INSTITUT FÜR KERNPHYSIK, UNIVERSITÄT FRANKFURT
D - 60486 Frankfurt, August–Euler–Strasse 6, Germany

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On J/ψ Production in Nuclear Collisions

Marek Gaździcki[1]

Institut für Kernphysik, Universität Frankfurt
August–Euler–Strasse 6, D - 60486 Frankfurt, Germany

Abstract

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 these collisions. This observation is difficult to understand within current models of J/ψ production in nuclear collisions based on the assumption of hard QCD production of charm quarks.

[1]E–mail: marek@ikf.uni–frankfurt.de

1 Introduction

According to the factorization theorem of perturbative QCD [1] inclusive cross section 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 a $c\bar{c}$ 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 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 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 (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/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 [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/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 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 [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/ψ 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/ψ production can be conveniently parametrized by [14]:

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

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. 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 π^-–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 $\langle h^- \rangle = (\langle h^- \rangle_{pp} + 2\langle h^- \rangle_{pn} + \langle h^- \rangle_{nn})/4$, 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 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.

3 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 200 A·GeV [16] and by the NA50 Collaboration for Pb+Pb interactions at 158 A·GeV [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/ψ cross section in minimum bias Pb+Pb collisions is:

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

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/ψ rapidity calculated in the c.m. system and θ_{CS} is the Collins–Soper angle [19]. In order to get an estimate of the total J/ψ cross section we assume that the J/ψ production for $y_{cm} > 1$ can be neglected and that the distribution in $cos\theta_{CS}$ 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 J/ψ yield at $y_{cm} > 1$ 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 [20]. In addition, the cross section presented by NA50 is corrected here for the branching ratio $J/\psi \rightarrow \mu^+ + \mu^-$ ($B_{\mu\mu} = 0.0601$) [13]. The cross section for J/ψ 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/ψ multiplicity can be calculated as

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

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. [21].

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 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 [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/ψ cross sections for oxygen and sulphur induced reactions are measured at 200 A·GeV [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/ψ multiplicity established for p+p interactions (see Section 2). Due to projectile–target asymmetry the x_F distribution of J/ψ is expected to be not 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 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 accepetance 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.

Finally we note that the ratio $\langle hard\ \ process \rangle / \langle h^- \rangle$ 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.

4 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]:

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

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/ψ decreases by a factor of about 10 from $x_F = 0$ to $x_F = 0.4$ [24]. 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 ($x_F \geq 0$) or from the data close to $x_F = 0$ range from 0.89 to 0.94. The results were obtained by various experiments [10, 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/ψ and h^- production the 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 ($\alpha = 0.72 \pm 0.01$) [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 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 10% change in the multiplicity ratio between p+N and p+Pb interactions. This can be compared to about 70% increase of the ratio $\langle hard\ \ process \rangle / \langle h^- \rangle$ 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 ($\alpha = 1$).

The measurements of J/ψ 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/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.

5 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 a question whether the generally accepted picture of J/ψ creation based on the factorization theorem of the perturbative QCD and subsequent suppression of the J/ψ 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/ψ production can not 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 [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/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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References

[1] J. C. Collins, D. E. Soper and G. Sterman, in *Perturbative Quantum Chromodynamics*, ed. A. H. Mueller, World Scientific, Singapore, 1989.

[2] *Hard Processes in Hadronic Interactions*, eds. H. Satz and X.–N. Wang, Special Issue of Int. J. Mod. Phys. **10** (1995) 2881.

[3] C. Gerschel and J. Hüfner, Z. Phys. **C56** (1992) 171.

[4] C. Gerschel and J. Hüfner, *Charmonium suppression in heavy–ion collisions*, hep–ph/9802245 (1998).

[5] H. Satz, *Colour Deconfinement and J/ψ Suppresion in High Energy Nuclear Collisions*, hep–ph/9711289 (1997).

[6] T. Alber et al. (NA35 Collab.), Eur. Phys. J. **C2** (1998) 643,
S. V. Afanasjev et al. (NA49 Collab.), Nucl. Phys. **A610** (1996) 188c,
H. Appelshauser et al. (NA49 Collab.), *Baryon Stopping and Charged Particle Distributions in Central Pb+Pb Collisions at 158 GeV per Nucleon*, nucl–ex/9810014 (1998), submitted to Phys. Rev. Lett.,
M. Gaździcki, J. Phys. **G23** (1997) 1881c.

[7] M. Gaździcki and M. I. Gorenstein, *On the Early Stage of Nucleus–Nucleus Collisions*, hep–ph/9803462 (1998).

[8] A. Bamberger et al., Nucl. Phys. **B134** (1978) 1.

[9] M. J. Corder et al., Phys. Lett. **98B** (1981) 220.

[10] J. Badier et al., Z. Phys. **C20** (1983) 101.

[11] E. Nagy et al., Phys. Lett. **60B** (1975) 96.

[12] C. Morel et al., Phys. Lett. **B252** (1990) 505.

[13] C. Caso et al. (Particle Data Group), Eur. Phys. J. **C3** (1998) 1.

[14] G. A. Schuler et al., Cern Report, CERN–TH.7170/94 (1994).

[15] M. Gaździcki and D. Röhrich, Z. Phys. **C65** (1995) 215.

[16] C. Baglin et al. (NA38 Collab.), Phys. Lett. **B270** (1991) 105.

[17] M. C. Abreu et al. (NA50 Collab.), Phys. Lett. **B410** (1997) 327.

[18] A. Romano et al. (NA50 Collab.), Proceedings of XXXIII Moriond Conference, March 22–29, 1998.

[19] J. C. Collins and D. E. Soper, Phys. Rev. **D16** (1977) 2219.

[20] V. Friese et al. (NA49 Collab.), J. Phys. **G23** (1997) 1837c.

[21] M. Anikina et al. Yad. Fiz. **38** (1983) 149.

[22] H. Pi, Computer Physics Commun. **71** (1992) 173.

[23] R. S. Towell et al. (E866 Collab.), Proceedings of XXXIII Moriond Conference, March 22–29, 1998.

[24] M. H. Schub et al., Phys. Rev. **52** (1995) 1307.

[25] D. M. Alde et al. (E772 Collab.), Phys. Rev. Lett. **66** (1991) 133.

[26] M. I. Leitch et al. (E789 Collab.), Phys. Rev. **D52** (1995) 4251.

[27] F. Fleure (NA38 and NA51 Collab.), Ph. D. Thesis, Ecole Polytechnique, Palaiseau (1997).

[28] A. S. Carroll et al., Phys. Lett. **80B** (1979) 319.

[29] M. E. Duffy et al. (E613 Collab.), Phys. Rev. Lett. **55** (1984) 1816.

[30] M. J. Leitch et al. (E789 Collab.), Phys. Rev. Lett. **72** (1994) 2542.

[31] E. Cobbaert et al. (WA78 Collab.), Phys. Lett. **B191** (1987) 456.

[32] C. A. Alves et al. (E769 Collab.), Phys. Rev. Lett. **69** (1992) 3147.

[33] M. Adamovich et al. (WA82 Collab.), Phys. Lett. **B284** (1992) 453.

[34] M. Adamovich et al. (Beatrice Collab.), Nucl. Phys. **B495** (1997) 3.

Table 1 The results on mean multiplicity of J/ψ 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]

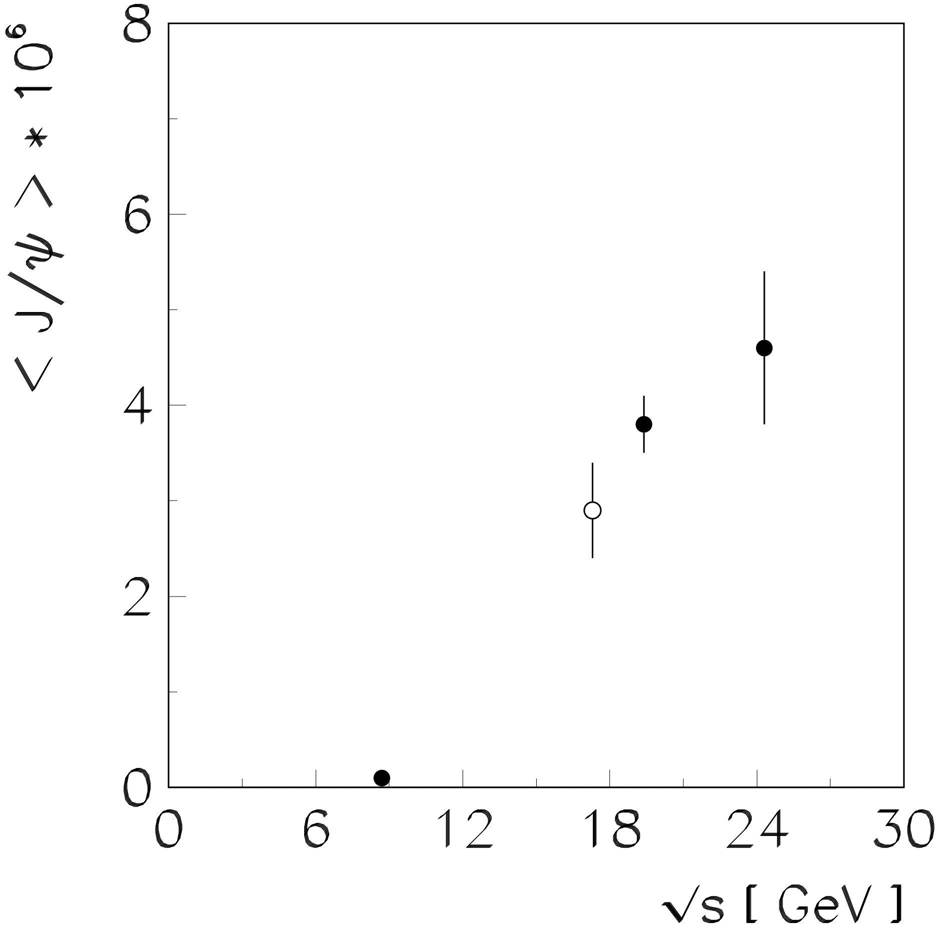

Figure 1: The multiplicity of J/ψ mesons produced in p+p interactions as a function of the collision energy. The filled circles indicated measured data. The open circle shows the estimated multiplicity at $\sqrt{s} = 17.3$ GeV.

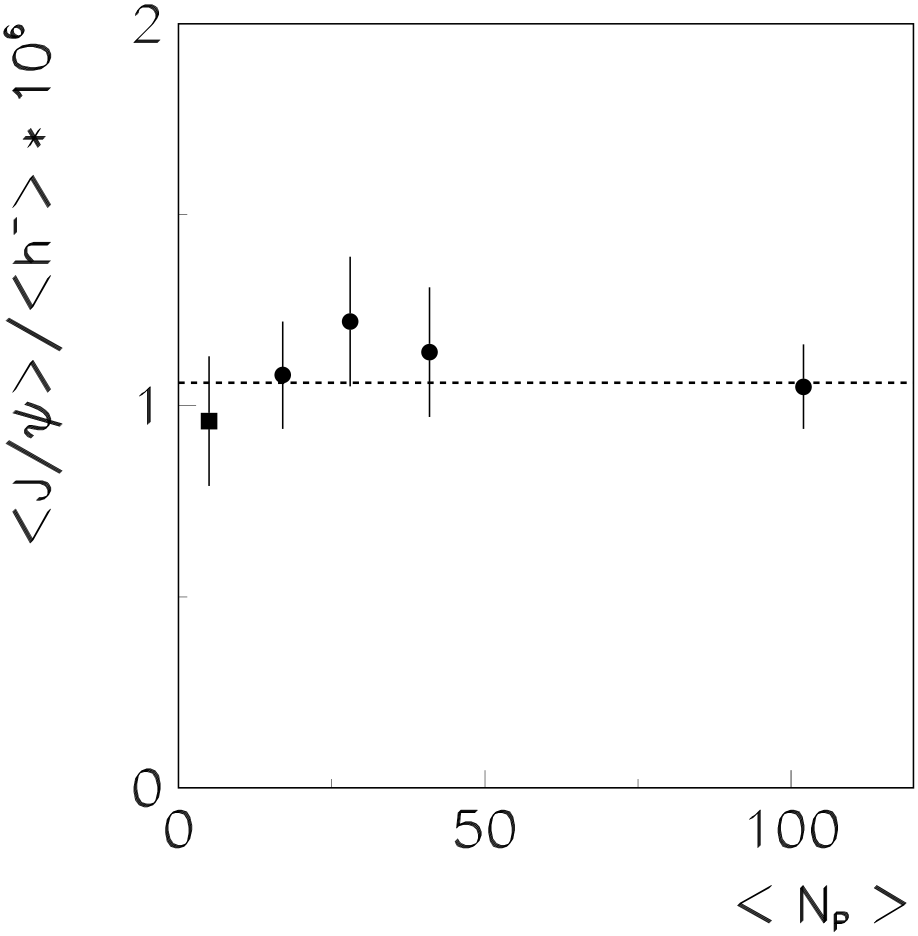

Figure 2: The ratio of the mean multiplicities of J/ψ mesons and negatively charged hadrons for inelastic nucleon–nucleon (square) and inelastic O+Cu, O+U, S+U and Pb+Pb (circles) interactions at 158 A·GeV plotted as a function of the mean number of participant nucleons. For clarity the N+N point is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

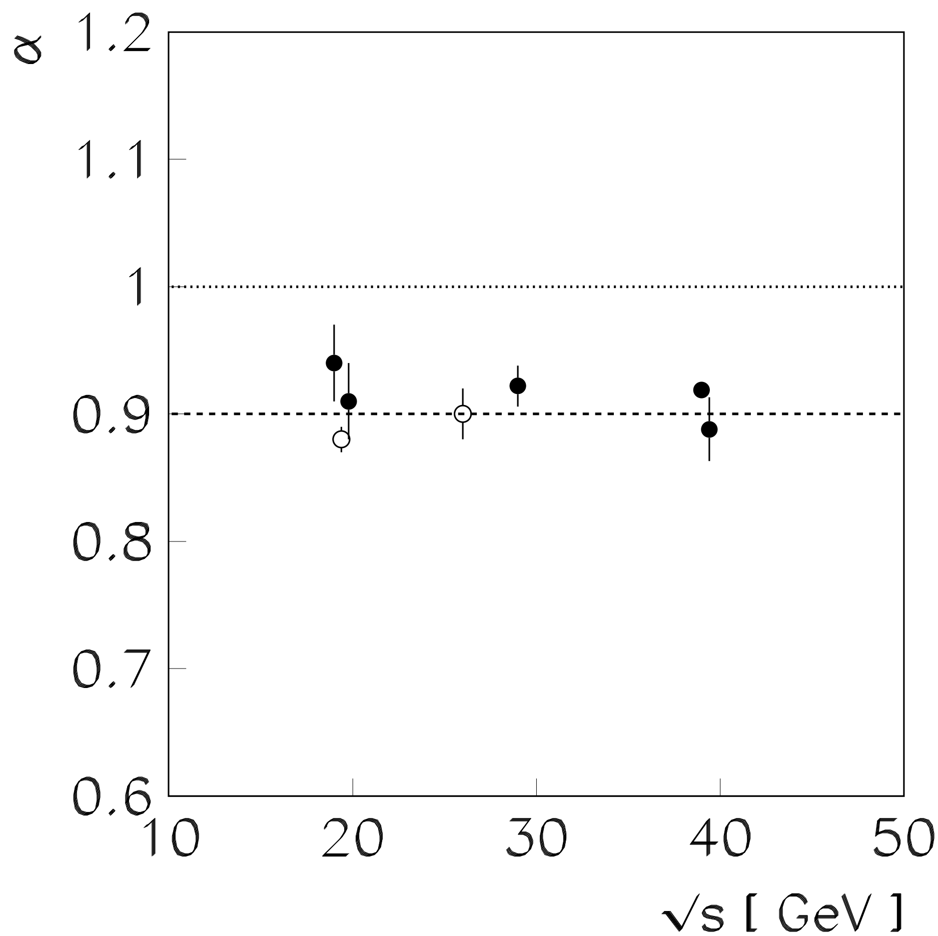

Figure 3: Comparison between $\alpha(J/\psi)$ (filled circles) and $\alpha(h^-)$ (open circles) for p+A interactions in the energy range 200–800 GeV. The dotted line shows the value $\alpha = 1$ characteristic for the A–dependence of total charm cross section obtained in models based on the perturbative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

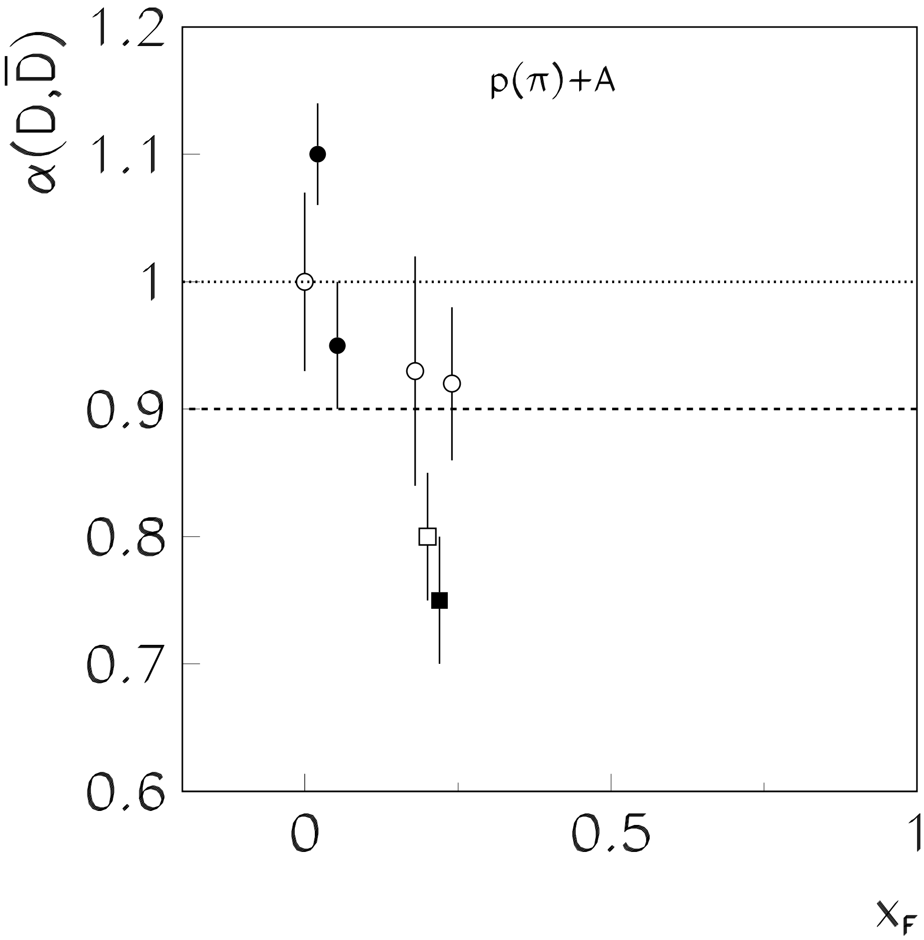

Figure 4: Dependence of $\alpha(D, \overline{D})$ on x_F for p+A interactions [29, 30] (filled symbols) and π+A interactions [31, 32, 33, 34] (open symbols) at 250–800 GeV. Circles indicate results obtained by reconstruction of D and $\overline{D}$ decays. Squares indicate data obtained by the analysis 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.