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J/ψ and ψ' production in p, O and S induced reactions at SPS energies

M.C. Abreu[1,a)], J. Astruc[2)], C. Baglin[3)], A. Baldit[4)], M. Bedjidian[5)], P. Bordalo[1,b)], A. Bohrani[6)], A. Bussière[3)], P. Busson[6)], J. Castor[4)], T. Chambon[4)], C. Charlot[6)], B. Chaurand[6)], I. Chevrot[4)], D. Contardo[5)], E. Descroix[5,c)], A. Devaux[4)], O. Drapier[5,d)], B. Espagnon[4)], J. Fargeix[4)], R. Ferreira[1)], F. Fleuret[6)], P. Force[4)], L. Fredj[4)], J. Gago[1,b)], C. Gerschel[2)], P. Gorodetzky[7,e)], J.Y. Grossiord[5)], A. Guichard[5)], J.P. Guillaud[3)], R. Haroutunian[5)], D. Jouan[2)], L. Kluberg[6)], R. Kossakowski[3)], G. Landaud[4)], C. Lourenço[1,8)], L. Luquin[4)], R. Mandry[5)], S. Mourgues[4)], F. Ohlsson-Malek[5,f)], S. Papillon[2)], J.R. Pizzi[5)], C. Racca[7)], S. Ramos[1,b)], A. Romana[6)], B. Ronceux[3)], P. Saturnini[4)], S. Silva[1)], P. Sonderegger[8,b)], X. Tarrago[2)], J. Varela[1,b,d)], F. Vazeille[4)]

NA38 Collaboration

Abstract

The production of the J/ψ and ψ' charmonia states has been studied, through their dimuon decay, in proton, Oxygen and Sulphur induced reactions, by the NA38 experiment at the CERN SPS. The proton data was collected with beams of 200 and 450 GeV, while the ion beams had an energy of 200 GeV per incident nucleon. The J/ψ production cross-section per nucleon-nucleon collision exhibits a remarkably continuous pattern, as a function of the product of the mass numbers of the interacting nuclei, from pp up to S-U reactions. The same pattern is observed within S-U collisions, as a function of the collision centrality. While in p-A interactions both charmonia states exhibit the same A-dependence, in S-U collisions the ψ' production is very strongly suppressed.

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[1] LIP, Av. Elias Garcia 14, P-1000 Lisbon, Portugal
[2] IPN, IN2P3-CNRS and Université de Paris-Sud, F-91406 Orsay Cedex, France
[3] LAPP, IN2P3-CNRS, F-74941 Annecy-le-Vieux Cedex, France
[4] LPC Clermont-Ferrand, IN2P3-CNRS and Université Blaise Pascal, F-63177 Aubière Cedex, France
[5] IPN Lyon, IN2P3-CNRS and Université Claude Bernard, F-69622 Villeurbanne Cedex, France
[6] LPNHE, Ecole Polytechnique, IN2P3-CNRS, F-91128 Palaiseau Cedex, France
[7] IRes, IN2P3-CNRS and Université Louis Pasteur, F-67037 Strasbourg Cedex, France
[8] CERN, CH-1211 Geneva 23, Switzerland
[a] Also at UCEH, Universidade do Algarve, Faro, Portugal
[b] Also at IST, Universidade Técnica de Lisboa, Lisbon, Portugal
[c] Now at Université Jean Monnet, Saint-Etienne, France
[d] Now at CERN, Geneva, Switzerland
[e] Now at PCC Collège de France, Paris, France
[f] Now at ISN, Grenoble, France

1 Introduction

The NA38 and NA51 collaborations have recently published their final results on charmonia production in interactions induced by proton [1, 2] and light ion [3] beams, at the CERN SPS. In this letter we present a global study of these results, evaluating if charmonia production in Oxygen and Sulphur-induced reactions follows the pattern established by the p-A data or if some anomaly sets in these (light) nucleus-nucleus collisions. This work is done in the context of the study of J/ψ and ψ' production and suppression in heavy ion collisions, as a signal of the formation of a state of deconfined quarks and gluons [4].

2 Data analysis

In order to compare the production of hard processes, such as charmonium production, from pp to nucleus-nucleus collisions it is appropriate to use the "cross-section per nucleon-nucleon collision". This quantity is obtained dividing the measured charmonium cross-section by the product of the mass numbers of the interacting nuclei, A×B. For a study as a function of centrality, in nucleus-nucleus collisions, the product A×B can be replaced by the measured Drell-Yan cross-section which is well known, both experimentally and theoretically, to be proportional to the number of elementary nucleon-nucleon collisions [5].

The several data sets studied in this paper were obtained with different incident beams and targets but always using the same basic apparatus. The different experimental setups have to be properly accounted for. All the data have been collected in the same dimuon rapidity range, $3.0 < y_{\rm lab} < 4.0$. The 450 GeV proton cross-sections are therefore measured in the center of mass rapidity range $-0.4 < y^* < 0.6$ whereas the corresponding range for the 200 GeV data is $0.0 < y^* < 1.0$. For comparison purposes, it is necessary to rescale the 450 GeV proton data to the kinematical conditions of the ion data.

It is common practice to parametrise production cross-sections in p-A collisions using only two parameters, with the power law $\sigma_0\ {\rm A}^\alpha$. In nucleus-nucleus collisions, the natural extension of this parametrisation of the A-dependence of charmonium hadroproduction is $\sigma_{\rm AB} = \sigma_0\ ({\rm A} \times {\rm B})^\alpha$, where A and B are the mass numbers of the projectile and target nuclei.

Using this expression to fit the J/ψ cross-sections measured with the 450 GeV p-A data, we obtain the value $\alpha^\psi_{450} = 0.919 \pm 0.015$, while the corresponding fit to the data collected at 200 GeV leads to $\alpha^\psi_{200} = 0.911 \pm 0.034$. Figure 1 shows the measured values and the fitted curves. The remarkable compatibility of the two values justifies a simultaneous fit to the two sets of points imposing a single α exponent. This global fit leads to $\alpha^\psi = 0.918 \pm 0.015$.

From the global fit we also determine the ratio between the values of σ_0 for the 200 and 450 GeV data sets: 0.38 ± 0.04. We can use this factor to rescale the 450 GeV measurements to the 200 GeV kinematical conditions. Notice that besides

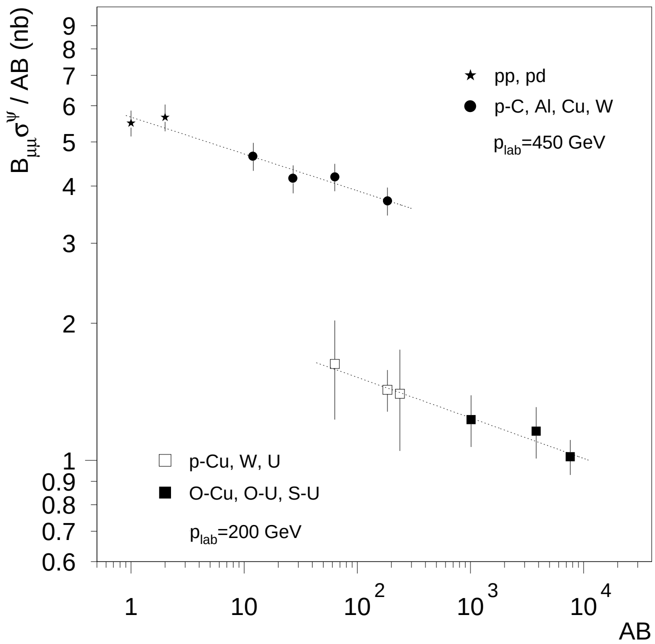

Figure 1: The 450 and 200 GeV J/ψ cross-sections per nucleon (times branching ratio into dimuons, $B_{\mu\mu}$), in the rapidity domain $3.0 < y_{\rm lab} < 4.0$, as a function of A×B. The lines are the best fits to the function $B_{\mu\mu}\,\sigma_0\ ({\rm A \times B})^{\alpha-1}$.

the change in $\sqrt{s}$ the rescaling factor also reflects the change in rapidity domains. The same factor can be used to rescale the 450 GeV ψ' cross-sections to the incident momentum and rapidity range of the 200 GeV data. In fact, the ratio between ψ' and J/ψ production cross-sections, in p-A collisions, seems to be independent of $\sqrt{s}$, within the energy domain covered by the currently existing measurements [6].

3 Absolute charmonia cross-sections

The J/ψ cross-sections per nucleon-nucleon collision, rescaled if necessary as described above, are listed in Table 1 and shown in Fig. 2. The excellent agreement between the 200 and 450 GeV data sets can be easily judged in the case of the p-Cu and p-W collision systems, for which both measurements exist.

The fact that the measured J/ψ yield, in p-A collisions, scales less than linearly with A, is commonly interpreted as due to final state interactions, between the produced charmonium state and the surrounding matter. This interpretation is supported by the linear A-dependence exhibited by Drell-Yan production [8], also a hard process (quark-antiquark annihilation rather than gluon fusion) but for which there are no final state interactions. According to this standard interpretation, the number of produced $c\bar{c}$ pairs is proportional to the number of nucleon-nucleon colli-

Table 1: J/ψ cross-sections per nucleon (times b.r. into dimuons, $B_{\mu\mu}$), rescaled to 200 GeV and to the rapidity window $0 < y^* < 1$. The error bars include statistical and systematical uncertainties.

	$p_{\rm beam}$ (GeV/c)	Ref.	L (fm)	$B_{\mu\mu}\sigma^{\psi}$ / AB (nb)
pp	450	[1]	0	2.11 ± 0.24
pd	450	[1]	0.13	2.18 ± 0.25
p-C	450	[2]	1.22	1.79 ± 0.24
p-Al	450	[2]	1.90	1.60 ± 0.21
p-Cu	450	[2]	2.62	1.61 ± 0.19
p-Cu	200	[7]	2.62	1.63 ± 0.40
p-W	450	[2]	3.93	1.43 ± 0.18
p-W	200	[2]	3.93	1.43 ± 0.15
p-U	200	[2]	4.56	1.40 ± 0.35
O-Cu	200	[7]	3.98	1.23 ± 0.16
O-U	200	[7]	5.92	1.16 ± 0.15
S-U	200	[3]	6.48	1.02 ± 0.09

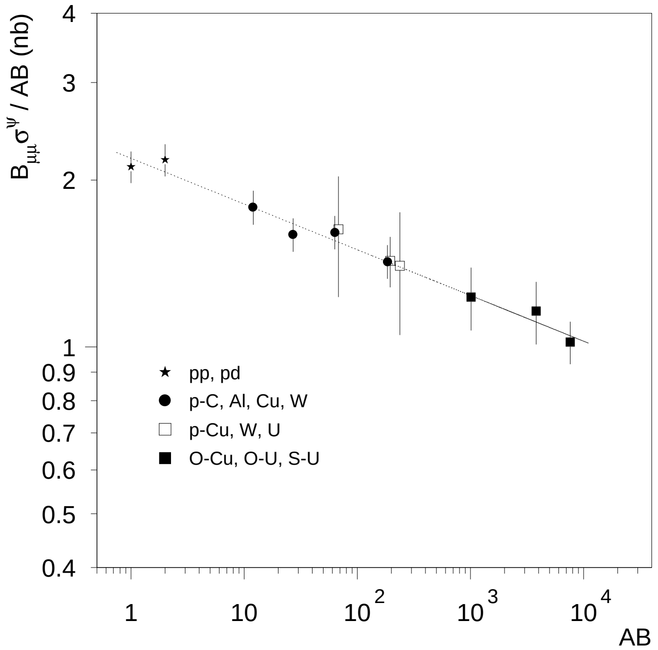

Figure 2: J/ψ cross-sections per nucleon, times b.r., plotted as a fuction of A×B. The 450 GeV values are rescaled to 200 GeV and recomputed in the c.m.s. rapidity range 0.0–1.0. The line corresponds to the best fit to the function $B_{\mu\mu}\,\sigma_0\ (\mathrm{A} \times \mathrm{B})^{\alpha-1}$.

sions, like for Drell-Yan, but the formed bound states can be destroyed by (strong) interactions while moving through the target nucleus, so that the number of finally observed charmonia states is suppressed relative to the linear A-dependence.

Recent measurements of D meson hadroproduction have confirmed that open charm scales linearly with the number of nucleons in the target [9], as expected for hard processes, supporting final state absorption of bound $c\bar{c}$ states as the correct explanation of the J/ψ results collected with nuclear targets.

An appropriate variable to parametrise the measured J/ψ cross-sections should then be the number of nucleons that the created state can potentially interact with [10]. This number can be calculated as the product $\rho\, L$, where ρ is the nuclear density distribution and L is the length of nuclear matter the $c\bar{c}$ state traverses while escaping from the interaction region. In our calculations we have used Woods-Saxon nuclear densities, with the numerical values of Ref. [11]. The path length L is calculated, for each impact parameter of the collision, b, as an average over a realistic distribution of $c\bar{c}$ production points, following the Glauber formalism [12]. The calculated values are reported in Table 1.

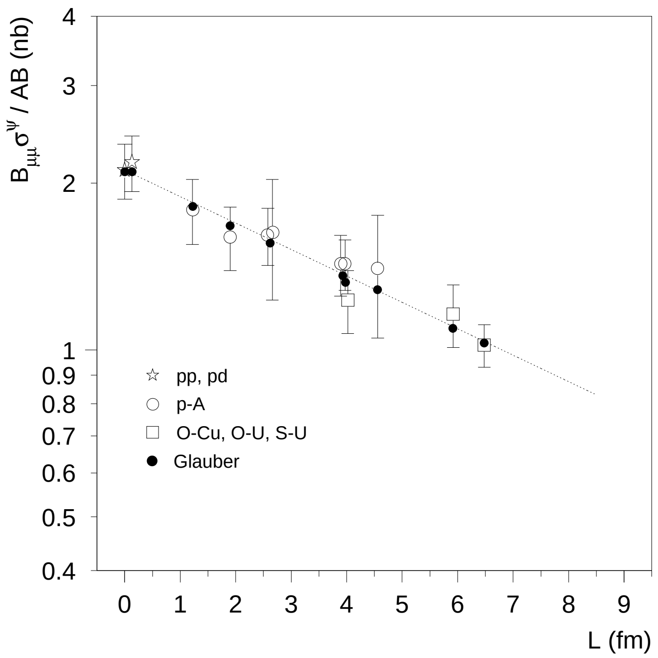

Figure 3: J/ψ cross-sections per nucleon, times b.r., plotted as a function of L. The 450 GeV values are rescaled to the 200 GeV kinematics. The dotted line shows the best fit to the simple function $\exp(-\sigma^{\psi}_{\rm abs}\,\rho_0\,L)$, while the closed circles are the result of a more refined 'Glauber' calculation (see the text for details).

Figure 3 shows the measured J/ψ cross-sections per nucleon-nucleon collision as a function of the average value of L. As a first order approximation, the charmonium "survival probability" can be simply parametrised as $\exp(-\sigma^{\psi}_{\rm abs}\,\rho_0\,L)$, where ρ_0 is the average nuclear density, 0.17 nucleon/fm^3. The dotted line in Fig. 3 corresponds to the best fit to this function, resulting in $\sigma^{\psi}_{\rm abs} = 6.5 \pm 1.0$ mb. A more refined analysis, based on the Glauber formalism and described in Ref. [12], leads to a very similar $\sigma^{\psi}_{\rm abs}$ value, 7.2 ± 1.2 mb (closed circles in Fig. 3).

The fact that this parametrisation provides a good description of the available data suggests that the A-dependence of J/ψ production can be properly accounted for by final state nuclear absorption, up to and including S-U reactions. In particular, there is no indication for any new absorption mechanism, which would suppress the S-U value relative to the reference baseline established by the p-A systematics.

We now turn to the study of ψ' production, from pp to S-U collisions. Table 2 and Fig. 4 show the ratio between the ψ' and the J/ψ production cross-sections (times their branching ratios into dimuons), $B'_{\mu\mu}\sigma^{\psi'} \,/\, B_{\mu\mu}\sigma^{\psi}$. This ratio is not affected by the uncertainties related to absolute normalisations and, as explained above, no rescaling factors have to be applied. The figure includes, for comparison, p-A results obtained by other experiments [13], with different targets, beam energies and kinematical windows.

Table 2: Ratio between the ψ' and the J/ψ production cross-sections, times their branching ratios into dimuons.

	$p_{\rm beam}$ (GeV/c)	Ref.	$B'_{\mu\mu}\sigma^{\psi'} \,/\, B_{\mu\mu}\sigma^{\psi}$ (%)
pp	450	[1]	1.60 ± 0.04
pd	450	[1]	1.71 ± 0.04
p-C	450	[2]	1.90 ± 0.13
p-Al	450	[2]	1.36 ± 0.35
p-Cu	450	[2]	1.74 ± 0.11
p-W	450	[2]	1.59 ± 0.13
p-W	200	[2]	1.80 ± 0.17
p-U	200	[2]	1.77 ± 0.22
S-U	200	[3]	0.76 ± 0.08

A fit of all the presently available p-A data to the function $(\mathrm{A} \times \mathrm{B})^{(\alpha'-\alpha)}$ leads to $\alpha' - \alpha = 0.016 \pm 0.009$, with $\chi^2/\mathrm{ndf} = 0.96$ (dotted line in Fig. 4). This result suggests that the two charmonia states suffer the same nuclear absorption, in p-A collisions, in the kinematical window probed by these measurements (positive x_F). The average $B'_{\mu\mu}\sigma^{\psi'} \,/\, B_{\mu\mu}\sigma^{\psi}$ ratio is 1.64 ± 0.03 % (dashed line in Fig. 4).

The S-U ψ' cross-section, on the contrary, shows a clear departure from the general trend established by the proton data. It lies more than a factor of two below the value expected by extrapolating the p-A results. While in p-A collisions the nuclear medium acts in the same way on both resonances, the S-U collisions provide a more extended surrounding matter that clearly distinguishes the two states, strongly suppressing the ψ' yield.

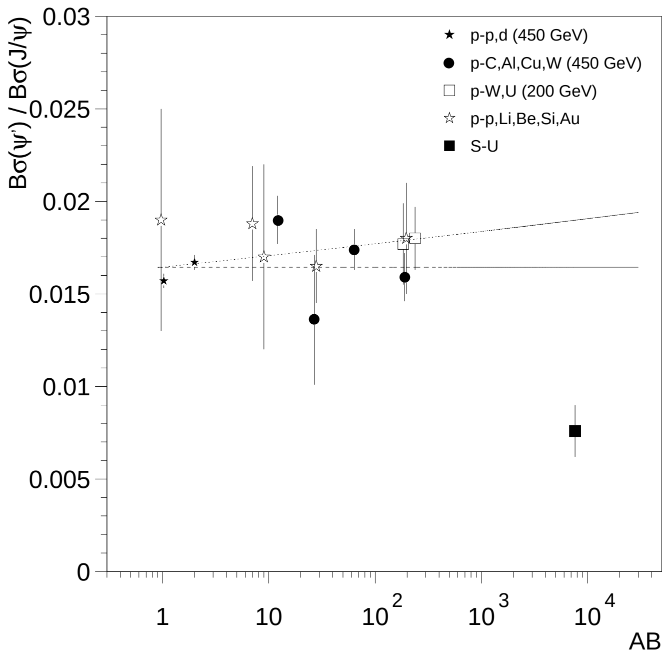

Figure 4: Ratio between ψ' and J/ψ production cross-sections, $B'_{\mu\mu}\sigma^{\psi'}$ / $B_{\mu\mu}\sigma^{\psi}$, as a function of A×B. See the text for the meaning of the lines.

These results support the idea that charmonia production proceeds through a two-step process. First the $c\bar{c}$ pair is created, maybe in a color octet state accompanied by a colinear gluon [14]. After travelling through the surrounding medium for some (formation) time it becomes a fully formed bound state, either a J/ψ or a ψ'. The formation time of the (fast) J/ψ and ψ' particles detected in current p-A experiments is larger than the size of the biggest nucleus, explaining why the ratio ψ'/ψ is not sensitive to a change in the size of the target nuclei. Once the physical states are formed, if there is still some matter to be crossed, as is probably the case in S-U interactions, we expect the ψ' to be more absorbed than the J/ψ because of the bigger size of the ψ' and because it is a more loosely bound state.

4 Centrality dependence of charmonia production

In this section we extend the previous study by exploring the S-U results as a function of the collision centrality. As explained in detail in Ref. [3], the S-U data sample was divided in five centrality bins, according to the neutral transverse energy, E_{T}, measured in each collision. For each E_{T} bin, the ratio between the J/ψ and the Drell-Yan cross-sections was derived from a fit to the dimuon mass spectra. The Drell-Yan yield is, in each centrality bin, proportional to the number of nucleon-nucleon collisions.

The values obtained cannot be directly compared with the corresponding ψ/DY values measured in p-A collisions, since the Drell-Yan cross-section depends on the proton and neutron content of the interacting nuclei. Also a kinematical correction has to be calculated to rescale the ψ/DY ratio measured with 450 GeV protons to the $\sqrt{s}$ and rapidity domain of the S-U data.

To rescale the Drell-Yan cross-sections, we have done a leading order calculation using the MRS A [15] parametrisation of the quark distribution functions. The isospin correction factors, calculated to convert all the Drell-Yan cross-sections to systems of projectiles and targets only made of protons, are 1 for pp, 0.875 for pD, 0.83 for p-W and p-U, and 0.99 for S-U. The kinematical correction factors are 0.44 for pp and 0.48 for pD.

As already mentioned above, L is a function of the impact parameter and can be used to investigate the centrality dependence of charmonium production. The ratios $B_{\mu\mu}\sigma^{\psi} \,/\, \sigma^{\rm DY}$ and $B'_{\mu\mu}\sigma^{\psi'} \,/\, \sigma^{\rm DY}$, recomputed as explained above, are listed in Table 3 and plotted in Fig. 5, as a function of L.

Table 3: J/ψ and ψ' cross-sections per nucleon-nucleon collision, as estimated from the ratios relative to the Drell-Yan cross-section (normalised in the mass window 2.9–4.5 GeV/c^2). The 450 GeV pp and pd values are rescaled to 200 GeV and to the rapidity window $0 < y^* < 1$.

	L (fm)	$B_{\mu\mu}\sigma^{\psi} \,/\, \sigma^{\rm DY}$	$B'_{\mu\mu}\sigma^{\psi'} \,/\, \sigma^{\rm DY}$
pp	0	46.6 ± 5.0	0.75 ± 0.09
pd	0.13	48.4 ± 4.8	0.83 ± 0.09
p-W	3.93	33.8 ± 3.3	0.59 ± 0.07
p-U	4.56	36.3 ± 5.0	0.65 ± 0.11
S-U	4.8	29.7 ± 2.4	0.34 ± 0.06
S-U	6.0	26.9 ± 1.8	0.24 ± 0.05
S-U	6.7	24.7 ± 1.6	0.19 ± 0.04
S-U	7.3	23.7 ± 1.4	0.13 ± 0.03
S-U	7.6	22.6 ± 1.5	0.09 ± 0.03

A fit of these data points to the simple function $\exp(-\sigma_{\rm abs}\,\rho_0\,L)$, which describes the effect of nuclear absorption, leads to $\sigma^{\psi}_{\rm abs} = 5.9 \pm 0.6$ mb, while the Glauber calculation leads to $\sigma^{\psi}_{\rm abs} = 6.4 \pm 0.8$ mb, in good agreement with the values found from the absolute J/ψ cross-sections (see previous section). Therefore, the J/ψ absorption from peripheral to central S-U collisions, relative to the Drell-Yan yield, follows the same pattern as observed on the absolute J/ψ cross-sections from pp to S-U.

The case is significantly different for the ψ', which exhibits a completely different behaviour in p-A and S-U reactions. In order to quantify this difference, a separate fit has been made using only the S-U ψ' data points, leading to $\sigma^{\psi'}_{\rm abs} = 24 \pm 5$ mb. The line in the right panel of Fig. 5 shows the ψ' suppression pattern expected if we assume similar suppressions for the J/ψ and ψ' resonances. The measured S-U values are clearly different from such a p-A extrapolation.

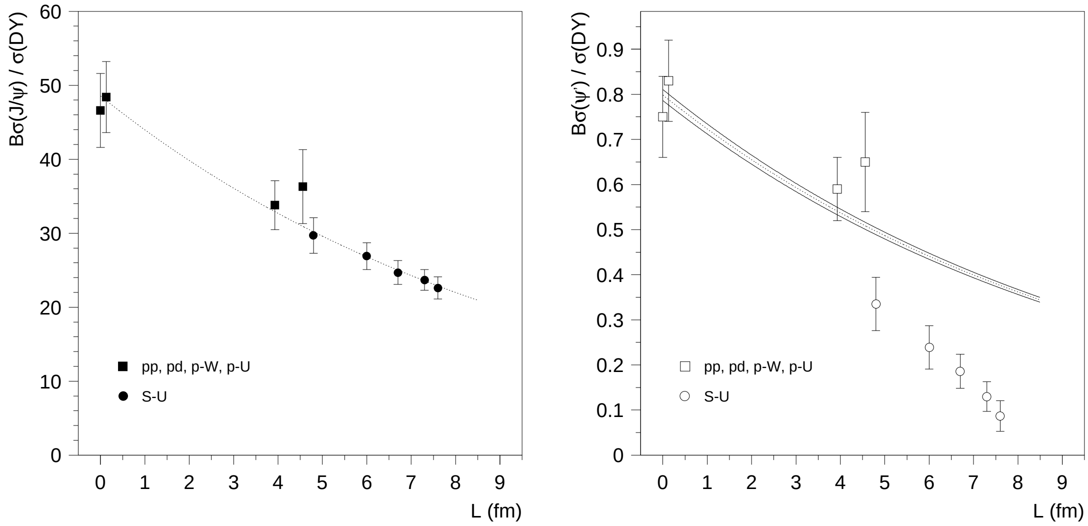

Figure 5: Values of Table 3, plotted as a function of L (J/ψ on the left, ψ' on the right). The line on the left figure is the best fit to the expression $\exp(-\rho\,\sigma_{\rm abs}\,L)$. The band in the right figure corresponds to the same line, scaled by 1.64 ± 0.03 %.

5 Conclusions

The comparison of charmonium production as measured from p-induced reactions at 450 and 200 GeV/c incident momentum with results obtained from Oxygen and Sulphur-induced reactions at 200 GeV/c per incident nucleon shows that, as a function of the mass numbers of the interacting nuclei, J/ψ production exhibits a remarkably continuous decreasing pattern from pp up to S-U reactions. The same pattern is observed in the production of J/ψ in S-U reactions as a function of centrality. This evolution of the J/ψ cross-section can be properly accounted for by nuclear absorption.

In p-A reactions the suppression pattern is identical for the J/ψ and ψ' resonances. In S-U collisions, however, the ψ' yield shows a clear departure from this common behaviour, and is significantly lower than expected from the p-A results. The extra suppression of ψ' production in the S-U data could be due to the extended volume of matter created in these collisions and traversed by the fully formed charmonia resonances. Since the ψ' state is very loosely bound (with a binding energy of only ~ 50 MeV), it can be broken into "open" charm mesons by purely hadronic interactions without probing if the produced matter is in a confined or deconfined state.

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