Hidden charm mesons in nuclear matter and nuclei

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Recent results for the η_c- and J/ψ-nucleus bound state energies for various nuclei are presented. The attractive potentials for the η_c and J/ψ mesons in the nuclear medium originate, respectively, from the in-medium enhanced DD^* and $D\bar{D}$ loops in the η_c and J/ψ self energies. Our results suggest that the η_c and J/ψ mesons should form bound states with all the nuclei considered

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1. Introduction

The study of the interactions between charmonium states, such as η_c and J/Ψ, and atomic nuclei offers an important opportunity to extend our knowledge of the strong force and strongly interacting matter. Since charmonia and nucleons do not share light quarks, the Zweig rule suppresses interactions mediated by the exchange of mesons made of light quarks. Thus, it is important to explore other mechanisms that could lead to the binding between charmonia and atomic nuclei.

Recent studies [1] have shown that modifications induced by the strong nuclear mean fields on the D mesons' light-quark content enhance the J/Ψ self-energy in such that there is an attractive J/Ψ-nucleus effective potential. Here we update our previous study on the J/Ψ [1] and extend it to the case of η_c [2] by considering an intermediate DD^* state in the η_c self-energy with the light quarks created from the vacuum. Furthermore, recently, we have extended this approach to the case of bottomonium [3].

2. η_c and J/Ψ scalar potentials in symmetric nuclear matter

For the computation of the η_c and J/Ψ scalar potentials in nuclear matter we use an effective Lagrangians approach at the hadronic level–see Ref. [2] and referenes therein. The interaction Lagrangians for the $\eta_c DD^*$ and $J/\Psi DD$ vertices are given by

$$\mathcal{L}_{\eta_c DD^*} = ig_{\eta_c}(\partial_\mu \eta_c)\left[\bar{D}^{*\mu} \cdot D - \bar{D} \cdot D^{*\mu}\right], \quad \mathcal{L}_{\psi DD} = ig_\psi \psi^\mu \left[\bar{D} \cdot (\partial_\mu D) - (\partial_\mu \bar{D}) \cdot D\right], \quad (1)$$

where we have denoted the J/Ψ vector field by ψ, $D^{(*)}$ represents an isospin doublet, and g_{η_c} and g_ψ are, respectively the coupling constants for the vertices $\eta_c DD^*$ and $J/\Psi D\bar{D}$.

We use an effective Lagrangian, such as Eq. (1), to compute the η_c and J/Ψ scalar potentials in nuclear matter and nuclei, following our previous works [1, 4]. In explaining our approach, we focus on the η_c meson [2] but similar expressions can be obtained for the J/Ψ–see Refs. [1]; however, we will show the correspondig results for the J/Ψ.

The starting point is the computation of the η_c mass shift in nuclear matter, which is given by $\Delta m_{\eta_c} = m^*_{\eta_c} - m_{\eta_c}$, where $m^*_{\eta_c}$ (m_{η_c}) is the in-medium (vacuum) mass of the η_c. These masses are obtained by solving $m^2_{\eta_c} = (m^0_{\eta_c})^2 + \Sigma_{\eta_c}(k^2 = m^2_{\eta_c})$, where $m^0_{\eta_c}$ is the bare η_c mass and $\Sigma_{\eta_c}(k^2)$ is the η_c self-energy, which is calculated for a η_c at rest and considering only the DD^* intermediate state, and is given by $\Sigma_{\eta_c}(k^2) = (8g^2_{\eta_c DD^*}/\pi^2)\int_0^\infty dq\, q^2 I(q^2)$.

The integreal $I(k^2)$, given in Eq. (3) of Ref. [2], is divergent and will be regulated with a phenomenological vertex form factor, as in Refs [1–4], with cutoff parameter Λ_D ($= \Lambda_{D^*}$), which we vary in the range 1500-3000 MeV, for both the η_c and J/Ψ, to quantify the sensitivity of our results to its value. For the coupling constants we use the values $g_{\eta_c} = (0.6/\sqrt{2})g_{J/\Psi} = 3.24$ and $g_{J/\Psi} = 7.64$ [5, 6]. The η_c mass in the nuclear medium is computed with the self-energy calculated with the medium-modified D and D^* masses [2]. The nuclear density dependence of the η_c (J/Ψ) mass originates from the interactions of the intermediate DD^* ($D\bar{D}$) state with the nuclear medium through their medium-modified masses, m^*_D and $m^*_{D^*}$. These masses, calculated within the quark-meson coupling (QMC) model [1], are shown in Fig. 1 as a function of ρ_B/ρ_0, where ρ_B is the baryon density of nuclear matter and $\rho_0 = 0.15$ fm^{-3} is the saturation density of
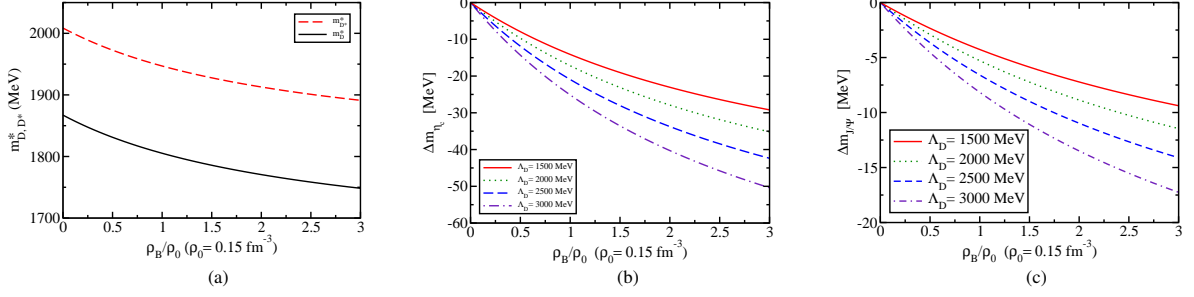
Figure 1: D and D^* masses and η_c and J/Ψ mass shifts in nuclear matter.
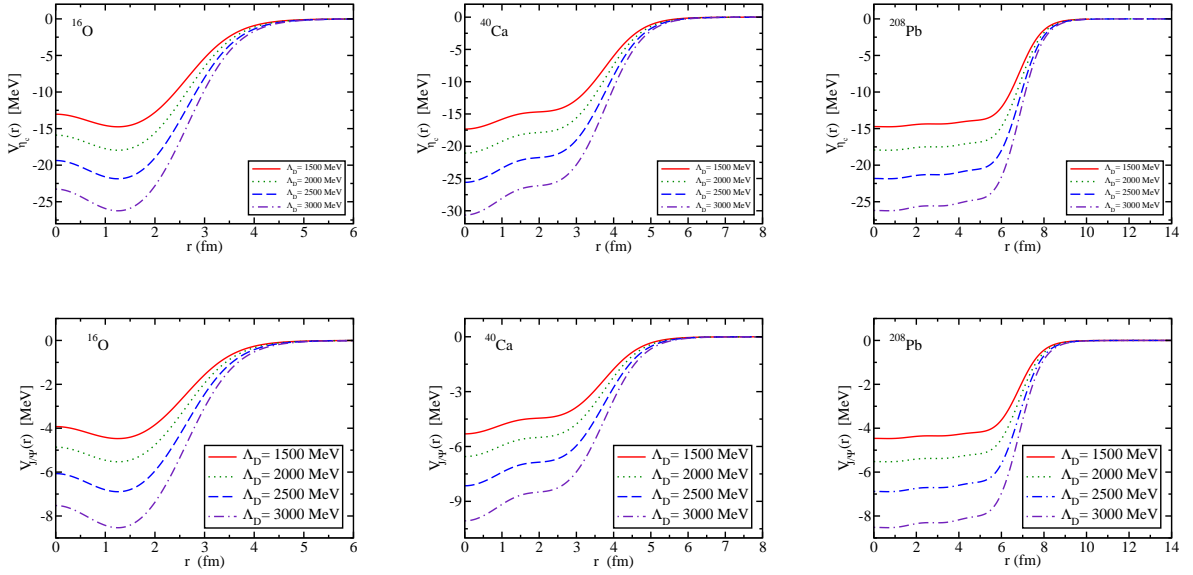
Figure 2: η_c- and J/Ψ-nucleus potentials for various nuclei and values of the cutoff parameter Λ_D.

symmetric nuclear matter. As can be seen from Fig. 1 the masses of the D and D^* mesons decrease in the nuclear medium.

In Fig. 1 we present the η_c mass shift in nuclear matter. Also, in Fig. 1 we show our updated corrresponding results for the J/Ψ mass shift. As can be seen from Fig. 1 the effect of the nuclear medium on the η_c and J/Ψ is to provide attraction to these mesons and this could potentially lead to the binding of these mesons to nuclei since, in each case, the mass shift is significant for $\rho_B/\rho_0 \sim 1$.

3. Charmonium-nucleus bound states

We now consider the binding of the η_c and J/Ψ mesons to nuclei when these mesons are produced inside nucleus A with baryon density distribution $\rho_B^A(r)$; see Ref. [2]. The nuclear density distribution for the nuclei we consider here are calculated within the QMC model, except for ^{4}He, whose parametrization was obtained in Ref. [7].

	$n\ell$	Bound state energies (E)			
		$\Lambda_D = 1500$	$\Lambda_D = 2000$	$\Lambda_D = 2500$	$\Lambda_D = 3000$
$^{4}_{\eta_c}$He	1s	-1.49	-3.11	-5.49	-8.55
$^{16}_{\eta_c}$O	1s	-7.35	-9.92	-13.15	-16.87
	1p	-1.94	-3.87	-6.48	-9.63
$^{40}_{\eta_c}$Ca	1s	-11.26	-14.42	-18.31	-22.73
	1p	-7.19	-10.02	-13.59	-17.70
$^{208}_{\eta_c}$Pb	1s	-12.99	-16.09	-19.82	-24.12
	1p	-11.60	-14.64	-18.37	-22.59
	1d	-9.86	-12.83	-16.49	-20.63

	$n\ell$	Bound state energies (E)			
		$\Lambda_D = 1500$	$\Lambda_D = 2000$	$\Lambda_D = 2500$	$\Lambda_D = 3000$
$^{4}_{J/\Psi}$He	1s	n	n	-0.01	-0.02
$^{16}_{J/\Psi}$O	1s	-0.52	-1.03	-1.81	-2.87
$^{40}_{J/\Psi}$Ca	1s	-1.92	-2.78	-3.96	-5.45
	1p	n	-0.38	-1.18	-2.32
$^{208}_{J/\Psi}$Pb	1s	-3.28	-4.26	-5.53	-7.08
	1p	-2.24	-3.16	-4.38	-5.87
	1d	-1.02	-1.84	-2.97	-4.38

Table 1: η_c- and J/Ψ-nucleus bound state energies for various nuclei. Dimensionful quantities are in MeV.

3.1 η_c-nucleus bound states

Using a local density approximation, the η_c-meson potential inside nucleus A is given by $V_{\eta_c A}(r) = \Delta m_{\eta_c}(\rho_B^A(r))$, where Δm_{η_c} is the η_c mass shift shown in Fig. 1, and r is the distance from the center of the nucleus.

In Fig. 2 we present the η_c potentials for the various nuclei. From Fig. 2, we can see that all η_c potentials are attractive but their depths depend on Λ_D. Next, we calculate the η_c–nucleus bound state energies by solving the Klein-Gordon equation $\left(-\nabla^2 + m^2 + 2mV(\vec{r})\right)\phi_{\eta_c}(\vec{r}) = \mathcal{E}^2\phi_{\eta_c}(\vec{r})$, where m is the reduced mass of the η_c–nucleus system in vacuum and $V(\vec{r})$ is the η_c-nucleus potential shown in Fig. 2.

The bound state energies (E) of the η_c-nucleus system, given by $E = \mathcal{E} - m$, are listed in Table 1. These results show that the η_c is expected to form bound states with all the nuclei considered, independently of the value of Λ_D. Expectedly, the particular values for the bound state energies are dependent on Λ_D. This dependence is an uncertainty in the results obtained in our approach. Finally, note that the η_c is predicted to be bound more strongly to heavier nuclei.

3.2 J/Ψ-nucleus bound states

Using a similar approach to the one just described for the η_c, the J/Ψ mass shift in nuclear matter and J/Ψ–nucleus bound state energies were calculated in Ref. [1]. In these studies, the J/Ψ self-energy involved the D, $\bar{D}$, D^*, and $\bar{D}^*$ mesons as intermediate states. However, it turned out that the loops involving the D^* and $\bar{D}^*$ mesons gave a larger contribution to the J/Ψ self-energy, which is unexpected. The reason for this could be that in those studies the coupling constants for all the vertices were assumed to be equal to the $J/\Psi D\bar{D}$ coupling and, furthermore, that the same cutoff (Λ_D) was used in all vertex form factors. This latter issue, in particular, should play an important role, as heavier intermediate states induce fluctuations from shorter distances and a corresponding readjustment of the cutoffs might be required to compensate for such fluctuations. These issues call for further investigations in the future. The following updated results are obtained by considering only the lightest intermediate state in the J/Ψ self-energy, namely the $D\bar{D}$ loop.

In Fig. 1 we present results for the J/Ψ mass shift in nuclear matter. These results show an attractive scalar potential for the J/Ψ in nuclear matter in all cases. In Fig. 2 we present the J/Ψ potentials in nuclei, from which we can see, as in the η_c case, that these are all attractive but their depths are sensitive to the value of the cutoff parameter. Note that the η_c potentials are more attractive than those of the J/Ψ. The bound state energies for the J/Ψ for various nuclei are listed in Table 1. These results show that the J/Ψ is expected to form bound states for all the cases

considered, but only in some cases for ^{4}He. Thus, it will be possible to search for the bound states in a ^{208}Pb nucleus at JLab now that the 12 GeV upgrade has been completed. In addition, one can expect a rich spectrum of states for medium and heavy mass nuclei.

4.　Summary and conclusions

We have calculated the spectra of η_c- and J/Ψ-nucleus bound states for various nuclei. The meson-nucleus potentials were calculated using a local density approximation, by including only the DD^* ($D\bar{D}$) meson loop in the η_c (J/Ψ) self-energy. The nuclear density distributions, as well as the in-medium D and D^* meson masses in nuclear matter were calculated within the QMC model. Then, using these potentials in nuclei, we solved the Klein-Gordon equation and obtained meson–nucleus bound state energies. Our results show that one should expect the η_c and J/Ψ to form bound states for all the nuclei studied, even though the precise values of the bound state energies are dependent on the cutoff mass values used in the form factors. The sensitivity of our results to the cutoff parameter used has also been explored.

5.　Acknowledgments

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