J/ψ production in In-In and p-A collisions

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Abstract.

The NA60 experiment studies dimuon production in In-In and p-A collisions at the CERN SPS. We report recent results on J/ψ production, measured through its muon pair decay. As a function of centrality, we show that in In-In the J/ψ yield is suppressed beyond expectations from nuclear absorption. We present also for the first time results on J/ψ production in p-A collisions at 158 GeV, the same energy of the nucleus-nucleus data. For both p-A and In-In we show preliminary results on ψ′ suppression. Finally, we have studied the kinematical distributions of the J/ψ produced in In-In collisions. We present results on transverse momentum and rapidity, as well as on the angular distribution of the J/ψ decay products.

1. Introduction and data analysis

The production of the charmonium states in ultrarelativistic heavy-ion collisions has been recognized as a key observable for the occurrence of deconfinement since the very beginning of the studies in this field [1]. A suppression of the charmonium yield beyond expectations from a pure nuclear absorption scenario has been observed both at SPS and RHIC energies by the NA38/NA50 [2] and PHENIX [3] experiments, respectively. However, the interpretation of the experimental observations is still under debate, with explanations including, among others, the production of a fully thermalized QGP [4], of a percolating partonic condensate [5], or of a very dense hadron gas [6, 7]. Therefore, accurate experimental investigations, carried out with several projectile-target systems, are mandatory in order to confirm or exclude the various proposed scenarios. Clearly, in order to claim a suppression signal beyond nuclear absorption, accurate p-A reference data, taken in the same energy/kinematical conditions as those for the nucleus-nucleus data, are also necessary. In parallel to these studies, the investigation of the kinematical distributions of charmonia provides interesting and complementary insights to the physics picture, giving information on production mechanisms and initial state effects.

All of these aspects of charmonia production are presently being studied, at the SPS, by the NA60 experiment. The apparatus consists of a muon spectrometer, inherited from NA50, which is also used for triggering on the production of a muon pair. A vertex

‡ For the full list of NA60 authors and acknowledgements, see Appendix ‘Collaborations’ of this volume
spectrometer, made of 16 Si pixel planes, tracks the charged particles produced in the angular acceptance of the muon spectrometer (roughly 0< $y_{CM}$ <1 for a 158 GeV/c incident beam), giving precise information on the position of the interaction vertex ($\sim$ 20$\mu$m in the transverse direction, $\sim$ 200$\mu$m in the longitudinal one). Furthermore, by matching muon tracks detected in the muon spectrometer with the corresponding tracks in the vertex spectrometer, it is possible to i) significantly improve the invariant mass resolution (from $\sim$70 to $\sim$20 MeV at the $\omega$, from $\sim$100 to $\sim$70 MeV at the J/$\psi$) and ii) determine, with a $\sim$40 $\mu$m resolution, the offset of the production point of the muons with respect to the interaction vertex. Finally, a Zero-Degree Calorimeter is used to provide a centrality selection through the measurement of the energy $E_{ZDC}$ carried away by spectator nucleons. The whole apparatus, including details on the matching procedure, is described in [8, 9, 10]. NA60 has studied In-In collisions at 158 GeV/nucleon and p-A collisions at 158 and 400 GeV. The results presented here refer to In-In and p-A at 158 GeV, while the analysis of the 400 GeV data sample is still in progress. The event selection procedures, as well as details on the acceptance calculation and on the extraction of the physics signal, can be found in [11]. After data reduction, we end up with about 3$\cdot$10$^4$ J/$\psi$ events in In-In and a similar number in p-A.

2. J/$\psi$ suppression in In-In collisions

The study of the J/$\psi$ suppression in In-In has been carried out using two different and complementary approaches. In the first, identical to the one adopted by NA38/NA50, the J/$\psi$ yield has been normalized to the measured Drell-Yan events in the mass region 2.9 < $m_{\mu\mu}$ < 4.5 GeV/c$^2$. This quantity has the advantage of being free from the systematic errors connected with efficiency and luminosity calculations, but suffers from the low Drell-Yan statistics. In NA60, this analysis can be meaningfully performed only with a very limited number of centrality bins. The ratios $\sigma_{J/\psi}/\sigma_{DY}$ are then compared with the expected values in case of pure nuclear absorption. Such values have been obtained with the Glauber model, starting from the value $\sigma_{J/\psi}^{abs}$=4.18 $\pm$ 0.35 mb, measured by NA50 [2] in p-A collisions at 450 GeV. The result is plotted in Fig. 1(left). Clearly, to increase the statistical significance, the use of Drell-Yan should be avoided. This choice is the foundation of the second analysis approach, where the measured d$N_{J/\psi}$/d$E_{ZDC}$ has been directly compared to a calculated reference spectrum corresponding to a pure nuclear absorption scenario. The shape of such a reference has again been calculated in the frame of the Glauber model, with $\sigma_{J/\psi}^{abs}$=4.18 mb. We do not have yet for our In-In data an absolute determination of the cross section d$\sigma_{J/\psi}$/d$E_{ZDC}$. Therefore, we simply require the relative normalization between the measured and expected distributions to be equal, when integrated over centrality, to the same quantity obtained from the study of $\sigma_{J/\psi}/\sigma_{DY}$, i.e. 0.87$\pm$0.05. The result of this analysis is also plotted in Fig. 1(left). Of course, the agreement between the results of the two analyses is significant only in terms of shape, since the normalization of the second analysis has been forced to be the same of the first one. Since with this approach
the statistical errors are negligible (∼2%, with the chosen centrality binning) a careful estimate of the systematic errors is mandatory. It turns out that there is a ∼10% error, independent of centrality, essentially due to uncertainties in the Glauber model parameters and in our knowledge of the inputs that enter in the nuclear absorption calculation. On top of that, (small) uncertainties on the link between $E_{ZDC}$ and the number of participant nucleons $N_{\text{part}}$, due to the contribution of non-spectator energy to the measured signal, induce a non-negligible systematic error for very central events. Of course, most effects discussed here also affect the determination of $\sigma_{J/\psi}/\sigma_{DY}$, although their effect in absolute terms is in this case much less important. The result plotted in Fig. 1(left) clearly indicates an anomalous suppression of the $J/\psi$ yield for $N_{\text{part}} > 80$, with a saturation of the effect for central In-In collisions. In Fig. 1(right) we compare the suppression pattern obtained by NA60 with the NA50 results for Pb-Pb collisions [2]. Within errors, the two behaviours look compatible, showing that $N_{\text{part}}$ could be a good scaling variable for the onset of the anomalous suppression.

Several theoretical predictions for the In-In suppression pattern were formulated before the NA60 experimental results became available. They include a model where the anomalous suppression is due to interaction with hadronic comovers [6], another where the effect of dissociation and regeneration in a fully thermalized QGP and in the later hadronic stage is considered [12], and finally a model where parton percolation occurs, with an onset at $N_{\text{part}} \sim 140$ [5]. It is interesting to note that although these models were explicitly tuned on the already available Pb-Pb results, none of them, as can be seen in Fig. 2(left) is able to quantitatively reproduce the In-In points (even if the overall size of the effect is reasonably reproduced). More recently, a study of the effect...
of a thermalized hadronic gas on the J/$\psi$ has been carried out \[7\] in the frame of the Constituent Quark-Meson model. The comparison of this calculation with data shows that for both Pb-Pb and In-In hadronic effects alone cannot account for the observed anomalous suppression.

![Graph](image)

**Figure 2.** (left) Comparison between the In-In suppression pattern and the theoretical predictions of Ref. \[6\](dotted line), \[12\](dashed-dotted line), \[5\](dashed line). (right) Compilation of the $\sigma_{J/\psi}/\sigma_{DY}$ values measured in p-A and nucleus-nucleus collisions at the SPS, rescaled, when necessary, to 158 GeV incident energy. The lines indicate the results of a Glauber fit to the p-A data and the size of the error. The full circle indicates the preliminary NA60 result for p-A collisions at 158 GeV.

### 3. J/$\psi$ suppression in p-A collisions

In order to claim that an anomalous suppression of the J/$\psi$ has been observed, the production in p-A collisions must be accurately known. Up to now, at SPS energy, such knowledge came from measurements performed at 450 and 400 GeV, covering the rapidity range $-0.5 < y_{cm} < 0.5$ \[13\]. Performing an analysis in the frame of the Glauber model, two parameters are needed in order to fit the data, the cross section for elementary collisions ($\sigma_{J/\psi}/\sigma_{DY}$)$_{pp}$ at the energy $E_0$ under consideration and the nuclear absorption cross section for the produced J/$\psi$, $\sigma_{abs}^{J/\psi}$. In order to obtain the expected yield for the rather different energy and kinematical domain of the heavy-ion data (158 GeV/nucleon and $0 < y_{cm} < 1$), a rescaling of these parameters becomes necessary. Up to now, it was assumed that $\sigma_{abs}^{J/\psi}$ does not change as a function of the incident proton energy, and the cross section for elementary collision was rescaled using a procedure detailed in \[2\], \[14\]. In order to avoid the systematic errors connected with this procedure, NA60 has measured J/$\psi$ production in p-A collisions at 158 GeV, in the same kinematical domain of the nucleus-nucleus data. A target box containing nine subtargets, made of seven different materials (Be, Al, Cu, In, W, Pb and U) has been used, with the vertex spectrometer helping to recognize the target where the muon pair...
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has been produced. An analysis of the A-dependence of the J/ψ production cross section would require of course a complete understanding of the local efficiency of the vertex tracker, since its angular coverage for the various targets is slightly different. Since this work is still in progress, for the moment a preliminary analysis has been performed, using only the muon spectrometer information. More in detail, one simply requires the extrapolation of the muon tracks to the target region to lie inside the target box. This cut has not enough resolution to identify the target where the interaction has taken place, but nevertheless efficiently rejects the background due to parasitic interactions outside the target region (e.g. in the hadron absorber). In this way, one can determine an average σ_{J/ψ}/σ_{DY} ratio, that can be now plotted together with the previous results, as a function of L, the mean thickness of nuclear matter crossed by the produced J/ψ. Taking into account the nuclear composition of the target system, we have, for this set of data, ⟨L⟩ = 3.4 fm. In Fig. 2(right) we show such a plot, where the closed circle indicates our preliminary result. It can be seen that there is a very good agreement with the set of p-A data taken at higher energy, and rescaled to 158 GeV. This result shows that the rescaling of the elementary production cross section is indeed correct, and reinforces the claim that the suppression observed for In-In and Pb-Pb collisions is not compatible with a pure nuclear absorption scenario.

4. ψ′ suppression in p-A and In-In collisions

In addition to the J/ψ, NA60 can also detect the ψ′ through its muon pair decay. The significance of this study, contrary to that of the J/ψ, is limited by the reduced available statistics (about 300 events in both In-In and p-A). In this paper we present preliminary results on the ratio σ_{ψ′}/σ_{DY}. For In-In collisions, three centrality bins have been defined. The result is shown in Fig. 3(left), as a function of L, and compared with previous findings by NA38 and NA50 [15]. One can again note, as for the J/ψ, that the production yield in p-A collisions is fairly consistent with data taken at higher energies and then extrapolated to 158 GeV. Concerning nucleus-nucleus data, the In-In points are found to be in fair agreement with the other measured nuclear systems. By comparing Fig. 3(left) with Fig. 2(right), we see that for the ψ′ the onset of an anomalous suppression might occur for more peripheral reactions than for the J/ψ. Obviously, a larger statistics would be useful for reaching sharper conclusions.

5. Kinematical distributions of the J/ψ produced in In-In collisions

Several important aspects of the charmonium production and interaction in nuclear collisions can be addressed by studying the kinematical distributions of the produced J/ψ. In particular, the transverse momentum distributions are expected to be influenced by initial-state multiple scattering of the gluon [16], while the study of the rapidity distributions may be sensitive to details of the hadronization mechanism of the c̅c pair [17]. Furthermore, the study of the angular distribution of the decay products gives
indications on the J/ψ polarization. This information is related to the charmonium formation mechanism [18] and may be affected by the presence of a deconfined medium [19]. From the experimental point of view, the J/ψ kinematical distributions have been obtained by performing a 3-D acceptance correction. Events were generated with a flat distribution in $p_T, y, \cos \theta_H$ ($\theta_H$ is the decay angle of the $\mu^+$, taken in the charmonium rest frame, with respect to the J/ψ direction in the CM system), tracked and reconstructed in the set-up. A differential acceptance has then been calculated in narrow bins (0.1 GeV/c in $p_T$, 0.05 units in $y$ and 0.1 in $\cos \theta_H$). Finally, the acceptance correction has been performed in the kinematical domain where it is larger than 1%. The whole procedure has been successfully tested on Monte-Carlo generated sample distributions; furthermore, the effect of the $\sim 3\%$ background below the J/ψ peak has been found to be negligible. In Fig. 3(right) we show the acceptance corrected $p_T$ distributions, integrated over centrality and for various centrality bins. The plots refer to the kinematical region $0.1 < y_{CM} < 0.9, -0.4 < \cos \theta_H < 0.4$. By fitting the distributions with the function $1/p_T dN/dp_T = e^{-m_{T}/T}$ we obtain $T$ values increasing with centrality and ranging from 204 to 234 MeV. For the centrality integrated distribution we get $T=231\pm 2$ MeV. In Fig. 4(left) we show the increase of $\langle p_T \rangle_{J/\psi}$ with centrality. The In-In points are compared with Pb-Pb results obtained by NA50 [20]. Both data sets show a roughly linear increase of $\langle p_T \rangle_{J/\psi}$ with $L$. Such a $p_T$ broadening is consistent with the occurrence of initial-state multiple scattering of the gluon. In Fig. 4(right) we show the centrality integrated $y$ distribution of the produced J/ψ, where the points on the plot are obtained for $0 < p_T < 5$ GeV/c, $-0.4 < \cos \theta_H < 0.4$. The distribution is well reproduced by a gaussian fit, with $\sigma_y=0.68\pm0.02$. Although not shown here, we find no
significant dependence of the $y$ width on the centrality.

Finally, in Fig. 5 we show the first results on the polarization of the $J/\psi$ produced in heavy-ion collisions. The angular distributions of the decay products have been fitted using the relation $d\sigma/d\cos\theta_H = 1 + \alpha \cos^2 \theta_H$, where $\theta_H$ is the polar decay angle of the positive muon in the helicity frame. $\alpha$ values larger than 0 would indicate a transverse polarization for the $J/\psi$, while $\alpha < 0$ corresponds to a longitudinal polarization. NRQCD calculations [18] predict a significant transverse polarization at high $p_T$, that was not observed neither at fixed target experiments [21] nor at hadron colliders [22]. Furthermore, in nucleus-nucleus collisions, the occurrence of a transition to a QGP might further enhance the observed polarization [19]. Our preliminary results clearly indicate that, as a function of centrality, $p_T$ and $y$, the $J/\psi$ produced in In-In collisions do not exhibit any significant polarization.

6. Conclusions

The NA60 experiment has carried out a high-quality study of $J/\psi$ production in In-In collisions at the SPS. The results confirm, for a much lighter system, the anomalous suppression seen in Pb-Pb collisions by NA50, with an onset at $N_{\text{part}} \sim 80$, corresponding to $\epsilon_B \sim 1.5 \text{ GeV/fm}^3$. First, preliminary results from p-A collisions at 158 GeV, the same energy of the nucleus-nucleus data, strengthen our understanding of the effects of nuclear absorption on the $J/\psi$ and show that the results for peripheral In-In and Pb-Pb collisions can be understood in terms of cold nuclear effects. Preliminary results on $\psi'$ also show an anomalous suppression, that sets in earlier than that of the $J/\psi$ and
increases for more central In-In collisions. Finally, the kinematical distributions of the \(J/\psi\) produced in In-In have been studied. In particular, the first preliminary results on the angular distributions of decay muons show that the \(J/\psi\) is produced without a significant polarization.

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