J/ψ production in p-A and A-A collisions at fixed target experiments

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Abstract

Charmonia suppression is one of the main signatures for the formation of a deconfined medium. However, also nuclear effects, not related to the production of a hot medium, can affect the J/ψ yield. The determination, from the study of p-A collisions, of the J/ψ behaviour in nuclear matter is, therefore, extremely important to correctly quantify the amount of charmonia suppression induced by the deconfined medium. In this paper the new NA60 results collected at 158 GeV incident energy, i.e. under the same kinematical conditions as the In-In (NA60) and Pb-Pb (NA50) data, are presented and compared with p-A measurements from other fixed target experiments. Results on A-A collisions are also reviewed taking into account the new available information on the influence of cold nuclear matter on the J/ψ production yield. Finally, results on the J/ψ polarization are shown for p-A and A-A collisions.

1. Introduction

J/ψ suppression in A-A collisions is considered to be one of the main signatures for the phase transition from an hadronic to a deconfined medium \cite{1}. However, the J/ψ production can be affected also by cold nuclear matter effects, as, for example, the final state absorption of the c\bar{c} pair in the nuclear medium, the parton shadowing or the initial and final state energy loss. The amplitude of these effects, not related to the formation of a deconfined medium, is determined from p-A collisions and then extrapolated to A-A interactions to be compared with the measured J/ψ yield.

At SPS energies, cold nuclear matter effects are usually parameterized, in the frame of the Glauber model, by fitting the A-dependence of the J/ψ production cross section per nucleon-nucleon collision. These nuclear effects are quantified through the value of $\sigma_{abs}^{J/\psi}$ extracted, up to now, from the NA50 data at 400/450 GeV ($\sigma_{abs}^{J/\psi} = 4.2 \pm 0.5$ mb) \cite{2}. Another way to parameterize cold nuclear matter effects is based on a fit to the A-dependence of the J/ψ production cross section using a $A^\alpha$ power law. A value of $\alpha$ different from unity indicates how much the J/ψ yield is modified by the nuclear medium. It should be noted that both $\alpha$ and $\sigma_{abs}^{J/\psi}$ are effective quantities, since they represent the amount of cold nuclear matter effects reducing the J/ψ yield, but they do not allow to disentangle the different contributions (e.g. shadowing, nuclear absorption) playing a role in this reduction. Nuclear effects, evaluated from p-A data at 400/450 GeV, are then extrapolated to A-A collisions at a lower energy (158A GeV) assuming in both cases a scaling with L, the mean thickness of nuclear matter seen by the c\bar{c} pair in its way out through the nucleus, and imposing $\sigma_{abs}^{J/\psi}$ to be energy independent. The expected J/ψ yield is then compared with the measured one, as a function of centrality. Following the aforementioned approach, a
further suppression (the so called “anomalous” $J/\psi$ suppression), exceeding cold nuclear matter effects, is indeed observed at SPS in Pb-Pb [3] and In-In [4] collisions. It is clear that to correctly quantify the amount of suppression due to the formation of a hot medium, the $J/\psi$ behaviour in the normal nuclear matter must be determined with high precision.

Several results on $J/\psi$ production in p-A collisions at fixed target experiments are available, covering different kinematic and energy domains. HERA-B at HERA, for example, has studied p-Cu, Ti, W reactions at 920 GeV [5], E866 at FNAL p-Be, Fe, W collisions at 800 GeV [6], NA50 at SPS proton induced collisions on several nuclei (Be, Al, Cu, Ag, W, Pb) at 400/450 GeV [2] and finally NA3 at SPS p-H$_2$, Pt collisions at 200 GeV [7]. It is important to note that none of these existing results has been obtained under the same conditions, in terms of energy and kinematic domain, as the SPS A-A collisions collected at 158A GeV. This implies that several assumptions (as the energy independence of $\sigma_{J/\psi}$) had to be done, in order to extrapolate cold nuclear matter effects from p-A to A-A collisions.

2. NA60 p-A results

For the first time the NA60 experiment has studied the $J/\psi$ production in p-A collisions at 158 GeV [8], in order to provide a reference collected under the same kinematic and energy conditions as the A-A data.

The experimental apparatus of NA60 is based on a traditional muon spectrometer coupled with a vertex telescope made of Si pixel planes, close to the target region. The matching, based on the tracks coordinates and momentum between the tracks reconstructed in the two spectrometers, allows an accurate measurement of the muon kinematics and therefore an improvement in the quality of the results with respect to previous experiments. For details on the apparatus see [9]. The target system of NA60, during the p-A data taking, was based on 7 different targets (Be, Al, Cu, In, W, Pb, U) simultaneously exposed to the beam. NA60 has also collected data at 400 GeV, with the same experimental setup as the one of the 158 GeV data taking period, to be used as a cross-check of the NA50 results taken at the same energy.

2.1. $J/\psi$ kinematical distributions

The investigation of the $J/\psi$ kinematical distributions may help to obtain further insights in the understanding of the charmonium production and initial state effects. In Fig.1 the rapidity ($y_{CM}$) distributions corresponding to p-A collisions at 158 GeV and 400 GeV are shown. A 1-D acceptance correction has been performed assuming realistic transverse momentum distributions and a flat $\cos\theta_{CS}$ shape (see Sec.4 for this definition). Within the narrow rapidity coverage of NA60 (one rapidity unit), the distributions can be reproduced by a Gaussian function. A simultaneous fit to the distributions corresponding to the different p-A collisions indicates that, at 158 GeV, the data can be described by a gaussian centered at midrapidity ($\mu_y = 0.05 \pm 0.05$) with a width $\sigma_y = 0.51 \pm 0.02$. At 400 GeV, because of the wider distributions, the peak position is less constrained. In this case the fit is performed imposing the slightly negative mean value ($\mu_y = -0.2$) measured by NA50 with a high statistics data set at the same energy [2]. As expected, because of the higher energy, a larger rapidity width ($\sigma_y = 0.81 \pm 0.03$) is obtained, in agreement, within errors with the NA50 value ($\sigma_y \sim 0.85$). Unfortunately, the precision of these results do not allow to investigate the negative rapidity shift observed by NA50, neither to confirm the smaller A-dependent shift of the center of the $x_F$ (and therefore $y$) distributions observed by HERA-B [5].
The $J/\psi$ transverse momentum ($p_T$) distributions have also been studied. The spectra are corrected with an 1-D acceptance, obtained assuming a flat $p_T$ distribution and realistic $y$ and $\cos\theta_{CS}$ shapes. A broadening of the $p_T$ distributions as a function of $A$ is measured at both 158 and 400 GeV. This confirms previous observations from other experiments [5, 7, 10, 11, 12, 13, 14] and is usually interpreted as initial state multiple scattering of the incoming gluons (Cronin effect) before the hard scattering which will produce the $c\bar{c}$ pair. The average $<p_T^2>$ dependence on the mass number can be parameterized with $<p_T^2> = <p_T^2>_{pp} + \rho (A^{1/3} - 1)$ [5], where $A^{1/3} - 1$ is roughly proportional to the length $L$. As shown in Fig. 2 (left) the $<p_T^2>_{pp}$ values are compatible with a linear growth with the square of the center of mass energy $s$. On the other hand, the slope of the parameterization $\rho$ shows an almost energy independent pattern, apart from a hint of decrease at low energy, corresponding to the NA60 158 GeV result.

2.2. Cold nuclear matter effects

New NA60 results on the nuclear effects affecting the $J/\psi$ at 158 GeV have been presented at this conference [8]. Results, integrated over the full $p_T$ range are given in the rapidity region, covered by all the subtargets, corresponding to $0.28 < y_{CM} < 0.78$. Nuclear effects are evaluated comparing the cross section ratio, $\sigma_{pA}/\sigma_{pBe}$, between the target with mass number $A$ and the lightest one (Be). By computing this ratio, the beam luminosity factors cancel out, apart from a small beam attenuation factor. However, since the sub-targets see the vertex telescope under a slightly different angle, the track reconstruction efficiencies do not completely cancel out. Therefore an accurate evaluation of such quantities and their time evolution has been performed target by target, with high granularity down to the single pixel level, and on a run-per-run basis.

$J/\psi$ cross-section ratios are shown in Fig. 2 (right) as a function of $L$. In the same figure, also results from a similar analysis performed on the 400 GeV data sample are shown. In this case, the results refer to the kinematical region $-0.17 < y_{CM} < 0.33$, corresponding to the same rapidity range, in the laboratory frame, as the 158 GeV one. Systematic errors include uncertainties on the target thickness, on the $y$ distribution used in the acceptance calculation and on the reconstruction
efficiency. Only the fraction of systematic error, not in common to all the points, is shown, since it is the one affecting the evaluation of the nuclear effects.

Performing a Glauber fit to the data, or using the $\alpha$ parameterization, the following results are obtained for the new NA60 p-A data: $\sigma^{J/\psi}_{abs} = 7.6 \pm 0.7$ (stat.) $\pm 0.6$ (syst.) mb ($\alpha = 0.882 \pm 0.009 \pm 0.008$) at 158 GeV and $\sigma^{J/\psi}_{abs} = 4.3 \pm 0.8$ (stat.) $\pm 0.6$ (syst.) mb ($\alpha = 0.927 \pm 0.013 \pm 0.009$) at 400 GeV. It has to be stressed that the $\sigma^{J/\psi}_{abs}$ result at 400 GeV is smaller with respect to the one extracted from the 158 GeV, pointing to an energy dependence of this quantity. Furthermore, the obtained value is in very good agreement with a previous result obtained by NA50 at the same energy [2].

The comparison with results from previous experiments (HERA-B, E866 and NA50) can be done in terms of the extracted $\alpha$ [8] or $\sigma^{J/\psi}_{abs}$ values, as a function of the Feynman $x_F$ variable ($x_F^0$). As shown in Fig.3 (left), where all the available measurements are compared, a strong dependence of $\sigma^{J/\psi}_{abs}$ on $x_F$ and on the beam energy is clearly visible. Cold nuclear matter effects are stronger at high $x_F$ and for a fixed $x_F$ value their importance increases while lowering the beam energy. As shown in the figure, the new NA60 results at 400 GeV confirm the NA50 values obtained at a similar energy. On the other hand, the 158 GeV data seem to point to higher $\sigma^{J/\psi}_{abs}$ values, with a hint for an increase in the narrow explored $x_F$ region. It is also worthwhile to note that older NA3 results [7] on $J/\psi$ production are in partial contradiction with these observations, showing lower $\sigma^{J/\psi}_{abs}$ values, rather similar to those obtained with the higher energy data samples.

Although not shown here, the results do not present any scaling with $x_2$, the fraction of nucleon momentum carried by the target colliding partons. Since $x_2$ is the variable driving the shadowing effects, the break of this scaling confirms the fact that parton shadowing can not be the only mechanism invoked to describe the data. It is, therefore, clear that the interpretation of the kinematical dependence of the cold nuclear matter effects is extremely complicated since there are many competing mechanisms affecting the $J/\psi$ production and propagation into the nuclei. A theoretical description of the cold nuclear matter effects over the full kinematic range is extremely complex and not yet available [15, 16, 17].
As discussed, the $\alpha$ or the $\sigma_{J/\psi}^{\text{abs}}$ values are effective quantities used to describe the convolution of all the cold nuclear effects not related to the formation of a deconfined medium. At this conference, a first attempt to take explicitly into account the parton shadowing contribution to the NA60 data has been proposed. It must be noted that at SPS energies, the charmonia production explores a range of $x$ (the fraction of the nucleon momentum carried by the parton) corresponding to the antishadowing region, where parton densities in the nuclei are enhanced with respect to those of the free nucleons. The antishadowing, evaluated with the EKS98\cite{18} parameterization for the nuclear modification of the parton distribution functions (PDF), causes an enhancement of the charmonium production cross section per nucleon-nucleon collision. Therefore, if this initial-state contribution is explicitly taken into account, a larger $\sigma_{J/\psi}^{\text{abs}}$ value is needed to describe the measured data ($\sigma_{J/\psi}^{\text{abs}}(158\text{GeV}) = 9.3 \pm 0.7 \pm 0.7 \text{ mb}$ and $\sigma_{J/\psi}^{\text{abs}}(400\text{GeV}) = 6.0 \pm 0.9 \pm 0.7 \text{ mb}$). Results depend on the adopted parameterization of the PDF nuclear modifications. Slightly higher $\sigma_{J/\psi}^{\text{abs}}$ values ($\sim 5 - 10\%$), for example, are obtained if the EPS08\cite{19} parameterization is used.

![Figure 3: Left: Compilation of $\sigma_{J/\psi}^{\text{abs}}$ values versus $x_F$. Right: $J/\psi$ suppression pattern in In-In (circles) and Pb-Pb (triangles). Boxes around the points correspond to the correlated systematic errors, while the filled box on the right is the uncertainty on the absolute normalization of the In-In points. A further global 12\% error, not shown, is due to the uncertainty on $\sigma_{J/\psi}^{\text{abs}}$.](image)

3. Anomalous $J/\psi$ suppression in In-In and Pb-Pb collisions

As previously discussed, the cold nuclear matter reference used up to now for $A$-$A$ collisions by NA50\cite{3} and NA60\cite{4} was based on the $\sigma_{J/\psi}^{\text{abs}}$ value obtained from $p$-$A$ collisions at 400/450 GeV, assuming $\sigma_{J/\psi}^{\text{abs}}$ to be independent of the incident energy and $\gamma_{\text{CM}}$ range. As shown in Fig.3 (left), this is not the case, since the cold nuclear matter effects strongly depend on the energy and kinematical domain. Therefore the evaluation of the size of the effects affecting $A$-$A$ collisions at 158A GeV must be based on the new $p$-$A$ NA60 results at the same energy. The expected shape for the $J/\psi$ distribution in cold nuclear matter is computed within a Glauber model, assuming the $J/\psi$ production as a function of centrality (determined measuring the energy, $E_{ZDC}$, released
in a Zero Degree Calorimeter) \( dN_{J/\psi}^{exp} / dE_{ZDC} \) to scale with the number of binary collisions. The nuclear effects affecting the \( J/\psi \) are then implemented assuming \( \sigma_{J/\psi}^{abs} = 7.6 \pm 0.7 \pm 0.6 \text{ mb} \), as discussed in the previous section. This reference curve is then compared with the measured In-In \( dN_{J/\psi}^{meas} / dE_{ZDC} \) distribution, following the procedure described in [4]. As expected, since the \( \sigma_{J/\psi}^{abs} \) value directly obtained at 158 GeV is higher than the one extracted from p-A data at 400/450 GeV, the amount of anomalous suppression will be smaller with respect to the previous estimates. Furthermore, in the procedure followed up to now to build the reference curve, shadowing effects were not explicitly taken into account. While in p-A data only partons in the target are affected by shadowing, in A-A collisions also the projectile is involved and this further contribution has to be included when extrapolating the cold nuclear effects from p-A to A-A [20]. It turns out that if the shadowing is neglected in this extrapolation, a small bias is introduced, resulting in a \( \sim 5\% \) artificial contribution to the suppression of the \( J/\psi \) yield (if the EKS98 parameterization is used for the shadowing evaluation). Therefore, if shadowing is properly taken into account in the extrapolation from p-A to A-A, a further reduction of the \( J/\psi \) suppression is observed. This is shown in Fig.3 (right), where the final ratio of the measured and expected \( J/\psi \) yield is presented as a function of the number of participants (\( N_{\text{part}} \)) for both In-In and Pb-Pb data. Even within this new definition of the reference curve, for very central Pb-Pb collisions (\( N_{\text{part}} > 200 \)) an anomalous \( J/\psi \) suppression, of the order of 20-30\%, is still visible.

4. \( J/\psi \) polarization

The measurement of the \( J/\psi \) polarization is an important tool to clarify the quarkonium production mechanism, since different theoretical models predict different degrees of polarization [21]. For example, polarization is expected to be sensitive to the spin states of the \( c\bar{c} \) pair [22], therefore its measurement can shed some light on the color-singlet and color-octet contributions to the production process. Contrary to other observables, as the differential cross-sections, in the polarization predictions uncertainties related to the theoretical inputs cancel out, therefore providing well-defined expected values. However, quarkonium polarization has always represented a puzzle, since, at collider experiments, the theoretical models, which were able to predict the observed \( J/\psi \) production cross section, clearly failed in the description of the \( p_T \) dependence of the polarization [23].

Experimentally, the \( J/\psi \) polarization is measured from the full angular distribution of the quarkonium decay products:

\[
\frac{dN}{dcos\theta d\phi} = 1 + \lambda cos^2\theta + \mu sin2\theta cos\phi + \nu \frac{3}{2} sin^2\theta cos2\phi \tag{1}
\]

where the polar angle \( \theta \) is determined by the direction of the positive muon, in the quarkonium rest frame, and a chosen \( \vec{z} \) polarization axis (defining the decay plane). \( \phi \) is the azimuthal angle between the reaction plane, containing the colliding hadrons and the decay plane. The \( \lambda \) parameter is traditionally called “polarization”: zero value for \( \lambda \) indicates that the \( J/\psi \) are not polarized, while \( \lambda=1(-1) \) means transverse (longitudinal) polarization. Non zero values of \( \mu \) and \( \nu \) indicate an azimuthal anisotropy of the distributions. \( \lambda, \mu \) and \( \nu \) depend on the chosen definition of the \( \vec{z} \) axis. It is, therefore, useful, to determine these parameters in more than one reference frame. However, it can be noted that the knowledge of the full set of coefficients allows to analytically calculate their values in other frames, through appropriate transformations and knowing the \( J/\psi \)
kinematics [24]. Of course, this is not the case if only the $\lambda$ parameter is measured. In the literature the most commonly used frames are the Collins-Soper (CS) one, where the $\vec{z}$ axis is parallel to the bisector of the angle between the projectile and target directions in the $J/\psi$ rest frame, and the helicity (HE) one, where the $\vec{z}$ axis coincides with the quarkonium direction in the target-projectile center of mass frame. It is important to note that because of the $\lambda$, $\mu$ and $\nu$ dependence on a chosen reference frame, polarization results from different experiments can be compared only if the same frame is adopted. Most previous polarization analyses up to now were limited to the choice of only one specific reference frame and were restricted to the measurement of the polar angle distribution. On the contrary, recent results from HERA-B [25] and NA60 [8] have been obtained measuring for the first time the full angular distribution of the decay products of charmonia and comparing different frames.

NA60 results are obtained applying a 1-D acceptance correction, assuming realistic $\gamma_{\text{CM}}$ and $p_T$ distributions and a flat $\cos\theta$ and $\phi$ spectra. The measured polarization values present a dependence on the $J/\psi$ transverse momentum, as shown in Fig.4 (left) for the helicity frame. In particular, HERA-B $\lambda$ results indicate an increase of the $J/\psi$ polarization, moving from slightly negative values (corresponding to longitudinal polarization) at low $p_T$ to values close to zero (absence of polarization) at higher $p_T$. The first polarization results obtained in p-A collisions at 158 GeV and 400 GeV by the NA60 experiment confirm, within errors, the observed trend.

In Fig.4 (left) results on the the azimuthal parameter $\nu$ are also shown, always in the helicity frame. In this case no clear dependence on the $J/\psi$ kinematics is visible. Also the $\mu$ parameter is consistent with zero everywhere. Although not shown here, both HERA-B and NA60 results in the Collins-Soper reference frame give $\lambda$ values which tend to be more negative and larger in absolute value with respect to the ones measured in the helicity frame. This is an confirmation of the fact that the polarization parameters have a clear dependence on the chosen frame.

The HERA-B and NA60 new polarization results clearly will shed some light on the polariza-
tion issue, in the attempt of describing all the available polarization measurement in a common scenario.

NA60 has also provided, for the first time, results on the full angular distribution of the \( J/\psi \) decay products in In-In collisions. The \( \lambda \) values, in the helicity frame, do not show a dependence on the \( J/\psi \) \( p_T \) as shown in Fig. 4(a) and they are almost consistent with zero everywhere. Also the azimuthal coefficient \( \nu \) is rather small, pointing to a positive value only for \( p_T \sim 1 \text{ GeV}/c \), as shown in Fig. 4(b). The \( \lambda \) and \( \nu \) values do not present any dependence even on the centrality of the collision, as shown in Fig. 4(c,d). The pattern of these results is confirmed also if the Collins-Soper frame is adopted. In principle, it may be expected that the formation of a hot medium may affect the \( J/\psi \) polarization, as proposed in [26]. Therefore, quantitative predictions are needed, in order to clarify the observed results.

5. Conclusions

New NA60 results obtained in p-A collisions at 158 and 400 GeV have been presented and compared with the already existing measurements from other fixed target experiments. Cold nuclear matter effects, determined from p-A interactions, exhibit a rather strong energy and kinematical dependence. Therefore the use of the new p-A results at 158A GeV, the same energy as the A-A data, allows a more precise definition of the expected cold nuclear matter effects in nuclear collisions. Apart from very central Pb-Pb collisions, where the anomalous suppression is still sizeable, a smaller effect with respect to previous estimates is observed. Results on \( J/\psi \) polar and azimuthal parameters have also been presented for both p-A and A-A collisions.

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