J/ψ and muon-pair cross-sections in proton-nucleus and nucleus-nucleus collisions at 200 GeV per nucleon

NA38 Collaboration

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Abstract : *Muon-pair production has been measured in p-Cu, p-U, O-Cu, O-U and S-U collisions at 200 GeV per nucleon. The cross-sections are compatible with the atomic number dependence* $(A_{proj.}A_{targ.})^{\alpha}$ *where* $\alpha = 0.91 \pm 0.04$ *for the* J/ψ *resonance and* $\alpha = 1.01 \pm 0.04$ *for muon-pairs produced in the mass continuum between 1.7 and 2.7* GeV/c^2.

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The J/ψ yield relative to muon-pair production in the mass continuum has been studied by the NA38 collaboration in collisions of 200 GeV per nucleon oxygen and sulphur ions with an uranium target [1]. This ratio has been found to decrease with increasing centrality of the collisions according to the prediction of quark-gluon plasma formation [2]. Consequently, questions have been raised concerning the J/ψ and continuum behaviour separately, and the connection with nuclear effects already measured in hadron-nucleus experiments. A simple geometrical model, accounting for the neutral transverse energy distributions of the collisions, indicates that the observed effect is due to a suppression of the J/ψ rather than to an enhancement of the continuum production rate [3]. In this letter we address these questions, considering the J/ψ and continuum muon-pair cross-sections for proton and ion-induced reactions, all obtained under similar experimental conditions.

The detector [1] consists of a muon spectrometer which accepts muon-pairs in the rapidity range [2.8,4.0]. A segmented active target of 20% total interaction length is used to minimize the number of secondary interactions and to identify the primary vertex. The latter information together with the energy flow measured in an electromagnetic calorimeter leads to the neutral transverse energy (E_T) released in the collision in the pseudo-rapidity range [1.7,4.1]. A scintillator hodoscope measures the beam intensity while three scintillator telescopes, pointing at the target allow to monitor the interaction rate. The proton beam is produced on a secondary target and two gas Čerenkov counters are used to select the incident protons and reject the pions which amount to 40% of the total incident beam. During the different data acquisition periods, the maximum available beam intensities were used, up to 10^7 particles per second. Details on the event selection criteria can be found elsewhere [1,4]. In the study presented in this paper, the same cuts are applied to the data with the following exception. For the study of the integrated cross-section, events with E_T biased by pile-up or by secondary interactions have not been discarded as this specific determination is obviously E_T-independent.

The signal is obtained from a maximum likelihood fit to the observed muon-pair mass distribution, taking into account the background, acceptance and smearing effects, according to :

$$N_{data}^{\mu^+\mu^-}(M) = \left[\sum_{M'} S(M,M')A(M')N_{signal}^{\mu^+\mu^-}(M') \right] + N_{bg}^{\mu^+\mu^-}(M)$$

Where :

- $N_{data}^{\mu^+\mu^-}(M)$ is the measured opposite sign muon-pair mass distribution corrected for the vertex identification inefficiency. This correction which amounts globally to about 25%, depending on the reaction, is a function of the centrality of the collision and is thus applied on an event by event basis, according to the calorimetry measurement.

- $N_{bg}^{\mu^+\mu^-}(M)$ represents the background originating from uncorrelated decays of pions or kaons. It is fitted on like sign muon-pair mass distributions according to the method described in ref. [4].

- $N_{signal}^{\mu^+\mu^-}(M')$ is the signal mass distribution which is adjusted to the data between 1.7 and 5.1 GeV/c^2. The continuum is parametrized as a negative power of the mass while a delta function at 3.097 GeV/c^2 accounts for the J/ψ. The ψ', although included in the fit, has a too small contribution to allow any significant conclusion on its behaviour.

- $S(M,M')$ and $A(M')$ are the smearing and acceptance matrices estimated from an iterative Monte-Carlo simulation of the apparatus. The convergence is obtained when all the independent kinematical variable distributions of the muon-pairs, generated and tracked through the detector, reproduce the experimental data [4,5]. The resolution at the J/ψ mass is 10% (FWHM) and the acceptance 9.8%. Fig. 1 shows the acceptance mass dependence for the continuum muon-pairs produced in sulphur-uranium collisions. The other reactions have been studied in similar experimental conditions, leading to the very same acceptances.

Table 1 summarizes, for the different projectile and target systems, the distributions for the mass M, the transverse momentum P_T, the Feynman variable X_F, the polar variable *cosθ* in the Collin-Soper frame and the azimuthal angle ϕ, both for the J/ψ and continuum events. The cross-section integration limits for each of these variables are also specified. They were determined according to the apparatus acceptance ranges, with the two following exceptions. The *cosθ* variable has been extrapolated from the measured interval [-0.5,0.5] to the whole interval [-1,1] and the mass continuum has been considered only between 1.7 and 2.7 GeV/c^2. This region is free from low mass resonance decay contamination and contains almost all the events which determine the continuum amplitude in the mass fit. Transverse momentum distributions have been studied in ref. [4,5]. They depend on the reaction and relevant parameters are given in table 2 together with the mass fit results. The adjustment for sulphur-uranium opposite sign muon-pairs is shown on fig.2, where the estimated background is also displayed. The number of J/ψ and continuum events obtained from the fit are given in table 3 with the integrated beam intensity, the effective target thickness and the trigger efficiency which provide the absolute normalization factor. Correction for the branching ratio of J/ψ into muon-pairs is not applied. The cross-sections obtained for all the projectile and target combinations are summarized in table 4 with the statistical and systematic uncertainties. In the case of ion-nucleus reactions, the neutral transverse energy distributions associated with the J/ψ and the continuum muon-pairs were extracted as in ref. [3] and normalized to the cross-sections. They are displayed on fig. 3.

In order to compare proton and ion data, the cross-sections have been fitted to $\sigma_0(A_{proj.}A_{targ.})^\alpha$. When doing this, systematic and statistical uncertainties were quadratically added. We obtain $\alpha = 1.01\pm0.04$ and $\sigma_0 = 1.9\pm0.6$ nb for the continuum and $\alpha = 0.91\pm0.04$ and $\sigma_0 = 5.0\pm1.5$ nb for the J/ψ (fig. 4). From the α value, it follows that the continuum muon-pair cross-section is proportional to the product of the target and projectile nucleon numbers as it is the case for incoherent processes. This feature, observed for the Drell-Yan mechanism measured above the ψ' mass with incident hadrons

[6,7], corroborates the assumption of a similar dominant origin of the muon-pairs, although the exact contributions from the soft production and the decay muons of $D\bar{D}$ or correlated pion or kaon pairs are not estimated. Anyhow, it leads to the same conclusion stated in ref. [3] that the measured muon-pair production in the continuum, provides a good reference to study the J/ψ suppression as a function of the neutral transverse energy of the collisions, according to the Matsui and Satz prescription for quark-gluon plasma formation [2]. The lower α value for the J/ψ cross-section is usually interpreted as due to absorption in the nuclear medium [12]. A comparison of the present data with previous measurements of J/ψ production by protons at the same nucleon-nucleon center of mass energy $\sqrt{s} = 19.4$ GeV [9], and at 20.6 and 16.8 GeV [7,8] is shown on fig. 4(a). These results are compatible with our measured value of α. However, following the model described in ref. [3], $\alpha = 0.91 \pm 0.04$ is equivalent to a J/ψ (or $c\bar{c}$ pair) absorption cross-section of 7.7 ± 3.5 mb as compared to 5.0 ± 2.5 mb for the 0.94 ± 0.03 value quoted in ref. [9]. Thus, the 3% experimental error bar on α could be associated to a 50% uncertainty on the J/ψ absorption cross-section. It is then difficult to conclude, from this parameter, on a different origin of the suppression when comparing ion and proton induced reactions. Other hadron-nucleus or photoproduction experiments [10,11] do not lead to a significantly different determination of α, the comparisons being complicated since this parameter could depend on the nature of the projectile, its incident energy and the J/ψ momentum. Finally, it has to be noted that initial state differences such as isospin or quark and gluon densities are not taken into account before comparing proton and ion reactions. From the Drell-Yan process, it is expected that the different quark content of the proton and the neutron should lead, with incident neutrons, to a smaller production of the continuum muon-pairs. This is not the case for the J/ψ production which is believed to be dominated by gluon-gluon fusion at the present energy. The structure function modifications inside the nucleus could also lead to a different cross-section for reactions induced by free or bound nucleons. In our experimental acceptance such effects are expected to be small since at a mass of 2.0 (3.0) GeV/c^2 the mean values of the Bjorken's variable x for the projectile and target are

respectively $< x_{proj.} > = 0.2$ (0.25) and $< x_{targ.} > = 0.05$ (0.1). As no quantitative estimate is available, the reported parametrizations of the cross-sections, as a function of the projectile and target atomic numbers, actually reflect both the final and initial state effects.

To conclude, we have presented for the first time the cross-sections of the J/ψ and continuum muon-pairs produced in 200 GeV per nucleon O-Cu, O-U and S-U collisions. The results are compared to p-Cu and p-U data obtained in the same experiment. Muon-pairs between 1.7 and 2.7 GeV/c^2 and those produced via the Drell-Yan mechanism previously measured above the ψ' mass show a similar trend as a function of the projectile and target nucleon numbers. The J/ψ cross-sections are compatible with the observed ones in other proton-nucleus experiments. The accuracy of the measurement is not good enough to conclude on a stronger J/ψ absorption in ion-ion interactions. Anyhow, at the present beam energy and projectile masses, the total J/ψ cross-section is not expected to be very sensitive to a quark-gluon plasma formation which is predicted to occur preferentially at the highest energy densities only accessible in central collisions.

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Muon-pair kinematical distributions and ranges	J/ψ	Continuum
M (1.7 $\rightarrow$ 2.7 GeV/c^2)	$\delta(M-3.097)$	M^{-a}
P_T (0.0 $\rightarrow$ 5.0 GeV/c)	$P_T\ e^{-\left(\frac{P_T}{P_{T0}}\right)^b}$	$P_T\ e^{-\left(\frac{P_T}{P_{T0}}\right)^b}$
X_F (0.0 $\rightarrow$ 0.5)	$\frac{1}{1-X_F^2}\ e^{-\frac{1}{2\ (0.4)^2}\left[\ln\left(\frac{1+X_F}{1-X_F}\right)\right]^2}$	$\frac{1}{1-X_F^2}\ e^{-\frac{1}{2\ (0.4)^2}\left[\ln\left(\frac{1+X_F}{1-X_F}\right)\right]^2}$
$\cos\theta$ ($-1 \rightarrow 1$)	$uniform$	$1+\cos^2\theta$
ϕ ($0 \rightarrow 2\pi$)	$uniform$	$uniform$

Table 1 : *Analytical distributions dN/dM, dN/dP_T, dN/dX_F, $dN/d(\cos\theta)$, $dN/d\phi$, and cross-section integration limits for the J/ψ and muon-pairs in the mass continuum.*

Reaction	J/ψ		Continuum		
	P_{T0}(GeV/c)	b	a	P_{T0}(GeV/c)	b
p-Cu	1.03 ± 0.05	1.67 ± 0.08	5.11 ± 0.17	0.66 ± 0.07	1.36 ± 0.11
p-U	1.00 ± 0.06	1.56 ± 0.09	5.46 ± 0.20	0.75 ± 0.08	1.49 ± 0.14
O-Cu	1.09 ± 0.04	1.71 ± 0.08	6.03 ± 0.13	0.74 ± 0.07	1.48 ± 0.13
O-U	1.12 ± 0.04	1.67 ± 0.06	5.53 ± 0.11	0.73 ± 0.06	1.44 ± 0.09
S-U	1.17 ± 0.03	1.73 ± 0.05	5.71 ± 0.14	0.63 ± 0.06	1.25 ± 0.08

Table 2 : *Parameters of the transverse momentum and mass distributions, obtained in the various reactions.*

Reaction	Number of J/ψ events	Number of continuum events $1.7 < M < 2.7$ GeV/c^2	Beam X10^{-12}	Effective target thickness(g/cm^2)	Trigger efficiency
p-Cu	43216 ± 456	21649 ± 744	1.175	18.61	0.94
p-U	27774 ± 381	17747 ± 707	0.558	30.00	0.94
O-Cu	89893 ± 796	71657 ± 1542	0.330	11.45	0.94
O-U	100723 ± 912	83966 ± 1609	0.363	12.33	0.94
S-U	75884 ± 852	65607 ± 1652	0.177	10.98	0.94

Table 3 : *Number of J/ψ and events in the mass continuum corrected for acceptance, smearing and vertex determination inefficiency. Beam intensity, target effective thickness and trigger efficiency for the various reactions.*

Reaction	J/ψ $B\sigma \pm \Delta B\sigma_{stat.} \pm \Delta B\sigma_{syst.} (\mu b)$	Continuum $\sigma \pm \Delta\sigma_{stat.} \pm \Delta\sigma_{syst.} (\mu b)$
p-Cu	$0.223 \pm 0.010 \pm 0.044$	$0.111 \pm 0.006 \pm 0.022$
p-U	$0.698 \pm 0.037 \pm 0.140$	$0.446 \pm 0.029 \pm 0.089$
O-Cu	$2.69 \pm 0.09 \pm 0.27$	$2.15 \pm 0.08 \pm 0.22$
O-U	$9.45 \pm 0.29 \pm 0.95$	$7.88 \pm 0.27 \pm 0.79$
S-U	$16.33 \pm 0.60 \pm 1.63$	$14.12 \pm 0.60 \pm 1.41$

Table 4 : *Cross-sections of the J/ψ decaying into two muons and of the continuum muon-pairs with mass between 1.7 and 2.7 GeV/c^2 for the various reactions. B is the J/ψ decay branching ratio into two muons. Results are given for Feynman's variable* $0. < X_F < 0.5$.

figure captions

fig.1 : Acceptance of the apparatus as a function of the continuum muon-pair mass for the S-U reaction.

fig.2 : Opposite sign muon-pair mass distribution measured in S-U collisions. The solid line is the result of the fit described in the text. The dashed line represents the background. The dotted line is the sum of the fitted continuum and background.

fig.3 : (a) J/ψ and (b) continuum muon-pair cross-sections as a function of the neutral transverse energy released in the collision for O-Cu, O-U and S-U interactions. The ΔE_T bins are respectively 4.2, 5.8 and 9.0 GeV. Uncertainties are statistical only. B is the J/ψ decay branching ratio into two muons.

fig.4 : Cross-sections per nucleon measured in p-Cu, p-U, O-Cu, O-U and S-U interactions, (a) for J/ψ muon-pairs, (b) for muon-pairs in the mass continuum. The lines represent the results of the fit $\sigma = \sigma_0(A_{proj.}A_{targ.})^{\alpha}$ with (a) $\alpha = 0.91\pm0.04$ and $\sigma_0 = 5.0\pm1.5$ nb, (b) $\alpha = 1.01\pm0.04$ and $\sigma_0 = 1.9\pm0.6$ nb. The p-p, p-Be, p-C and p-Pt cross-sections are from experiments discussed in the text. All error bars include systematic uncertainties. B is the J/ψ decay branching ratio into two muons.