

J/ψ Production in Indium-Indium Collisions at 158 GeV/Nucleon

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The NA60 experiment studies muon pair production at the CERN Super Proton Synchrotron. In this Letter we report on a precision measurement of J/ψ in In-In collisions. We have studied the J/ψ centrality distribution, and we have compared it with the one expected if absorption in cold nuclear matter were the only active suppression mechanism. For collisions involving more than ~ 80 participant nucleons, we find that an extra suppression is present. This result is in qualitative agreement with previous Pb-Pb measurements by the NA50 experiment, but no theoretical explanation is presently able to coherently describe both results.

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The suppression of the charmonium states by color screening has been predicted as a signature of the phase transition from hadronic matter towards a quark-gluon plasma [1]. Recently, it has been pointed out that the relatively loosely bound states ψ' and χ_c should indeed melt for temperatures around the critical temperature T_c , while the tightly bound J/ψ could survive, even if with strong medium-induced modifications, up to $\sim 2T_c$ [2–4]. However, the description of the evolution of a $c\bar{c}$ pair formed by gluon fusion at early times in the history of the collision, which may eventually lead to the formation of a bound state, is still not fully explained by theory. The influence of the medium, a percolating partonic condensate [5], or a fully thermalized quark-gluon plasma [6], or even a dense hadronic gas [7,8] has been investigated in detail, but this physics topic is still largely data driven, and accurate experimental data are clearly needed.

At the CERN Super Proton Synchrotron (SPS), the NA38 and NA50 experiments have already studied J/ψ production in various colliding systems, including p -A [9], S-U [10], and Pb-Pb [11]. Proton-nucleus data provide an important reference, describing the expected absorption of J/ψ in cold nuclear matter. By comparing the centrality dependence of the J/ψ yield observed in nucleus-nucleus collisions to this reference, one can look for suppression

mechanisms connected with the formation of a strongly interacting medium. In particular, the NA50 experiment has observed, in Pb-Pb collisions, that below a certain centrality threshold the J/ψ production is well described invoking nuclear absorption as the only suppression mechanism; on the contrary, above that threshold, an extra suppression (also known as “anomalous” suppression) sets in. Such an interesting observation needs to be complemented by further sets of accurate measurements obtained with different collision systems. In this way one can study in more detail the onset of the anomalous suppression, and understand which is the physics mechanism at its origin.

The NA60 experiment [12] has studied J/ψ production in In-In collisions at 158 GeV/nucleon at the CERN SPS, through its decay into two muons. The experimental apparatus is based on a muon spectrometer (MS), inherited from the NA50 experiment [13], used for triggering on muon pair production and for tracking purposes. A $12\lambda_i$ thick hadron absorber, mostly made of graphite, separates the MS from the target region, equipped with a beam tracker (BT) and a vertex tracker (VT), placed inside a 2.5 T dipole magnet. Finally, a zero-degree calorimeter (ZDC) [14] provides an estimate of the centrality of the collisions. The VT is a radiation-tolerant Si pixel detector, which tracks the charged particles produced in the collision. By

matching the tracks measured in the MS with the corresponding tracks in the VT, one can access the kinematical variables of the muons before their distortion due to multiple scattering and energy loss fluctuations in the hadron absorber [15,16].

The results presented in this Letter refer to the full In-In data sample collected by the NA60 experiment, corresponding to $\sim 230 \times 10^6$ events, taken at a beam intensity of 10^7 s^{-1} . Only the events having at least one interaction vertex with ≥ 4 tracks attached to it are selected for the analysis. The distribution of the longitudinal coordinate of the vertices allows us to identify the target where the interaction took place with $\sim 200 \mu\text{m}$ accuracy. We require the interaction vertex to lie, within this tolerance, in one of the 7 In subtargets, 1.5 mm thick each and spaced by 7.5 mm. Matching of tracks in the VT with the MS tracks is then carried out in coordinate and momentum space. The matching efficiency, of the order of $\sim 60\%$ for events where a J/ψ has been detected in the MS, shows no significant centrality dependence. In principle, MS tracks could be wrongly matched to VT tracks. However, in the J/ψ mass region, this effect is negligible ($< 1\%$).

Two kinds of event selection have been applied, corresponding to the two different analysis techniques detailed hereafter. In the first, the matching of the muon tracks is not performed, retaining in this way a larger event sample. As a quality check, we perform a cut on the transverse distance between the extrapolated MS track at the target position and the beam axis, weighted by the momentum of the track itself. The level of this cut has been set at 10% of the χ^2 probability for each muon, a value that allows us to efficiently reject muons produced downstream of the target. In the second selection, matching is applied and we require that the tracks matched to those detected in the MS originate from the reconstructed vertex or from the most upstream one, when more than one is found. In this way, we reject the small percentage ($\sim 4\%$) of events where the J/ψ originates from a downstream interaction of a nuclear fragment produced in a primary In-In collision. For both selections, we apply a beam pileup rejection cut, based on the BT, requiring two subsequent ions to be separated in time by at least 12 ns. In this way we avoid a superposition of signals in the readout gate of the ZDC, that would bias the determination of the zero-degree energy E_{ZDC} . Finally, in order to reject events at the edges of the MS acceptance we apply the kinematical cuts $0 < y_{\text{c.m.s.}} < 1$ and $-0.5 < \cos\theta_{\text{CS}} < 0.5$, where θ_{CS} is the polar angle of the muons in the Collins-Soper reference frame. In the end, we are left with samples of $\sim 45\,000$ J/ψ for the first event selection, and $\sim 29\,000$ for the second.

In the first analysis the J/ψ yield is normalized to the corresponding Drell-Yan (DY), a hard process unaffected by final-state interactions in the medium [17]. The ratio $\sigma_{J/\psi}/\sigma_{\text{DY}}$ has the further advantage of being free from systematic errors connected with the experimental inefficiencies and the integrated luminosity. It is extracted from

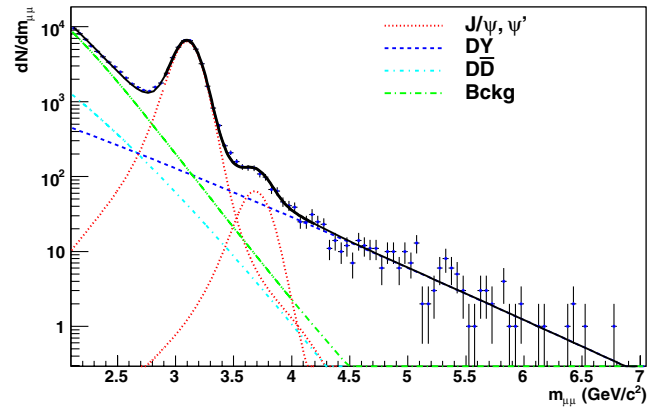


FIG. 1 (color online). The fit to the $\mu^+\mu^-$ invariant mass spectrum, integrated over centrality.

a fit of the $\mu^+\mu^-$ invariant mass spectrum (in the region $m_{\mu\mu} > 2.2 \text{ GeV}$) to a superposition of the expected contributions, namely, the J/ψ and the ψ' resonances, a continuum composed of Drell-Yan events and semimuonic decays of D and \bar{D} mesons, and a combinatorial background from π and K decays. The expected mass shapes of the signals and their acceptances are evaluated through a Monte-Carlo simulation based on PYTHIA [18] with GRV94LO [19] parton distribution functions. The combinatorial background has been estimated from the measured sample of like-sign pairs and its contribution is negligible. Figure 1 shows the $\mu^+\mu^-$ invariant mass spectrum, together with the result of the fit.

The ratios of cross sections, $\sigma_{J/\psi}/\sigma_{\text{DY}}$, uncorrected for the J/ψ decay branching ratio, are given in Table I for three centrality bins corresponding to different values of $\langle N_{\text{part}} \rangle$, the average number of participant nucleons in the bin. $\langle N_{\text{part}} \rangle$ has been obtained from E_{ZDC} using the Glauber model and taking into account the smearing induced by the detector resolution. The Drell-Yan yield refers to the mass interval $2.9 < m_{\mu\mu} < 4.5 \text{ GeV}/c^2$. Its low statistics (320 events for $m_{\mu\mu} > 4.2 \text{ GeV}/c^2$) limits the statistical significance of our result and prevents a finer binning in centrality.

The values shown in Table I indicate that for semicentral and central collisions the $\sigma_{J/\psi}/\sigma_{\text{DY}}$ ratio is significantly lower than for peripheral reactions. In order to understand how much of the observed reduction is due to cold nuclear matter effects, we have calculated, in the frame of the Glauber model, $\sigma_{J/\psi}/\sigma_{\text{DY}}$ as a function of centrality in a

TABLE I. Values of $\sigma_{J/\psi}/\sigma_{\text{DY}}$, uncorrected for the J/ψ decay branching ratio, as a function of centrality.

Centrality bin	$\langle N_{\text{part}} \rangle$	$\sigma_{J/\psi}/\sigma_{\text{DY}}$
$E_{\text{ZDC}} > 11 \text{ TeV}$	63	26.8 ± 3.2
$7 < E_{\text{ZDC}} < 11 \text{ TeV}$	123	16.1 ± 1.6
$E_{\text{ZDC}} < 7 \text{ TeV}$	175	17.8 ± 1.6

pure nuclear absorption scenario. This calculation requires as inputs the J/ψ absorption cross section in cold nuclear matter as well as the ratio of the J/ψ and DY elementary production cross sections at 158 GeV. Measurements performed by the NA50 experiment [11,20] in p -A collisions at 450 GeV provide $\sigma_{J/\psi}^{\text{abs}} = 4.18 \pm 0.35$ mb and $(\sigma_{J/\psi}/\sigma_{\text{DY}})_{450}^{\text{pp}} = 57.5 \pm 0.8$. The latter quantity has been rescaled to 158 GeV/nucleon incident energy, using a procedure detailed in Ref. [11], obtaining $(\sigma_{J/\psi}/\sigma_{\text{DY}})_{158}^{\text{pp}} = 35.7 \pm 3.0$. Figure 2 shows the measured $\sigma_{J/\psi}/\sigma_{\text{DY}}$, divided by the calculated reference and plotted as a function of N_{part} . Even if statistical errors are large, a suppression signal of the J/ψ beyond nuclear absorption can be seen.

In the second analysis, we directly compare the measured J/ψ yield to the centrality distribution of J/ψ calculated for the case of pure nuclear absorption, using the input parameters detailed above. In this approach, the measured J/ψ yield has been obtained, in 1 TeV E_{ZDC} bins, by means of a simple fitting procedure that allows us to subtract the small amount of Drell-Yan ($< 4\%$) and combinatorial background ($< 1\%$) under the resonance peak. In Fig. 3 we compare the J/ψ distribution with the expectation from nuclear absorption. The relative normalization between data and the reference curve is not determined *a priori*; therefore we fix the ratio between data and the nuclear absorption curve, integrated over centrality, to the same value (0.87 ± 0.05) as obtained within the previous analysis. Because of small inefficiencies of the BT, our data sample could be contaminated by high- E_{ZDC} events, where a noninteracting pileup ion is superimposed to the interacting one. A Monte-Carlo simulation shows that this effect is negligible in our analysis domain, i.e., $E_{\text{ZDC}} < 16$ TeV (corresponding to $N_{\text{part}} > 50$).

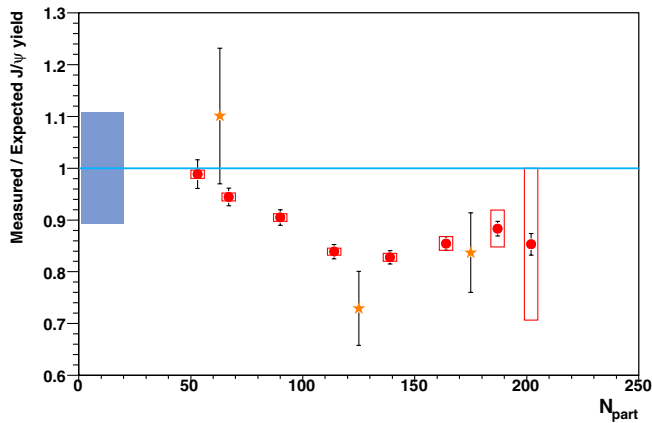


FIG. 2 (color online). Centrality dependence of the J/ψ suppression measured in In-In collisions. The stars correspond to the ratio between measured and expected $\sigma_{J/\psi}/\sigma_{\text{DY}}$, while the circles refer to the ratio between the measured J/ψ yield and nuclear absorption calculations. The box on the left shows the common systematic error, while the boxes around the points represent the error related to the centrality determination.

Figure 2 shows the ratio between the measured and expected J/ψ yield, rebinned in order to further reduce statistical fluctuations. Since statistical errors are very small ($< 2\%$), this analysis requires a careful estimate of systematic errors. We find that they are connected with the determination of the shape and normalization of the nuclear absorption reference, and with the calculation of N_{part} starting from E_{ZDC} . In particular, the uncertainties on $(\sigma_{J/\psi}/\sigma_{\text{DY}})_{158}^{\text{pp}}$ and $\sigma_{J/\psi}^{\text{abs}}$ give an 8% and 4% systematic error on the normalization of the absorption curve, respectively. We then have a 6% error, originating from the centrality integrated value of $\sigma_{J/\psi}/\sigma_{\text{DY}}$ used for the normalization. Concerning centrality determination, by varying within errors the input parameters used in the Glauber model, we get a negligible influence on the nuclear absorption reference, except for very central events ($E_{\text{ZDC}} < 3$ TeV), where the size of the effect is $\sim 12\%$. Furthermore, the ZDC does not measure only spectator nucleons, but also a small amount of energy released by forward secondary particles emitted in the acceptance of the calorimeter ($\eta > 6.3$). This contribution, important only for central collisions, is taken into account when calculating N_{part} from E_{ZDC} . By conservatively assuming a 10% uncertainty on this quantity we get, for events with $E_{\text{ZDC}} < 3$ TeV, a 9% error on the absorption curve. For more peripheral events the effect is negligible. Combining the various sources in quadrature, we end up with a $\sim 11\%$ systematic error, independent of centrality. On top of that, the most central bins are affected by a further, sizable systematic error relatively to the others. It must be noted that the systematic error plotted in Fig. 2, except for the fraction due to the 6% normalization error quoted above, also affects the results on $\sigma_{J/\psi}/\sigma_{\text{DY}}$.

The results obtained by the NA60 experiment in In-In collisions show that in the region $50 < N_{\text{part}} < 100$ an anomalous suppression of the J/ψ sets in. Taking into account the N_{part} smearing due to the E_{ZDC} resolution, the effect seen is compatible with the occurrence of a $\sim 15\%$ drop of the J/ψ yield at $N_{\text{part}} \sim 80$, followed by a

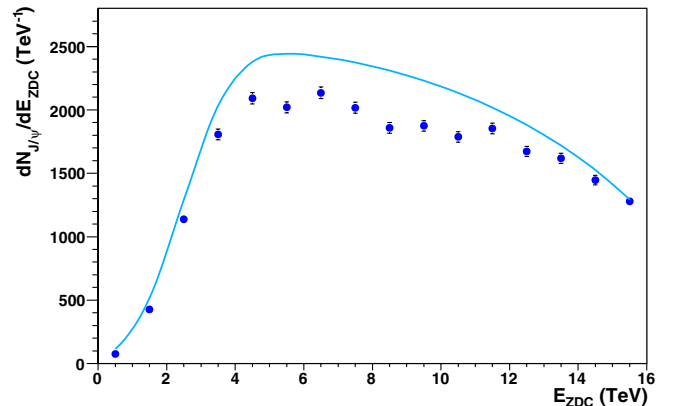


FIG. 3 (color online). The J/ψ E_{ZDC} distribution (circles), compared with expectations from nuclear absorption (line).

more or less constant behavior. When expressed in terms of the Bjorken energy density, the onset of the anomalous suppression roughly corresponds to $1.5 \text{ GeV}/\text{fm}^3$ (using $\tau_0 = 1 \text{ fm}/c$ and the VENUS [21] estimate for the charged multiplicity as a function of centrality). In Fig. 4 we compare our result with the J/ψ suppression pattern obtained by the NA50 experiment in Pb-Pb collisions [11]. The systematic errors on the determination of the nuclear absorption reference from the p -A data sample amount to $\pm 9\%$ and are not shown in this comparison plot since they affect Pb-Pb and In-In results in a similar way. Within errors, the two patterns look compatible in the N_{part} region explored by both systems, indicating that N_{part} might be, at SPS energy, a scaling variable for the anomalous suppression. A detailed investigation of the scaling properties of J/ψ suppression as a function of several centrality variables would give valuable insights into the origin of the observed effect. However, a meaningful comparison would require Pb-Pb results with error bars similar to the ones obtained for the In-In analysis.

Several theoretical predictions, tuned on already available Pb-Pb results from the NA50 experiment, were formulated for J/ψ suppression in In-In collisions [5,7,22]. We find that none of them is able to quantitatively reproduce the suppression pattern measured by the NA60 experiment [23]. Recent results from the PHENIX Collaboration [24] have shown that also in Au-Au collisions at $\sqrt{s} = 200 \text{ GeV}/\text{nucleon}$ the J/ψ is suppressed beyond nuclear absorption, and that the suppression is larger at forward rapidities. A coherent interpretation of the results at SPS and Relativistic Heavy Ion Collider energies is now mandatory in order to understand the physics mechanisms affecting charmonia in a dense partonic or hadronic environment. The results obtained by the NA60 experiment represent the most accurate measurement of J/ψ suppression in nuclear collisions available today and are a key element to strictly constrain theoretical

models. Further studies on the y and p_T dependence of the J/ψ suppression are under way and will be the subject of future publications.

In summary, we have measured J/ψ suppression in In-In collisions at $158 \text{ GeV}/\text{nucleon}$. Comparing the J/ψ centrality distribution with the expectation from a pure nuclear absorption scenario, we find an anomalous suppression that sets in for $N_{\text{part}} \sim 80$, and saturates for more central events. The statistical errors are negligible (of the order of 2%). Most of the systematic errors are centrality independent and therefore do not affect the measured shape of the J/ψ suppression pattern. None of the existing theoretical models, tuned on the measured J/ψ suppression in Pb-Pb collisions, is able to quantitatively reproduce the results shown in this Letter.

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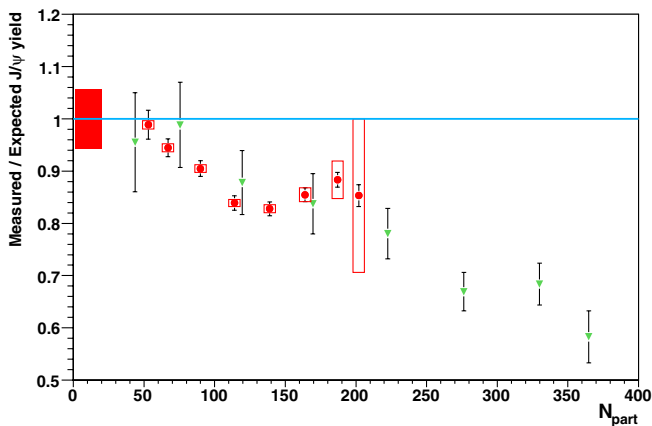


FIG. 4 (color online). Comparison between the In-In (NA60, circles) and Pb-Pb (NA50, triangles) suppression patterns. The box on the left shows the 6% systematic error related to the normalization procedure of the In-In points.

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