ϕ and J/Ψ mesons in cold nuclear matter

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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

- Kazuo Tsushima–Laboratório de Física Teóorica 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.

Vector mesons

- There has been much theoretical and experimental interest over the last few decades.
- There is still, however, experimental controversy in the measurements of the mass shift–specially for the ϕ.
- There are planned experiments at JLab, KEK, and GSI.
- Partial restoration of chiral symmetry at high densities.
- The mass shift of the ϕ-meson is related to the strangeness content of the nucleon.
- As the ϕ-meson is nearly pure $s\bar{s}$ state and gluonic interactions are flavor blind studying it (in nuclear matter) serves to test theories of multi-gluon interactions.
- Role of QCD van der Waals forces, which are believed to play a role in the binding of J/Ψ and other exotic heavy-quarkonia to matter.

ϕ-meson in nuclear matter

- We are interested in the vector-meson mass shift in nuclear matter

$$\Delta m^*_\phi = m^*_\phi - m^{\text{vac}}_\phi$$

  - m^*_ϕ is the ϕ meson mass in nuclear matter.
  - $m^{\text{vac}}_\phi = 1020$ MeV its vacuum value
- 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 (QMC) model (See talks of K. Tsushima, P. Hutauruk, and T. Miyatsu)

Effective Lagrangians approach

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

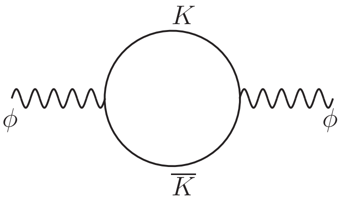
$$D_{\mu\nu}(p) = \frac{1}{p^2 - m_\phi^2 - \Pi_{\phi(p)}} \left(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2} \right) + \frac{p^\mu p^\nu}{m^4}$$

- Both m_ϕ^* and Γ_ϕ^* will be computed from $\Pi_\phi(p)$.
- We use an effective Lagrangian to compute the ϕ meson self-energy $\Pi_\phi(p)$:

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

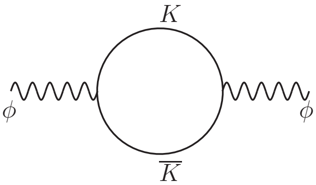
where $K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}$, $\overline{K} = \begin{pmatrix} K^- & \overline{K}^0 \end{pmatrix}$.

- At order g_ϕ^2:



Effective Lagrangians approach to $\Pi_\phi(p)$

- At order g_ϕ^2



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

- $\Pi_\phi(p)$ acquires an imaginary part when $m_\phi > 2m_K$ ($m_\phi = 1020$ MeV, $m_K = 497$ MeV).
- The ϕ meson mass and decay width in vacuum (m_ϕ, Γ_ϕ) and in nuclear matter $(m_\phi^*, \Gamma_\phi^*)$ are determined self-consistently by

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

Effective Lagrangians approach to $\Pi_\phi(p)$

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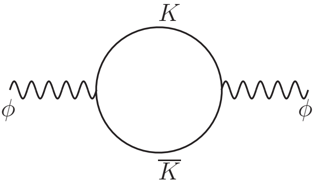

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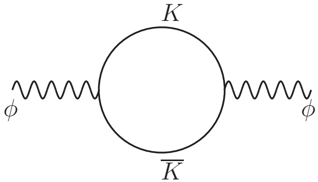
- Essentially, in nuclear matter $m_\phi \to m_\phi^*$, $\Gamma_\phi \to \Gamma_\phi^*$, $m_K \to m_K^*$.

Effective Lagrangians approach to $\Pi_\phi(p)$

- At order g_ϕ^2



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\end{aligned}
$$

- 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).

Effective Lagrangians approach to $\Pi_\phi(p)$

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

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

- $D_K(q) = \left(q^2 - m_K^2 + \mathrm{i}\epsilon\right)^{-1}$ is the kaon propagator.
- m_K the kaon mass.
- The integral in $\Pi_\phi(p)$ divergent and needs regularization.
- We use a phenomenological form factor, with a cutoff parameter Λ_K:

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

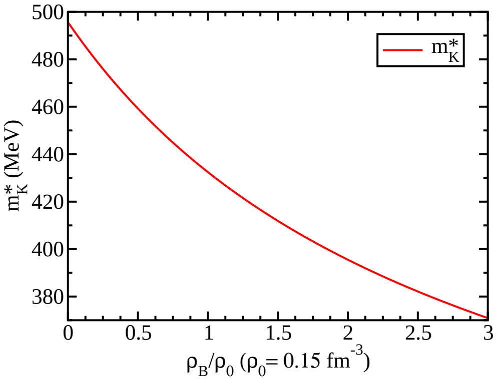
- We study the dependence on Λ_K.

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)]

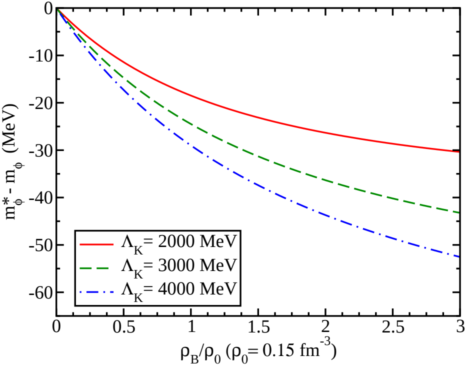
- QMC results for the in-medium kaon mass m_K^*:



- 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 nuclear matter

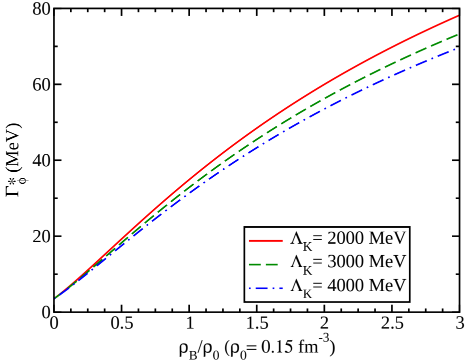
- Recall $m_\phi^2 = (m_\phi)^2 + \Re\Pi_\phi(m_\phi^2)$



- 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 in nuclear matter

- 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

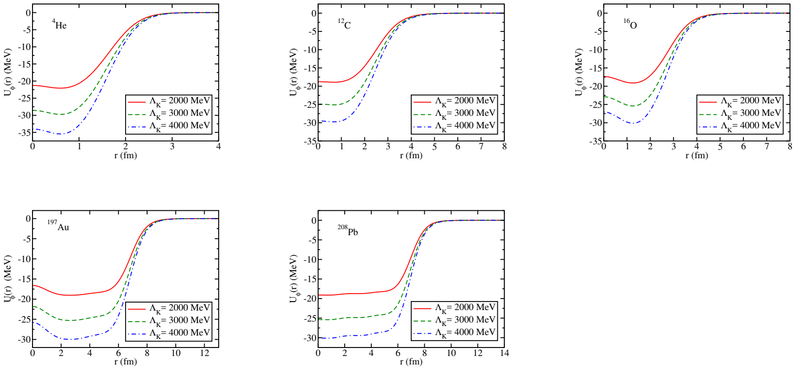
- We now discuss the situation where the meson is "placed" in a nucleus.
- The nuclear density distributions for ^{12}C, ^{16}O, ^{40}Ca, ^{48}Ca, ^{90}Zr, ^{197}Au, and ^{208}Pb are obtained using the QMC model (For ^{4}He, we used PRC 56, 566 (1997)).
- Then, using a local density approximation we 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).

Part II: phi-meson-nuclear bound states

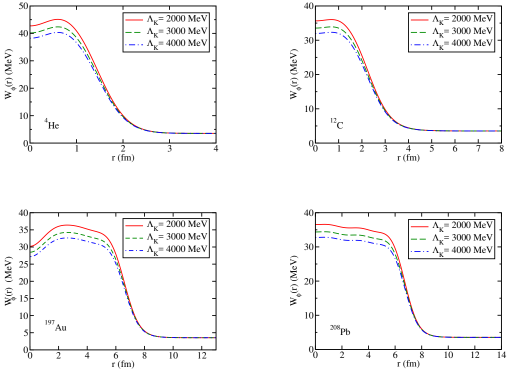
- ϕ meson potentials: real part



- $U_\phi(r)$ 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

- $W_\phi(r) = 0$

		$\Lambda_K = 2000$	$\Lambda_K = 3000$	$\Lambda_K = 4000$
		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

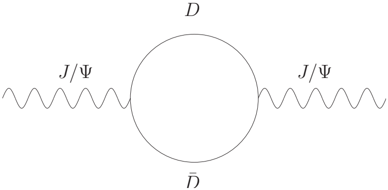
- $W_\phi(r)$ is repulsive: some bound states disappear completely, even though they were found when $W_\phi(r) = 0$.
- Whether or not the bound states can be observed experimentally, is sensitive to the value of Λ_K.

Summary and Conclusions I

- We have calculated the ϕ-mesonnucleus 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.
- 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 ($\phi \to J/\Psi$, $K \to D$)



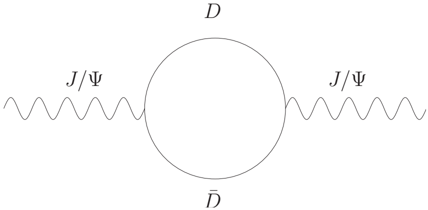
- The effective Lagrangian to compute Π_ψ: (ψ denotes the J/Ψ)

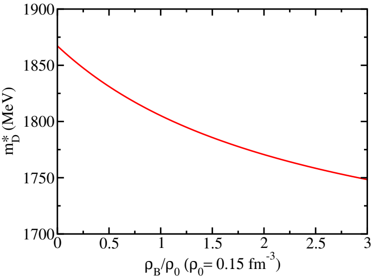
$$\mathcal{L}_{\psi D\overline{D}} = \mathrm{i} g_\psi \psi^\mu \left[\overline{D}(\partial_\mu D) - (\partial_\mu \overline{D}) D\right],$$

- $g_\psi = 7.64$ 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)

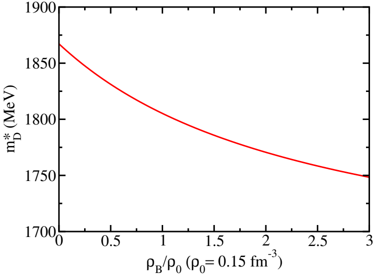
- The D meson mass is computed in the QMC model

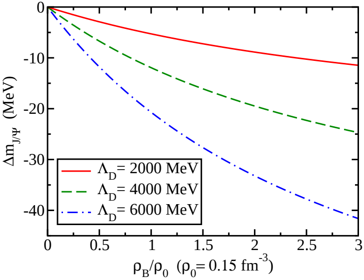




- At ρ_0, the QMC predicts a 62 MeV decrease for the D meson mass.
- This will induce a downward shift in the J/ mass, which means that the nuclear mean field provides attraction.

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

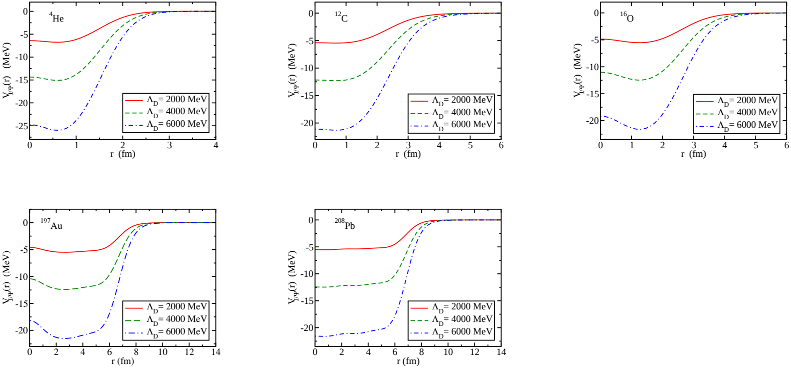




- At ρ_0, there is a mass shift ranging from -5 MeV to -20 MeV, depending on the value of Λ_D.
- This is enough for the formation of bound states.

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

- ϕ meson potentials: real part



- 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.

		Bound state energies		
	$n\ell$	$\Lambda_D = 2000$	$\Lambda_D = 4000$	$\Lambda_D = 6000$
$^{4}_{J/\Psi}$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 I

- 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-mesonnucleus 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.