Charmonium in nuclear matter and nuclei

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Plan for this presentation

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This presentation is mainly based on

- "η_c-nucleus bound states"
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In collaboration with

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- 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 potentially lead to 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

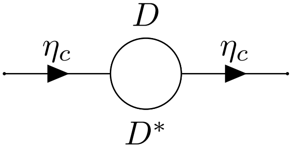
- For the computation of the η_c self-energy Σ_{η_c} we use an effective Lagrangian approach at the hadronic level
- The interaction Lagrangian for the $\eta_c DD^*$ vertex is given by

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

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

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

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



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

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

- 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

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

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

- 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

$$u_{D^{(*)}}(k^2) = \left(\frac{\Lambda^2_{D^{(*)}} + m^2_{\eta_c}}{\Lambda^2_{D^{(*)}} + 4\omega^2_{D^{(*)}}(k^2)} \right)^2 ,$$

  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 $\Lambda \approx 2500\,\mathrm{MeV}$–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

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

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

$$\begin{aligned} g_{\eta_c} &= 0.60\, g_{\psi DD} \quad \text{(PRD 93, 016004 (2016))} \\ g_{\psi DD} &= 7.64 \quad \text{(PRC 62, 034903 (2000))} \end{aligned}$$

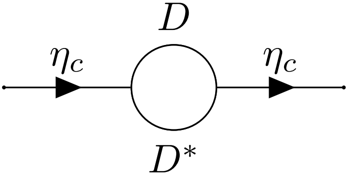
- The first value was obtained as the residue at the pole of suitable form factors using a dispersion formulation of the relativistic constituent quark model; the second value was estimated using the vector meson dominance model

Results for η_c in nuclear matter

η_c in nuclear matter

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

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



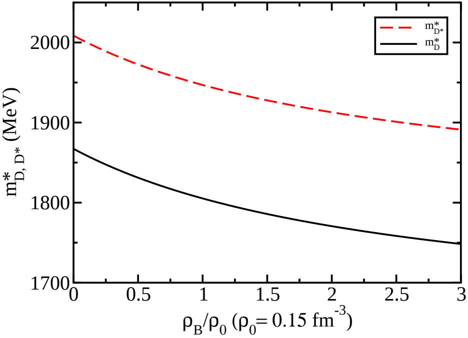
- The η_c mass in medium, $m^*_{\eta_c}$, is obtained with the self-energy Σ_{η_c} calculated with the medium-modified D and D^* masses, m^*_D and $m^*_{D^*}$
- m^*_D and $m^*_{D^*}$ are computed in the quark meson coupling model (QMC)

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 confined light quarks in the nucleon bags (MIT bag) self-consistently 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)]

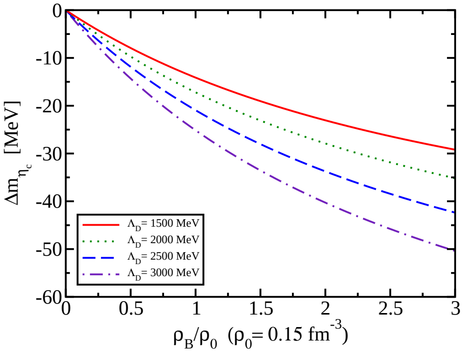
- QMC results for m_D^* and $m_{D^*}^*$ in nuclear matter:

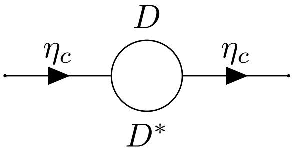


- The mass shifts for the D and D^* mesons are nearly the same–each decreasing by around 60 MeV at $\rho_B = \rho_0$

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

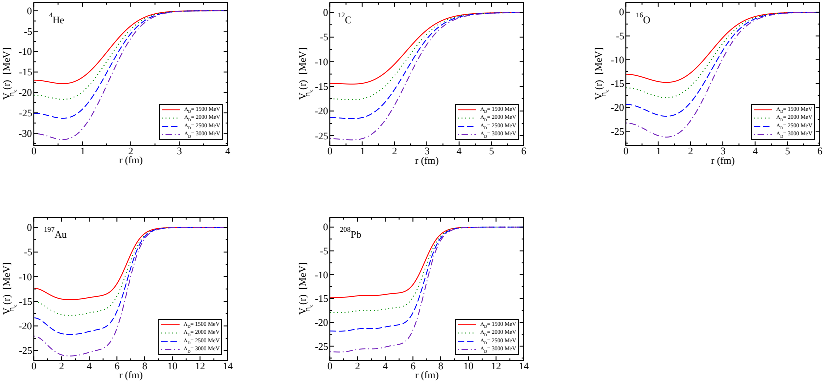
- We now discuss the situation where the η_c-meson is produced inside a nucleus A with baryon density distribution $\rho_B^A(r)$.
- The nuclear density distributions for ^{12}C, ^{16}O, ^{40}Ca, ^{48}Ca, ^{90}Zr, ^{197}Au, and ^{208}Pb are calculated with the QMC model
(For ^{4}He, we used PRC 56, 566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



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

η_c-nucleus bound states

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

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

  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

η_c-nucleus bound states

- Results for η_c-nucleus bound states

	$n\ell$	Bound state energies			
		$\Lambda_D = 1500$	$\Lambda_D = 2000$	$\Lambda_D = 2500$	$\Lambda_D = 3000$
$^{4}_{\eta_c}$He	1s	-1.49	-3.11	-5.49	-8.55
$^{12}_{\eta_c}$C	1s	-5.91	-8.27	-11.28	-14.79
	1p	-0.28	-1.63	-3.69	-6.33
$^{16}_{\eta_c}$O	1s	-7.35	-9.92	-13.15	-16.87
	1p	-1.94	-3.87	-6.48	-9.63
$^{197}_{\eta_c}$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
$^{208}_{\eta_c}$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.