Transverse momentum of J/ψ produced in p-Cu, p-U, ^{16}O-Cu, ^{16}O-U and ^{32}S-U collisions at 200 GeV per nucleon

NA38 Collaboration

C. Baglin, A. Baldisseri[1], A. Bussière, J.P. Guillaud, R. Kossakowski, P. Liaud, F. Staley[1]
Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS,
BP 110, F-74941 Annecy-le-Vieux Cedex, France

A. Baldit, J. Castor, T. Chambon, A. Devaux, J. Fargeix, X. Felgeyrolles, P. Force, L. Fredj, G. Landaud, F. Vazeille
Laboratoire de Physique Corpusculaire de Clermont-Ferrand, IN2P3-CNRS et Université Blaise Pascal,
F-63177 Aubière Cedex, France

P. Sonderegger
CERN, CH-1211 Geneva 23 Switzerland

M.C. Abreu[2], P. Bordalo[3], R. Ferreira, J.M. Gago[3], C. Lourenço[4], L. Peralta[2], S. Ramos[3], S. Silva, J. Varela[3]
LIP, Av. E.Garcia, 14-1, P-1000 Lisbon, Portugal

C. Gerschel, D. Jouan, S. Papillon, X. Tarrago
Institut de Physique Nucléaire, IN2P3-CNRS et Université de Paris-Sud,
F-91406 Orsay Cedex, France

P. Busson, C. Charlot, B. Chaurand, L. Kluberg, A. Romana, R.A. Salmeron
Ecole Polytechnique, IN2P3-CNRS, Laboratoire de Physique Nucléaire des Hautes Energies,
F-91128 Palaiseau Cedex, France

P. Gorodetzky, B. Grosdidier, C. Racca
Centre de Recherches Nucléaires, IN2P3-CNRS et Université Louis Pasteur,
BP 20, F-67037 Strasbourg Cedex, France

R. Cases
IFIC, Centro Mixto Universidad de Valencia-CSIC, E-46100 Burjasot, Valencia, Spain

M. Alimi[5], M. Bedjidian, D. Contardo, E. Descroix, O. Drapier, J.Y. Grossiord, A. Guichard, R. Haroutunian, J.R. Pizzi
Institut de Physique Nucléaire de Lyon, IN2P3-CNRS et Université Claude Bernard,
43 boulevard du 11 Novembre 1918 - F-69622 Villeurbanne Cedex, France

Abstract : Muon-pair production was measured in interactions of p and ^{16}O with Cu and U and in ^{32}S-U collisions at 200 GeV per nucleon incident energy. The transverse momentum distribution of the J/ψ and of muon pairs in the mass continuum has been studied. For the J/ψ, the average values of the transverse momentum $<P_T>$ and $<P_T{}^2>$ show a clear increase with the energy density reached in ^{16}O and ^{32}S induced reactions, which is not observed for muon pairs in the mass continuum.

1 Present address : DSM, Saclay, F91191 Gif sur Yvette, France
2 Also at FCUL, Universidade de Lisboa. 3 Also at IST, Universidade Técnica de Lisboa. 4 Also at ISEL.
5 Deceased

The study of muon pair production in oxygen-uranium and sulphur-uranium [1] at 200 GeV per nucleon has shown that the J/ψ yield relative to muon pairs in the mass continuum decreases with increasing transverse energy E_T produced in the collision. We have observed [2], in addition, that such a suppression in oxygen-uranium is enhanced at low transverse momentum (P_T). These results are in agreement with the predictions of quark-gluon plasma (QGP) models where the deconfined quark and gluon medium screens the c-$\bar{c}$ binding, hindering the formation of the J/ψ [3]. However, alternative explanations, based on more conventional models, are also possible. It is therefore interesting to study the P_T dependence of the dimuon production for several projectile-target systems as a function of the energy density reached in the collision. In this paper, results on transverse momentum distributions for ^{16}O-Cu, ^{16}O-U, ^{32}S-U together with p-Cu and p-U are reported for J/ψ and continuum dimuons.

Measurements were carried out with the highest available intensity (up to 10^7 ions/s) 200 GeV per nucleon ^{16}O, ^{32}S and proton beams from the CERN SPS, using the NA38 detector. Opposite sign (OS) as well as like sign (LS) dimuons were detected with a toroidal magnetic field spectrometer in the lab rapidity range $2.8 < y < 4.1$. The neutral transverse energy E_T^0 produced in the collisions was deduced from the energy flow measured with a lead-scintillating fiber calorimeter in the lab pseudorapidity range $1.7 < \eta_{lab} < 4.1$, after correcting for the charged hadron contribution [4]. More details on the experimental set-up can be found elsewhere [1,2]. The event samples were filtered according to cuts similar to those described in ref. [1,2]. However, the pile-up rejection, which is required in order to have an unbiased measurement of the transverse energy, is not applied for proton data for which no analysis as a function of E_T^0 has been done (see later).

The signal in OS muon pairs originates mainly from vector meson decays (ρ,ω,ϕ,J/ψ, ψ'), semi-leptonic decays of $D\bar{D}$ pairs and from the Drell-Yan mechanism. Muons coming from pion and kaon decays contribute to the opposite as well as like sign dimuon spectra. The background in the OS sample, due to these decays, is estimated from the LS pair distributions to amount to :

$$2\sqrt{N^{++}N^{--}}$$

where N^{++} (N^{--}) is the number of $\mu^+\mu^+$ ($\mu^-\mu^-$) pairs obtained from the corresponding distributions in the kinematical variable of interest such as mass $M_{\mu\mu}$, P_T, Feynman's variable X_F, polar and azimuthal angles θ and ϕ.

Due to the mass resolution of our apparatus (0.30 GeV/c^2 FWHM), J/ψ's are defined as events with measured mass $M_{\mu\mu}$ between 2.7 and 3.5 GeV/c^2. Continuum dimuons considered here are such that $1.7 < M_{\mu\mu} < 2.7$ GeV/c^2 or $M_{\mu\mu} > 3.5$ GeV/c^2. A summary of the number of opposite sign and like sign selected events in the different reactions is given in table 1.

In order to obtain the transverse momentum distributions, the acceptance and smearing effects of the apparatus have to be taken into account. The same treatment based on an iterative Monte-Carlo method, as detailed in ref. [2,5], is used. We recall that the OS spectrum in each kinematical variable is represented by a sum of three terms, two of them parametrizing the background distribution for each sign of the magnetic field of the spectrometer, and the other one being related to the signal physical distribution via a convolution with acceptance and smearing functions (see ref. [2]). These functions are determined through an iterative procedure, which simulates the NA38 detector and where dimuons are generated according to phenomenological laws in each kinematical variable. Parameters of the different laws are obtained through a simultaneous fit to the OS and LS spectra using the maximum likelihood method. No correlation between the different variables has been taken into account since a specific study [5] has shown that they can be neglected, leading only to systematic errors. The generating functions as well as the generation range used to compute the acceptance and smearing functions in the different kinematical variables are gathered in table 2. As compared to ref. [2], we have used another X_F distribution, proposed in ref. [6], which gives a slightly better representation of the X_F data. Such a procedure is applied separately for the J/ψ and continuum events. Note that for the J/ψ, the two background terms are dropped as the number of LS events is small. The weak contamination (about 7%) of the J/ψ events by continuum dimuons is taken into account.

The results of the fits for J/ψ events are diplayed in fig. 1a for p-U and in fig. 1b for ^{32}S-U. The fitted P_T distribution parameters, P_{T0} and β, which describe the spectra according to :

$$P_T \; e^{-\left(\frac{P_T}{P_{T0}}\right)^{\beta}}$$

are listed in table 3 for the different systems, for the J/ψ and continuum dimuons.

In order to investigate the P_T dependence as a function of the energy density, the same analysis was performed for different bins of the neutral transverse energy E_T^0 spectra. The average values of P_T and ${P_T}^2$, deduced from the fitted P_T distributions for $P_T < 3.3$ GeV/c, are shown in table 4. The quoted errors are statistical only. The $<P_T>$ and $<{P_T}^2>$ systematic error is estimated to be about 1% and 2% respectively for the J/ψ, and twice as big for the continuum. Results concerning ^{16}O-U agree very well with values of ref. [2], for which the selected data sample was slightly different. No analysis as a function of centrality has been done for the proton induced reactions as E_T^0 and impact parameter are loosely correlated. In order to take into account the different sizes of the systems under investigation, the energy density ε reached in the collisions is calculated using the Bjorken formula, *i.e.* :

$$\varepsilon \;=\; \frac{3 \;< E_T^0 >}{\Delta\eta \; \tau_0 \; \bar{S}}$$

where $<E_T^0>$ is the mean neutral transverse energy measured in the pseudorapidity range $\Delta\eta$, and $\bar{S}$ is the mean overlap area of the colliding nuclei at the time $\tau_0 = 1$fm/c, evaluated using the geometrical model described in ref. [7]. The $<P_T>$ and $<{P_T}^2>$ values as a function of ε are plotted in fig. 2 for J/ψ and in fig. 3 for continuum events. One can see from the fig. 3 and table 4 that, in the case of the continuum dimuons, values of $<P_T>$ and $<{P_T}^2>$ for ^{16}O-Cu, ^{16}O-U and ^{32}S-U collisions are, within statistic uncertainties, compatible with those obtained for p-Cu and p-U, and that their energy density dependence is quite weak. From fig. 2, it is apparent that the behaviour of the J/ψ is different, showing an increase of $<P_T>$ and $<{P_T}^2>$ with ε. Such a variation with ε is in agreement with quark-gluon plasma models [8-10], for which high P_T $c\bar{c}$ pairs can escape the deconfined region. However, for p-A reactions, an increase of $<{P_T}^2>$ with the atomic number A has been reported in ref. [11]. This is also suggested by our results, as shown in table 4. It has been interpreted as a consequence of multiple elastic scattering of the incident parton, leading to a difference $\Delta<{P_T}^2>$ between p-A and p-p values which behaves as $A^{1/3}$. This mechanism was extended to nucleus-nucleus interactions [12] and found to reproduce our previous results. In a forthcoming letter [13], an analysis along this line is presented and is shown to describe our data both for proton and ion induced collisions, indicating that, within this frame, any mechanism responsible for the observed J/ψ suppression should have a mild transverse momentum dependence. However, another approach of initial state interactions has been presented in ref. [14] where dimuon production in lowest order perturbative QCD leads to a $\Delta<{P_T}^2>$ variation which saturates with A. This proposed A dependence is not able to account for the rise of $<{P_T}^2>$ with E_T^0 observed for J/ψ in ^{16}O-U collisions. It is therefore of key importance for the interpretation of our results to know which A dependence of $\Delta<{P_T}^2>$represents best the experimental p-A data.

To investigate the transverse momentum dependence of the J/ψ suppression, the ratio $R(P_T)$ of the P_T distributions for the two extreme E_T^0 bins (*i.e.* the P_T distribution for events in the highest E_T^0 bin divided by the one corresponding to the lowest E_T^0 bin) in each nucleus-nucleus system has been computed. Each distribution was normalized to the number of continuum events at the J/ψ mass, which is obtained from a fit to the corresponding mass spectrum [1]. The ratio $R(P_T)$ is plotted on fig. 4 for ^{16}O-Cu, ^{16}O-U and ^{32}S-U interactions, and compared to the corresponding ratio calculated directly from the experimental data. The experimental ratio is to first order independent of acceptance and smearing effects and displays the same general behaviour. One can see that $R(P_T)$ is minimum for P_T=0, indicating more J/ψ suppression for low P_T values. $R(P_T)$ increases with P_T, more steeply for ^{16}O-U than for ^{32}S-U. It reaches one at about 2 GeV/c for ^{16}O-U and ^{16}O-Cu, and 3 GeV/c for ^{32}S-U. Here again, such a behaviour is predicted by quark-gluon plasma models, with a saturation of R(P_T) at high P_T values, although other calculations [15] lead to a much weaker P_T dependence. However, models considering parton multiple scattering in the entrance channel together with a J/ψ absorption by a dense hadron gas, are able to reproduce our data and predict that R(P_T) should be greater than one at high P_T. In addition, let us notice that parton multiple scattering should be present even if QGP was formed. In that case, it should manifest itself by a variation of the slope of R(P_T) instead of the predicted saturation. The present data, which are not precise enough and do not cover a sufficiently wide P_T range, do not permit to distinguish between both models.

As in ref. [2], results obtained using a transverse mass parametrization of the J/ψ P_T distribution, *i.e.* :

$$P_T \; e^{-\frac{\sqrt{P_T^2+M^2}}{T}}$$

are presented in table 5. This analytical form fits well the data and leads to similar values of $<P_T>$ and $<{P_T}^2>$. It is to be pointed out that such a choice implies an exponential rise of R(P_T) which does not reproduce the experimental values of fig. 4 above $P_T \sim 2$ GeV/c. Within this parametrization, the dependence of the parameter T, usually considered as a temperature in thermal models, has been fitted as a function of the energy density ε according to : $T = a\, \varepsilon^{\frac{1}{b}}$. With T expressed in GeV, the results of the fit, shown in fig. 5, are $a = 0.212 \pm 0.002$ and $b = 3.9 \pm 0.4$.

In conclusion, we have presented our results on transverse momentum distributions corrected for acceptance and smearing effects, for p-Cu, p-U, ^{16}O-Cu, ^{16}O-U and ^{32}S-U. $<P_T>$ and $<{P_T}^2>$ values show, for the J/ψ, a clear increase with the energy density reached in the interaction. Such a strong correlation is not seen for dimuons in the mass continuum. In addition, the data indicate that J/ψ with low P_T are strongly suppressed. As pointed out earlier, these results are expected from quark-gluon plasma models. However, alternative models including parton multiple scattering in the initial state account also for the data, which implies, in this case, that any mechanism responsible for the observed J/ψ suppression should be weakly dependent on P_T, at least in the 0.-3.2 GeV/c range. Finally, it is worth noticing that initial state interactions calculated in the frame of perturbative QCD leads to a completely different P_T behaviour of the J/ψ and supports a significant P_T dependence of its absorption mechanism. However, it is not clear at present whether such a description would reproduce p-A data.

References

[1] - NA38 Collab., C. Baglin et al., Phys. Lett. B 220 (1989) 471.

NA38 Collab., C. Baglin et al., Phys. Lett. B 255 (1991) 459.

[2] - NA38 Collab., C. Baglin et al., Phys. Lett. B 251 (1990) 465.

[3] - T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416.

[4] - X. Felgeyrolles, thesis, Université de Clermont-Ferrand (1989), unpublished.

[5] - O. Drapier, thesis, Université de Lyon (1990), unpublished.

[6] - E. Anassontzis et al., Phys. Rev. D 38 (1988) 1377.

[7] - NA38 Collab., C. Baglin et al., Phys. Lett. B 251 (1990) 472.

[8] - F. Karsch and R. Petronzio, Phys. Lett. B 212 (1988) 255.

[9] - M.C. Chu and T. Matsui, Phys. Rev. D 37 (1988) 1851.

[10] - J.P. Blaizot and J.Y. Ollitrault, Phys. Rev. D 39 (1989) 232.

[11] - NA3 Collab., J. Badier et al., Z. Phys. C 20 (1983) 101.

[12] - S. Gavin and M. Gyulassy, Phys. Lett. B 214 (1988) 241.

J. Hűfner, Y. Kurihara and H.J. Pirner, Phys. Lett. B 215 (1988) 218.

J.P. Blaizot and J.Y. Ollitrault, Phys. Lett. B 217 (1989) 392.

[13] - NA38 Collab., C. Baglin et al., Phys. Lett. B, to be published.

[14] - H. Satz, Phys. Lett. B 242 (1990) 107.

[15] - T. Matsui, Ann. Phys. 196 (1989) 182.

Reaction	J/ψ		Continuum	
	OS	LS	OS	LS
p-Cu	3751	3	1322	251
p-U	2366	7	981	149
^{16}O-Cu	3935	31	3502	1959
^{16}O-U	5582	77	7213	4642
^{32}S-U	9879	237	19746	15808

Table 1 : *Number of selected opposite sign (OS) and like sign (LS) events in the different reactions for the J/ψ and continuum mass regions.*

kinematical variable and range	J/ψ	Continuum
$M_{\mu\mu}$ (1.3 $\rightarrow$ 6. GeV/c^2)	$\delta(M-3.097)$	$protons\ :\ M^{-5.6}$ $ions\ :\ M^{-6}$
P_T (0. $\rightarrow$ 5. GeV/c)	$protons\ :\ P_T\ e^{-\left(\frac{P_T}{1.06}\right)^{1.7}}$ $ions\ :\ P_T\ e^{-\left(\frac{P_T}{1.14}\right)^{1.7}}$	$P_T\ e^{-\left(\frac{P_T}{0.71}\right)^{1.4}}$
X_F ($-0.17 \rightarrow 0.65$)	$\frac{1}{1-X_F^2}\ e^{-\frac{1}{2\ (0.4)^2}\left[\ln\left(\frac{1+X_F}{1-X_F}\right)\right]^2}$	$\frac{1}{1-X_F^2}\ e^{-\frac{1}{2\ (0.4)^2}\left[\ln\left(\frac{1+X_F}{1-X_F}\right)\right]^2}$
$\cos\theta$ ($-0.8 \rightarrow 0.8$)	$uniform$	$1+\cos^2\theta$
ϕ (0. $\rightarrow 2\pi$)	$uniform$	$uniform$

Table 2 : *Analytical functions dN/dM, dN/dP_T, dN/dX_F, $dN/d(\cos\theta)$ and $dN/d\phi$ used to compute the acceptance and smearing functions for the J/ψ and continuum dimuons.*

Reaction	J/ψ			continuum		
	P_{T0}	β	χ^2/dof	P_{T0}	β	χ^2/dof
p-Cu	1.03 ± 0.05	1.67 ± 0.08	1.1	0.66 ± 0.07	1.36 ± 0.11	0.6
p-U	1.00 ± 0.06	1.56 ± 0.09	1.1	0.75 ± 0.08	1.49 ± 0.14	0.6
^{16}O-Cu	1.09 ± 0.04	1.71 ± 0.08	1.3	0.74 ± 0.07	1.48 ± 0.13	1.2
^{16}O-U	1.12 ± 0.04	1.67 ± 0.06	0.8	0.73 ± 0.06	1.44 ± 0.09	1.
^{32}S-U	1.17 ± 0.03	1.73 ± 0.05	1.4	0.63 ± 0.06	1.25 ± 0.08	1.9

Table 3 : *Fitted P_T distribution parameters, P_{T0} (GeV/c) and β, for the J/ψ and continuum dimuons, obtained in the various reactions.*

Reaction	E_T^0 range (GeV)	ε (GeV/fm^3)	J/ψ $<P_T>$ (GeV/c)	J/ψ $<{P_T}^2>$ (GeV/c)^2	Continuum $<P_T>$ (GeV/c)	Continuum $<{P_T}^2>$ (GeV/c)^2
p-Cu	all E_T^0		1.04 ± 0.02	1.41 ± 0.04	0.83 ± 0.03	0.94 ± 0.05
p-U	all E_T^0		1.06 ± 0.02	1.49 ± 0.05	0.84 ± 0.03	0.96 ± 0.06
^{16}O-Cu	all E_T^0		1.08 ± 0.01	1.52 ± 0.04	0.84 ± 0.03	0.94 ± 0.06
	< 13	1.	1.03 ± 0.03	1.38 ± 0.06	0.83 ± 0.03	0.95 ± 0.08
	$13 - 21$	1.1	1.07 ± 0.03	1.47 ± 0.07	0.82 ± 0.05	0.91 ± 0.12
	$21 - 30$	1.3	1.15 ± 0.03	1.70 ± 0.08	0.85 ± 0.05	0.95 ± 0.11
	≥ 30	1.6	1.08 ± 0.03	1.52 ± 0.08	0.87 ± 0.06	1.06 ± 0.14
^{16}O-U	all E_T^0		1.12 ± 0.01	1.64 ± 0.03	0.85 ± 0.02	0.98 ± 0.05
	< 20	0.9	1.06 ± 0.02	1.46 ± 0.05	0.86 ± 0.03	0.97 ± 0.08
	$20 - 31$	1.3	1.12 ± 0.02	1.62 ± 0.07	0.84 ± 0.05	0.97 ± 0.10
	$31 - 39$	1.6	1.13 ± 0.03	1.65 ± 0.07	0.91 ± 0.05	1.08 ± 0.11
	$39 - 45$	1.8	1.16 ± 0.03	1.75 ± 0.09	0.80 ± 0.06	0.90 ± 0.13
	$45 - 52$	2.1	1.18 ± 0.03	1.82 ± 0.10	0.81 ± 0.07	0.86 ± 0.16
	≥ 52	2.5	1.20 ± 0.04	1.85 ± 0.12	0.86 ± 0.07	1.05 ± 0.16
^{32}S-U	all E_T^0		1.14 ± 0.01	1.69 ± 0.03	0.87 ± 0.02	1.06 ± 0.05
	< 34	1.2	1.09 ± 0.02	1.57 ± 0.04	0.88 ± 0.03	1.04 ± 0.07
	$34 - 49$	1.5	1.17 ± 0.02	1.75 ± 0.06	0.82 ± 0.04	0.95 ± 0.09
	$49 - 62$	1.6	1.16 ± 0.02	1.71 ± 0.06	0.83 ± 0.05	0.98 ± 0.10
	$62 - 71$	1.8	1.17 ± 0.03	1.77 ± 0.07	0.90 ± 0.06	1.15 ± 0.14
	$71 - 78$	2.	1.19 ± 0.03	1.83 ± 0.09	0.92 ± 0.06	1.18 ± 0.14
	≥ 78	2.3	1.17 ± 0.03	1.74 ± 0.08	0.94 ± 0.14	1.19 ± 0.24

Table 4 : *$<P_T>$ and $<{P_T}^2>$ calculated from J/ψ and continuum P_T distributions in the different systems and for various E_T^0 intervals.*

p-A reactions		^{16}O-Cu		^{16}O-U		^{32}S-U	
all E_T^0	T (MeV)	E_T^0 range (GeV)	T (MeV)	E_T^0 range (GeV)	T (MeV)	E_T^0 range (GeV)	T (MeV)
p-Cu	202 ± 3	all E_T^0	216 ± 3	all E_T^0	233 ± 3	all E_T^0	240 ± 2
		< 13	199 ± 6	< 20	209 ± 5	< 34	223 ± 3
p-U	211 ± 4	$13 - 21$	211 ± 6	$20 - 31$	231 ± 6	$34 - 49$	250 ± 6
		$21 - 30$	241 ± 7	$31 - 39$	234 ± 7	$49 - 62$	245 ± 6
		≥ 30	216 ± 7	$39 - 45$	249 ± 8	$62 - 71$	251 ± 7
				$45 - 52$	258 ± 9	$71 - 78$	260 ± 8
				≥ 52	265 ± 12	≥ 78	248 ± 8

Table 5 : *Fitted T corresponding to the transverse mass parametrization of the P_T distribution of the J/ψ.*

Figure captions

Fig. 1 : Experimental P_T distributions for J/ψ events in p-U and ^{32}S-U reactions. The solid curve is the fit using the procedure described in the text.

Fig. 2 : Distributions of $<P_T>$ (a) and $<{P_T}^2>$ (b) as a function of the energy density ε reached in the various collisions for J/ψ events.

Fig. 3 : Same as fig.2 for events in the mass continuum.

Fig. 4 : $R(P_T)$ distribution, represented by two curves which correspond to the functions with parameters within the covariance ellipsis, together with the ratio of the raw data for ^{16}O-Cu (a), ^{16}O-U (b) and ^{32}S-U (c).

Fig. 5 : T plotted as a function of the energy density ε, for the J/ψ. The solid line represents the fitted curve (see text).