J/ψ reaction mechanisms and suppression in the nuclear medium

R. Molina[1], C. W. Xiao[2] and E. Oset[2]

[1]Research Center for Nuclear Physics (RCNP),
Osaka University, Ibaraki, Osaka 567-0047, Japan,

[2]Instituto de Física Corpuscular (centro mixto CSIC-UV)
Institutos de Investigación de Paterna, Aptdo. 22085, 46071, Valencia, Spain

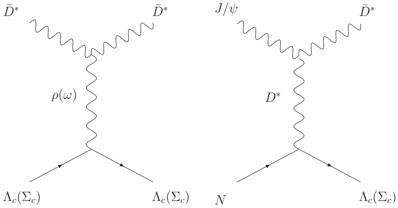
Outline

Introduction

- A suppression of the J/ψ has been proposed as a signature of the formation of Quark-Gluon Plasma in ultrarelativistic nucleus-nucleus collisions. T. Matsui and H. Satz, Phys. Lett. B (1986)
- The reaction mechanisms producing the J/ψ in a first place are not well understood N. Brambilla, Eur. Phys. J. C **71**, (2011)
- J/ψ suppression has been searched in p-nucleus collisions in several fixed target experiments NA3 , E772, NA38 , E866, E672/E706, NA50 and more recently in NA60.

The $J/\psi N \to J/\psi N$ interaction

- We consider a potential like Weinberg-Tomozawa interaction between the channels,
  - Heavy-light, Heavy-Heavy: $J/\psi N$, $\bar{D}\Lambda_c$, $\bar{D}\Sigma_c$
  - light-light ρN, ωN, ϕN, $K^*\Lambda$, $K^*\Sigma$
- First, we study the transitions between Heavy-light, Heavy-Heavy close to threshold, i. e. energies $\sim 4 - 4.4$ GeV



1. Phys. Rev. C **84**, 015202 (2011) "Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV" 2. Phys. Rev. Lett. **105**, 232001 (2010)

The hidden gauge formalism

- The transition potential is evaluated using the Hidden Gauge Formalism for the interaction between vector mesons. Bando, Kugo, Yamawaki (Phys. Rept. **164**, 217 (1988).)

Lagrangian

$$\mathcal{L} = \mathcal{L}^{(2)} + \mathcal{L}_{III} \tag{1}$$

$$\begin{aligned} \mathcal{L}^{(2)} &= \frac{1}{4} f^2 \langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + \chi^\dagger U \rangle \\ \mathcal{L}_{III} &= -\frac{1}{4} \langle V_{\mu\nu} V^{\mu\nu} \rangle + \frac{1}{2} M_V^2 \langle [V_\mu - \frac{i}{g} \Gamma_\mu]^2 \rangle \end{aligned} \tag{2}$$

$$D_\mu U = \partial_\mu U - ieQA_\mu U + ieUQA_\mu, \qquad U = e^{i\sqrt{2}P/f} \tag{3}$$

Inclusion of spin-1 fields

$$\frac{F_V}{M_V} = \frac{1}{\sqrt{2}g}, \qquad \frac{G_V}{M_V} = \frac{1}{2\sqrt{2}g}, \qquad F_V = \sqrt{2}f, \qquad G_V = \frac{f}{\sqrt{2}}, \qquad g = \frac{M_V}{2f} \tag{5}$$

$\mathcal{L}'s$

$$\begin{aligned}
\mathcal{L}_{V\gamma} &= -M_V^2 \frac{e}{g} A_\mu \langle V^\mu Q \rangle \\
\mathcal{L}_{V\gamma PP} &= egA_\mu \langle V^\mu (QP^2 + P^2 Q - 2PQP) \rangle \\
\mathcal{L}_{VPP} &= -ig \langle V^\mu [P, \partial_\mu P] \rangle \\
\mathcal{L}_{\gamma PP} &= ieA_\mu \langle Q[P, \partial_\mu P] \rangle \\
\widetilde{\mathcal{L}}_{PPPP} &= -\frac{1}{8f^2} \langle [P, \partial_\mu P]^2 \rangle .
\end{aligned} \tag{4}$$

1. M. Bando, T. Kugo, S. Uehara, K. Yamawaki and T. Yanagida, Phys. Rev. Lett. **54**, 1215 (1985).
2. M. Bando, T. Kugo and K. Yamawaki, Phys. Rept. **164**, 217 (1988).

The $VB \to VB$ interaction

$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu}V^{\mu\nu}\rangle \rightarrow \mathcal{L}^{(3V)}_{III} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle$$

$$\mathcal{L}^{(c)}_{III} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle$$

V_μ

$$\begin{aligned} V_{\mu\nu} &= \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu] \\ V_\mu &\equiv \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu \\ g &= \frac{M_V}{2f} \end{aligned} \quad (6)$$

The Baryon-baryon-vector vertex extended to SU(4)

$$\mathcal{L}_{BBV} = \frac{g}{2} \left(\langle \bar{B} \gamma_\mu [V^\mu, B] \rangle + \langle \bar{B} \gamma_\mu B \rangle \langle V^\mu \rangle \right)$$

1.Klingl,97; Palomar,02; E. Oset and A. Ramos, arXiv:0905.0973 (2009, Eur. Phys. J. A)

$$t_{B_1 \bar{B}_2 V} = \{ g_{15_1}\, C_{15_1}(20' \otimes \bar{20}') + g_{15_2}\, C_{15_2}(20' \otimes \bar{20}') + g_1\, C_1(20' \otimes \bar{20}') \} \bar{u}_{r'}(p_2) \gamma \cdot \epsilon\, u_r(p_1)$$

the reduced matrix elements, g_{15_1}, g_{15_2} and g_1 are evaluated demanding

1) The coupling $p\bar{p} \to J/\psi$ should be zero by OZI rules,
2) The coupling $p\bar{p} \to \phi$ should be zero by OZI rules,
3) The coupling $p\bar{p} \to \rho^0$ should be the one obtained in SU(3).

see J.Nieves, C.G.Recio for a more general treatment

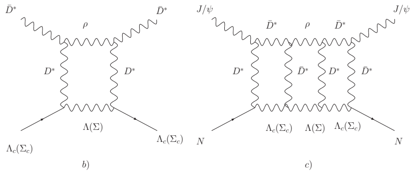
$$g_{15_1} = -g; \qquad g_{15_2} = 2\sqrt{3}\, g; \qquad g_1 = 3\sqrt{5}\, g\,. \tag{7}$$

with $g = M_V/2f$ and $f = 93 MeV$ the pion decay constant.

The transition potential is given between $J/\psi N, \bar{D}^*\Lambda_c, \bar{D}^*\Sigma_c$ is

$$V_{ij}^{WT} = -\frac{C_{ij}g^2}{p_{V^*}^2 - m_{V^*}^2}(E + E')\vec{\epsilon}\vec{\epsilon}', \qquad (8)$$

Light - light channels



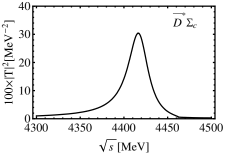
$$V_{ab} = V_{ab}^{WT} + \delta\tilde{V}_{ab}^{Box}, \qquad \delta\tilde{V}_{ab}^{Box} = \sum_c \tilde{V}_{al}\, G_l\, \tilde{V}_{lb}, \qquad (9)$$

$$l = \rho N,\ \omega N,\ \phi N,\ K^*\Lambda,\ K^*\Sigma$$

Prediction of narrow N^* and Λ^* resonances above 4.2 GeV

$$T = [I - VG]^{-1} V \epsilon \cdot \epsilon'$$

$$T_{ab} = \frac{g_a g_b}{\sqrt{s} - z_R}$$



(I,S)	M	Γ	Γ_i					
$(1/2,0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$
	4412	47.3	3.2	10.4	13.7			19.2
$(0,-1)$			$\bar{K}^*N$	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$
	4368	28.0	13.9	3.1	0.3	4.0	1.8	5.4
	4544	36.6	0	8.8	9.1	0	5.0	13.8

Table: Mass (M), total width (Γ), and the partial decay width (Γ_i) for the states from $VB \to VB$ with units in MeV.

Inelastic cross section of $J/\psi N \to J/\psi N$

$$\sigma_{tot} = -\frac{M_N}{P_{CM}^{J/\psi}\sqrt{s}} Im\, T_{J/\psi N \to J/\psi N}, \tag{10}$$

$$\begin{aligned}\sigma_{in} &= \sigma_{tot} - \sigma_{el} \\ &= -\frac{M_N}{P_{CM}^{J/\psi}\sqrt{s}} Im\, T_{J/\psi N \to J/\psi N} \\ &\quad -\frac{1}{4\pi}\frac{M_N^2}{s}\overline{\sum}\sum |T_{J/\psi N \to J/\psi N}|^2,\end{aligned}$$

In $e^- p$ collisions, for electrons around 10 GeV, the J/ψ is created with $\sqrt{s} \simeq 4050 - 5300$ MeV in the rest frame of the nucleons

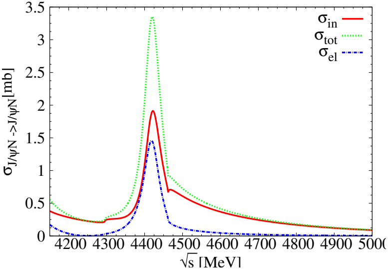


Figure: The total, elastic and inelastic cross sections.

The $J/\psi N \to \bar{D}\Lambda_c(\Sigma_c)$ cross section

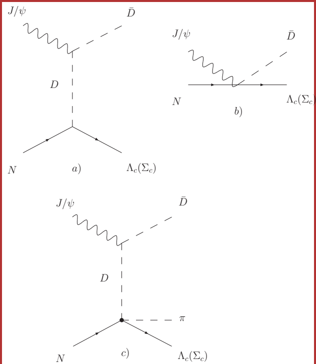
$$\mathcal{L}_{VPP} = -ig < [P, \partial_\mu P] V^\mu >,$$

$$-it_{J/\psi D^+(q) D^-(P-q)} = -i2g q_\mu \epsilon^\mu,$$

$$-it_{D^0 p \to \Lambda_c^+} = -\frac{1}{\sqrt{3}}\left(\frac{D+3F}{2f}\right)\vec{\sigma}\vec{q}$$

Kroll Rudermann

$$-it_{p\Lambda_c^+ J/\psi \bar{D}^0} = -\frac{g}{\sqrt{3}}\left(\frac{D+3F}{2f}\right)\vec{\sigma}\cdot\vec{\epsilon}$$



Requires a momentum $p_{J/\psi}^{\mathrm{cm}} = 405$ MeV for $\bar{D}\Lambda_c$ production

The $J/\psi N \to \bar{D}\Lambda_c(\Sigma_c)$ cross section

$J/\psi N \to \bar{D}\Lambda_c$(ex):

$$\overline{\sum}\sum |T|^2 = \frac{4}{3} g_D^2 \left[\frac{(P \cdot p_{\bar{D}})^2}{M_{J/\psi}^2} - m_{\bar{D}}^2\right] \times \frac{1}{2}\frac{1}{m_N m_{\Lambda_c}} (m_N + m_{\Lambda_c})^2$$

$$\times \quad (pp' - m_N m_{\Lambda_c}) \times \frac{1}{(q^2 - m_D^2)^2} \times \frac{1}{3}\left(\frac{3F + D}{2f}\right)^2$$

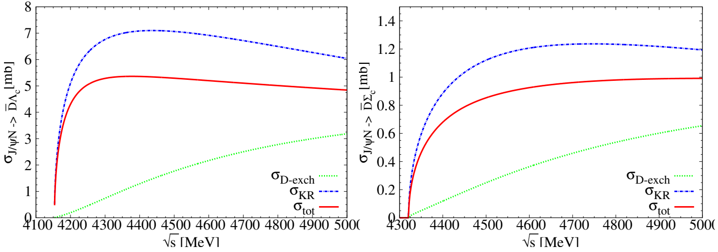


Figure: The cross section for $J/\psi N \to \bar{D}\Lambda_c$ (lf) and $J/\psi N \to \bar{D}\Sigma_c$ (rg).

The $J/\psi N \to \bar{D}\pi\Lambda_c(\Sigma_c)$ cross section

$J/\psi N \to \bar{D}\pi\Lambda_c$(ex):

$$\overline{\sum}\sum |T|^2 = \frac{4}{3} g_D^2 \Big[\frac{(P\cdot p_{\bar{D}})^2}{M_{J/\psi}^2} - m_{\bar{D}}^2\Big]\Big(\frac{1}{q^2 - m_D^2}\Big)^2 \times \frac{3}{2}\left|T^{I=1}_{DN\to\pi\Lambda_c}\right|^2$$

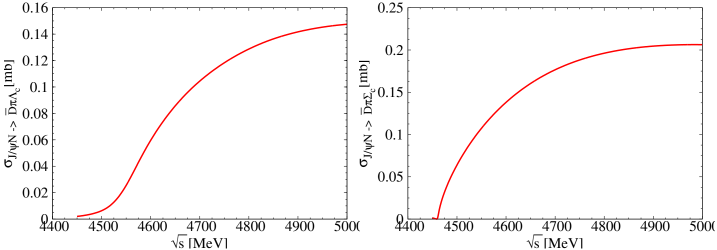


Figure: The cross section for $J/\psi N \to \bar{D}\pi\Lambda_c(\Sigma_c)$.

Total inelastic cross section

before and after including the fermi motion

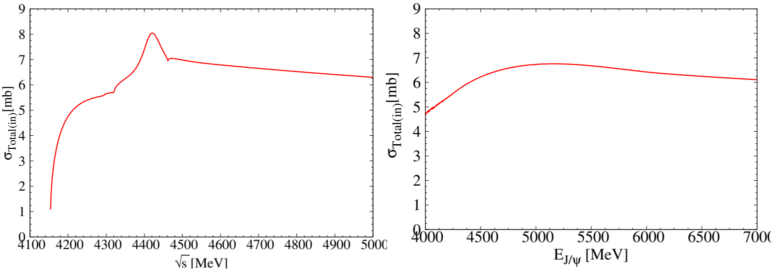


Figure: The total inelastic cross section of $J/\psi N$ without and with taking into account the Fermi motion of the nucleons

Fermi motion

- We do an average of the cross section over the femi sea nucleon momentum

$$s_N = (p_{J/\psi} + p_N)^2 = (E_{J/\psi} + E_N)^2 - (\vec{p}_{J/\psi} + \vec{p}_N)^2, \qquad (11)$$

$$\sigma(s) \to \bar{\sigma} = \int_{|\vec{p}_N|<p_F} \frac{d^3\vec{p}_N}{(2\pi)^3} \sigma(s_N) \Bigg/ \int_{|\vec{p}_N|<p_F} \frac{d^3\vec{p}_N}{(2\pi)^3}, \qquad (12)$$

where $p_F = (3\pi^2\rho/2)^{1/3}$ and we take$\rho \approx \rho_0/2,\ \rho_0 = 0.17 fm^{-3}$, the nuclear matter density.

Transparency ratio of $\gamma A \to J/\psi A'$

Definition

$$\tilde{T}_A = \frac{\sigma_{\gamma A \to J/\psi A'}}{A\sigma_{\gamma N \to J/\psi N}}$$

- Describes the loss of flux of J/ψ-mesons in the nuclei
- In the Eikonal Approximation,

$$\tilde{T}_A \propto \exp\left[\int_0^\infty dl \frac{\mathrm{Im}\Pi_{J/\psi}(\rho(\vec{r}\,'))}{|\vec{p}_{J/\psi}|}\right] \quad \text{"Survivalprobability"}$$

$$T_A = \frac{\pi R^2}{A\sigma_{J/\psi N}}\Big\{1 + (\frac{\lambda}{R})exp[-2\frac{R}{\lambda}] + \frac{1}{2}(\frac{\lambda}{R})^2(exp[-2\frac{R}{\lambda}] - 1)\Big\}.$$

where $\lambda = (\rho_0\sigma_{J/\psi N})^{-1}$. P. Muhlich and U. Mosel, Nucl. Phys. A

Transparency ratio of $\gamma A \to J/\psi A'$

before and after including the fermi motion

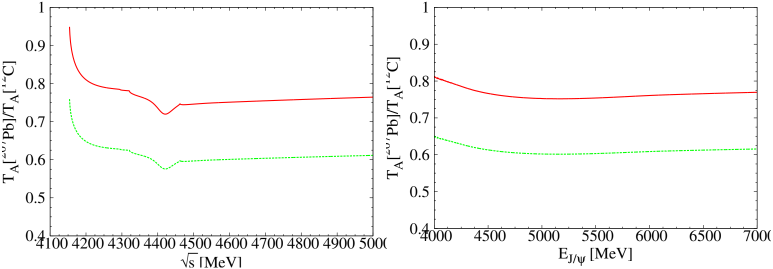


Figure: The transparency ratio of J/ψ photoproduction as a function of the energy in the CM of J/ψ with nucleons of the nucleus. Solid line: represents the effects due to J/ψ absorption. Dashed line: includes photon shadowing (Bianchi, PRC54,1688). Left: Without Fermi motion. Right: Considering Fermi motion

Transparency ratio of $\gamma A \to J/\psi A'$

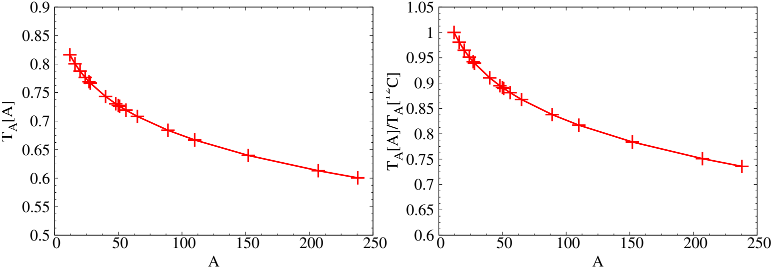


Figure: The transparency ratio of J/ψ in different nuclei. Left: T_A. Right: $T_A/T_{^{12}C}$

- The transparency ratio is of the order of $0.60-0.70$ for heavy nuclei indicating a depletion of about $30-35$ % in J/ψ production in nuclei.

Conclusions

- We find a total inelastic cross section of the order of 6-7 mb, coming from $J/\psi N \to J/\psi N$, $J/\psi N \to \bar{D}\Lambda_c$ ($\bar{D}$) exchange and Kroll Rudermann, which is sufficient to produce an appreciable suppression of J/ψ in its propagation through nuclei.
- We study the transparency ratio for electron induced J/ψ production in nuclei at about 10 GeV and find that 30 - 35 % of the J/ψ produced in heavy nuclei are absorbed inside the nucleus

Bibliography

- J. -J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. C **84**, 015202 (2011)
- J. -J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. Lett. **105**, 232001 (2010)
- N. Bianchi *et al.*, Phys. Rev. C **54**, 1688 (1996).