. In our opinion this experimental observation justifies the question of whether the generally accepted picture of J/ψ creation based on the hard production of charm quarks and subsequent suppression of the J/ψ yield by the interactions with the surrounding medium is valid. In this picture the observed scaling behavior of the data, $\langle J/\psi\rangle/\langle h^-\rangle \approx \mathrm{const}(A)$, can be treated only as due to accidental cancellation of several large effects.

We note that the ratio $\langle\psi'\rangle/\langle J/\psi\rangle$ is the same for $p+p$ and $p+A$ interactions but it is about two times lower for nucleus-nucleus (S+U and Pb+Pb) collisions [28]. Thus the values of the ratio of mean multiplicities of ψ' mesons and pions are concentrated around two different values: the value for $p+p$ and $p+A$ interactions and the value for nucleus-nucleus collisions. A similar behavior is observed for the strangeness to pion ratio. However in the latter case the value for nucleus-nucleus collisions is about two times higher than the value for $p+p$ and $p+A$ interactions [29].

It is obvious that the mechanism of J/ψ production cannot be understood without data on open charm creation. Published data on D and $\overline{D}$ production in $p+A$ interactions are insufficient. The results on the A dependence are summarized in Fig. 4, where $\alpha(D,\overline{D})$ is shown as a function of x_F for interactions at 400 GeV [30] and 800 GeV [31]. It is clear that these data do not allow us 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/ψ 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/ψ production to measure open charm yields in nucleus-nucleus collisions.

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