Vector mesons in nuclear matter and nuclei

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1. Introduction

2. Hadron-based approach
   - Nuclear matter
   - Finite Nuclei

A bit of advertising

Parts of this presentation are based on

- "Phi-meson mass and width in nuclear matter and nuclei"
  arXiv:1703.05367 [nucl-th] (Physics Letters B 771 (2017), 113-118)
- "Phi-meson nuclear bound states"
  arXiv:1705.06653 [nucl-th] Physical Review C 96 (2017) no.3, 035201.
- "η_c- and J/Ψ-nuclear bound states"–In Preparation.

In collaboration with

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- 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

- It is widely accepted that the vacuum expectation of $\langle \overline{q}q \rangle$ is non-zero due to the spontaneous breaking of chiral symmetry of the vacuum
- This $\langle \overline{q}q \rangle$-condensation is the major source of masses of low-lying hadrons such as protons, neutrons, and pions (more than 99% of the mass of the visible Universe).
- The properties of vector mesons at finite baryon density have attracted considerable experimental and theoretical interest over the last few decades, in part due to their potential to carry information on the partial restoration of chiral symmetry.
- The $\langle \overline{q}q \rangle$ expectation value (chiral order parameter) is a function of temperature and density (chemical potential), so that various experimental studies have been performed to detect the restoration of chiral symmetry

Motivation

- In 2007, the KEK-PS E325 experiment reported a 3.4% mass reduction of the ϕ meson mass–this result points towards the a possible restorarion of chiral symmetry in a nuclear medium.
- The CLAS experiment results at JLab can be interpreted as a huge broadening of the ϕ meson decay width in a nuclear medium without a mass shift.
- Similar results have recently obtained by other experiments (large decay width and no mass shift or very small)
- Therefore, the ϕ meson mass shift phenomena in nuclear matter is still controversial.
- The E16 experiment at J-PARC intends to collect a 100 times more statistics than previuos experiments at KEK-PS.
- Future experiments at J-PARC and JLab will be searching for a ϕ-nucleus bound states as a signal for the partial restoration of chiral symmetry.

ϕ-meson at finite nuclear density

- We are interested in the vector-meson mass shift at finite nuclear density ρ

$$\Delta m_\phi^* = m_\phi^* - m_\phi^{\mathrm{vac}}$$

  - m_ϕ^* is the ϕ meson mass in nuclear matter.
  - $m_\phi^{\mathrm{vac}} = 1020$ MeV its vacuum value
- (Recall that the ϕ mesons is a spin-1 bound state of an $s\bar{s}$ pair.)
- We are also interested in the ϕ decay width in nuclear matter Γ_ϕ^*.
- Both will be computed from the ϕ self energy in a hybrid approach:
  - Effective Lagrangians.
  - Quark meson coupling
  - The quark-based NJL model with flavour mixing.

Effective Lagrangians approach

- We use an effective Lagrangian to compute the ϕ meson self-energy $\Pi_\phi(p)$.
- The kinetic part is

$$
\begin{aligned}
\mathcal{L}_K &= \frac{1}{2}(\partial_\mu K)(\partial^\mu \overline{K}) - \frac{1}{2} m_K^2 K^2 \\
\mathcal{L}_\phi &= -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - m_\phi^2 \phi_\mu \phi^\mu, \quad F_{\mu\nu} = \partial_\mu \phi^\nu - \partial_\nu \phi^\mu
\end{aligned}
$$

- The interaction part is

$$
\mathcal{L}_{\phi K \overline{K}} = \mathrm{i} g_\phi \phi^\mu \left[\overline{K}(\partial_\mu K) - (\partial_\mu \overline{K}) K \right],
$$

where $K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}$, $\overline{K} = \begin{pmatrix} K^- & \overline{K}^0 \end{pmatrix}$.

ϕ meson self-energy $\Pi_\phi(p)$

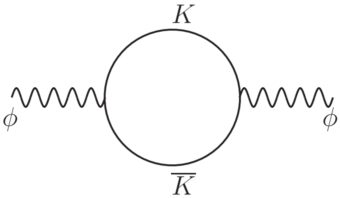
- $\Pi_\phi(p)$ renormalises the ϕ meson mass:

$$D_{\mu\nu}(p) = \frac{1}{p^2 - m_\phi^2 - \Pi_{\phi(p)}} \left(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2} \right)$$

- The mass m_ϕ and decay width Γ_ϕ can be computed from $\Pi_\phi(p)$.
- Interaction effective Lagrangian use to compute self-energy $\Pi_\phi(p)$:

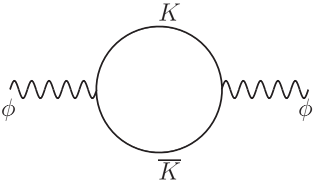
$$\mathcal{L}_{\phi K\overline{K}} = \mathrm{i} g_\phi \phi^\mu \left[\overline{K}(\partial_\mu K) - (\partial_\mu \overline{K})K \right],$$

- One-loop, order g_ϕ^2



ϕ meson self-energy $\Pi_\phi(p)$

- $\Pi_\phi(p) = -\frac{1}{3}\Pi_\phi^{\mu\nu}(p)$



- The ϕ meson mass m_ϕ and decay width in vacuum Γ_ϕ are determined self-consistently by

$$
\begin{aligned}
m_\phi^2 &= (m_\phi)^2 + \mathrm{Re}\,\Pi_\phi(m_\phi^2) \\
\Gamma_\phi(m_\phi) &= -\frac{1}{m_\phi}\,\mathrm{Im}\,\Pi(m_\phi^2)
\end{aligned}
$$

- $\Pi_\phi(p)$ has an imaginary part since $m_\phi > 2m_K$ ($m_\phi = 1020$ MeV, $m_K = 497$ MeV), i.e. the ϕ decays strongly to two K's

ϕ meson self-energy $\Pi_\phi(p)$

- For a ϕ meson at rest, $\Pi_\phi(p)$ is given by

$$\mathrm{i}\Pi_\phi(p) = -\frac{8}{3}g_\phi^2 \int \frac{d^4q}{(2\pi)^2}\vec{q}^{\,2} D_K(q) D_K(q-p),$$

- $D_K(q) = \left(q^2 - m_K^2 + \mathrm{i}\epsilon\right)^{-1}$ is the kaon propagator.
- m_K the kaon mass.
- The coupling constant g_ϕ is determined by the experimental width of the ϕ in vacuum

$$\Gamma_\phi(m_\phi) = -\frac{1}{m_\phi}\,\mathrm{Im}\,\Pi(m_\phi^2) = \frac{g_\phi^2}{24\pi} m_\phi \left(1 - \frac{4m_K^2}{m_\phi^2}\right)^{3/2}$$

- We find $g_\phi = 4.54$

ϕ meson self-energy $\Pi_\phi(p)$

- For a ϕ meson at rest

$$i\Pi_\phi(p) = -\frac{8}{3} g_\phi^2 \int \frac{d^4 q}{(2\pi)^2} \vec{q}^{\,2} D_K(q) D_K(q-p),$$

- The integral in $\Pi_\phi(p)$ divergent and needs regularization.
- We use a phenomenological form factor, with a cutoff parameter Λ_K:

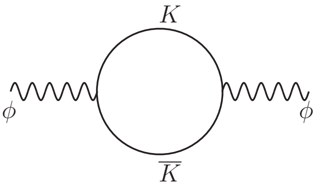
$$u(\vec{q}^2) = \left(\frac{\Lambda_K + m_\phi^2}{\vec{q}^2 + 4\omega_K^2(\vec{q}^2)} \right)^2, \;\; \omega_K(\vec{q}^2) = \left(\vec{q}^2 + m_K^2 \right)^{1/2}$$

- We study the dependence on Λ_K.

ϕ meson at finite nuclear density

- Recall that the m_ϕ and Γ_ϕ are determined self-consistently by

$$
\begin{aligned}
m_\phi^2 &= (m_\phi)^2 + \mathrm{Re}\,\Pi_\phi(m_\phi^2) \\
\Gamma_\phi &= -\frac{1}{m_\phi}\,\mathrm{Im}\,\Pi(m_\phi^2)
\end{aligned}
$$



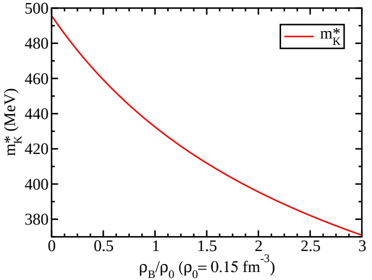
- The density dependence of the ϕ mass and decay width is driven by the interactions the $K\overline{K}$ intermediate state with the nuclear medium.
- Essentially, in nuclear matter $m_\phi \to m_\phi^*$, $\Gamma_\phi \to \Gamma_\phi^*$, $m_K \to m_K^*$.
- m_K^* is computed in the quark meson coupling model (QMC).

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

- Crucial for our results in nuclear matter is the in-medium kaon mass. m_K^* is calculated in the QMC model.
- 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 tremendous 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 dof.

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

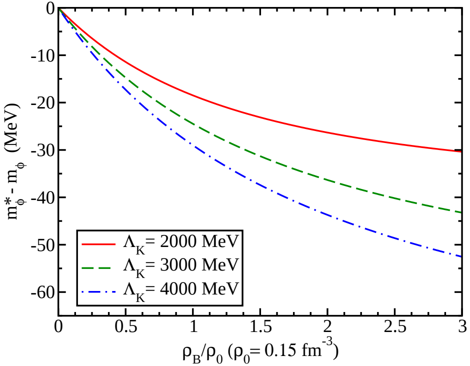
- The density dependence of the ϕ mass and decay width is driven by the interactions the $K\overline{K}$ intermediate state with the nuclear medium.
- QMC results for the in-medium kaon mass m_K^*:



- The m_K^* at normal nuclear matter density $\rho_0 = 0.15$ fm^{-3} decreases by 13%.

Results: ϕ mass shift and decay width in at finite nuclear matter density

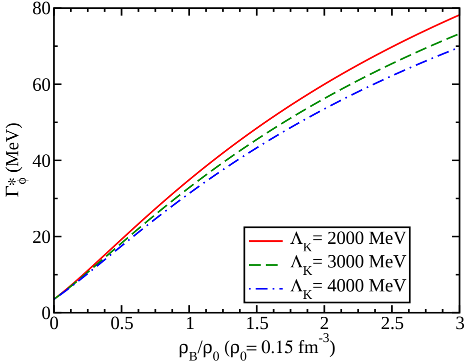
- Recall $m_\phi^2 = (m_\phi)^2 + \Re\Pi_\phi(m_\phi^2)$



- Mass shift average of -24 MeV (2% decrease) at ρ_0, with a 5 MeV spread.
- The mass shift depends on the value of Λ_K.

Results: ϕ mass shift and decay width at finite nuclear matter density

- Recall $m_\phi^2 = (m_\phi)^2 + \Re\Pi_\phi(m_\phi^2)$ and $\Gamma_\phi(m_\phi) = \frac{1}{m_\phi}\Pi(m_\phi^2)$



- The ϕ decay width broadens by an order of magnitude at ρ_0.
- This is important for the observability of bound states. (more later).

Part II: phi-meson-nuclear bound states

- A negative mass shift means that the nuclear mean field provides attraction to the vector meson.
- From a practical point of view, the important question is whether this attraction, if it exists, is sufficient to bind the ϕ to a nucleus.
- A simple argument: One knows that for an attractive spherical well of radius R and depth V_0, the condition for the existence of a non relativistic s-wave bound state of a particle of mass m is

$$V_0 > \frac{\pi^2 \hbar^2}{8 m R^2}$$

- Using $m = m^*_\phi(\rho_0)$ and $R = 5$ fm, one obtains $V0 > 2$ MeV.
- Therefore, the prospects of capturing a ϕ meson seem quite favorable, provided that the ϕ meson can be produced almost at rest in the nucleus.

Part II: phi-meson-nuclear bound states

- A negative mass shift means that the nuclear mean field provides attraction to the vector meson.
- The prospects of capturing a ϕ meson seem quite favorable, provided that the ϕ meson can be produced almost at rest in the nucleus.
- Mesic nuclei, as they are known, if discovered experimentally, are a new exotic state of matter involving the meson being bound inside the nucleus purely by the strong interaction.
- Despite the general agreement among theorist that mesic nuclei should exist, the predictions for their binding energies are quite disparate, and such systems remain to be discovered experimentally despite many attempts to produce them.
- The latest experimental programs in this area include ATHENNA as part of the 12-GeV upgrade at JLAB (US), PANDA at FAIR (GERMANY), and J-PARC (JAPAN).

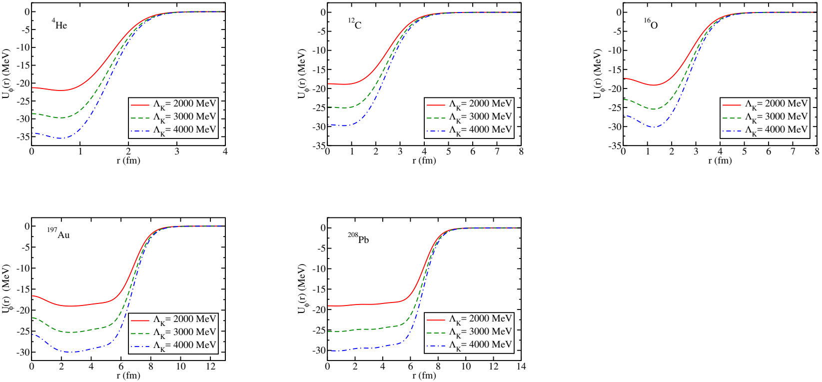
Part II: phi-meson-nuclear bound states

- We now discuss the situation where the ϕ meson is produced in a nucleus.
- The nuclear density distributions for ^{12}C, ^{16}O, ^{40}Ca, ^{48}Ca, ^{90}Zr, ^{197}Au, and ^{208}Pb are obtained using the QMC model (For ^{4}He, we used PRC 56, 566 (1997)).
- Then, using a local density approximation we calculate the ϕ-meson complex potentials for a nucleus A, which can be written as (r is the distance from the center of the nucleus)

$$
\begin{aligned}
V_{\phi A}(r) &= U_\phi(r) - (\mathrm{i}/2) W_\phi(r), \\
U_\phi(r) &= m^*_\phi(\rho_B(r)) - m_\phi \\
W_\phi(r) &= \Gamma_\phi(\rho_B(r)).
\end{aligned}
$$

  - $U_\phi(r)$ is determined by the mass shift.
  - $W_\phi(r)$ is determined by the decay width.
  - $\rho_B(r)$ is the baryon density distribution for the particular nucleus (A).

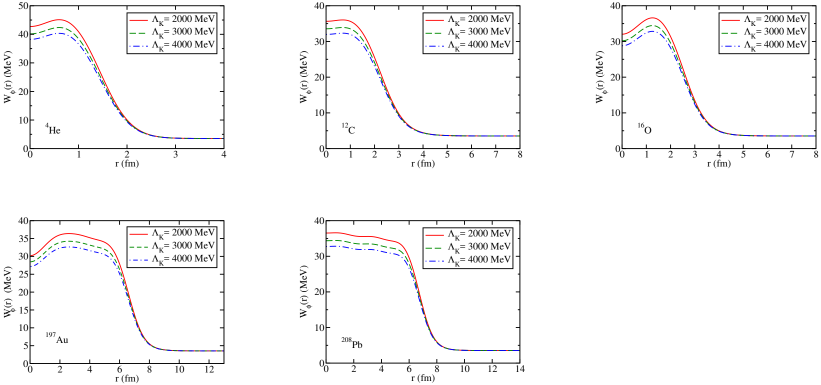
- ϕ meson potentials: real part



- $U_\phi(r)$ is deep enough to allow the formation of bound states.
- $U_\phi(r)$ is sensitive to Λ_K.

Part II: phi-meson-nuclear bound states

- ϕ meson potentials: imaginary part



- $W_\phi(r)$ is repulsive.
- These observations may well have consequences for the feasibility of experimental observation of the expected bound states.

Part II: phi-meson-nuclear bound states

- In this study we consider the situation where the ϕ-meson is produced nearly at rest, $\vec{p} = 0$.
- Then, it should be a very good approximation to neglect the possible energy difference between the longitudinal and transverse components of the ϕ-meson wave function ψ_ϕ^μ.
- After imposing the Lorentz condition, $\partial_\mu \psi_\phi^\mu = 0$, to solve the Proca equation becomes equivalent to solving the Klein-Gordon equation

$$\left(-\nabla^2 + \mu^2 + 2\mu V(\vec{r})\right) \phi(\vec{r}) = \mathcal{E}^2 \phi(\vec{r}),$$

  where is the reduced mass of the system.
- The calculated bound state energies (E) and widths (Γ) are related to the complex energy eigenvalue $\mathcal{E}$ by $E = \Re\mathcal{E} - \mu$ and $\Gamma = -2\Im\mathcal{E}$.

Part II: phi-meson-nuclear bound states

- The Klein-Gordon equation

$$\left(-\nabla^2 + \mu^2 + 2\mu V(\vec{r})\right) \phi(\vec{r}) = \mathcal{E}^2 \phi(\vec{r}),$$

- The pontetial $V(\vec{r})$ is complex.
- "Traditional" numerical methods that look for zeros in the wave function in order to obtain the energy eigenvalues do not work.
- The calculated bound state energies (E) and widths (Γ) are related to the complex energy eigenvalue $\mathcal{E}$ by $E = \Re\mathcal{E} - \mu$ and $\Gamma = -2\Im\mathcal{E}$.

Partial wave decomposition

- Consider as an example the NRSE

$$-\frac{1}{2\mu}\nabla^2\psi(\vec{r}) + V(\vec{r})\psi(\vec{r}) = E\psi(\vec{r})$$

- Fourier transform $\phi(\vec{p}) = \int \psi(\vec{r})\mathrm{e}^{\mathrm{i}\vec{p}\cdot\vec{r}}\mathrm{d}^3x$

$$\frac{p^2}{2\mu}\phi(\vec{p}) + \int V(\vec{q})\psi(\vec{p}')\mathrm{d}^3p' = E\phi(\vec{p})$$

- Partial wave decomposition

$$\begin{aligned}
\phi(\vec{p}) &= \sum_{nlm} C_{nlm}\phi_{nl}(p)Y_{lm}(\Omega) \\
V(\vec{q}) &= \sum_{l} \frac{2l+1}{2\pi} V_l(p,p')P_l(\cos\theta) \\
V_l(p,p') &= 2\pi\int_{-1}^{1} V(\vec{q})P_l(\cos\theta)\mathrm{d}\cos\theta
\end{aligned}$$

Partial wave decomposition

- Partial wave decomposition $V_l(p,p') = 2\pi \int_{-1}^{1} V(\vec{q}) P_l(\cos\theta) \mathrm{d}\cos\theta$

$$\frac{p^2}{2\mu}\phi_{nl}(p) + \int p'^2 V_l(p,p')\phi_{nl}(p')\mathrm{d}p' = E\phi_{nl}(p)$$

- In this way we can easily handle complex potentials. The numerical solution is found using matrix methods.
- The calculated bound state energies (E) and widths (Γ) are related to the complex energy eigenvalue $\mathcal{E}$ by $E = \Re\mathcal{E} - \mu$ and $\Gamma = -2\Im\mathcal{E}$.

Part II: phi-meson-nuclear bound states

- $W_\phi(r) = 0$

		$\Lambda_K = 2000$	$\Lambda_K = 3000$	$\Lambda_K = 4000$
		E	E	E
$^4_\phi$He	1s	-0.8	-1.4	-3.2
$^{12}_\phi$C	1s	-4.2	-7.7	-10.7
$^{16}_\phi$O	1s	-5.9	-10.0	-13.4
	1p	n	n	-1.5
$^{197}_\phi$Au	1s	-15.0	-20.8	-25.2
	1p	-11.6	-17.2	-21.4
	1d	-7.5	-12.7	-16.7
	2s	-6.1	-11.0	-14.9
	2p	-1.3	-5.3	-8.8
	2d	n	n	-2.7
$^{208}_\phi$Pb	1s	-15.5	-21.4	-26.0
	1p	-12.1	-17.8	-22.2
	1d	-8.1	-13.4	-17.6
	2s	-6.6	-11.7	-15.8
	2p	-1.9	-6.1	-9.8
	2d	n	-0.7	-3.7

- The ϕ-meson is expected to form bound states with all nuclei, including ^{4}He.
- However, E is dependent on Λ_K, increasing with Λ_K.

Part II: phi-meson-nuclear bound states

- $W_\phi(r) \neq 0$

		$\Lambda_K = 2000$		$\Lambda_K = 3000$		$\Lambda_K = 4000$	
		E	$\Gamma/2$	E	$\Gamma/2$	E	$\Gamma/2$
$^{4}_{\phi}$He	1s	n (-0.8)	n	n (-1.4)	n	-1.0 (-3.2)	8.3
$^{12}_{\phi}$C	1s	-2.1 (-4.2)	10.6	-6.4 (-7.7)	11.1	-9.8 (-10.7)	11.2
$^{16}_{\phi}$O	1s	-4.0 (-5.9)	12.3	-8.9 (-10.0)	12.5	-12.6 (-13.4)	12.4
	1p	n (n)	n	n (n)	n	n (-1.5)	n
$^{197}_{\phi}$Au	1s	-14.6 (-15.0)	16.9	-20.5 (-20.8)	16.1	-25.0 (-25.2)	15.5
	1p	-10.9 (-11.6)	16.2	-16.7 (-17.2)	15.5	-21.1 (-21.4)	15.0
	1d	-6.4 (-7.5)	15.2	-12.0 (-12.7)	14.8	-16.3 (-16.7)	14.4
	2s	-4.6 (-6.1)	14.6	-10.1 (-11.0)	14.3	-14.3 (-14.9)	14.0
	2p	n (-1.3)	n	-3.9 (-5.3)	13.0	-7.9 (-8.8)	12.9
	2d	n (n)	n	n (n)	n	-1.1 (-2.7)	11.4
$^{208}_{\phi}$Pb	1s	-15.0 (-15.5)	17.4	-21.1 (-21.4)	16.6	-25.8 (-26.0)	16.0
	1p	-11.4 (-12.1)	16.7	-17.4 (-17.8)	16.0	-21.9 (-22.2)	15.5
	1d	-6.9 (-8.1)	15.7	-12.7 (-13.4)	15.2	-17.1 (-17.6)	14.8
	2s	-5.2 (-6.6)	15.1	-10.9 (-11.7)	14.8	-15.2 (-15.8)	14.5
	2p	n (-1.9)	n	-4.8 (-6.1)	13.5	-8.9 (-9.8)	13.4
	2d	n (n)	n	n (-0.7)	n	-2.2 (-3.7)	11.9

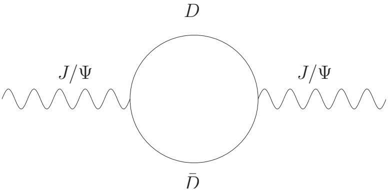
- $W_\phi(r)$ is repulsive: some bound states disappear completely, even though they were found when $W_\phi(r) = 0$.
- Whether or not the bound states can be observed experimentally, is sensitive to the value of Λ_K.

Summary and Conclusions I

- We have calculated the ϕ-meson–nucleus bound state energies and absorption widths for various nuclei.
- We expect that the ϕ-meson should form bound states for all nuclei selected studied, provided that the ϕ-meson is produced in (nearly) recoilless kinematics.
- Mesic nuclei, as they are known, if discovered experimentally, are a new exotic state of matter involving the meson being bound inside the nucleus purely by the strong interaction.
- Given the similarity of the binding energies and widths reported here, the signal for the formation of the ϕ-nucleus bound states may be challenging to identify experimentally.

J/Ψ ("η_c- and J/Ψ-nuclear bound states"–In Preparation)

- A similar game can be played with the J/Ψ ($\phi \to J/\Psi$, $K \to D$)



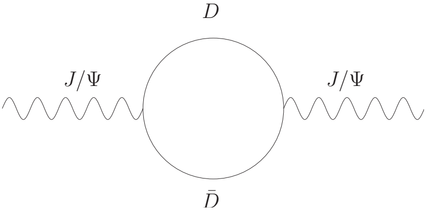
- The effective Lagrangian to compute Π_ψ: (ψ denotes the J/Ψ)

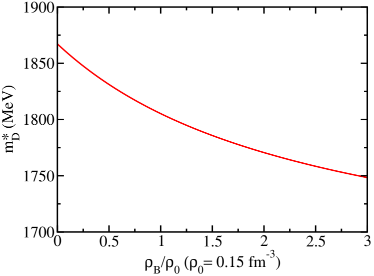
$$\mathcal{L}_{\psi D\overline{D}} = \mathrm{i} g_\psi \psi^\mu \left[\overline{D}(\partial_\mu D) - (\partial_\mu \overline{D})D\right],$$

- $g_\psi = 7.64$ is obtained from previous studies.
- From $\mathcal{L}_{\psi D\overline{D}}$ we compute Π_ψ and from there the mass shift for the J/Ψ in nuclear matter.

J/Ψ ("η_c- and J/Ψ-nuclear bound states"–In Preparation)

- The D meson mass is computed in the QMC model

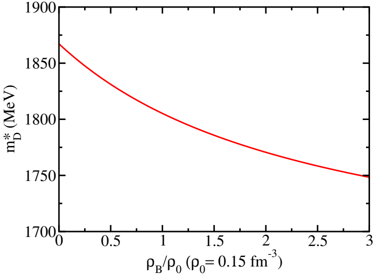


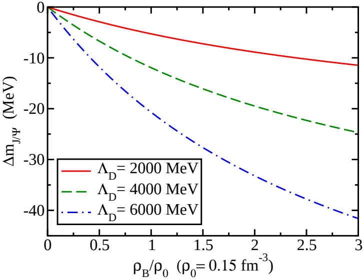


- At ρ_0, the QMC predicts a 62 MeV decrease for the D meson mass.
- This will induce a downward shift in the J/Ψ mass, which means that the nuclear mean field provides attraction.

J/Ψ ("η_c- and J/Ψ-nuclear bound states"–In Preparation)

- J/Ψ mass shift, $\Delta m_\psi = m^*_\psi - m^{\text{vac}}_\psi$

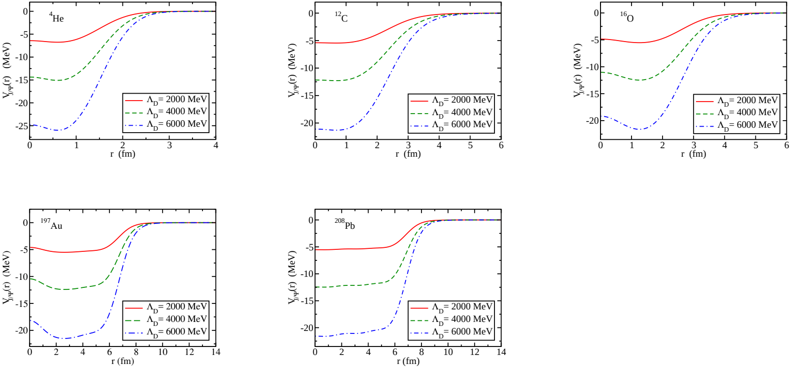




- At ρ_0, there is a mass shift ranging from -5 MeV to -20 MeV, depending on the value of Λ_D.
- This is enough for the formation of bound states.

J/Ψ (“η_c- and J/Ψ-nuclear bound states”–In Preparation)

- J/Ψ meson potentials



- The potentials are deep enough to allow the formation of bound states.

J/Ψ ("η_c- and J/Ψ-nuclear bound states"–In Preparation)

- The potentials are deep enough to allow the formation of bound states.

	$n\ell$	Bound state energies (MeV)		
		$\Lambda_D = 2000$	$\Lambda_D = 4000$	$\Lambda_D = 6000$
$^{4}_{J/\Psi}$He	1s	n	-0.70	-5.52
$^{12}_{J/\Psi}$C	1s	-0.53	-4.47	-11.28
$^{16}_{J/\Psi}$O	1s	-1.03	-5.73	-13.12
$^{197}_{J/\Psi}$Au	1s	-4.09	-10.49	-19.09
	1p	-2.98	-9.18	-17.64
	1d	-1.66	-7.53	-15.80
	2s	-1.23	-6.87	-15.00
	1f	-0.20	-5.64	-13.66
$^{208}_{J/\Psi}$Pb	1s	-4.26	-10.84	-19.67
	1p	-3.16	-9.53	-18.23
	1d	-1.84	-7.91	-16.41
	2s	-1.41	-7.26	-15.64
	1f	-0.39	-6.04	-14.30
	2p	-0.05	-5.11	-13.18

- The bound states energies depend on the cutoff parameter Λ_D.
- For the all Λ_D but D $=$ 2000 MeV we expect the formation of bound states with all nuclei.

Summary and Conclusions II

- We have calculated the ϕ and J/Ψ meson mass shift within an effective Lagrangian approach up to $\rho_B = 3\rho_0$.
- Essential to our results are m_K^* and m_D^*, both were calculated in the QMC model.
- A decrease in the masses of m_K^* and m_D^* induces a negative mass shift in the ϕ and J/Ψ mesons, respectively.
- A negative mass shift means that the nuclear mean field provides attraction.
- The vector-meson–nuclear potentials were calculated using a local density approximation, with the nuclear density distributions calculated in the QMC model.
- We have calculated the vector-meson–nucleus bound state energies (and absorption widths) for various nuclei.
- We expect that the vector-mesons studied should form bound states for all nuclei provided that the vector-meson is produced in (nearly) recoilless kinematics.