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J/ψ depletion in a nuclear medium

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In this talk, we have taken into account the main decay channel of J/ψ when travelling inside a nucleus. In analogy to all vector mesons in SU(3), where the main decay channel is to two pseudoscalars, in the case of the J/ψ the meson meson channel to which it couples strongly is $D\bar{D}$. Taking this into account we study the $J/\psi N \to \bar{D}\Lambda_c$ and $J/\psi N \to \bar{D}\Sigma_c$ mediated by D-exchange. To obtain the couplings we use an extension to SU(4) of the local hidden gauge Lagrangians as done in [1]. Analogously, we consider the mechanisms where the exchanged D collides with a nucleon and gives $\pi\Lambda_c$ or $\pi\Sigma_c$. The sum of these channels produces a $J/\psi N$ inelastic cross section which is larger than the elastic one and is responsible for the depletion of $J/\psi N$ when propagating through nuclear matter. The cross section has its peak around $\sqrt{s} = 4415$ MeV, where the virtual D and one N give rise to the $\Lambda_c(2595)$ resonance. We have studied the transparency ratio for photon induced J/ψ production in nuclei at 10 GeV and find that about 30 - 35 % of the J/ψ produced in heavy nuclei are absorbed inside the nucleus. This ratio is in line with depletions of J/ψ through matter observed in other reactions.

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1. Introduction

The J/ψ suppression in nuclei is an interesting subject in hadron physics [2] and many plausible reasons for it have been given. Reaction mechanisms of J/ψ with the nucleons are studied in [3, 4, 5]. Our aim is to exploit recent progress in the theoretical description of the interaction of vectors mesons with nucleons and apply these ideas to study mechanisms of J/ψ absorption in nuclei, keeping in mind the depletion of J/ψ in production reactions in nuclei induced by elementary particles, protons, photons, etc. What we use to deal with vector meson interactions is the effective Lagrangians of the local hidden gauge theory [6, 7, 8, 9]. Concerning the pseudoscalar interaction these Lagrangians are equivalent to the chiral Lagrangians [10, 11] assuming vector meson dominance. We evaluate the transparency ratio for photoproduction of J/ψ in nuclei to test the relevance of the J/ψ absorption. Then we look for the rate of production in different nuclei and we find a depletion of about 30 - 35 % for heavy nuclei.

2. Formalism and results

2.1 Vector-baryon coupled channels contribution

We start our ideas from a recent study of the vector-baryon interaction in the hidden charm sector around energies of 4 GeV [1, 12]. In the $I = 1/2, S = 0$ sector, there are three channels: $\bar{D}^*\Lambda_c$, $\bar{D}^*\Sigma_c$ and $J/\psi N$. The potential is evaluated using a SU(4) extrapolation of the local hidden gauge approach with symmetry breaking ingredients implemented [1, 12]. The amplitudes of Feynmann diagrams like those in Fig. 1 (left) are evaluated.

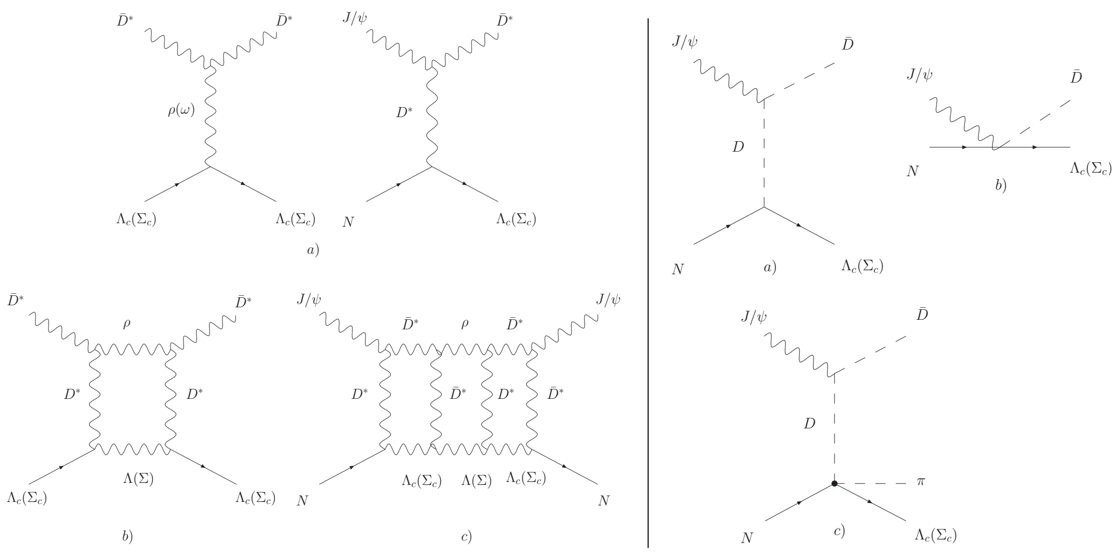

Figure 1: Left: a) Vector exchange diagrams for the vector-baryon interaction considered in [1, 12], b) Box diagram with $\rho\Lambda(\Sigma)$ in the intermediate state, c) $J/\psi N \to J/\psi N$ like-box diagram with $\rho\Lambda(\Sigma)$ in the intermediate state. Right: Feynman diagrams of $J/\psi N \to \bar{D}\Lambda_c(\Sigma_c)$, a) Vector exchange contribution. b) Kroll Ruderman term. c) The $J/\psi N \to \bar{D}\pi\Lambda_c(\Sigma_c)$ reaction.

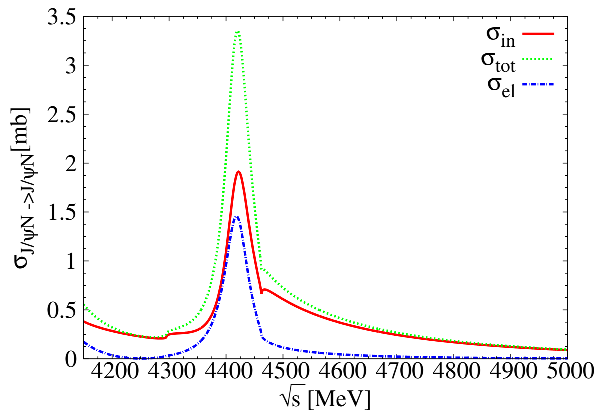

Figure 2: The total, elastic and inelastic cross sections.

It is worth noting that the $J/\psi N$ channel only can go to the light vector-light baryon channels through intermediate states with $\bar{D}^*\Lambda_c$, $\bar{D}^*\Sigma_c$, see Fig. 1 (left) c). Since the depletion has to do with the inelastic $J/\psi N$ cross section, we evaluate it by using the optical theorem that states in our normalization

$$\sigma_{tot} = -\frac{M_N}{P_{CM}^{J/\psi}\sqrt{s}} \text{Im}\, T_{J/\psi N \to J/\psi N}, \tag{2.1}$$

which allows then to separate the inelastic cross section: $\sigma_{in} = \sigma_{tot} - \sigma_{el}$.

In Fig. 2 we plot the results for these cross sections. We observe a peak around 4415 MeV, which corresponds to a hidden charm resonance found in [1, 12].

2.2 Considering $\bar{D}\Lambda_c$ and $\bar{D}\Sigma_c$ channels

The J/ψ couples to the $D\bar{D}$ channel. Although the channel is not open for decay, the channels $J/\psi N \to \bar{D}\Lambda_c$, $\bar{D}\Sigma_c$ are nearly opened. We then evaluate the cross section for the Feynman diagrams of Figs. 1 (right) a). The cross section for the process $J/\psi \to \bar{D}^0\Lambda_c^+$ is given by

$$\sigma = \frac{M_N M_{\Lambda_c}}{4\pi}\frac{1}{s}\frac{p'}{p}\overline{\sum}\sum |T|^2. \tag{2.2}$$

In Fig. 3 we can see both contributions: D-exchange (dashed line), Kroll Ruderman (dot-dashed line), and the sum, which takes into account interference (continuous line). We observe that for energies around 4400 MeV the KR term dominates, being about five times bigger than the D-exchange contribution in $\bar{D}\Lambda_c$. In the case of $\bar{D}\Sigma_c$, the sum is about one order of magnitude smaller than for $\bar{D}\Lambda_c$. The cross section for $J/\psi N \to \bar{D}\Lambda_c$ was also studied in [5] based on the same mechanism of Fig. 1 (right) a) and with similar results. We have also included here the Kroll Ruderman term following the developments of [13, 14, 15, 16, 17], which provides an important contribution to the total cross section.

2.3 The interactions of $J/\psi N \to \bar{D}\pi\Lambda_c(\Sigma_c)$

Next we study the reactions $J/\psi N \to \bar{D}\pi\Lambda_c, \bar{D}\pi\Sigma_c$. The diagrams are depicted in Fig. 1 (right) c). We are interest in these processes because the DN interaction leads to the $\Lambda_c(2595)$ and

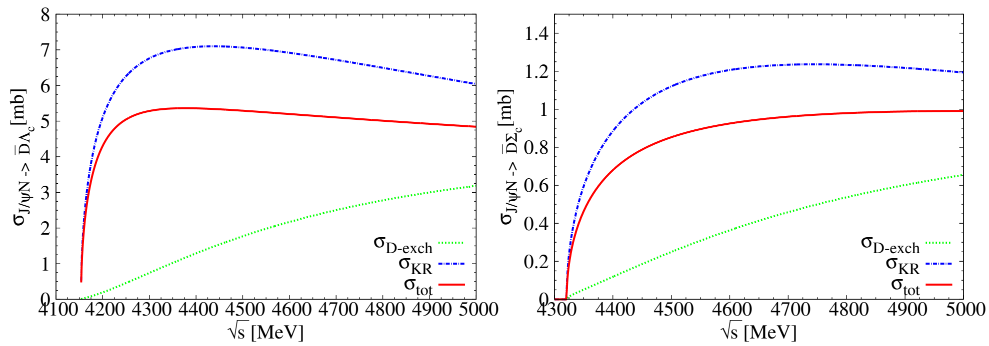

Figure 3: The cross section for $J/\psi N \to \bar{D}\Lambda_c$ (left) and $J/\psi N \to \bar{D}\Sigma_c$ (right).

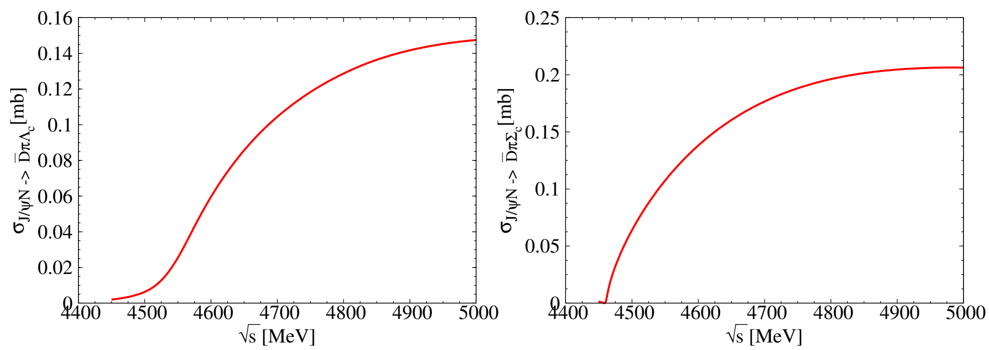

Figure 4: The cross section for $J/\psi N \to \bar{D}\pi\Lambda_c(\Sigma_c)$.

$\Sigma_c(2800)$ resonances studied in [18, 19, 20]. The scattering matrix for this process is calculated similarly as in the mechanisms of the former section and we find for $J/\psi N \to \bar{D}\pi\Lambda_c$,

$$\sigma = \frac{M_N M_{\Lambda_c}}{4 p_{J/\psi} s} \int dM_{23} \int_{-1}^{1} dcos\theta \, \frac{p_1 \tilde{p}_2}{(2\pi)^3} \overline{\sum} \sum |T|^2. \tag{2.3}$$

We show the cross section for Λ_c and Σ_c in the final state in Fig. 4. The cross sections found are small. The one for $J/\psi N \to \bar{D}\pi\Lambda_c$ is about 30 times smaller than the one for $J/\psi N \to \bar{D}\Lambda_c$, and the one for $J/\psi N \to \bar{D}\pi\Sigma_c$ about five times smaller than that of $J/\psi N \to \bar{D}\Sigma_c$.

2.4 Transparency ratio with the depletion of J/ψ

We now try to test this prediction. We look a $\gamma A \to J/\psi\, X$, depending on what is the elementary production of J/ψ, like $\gamma N \to J/\psi N, J/\psi \pi N, \cdots$. We define the transparency ratio

$$T_A = \frac{\sigma_A(J/\psi)}{A\sigma_N(J/\psi)}, T'_A = \frac{T_A}{T_{^{12}C}}. \tag{2.4}$$

the later one is to normalize to a light nucleus like ^{12}C. We take several nuclei and evaluate $\sigma_A(J/\psi)$ as a function of A. Given the fact that the J/ψ will move in the nucleus essentially forward in the lab frame of $J/\psi N$, with N a secondary nucleon in the nucleus which we consider at rest, we can use a simple formula derived in [21] which gives the transparency ratio as

$$T_A = \frac{\pi R^2}{A\sigma_{J/\psi N}} \Big\{ 1 + (\frac{\lambda}{R}) exp\big[-2\frac{R}{\lambda}\big] + \frac{1}{2}(\frac{\lambda}{R})^2 \big(exp\big[-2\frac{R}{\lambda}\big] - 1\big) \Big\}. \tag{2.5}$$

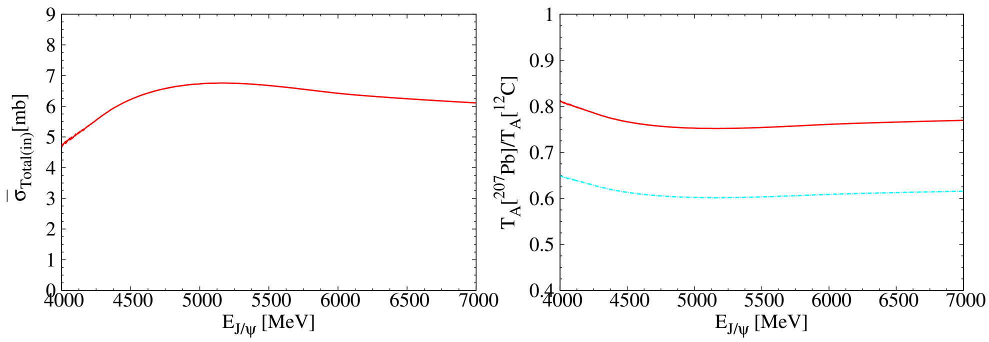

Figure 5: Left: the average inelastic cross section of $J/\psi N$. Right: the transparency ratio of J/ψ photoproduction as a function of the energy of $E_{J/\psi}$ using the $J/\psi N$ cross section averaged over the Fermi sea shown in the left figure. Solid line: represents the effects due to J/ψ absorption. Dashed line: includes photon shadowing [22].

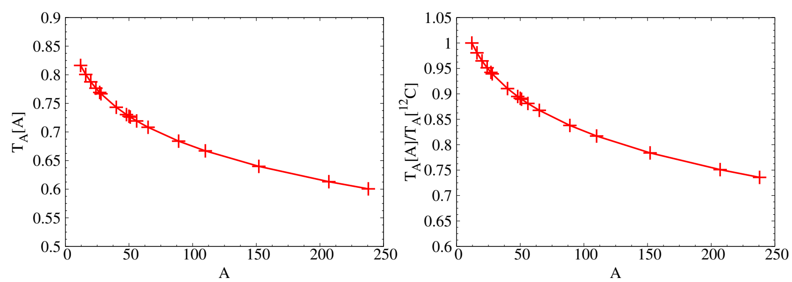

Figure 6: The transparency ratio of J/ψ in different nuclei. Left: T_A. Right: $T_A/T_{^{12}C}$

where $\lambda = (\rho_0 \sigma_{J/\psi N})^{-1}$, with $\sigma_{J/\psi N}$ the inelastic cross section of $J/\psi N$.

We plot in Fig. 5 (left) the total average $J/\psi N$ inelastic cross section, as sum of all inelastic cross sections discussed before averaged over the momenta distribution of the nucleons. We can see that the peak in Fig. 2 is removed by the effect of Fermi motion.

We can take now various energies of J/ψ and evaluate T_A for this energy as a function of A as shown in Fig. 6 for $\sqrt{s} = 4600$ MeV ($\sigma_{Total(in)} \simeq 6.8\, mb$), a typical energy which is not in the peak of the resonance (4415 MeV). We can see that the values of the transparency ratio are of the order of $0.60 - 0.70$ for heavy nuclei indicating a depletion of about $30 - 35$ % in J/ψ production in nuclei. Normalized to $T_{^{12}C}$ the ratio goes down to 0.75 for heavy nuclei.

In Fig. 5 (right) we plot the ratio $T_{^{207}Pb}/T_{^{12}C}$ as a function of energy. Because of Fermi motion, we can not see any dips in the transparency ratios at the energy of the resonance. It should be noted that the transparency ratio done with Eq. (2.5) does not consider the shadowing of the photons and assumes they can reach every point without being absorbed. Taking it into account is easy since one can multiply the ratio T'_A by the ratio of N_{eff} for the nucleus of mass A and ^{12}C. This ratio for ^{208}Pb to ^{12}C at $E_\gamma = 10$ GeV is of the order 0.8 [22]. We should then multiply $T'_A(^{208}Pb)$ in Fig. 5 (right) by this extra factor for a proper comparison with experiment.

3. Conclusion

We have investigated different sources of interaction of J/ψ with nucleons in order to obtain the inelastic $J/\psi N$ cross section. First we have used a model recently developed to study the vector-baryon interaction which produced a resonance at 4415 MeV. We have also considered the transitions $J/\psi N \to \bar{D}\Lambda_c$ or $\bar{D}\Sigma_c$ via D-exchange and Kroll Ruderman (contact term) diagrams. Furthermore, we evaluate the transitions $J/\psi N \to \bar{D}\pi\Lambda_c$ or $\bar{D}\pi\Sigma_c$. However, these latter processes have a small cross section in the range of energies studied here. We then study theoretically the transparency ratio for J/ψ electroproduction in nuclei, and find that the transparency ratios are in agreement with the typical rates of J/ψ suppression in most experimental reactions. Because of the $J/\psi N$ resonance found theoretically around $\sqrt{s} = 4415$ MeV, the J/ψ inelastic cross section would have a maximum around the energy of this resonance. The transparency ratio would have a dip around this energy in principle. However, when the Fermi motion of the nucleus is considered the cross section has to be substituted by its average over the nucleon momenta and the dip disappears.

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