

Hidden charm mesons in nuclear matter and nuclei

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"El saber de mis hijos
hará mi grandeza"

Plan for this presentation

1 Introduction and Motivation

2 η_c self-energy

3 η_c in nuclear matter

4 η_c in nuclei

A bit of advertising

This presentation is mainly based on

- “ η_c -nucleus bound states”
[Physics Letters B 811 \(2020\) 135882 \(arXiv:2007.04476\)](#)

In collaboration with

- **Kazuo Tsushima**—Laboratório de Física Teórica e Computacional, Universidade Cruzeiro do Sul, São Paulo, Brazil.
- **Gastão Krein**—Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil.
- **Anthony Thomas**—Special Research Centre for the Subatomic Structure of Matter University of Adelaide, Adelaide, Australia.

Motivation

- The study of the interactions of charmonium states, such as η_c and J/ψ , with atomic nuclei offers opportunities to gain new insight into the properties of the strong force and strongly interacting matter
- Because charmonia and nucleons do not share light quarks, the Zweig rule suppresses interactions mediated by the exchange of mesons made of light quarks
- It is therefore important to explore other potential sources of attraction which could lead to the binding of charmonia to atomic nuclei
- Mesic nuclei are a new exotic state of matter involving the meson being bound inside the nucleus purely by the strong interaction
- The discovery of such bound states would represent an important step forward in our understanding of the nature of strongly interacting systems

η_c self-energy

Effective Lagrangians approach

- For the computation of the η_c self-energy Σ_{η_c} we use an effective Lagrangian approach at the hadronic level— which is an $SU(4)$ -flavor extension of light-flavor chiral-symmetric Lagrangians of pseudoscalar and vector mesons
- The interaction Lagrangian for the $\eta_c DD^*$ vertex is given by

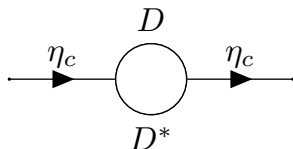
$$\begin{aligned}\mathcal{L}_{\eta_c DD^*} &= ig_{\eta_c}(\partial_\mu \eta_c) \left[\bar{D}^{*\mu} \cdot D - \bar{D} \cdot D^{*\mu} \right] \\ &\quad - ig_{\eta_c} \eta_c \left[\bar{D}^{*\mu} \cdot (\partial_\mu D) - (\partial_\mu \bar{D}) \cdot D^{*\mu} \right]\end{aligned}$$

- D and D^* represent isospin doublets
- g_{η_c} is the $\eta_c DD^*$ coupling constant—to be specified below

η_c meson self-energy $\Sigma_{\eta_c}(k)$

- Considering only the DD^* loop, the η_c self-energy is given by

$$\Sigma_{\eta_c}(k^2) = \frac{8g_{\eta_c}^2}{\pi^2} \int_0^\infty dk k^2 I(k^2)$$



where $(\omega_{D^{(*)}} = (k^2 + m_{D^{(*)}}^2)^{1/2})$

$$I(k^2) = \frac{m_{\eta_c}^2 (-1 + k^0^2/m_{D^*}^2)}{(k^0 + \omega_{D^*})(k^0 - \omega_{D^*})(k^0 - m_{\eta_c} - \omega_D)} \Bigg|_{k^0 = m_{\eta_c} - \omega_{D^*}} + \frac{m_{\eta_c}^2 (-1 + k^0^2/m_{D^*}^2)}{(k^0 - \omega_{D^*})(k^0 - m_{\eta_c} + \omega_D)(k^0 - m_{\eta_c} - \omega_D)} \Bigg|_{k^0 = -\omega_{D^*}},$$

- m_D and m_{D^*} are the D and D^* meson masses

η_c meson self-energy $\Sigma_{\eta_c}(k)$

- We are interested in the difference between the in-medium mass of the η_c , $m_{\eta_c}^*$, and its vacuum value, m_{η_c} ,

$$\Delta m_{\eta_c} = m_{\eta_c}^* - m_{\eta_c},$$

- The masses are obtained from

$$m_{\eta_c}^2 = (m_{\eta_c}^0)^2 + \Sigma_{\eta_c}(k^2 = m_{\eta_c}^2),$$

where $m_{\eta_c}^0$ is the bare η_c mass

- The in-medium mass $m_{\eta_c}^*$ is obtained with the self-energy Σ_{η_c} calculated with the medium-modified D and D^* masses

η_c meson self-energy $\Sigma_{\eta_c}(k)$

- The integral in Σ_{η_c} is divergent and therefore needs regularization
- We employ a phenomenological vertex form factor

$$u_{D^{(*)}}(k^2) = \left(\frac{\Lambda_{D^{(*)}}^2 + m_{\eta_c}^2}{\Lambda_{D^{(*)}}^2 + 4\omega_{D^{(*)}}^2(k^2)} \right)^2,$$

with cutoff parameter $\Lambda_{D^{(*)}}$

- The cutoff parameter Λ_D ($\Lambda_{D^*} = \Lambda_D$) is an unknown input to our calculation
- Λ_D has been estimated to be $\Lambda \approx 2500$ MeV—it serves as a reasonable guide to quantify the sensitivity of our results to its value.
- We present results for Λ_D in the interval 1500-3000 MeV

Parameters

- We use experimental values for the meson masses and empirical values for the coupling constants:

$$m_D = 1867.2 \text{ MeV}, \quad m_{D^*} = 2008.6 \text{ MeV}, \quad m_{\eta_c} = 2983.9, \text{ MeV}$$

- For the coupling constants g_{η_c} and $g_{\psi DD}$ we use

$$g_{\eta_c} = 0.60 g_{\psi DD} \quad (\text{PRD 93, 016004 (2016)})$$

$$g_{\psi DD} = 7.64 \quad (\text{PRC 62, 034903 (2000)})$$

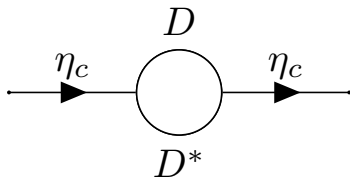
- The first value was obtained as the residue at the pole of suitable form factors using a dispersion formulation of the relativistic constituent quark model; the second value was estimated using the vector meson dominance model

Results for η_c in nuclear matter

η_c in nuclear matter

- m_{η_c} and $m_{\eta_c}^*$ are calculated by solving

$$m_{\eta_c}^2 = (m_{\eta_c}^0)^2 + \Sigma_{\eta_c}(k^2 = m_{\eta_c}^2)$$



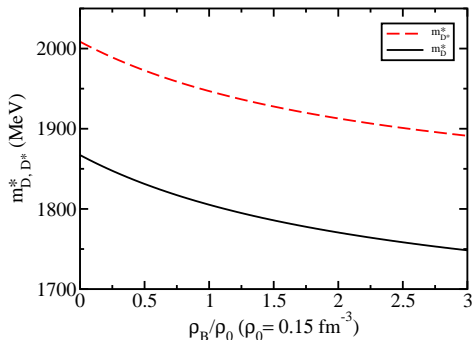
- The η_c mass in medium, $m_{\eta_c}^*$, is obtained with the self-energy Σ_{η_c} calculated with the medium-modified D and D^* masses, m_D^* and $m_{D^*}^*$
- m_D^* and $m_{D^*}^*$ are computed in the quark meson coupling model (QMC)

The quark meson coupling model [PPNP 58, 1 (2007)]

- The QMC model is a quark-based, relativistic mean field model of nuclear matter and nuclei.
- Here the relativistically moving and confined light quarks in the nucleon bags (MIT bag) interact directly with the scalar-isoscalar σ , vector-isoscalar ω , and vector-isovector ρ mean fields (Hartree approximation) generated by the light quarks in the other nucleons.
- The meson mean fields are responsible for nuclear binding.
- The self-consistent response of the bound light quarks to the mean field σ field leads to novel saturation mechanism for nuclear matter.
- The model has opened many opportunities for studies of the structure of finite nuclei and hadron properties in a nuclear medium (nuclei) with a model based on the underlying quarks degrees of freedom.

The quark meson coupling model [PPNP 58, 1 (2007)]

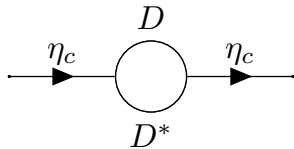
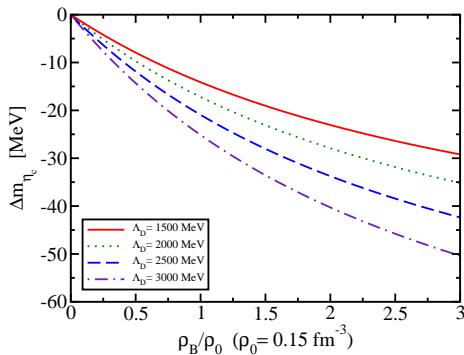
- QMC results for m_D^* and $m_{D^*}^*$ in nuclear matter:



- The mass shifts for the D and D^* mesons are nearly the same—each decreasing by around 60 MeV at $\rho_B = \rho_0$

η_c mass shift in nuclear matter

- Results for the η_c mass in nuclear matter



- The effect the nuclear medium is to decrease the η_c mass (attraction)
- This effect increases with the cutoff mass Λ_D

Results for η_c in nuclei

η_c -nucleus bound states

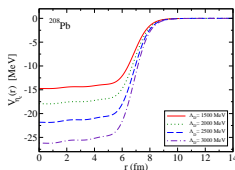
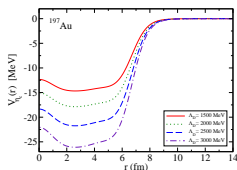
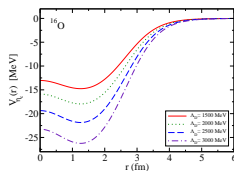
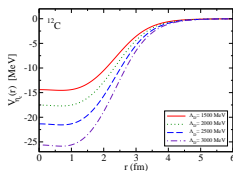
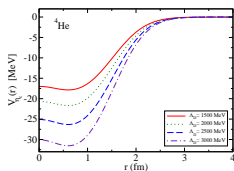
- We now discuss the situation where the η_c -meson is produced inside a nucleus A with baryon density distribution $\rho_B^A(r)$.
- The nuclear density distributions for ^{12}C , ^{16}O , ^{40}Ca , ^{48}Ca , ^{90}Zr , ^{197}Au , and ^{208}Pb are calculated with the QMC model (For ^4He , we used PRC 56, 566 (1997)).
- Using a local density approximation, the η_c -meson potential within 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 and r is the distance from the center of the nucleus.

η_c -nucleus bound states

- η_c potentials for ${}^4\text{He}$, ${}^{12}\text{C}$, ${}^{16}\text{O}$, ${}^{197}\text{Au}$, and ${}^{208}\text{Pb}$:



- The η_c potentials are attractive enough to allow for the formation of bound states—However, the depth of the potential depends on Λ_D .

- Using the η_c potentials we next calculate the η_c -nucleus bound state energies by solving the Klein-Gordon equation

$$(-\nabla^2 + \mu^2 + 2mV(\vec{r})) \phi_{\eta_c}(\vec{r}) = \mathcal{E}^2 \phi_{\eta_c}(\vec{r}), \quad (1)$$

where m is the reduced mass of the η_c -nucleus system and $V(\vec{r})$ is the η_c -nucleus potential

- The bound state energies (E) of the η_c -nucleus system are

$$E = \mathcal{E} - m$$

where \mathcal{E} is the energy eigenvalue in the KGE

- Results for η_c -nucleus bound states

		Bound state energies			
$n\ell$		$\Lambda_D = 1500$	$\Lambda_D = 2000$	$\Lambda_D = 2500$	$\Lambda_D = 3000$
$^4_{\eta_c}\text{He}$	1s	-1.49	-3.11	-5.49	-8.55
$^{12}_{\eta_c}\text{C}$	1s	-5.91	-8.27	-11.28	-14.79
	1p	-0.28	-1.63	-3.69	-6.33
$^{16}_{\eta_c}\text{O}$	1s	-7.35	-9.92	-13.15	-16.87
	1p	-1.94	-3.87	-6.48	-9.63
$^{197}_{\eta_c}\text{Au}$	1s	-12.57	-15.59	-19.26	-23.41
	1p	-11.17	-14.14	-17.77	-21.87
	1d	-9.42	-12.31	-15.87	-19.90
	2s	-8.69	-11.53	-15.04	-19.02
	1f	-7.39	-10.19	-13.70	-17.61
$^{208}_{\eta_c}\text{Pb}$	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
	2s	-9.16	-12.09	-15.70	-19.80
	1f	-7.85	-10.74	-14.30	-18.37

- The η_c is expected to form bound states with all the nuclei studied, independent of the value of Λ_D .
- Particular values for the bound state energies clearly depend on Λ_D
- Note also that the η_c binds more strongly to heavier nuclei

Summary and Conclusions

- We have calculated the η_c mass shift Δm_{η_c} in nuclear matter
- Essential to our results are m_D^* and $m_{D^*}^*$
- A negative mass shift Δm_{η_c} means that the nuclear mean field provides attraction
- The η_c potentials were calculated using a local density approximation, with the nuclear density distributions calculated in the QMC model
- We have calculated the η_c -nucleus bound state energies for various nuclei
- We expect that the η_c meson forms bound states for all nuclei
- The discovery of such bound states would represent an important step forward in our understanding of the nature of strongly interacting systems.