Partial restoration of chiral symmetry in cold nuclear matter: the phi meson case

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XXXI Reunión Anual de la División de Partículas y Campos
Sociedad Mexicana de Física
México City, México. Mayo 24-26, 2017

A bit of advertising

Presentation 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] (Submitted to Physical Review C)

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But why the ϕ meson?

- There has been much theoretical and experimental interest over the last few decades
- Partial restoration of chiral symmetry at high densities
- The mass shift of the ϕ is related to the strangeness content of the nucleon
- As ϕ 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
- There is still however experimental controversy in the measurements of the mass shift
- There are planned experiments at JLab, KEK, and GSI.

ϕ-meson mass shift in nuclear matter

- We are interested in the following quantity

$$\Delta m_\phi^* = m_\phi^* - m_\phi$$

- m_ϕ^* is the ϕ meson mass in nuclear matter; $m_\phi = 1020$ MeV its vacuum value.
- We will compute Δm_ϕ^* in an hybrid approach:
  - Effective lagrangians
  - Quark meson coupling model

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

- We use the effective Lagragians approach to compute the ϕ meson self-energy $\Pi_\phi(p)$:

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

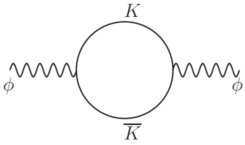
whit isospin doublets

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

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

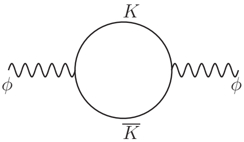
$$D^{\mu\nu}(p) = \frac{1}{p^2 - m_\phi^2 - \Pi_\phi(p)}\left(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}\right) + \frac{p^\mu p^\nu}{m_\phi^2 p^2}$$

- Order g_ϕ^2 computation: $\phi K\overline{K}$ coupling



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

- Order g_ϕ^2 computation: $\Pi_\phi(p) = -\frac{1}{3} g_{\mu\nu} \Pi_\phi^{\mu\nu}(p)$



- $\Pi_\phi(p)$ acquires an imaginary part when $m_\phi > 2m_K$ ($m_\phi = 1020$ MeV, $m_K = 497$ MeV), which is the case here,
- m_ϕ and Γ_ϕ in vacuum and in nuclear matter (m_ϕ^* and Γ_ϕ^*) are determined from

$$
\begin{aligned}
m_\phi^2 &= \left(m_\phi^0\right)^2 + \Re \Pi_\phi(m_\phi^2) \\
\Gamma_\phi &= -\frac{1}{m_\phi} \Im \Pi_\phi(m_\phi^2) \quad (\phi \to K\overline{K})
\end{aligned}
$$

- For the computation in nuclear matter we do the replacing $m_\phi \to m_\phi^*$, $m_K \to m_K^*$, etc
- m_K^* is computed in the quark meson coupling model

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

- For a ϕ-meson at rest the scalar self-energy is given by

$$\mathrm{i}\Pi_\phi(p) = -\frac{8}{3}g_\phi^2 \int \frac{\mathrm{d}^3 q}{(2\pi)^3}\, \vec{q}^{\,2} D_K(q) D_K(q-p), \tag{1}$$

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

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

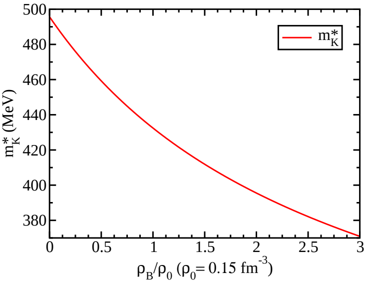
- For the vertex $\phi K\overline{K}$ we use the form factor $F_{K\overline{K}}(\vec{q}^2) = u_K(\vec{q}^2)^2$. We study the dependence on Λ_K of our results below.

Quark meson coupling model (Prog.Part.Nucl.Phys 58, 1 (2007))

- Crucial for our results in nuclear matter (ie at finite baryon density ρ_B) is the in-medium kaon mass m_K^*. This is calculated in the QMC model.
- The QMC model is a quark-based, relativistic mean field model of nuclear matter and nuclei
- Relativistic 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 degrees of freedom.

QMC results: in-medium kaon mass

- In-medium kaon mass

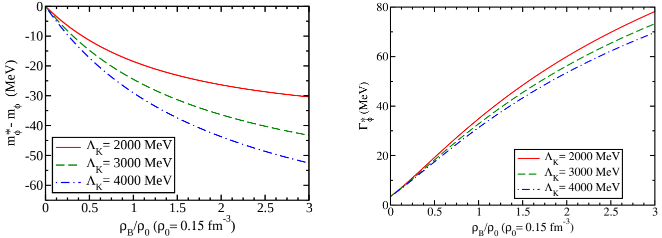


- The m^*_K at normal nuclear matter density $\rho_0 = 0.15$ fm^{-3} decreases by 13%.
- The vector-isoscalar ω-mean-field potentials arise both for the kaon and antikaon. However, they have opposite signs and can be eliminated by a variable shift in the ϕ self-energy

Results: ϕ mass shift and decay width in nuclear matter

- Recall

$$m_\phi^2 = \left(m_\phi^0\right)^2 + \Re\Pi_\phi(m_\phi^2)$$
$$\Gamma_\phi = -\frac{1}{m_\phi}\Im\Pi_\phi(m_\phi^2) \quad (\phi \to K\overline{K})$$



- Mass shift average of -24 MeV (2% decrease) at ρ_0, with a 5 MeV spread.
- The ϕ decay width broadens by an order of magnitude, at ρ_0.

Summary and Conclusions I

- We have calculated the ϕ meson mass and width in nuclear matter within an effective Lagrangian approach up to $\rho_B = 3\rho_0$
- Essential to our results is m_K^*,
- m_K^* is calculated in the QMC model, where the scalar and vector meson mean fields couple directly to the light u and d quarks (antiquarks) in the K $(\overline{K})$ mesons.
- The QMC model gives a sizable negative mass shift of 13% in the kaon mass
- At normal nuclear matter density and for a large variation of the cutoff parameter Λ_K, this induces only a few percent (2% on average) downward shift of the ϕ meson mass.
- On the other hand, it induces an order-of-magnitude broadening of the decay width.

PartII: phi-meson–nuclear bound states

- We now discuss the situation where the ϕ meson is "placed" in a nucleus
- The nuclear density distributions for ^{12}C, ^{16}O, ^{40}Ca, ^{48}Ca, ^{90}Zr, and ^{208}Pb are obtained using the QMC model (For ^{4}He, we use the parametrization for the density distribution obtained in Phys. Rev. C **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)

$$V_{\phi A}(r) = U_\phi(r) - \frac{\mathrm{i}}{2} W_\phi(r),$$

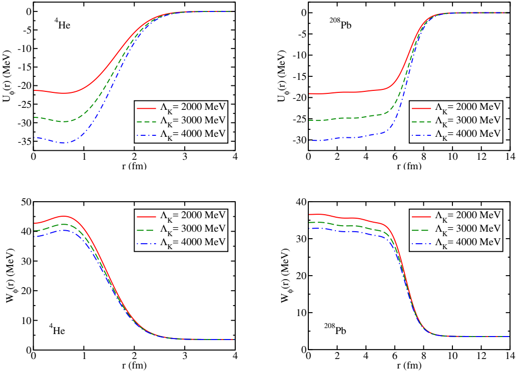
where

$$\begin{aligned} U_\phi(r) &= m^*_\phi(\rho_B(r)) - m_\phi \\ W_\phi(r) &= \Gamma_\phi(\rho_B(r)) \end{aligned}$$

are, respectively, the ϕ-meson mass shift and decay width in a nucleus A. $\rho_B(r)$ is the baryon density distribution for the particular nucleus.

phi-meson–nuclear bound states

- ϕ-meson–nuclear bound states



- The depth of $U_\phi(r)$ is sensitive to Λ_K; $W_\phi(r)$ does not vary much with Λ_K.
- These observations may well have consequences for the feasibility of experimental observation of the expected bound states.

phi-meson–nuclear bound states

- In this study we consider the situation where the ϕ-meson is produced nearly at rest
- 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

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

  where $\mu = m_\phi m_A/(m_\phi + m_A)$ is the reduced mass of the ϕ-meson-nucleus 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 $\Gamma = -2\Im\mathcal{E}$

phi-meson–nuclear bound states (E and Γ in MeV)

		$\Lambda_K = 2000$		$\Lambda_K = 3000$		$\Lambda_K = 4000$	
		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
$^{208}_{\phi}$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

- $W_\phi(r) = 0$: 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.
- $W_\phi(r) \neq 0$: Whether or not the bound states can be observed experimentally, is sensitive to the value of Λ_K.
- $W_\phi(r)$ is repulsive: some bound states disappear completely, even though they were found when $W_\phi(r) = 0$
- This feature is obvious for the ^{4}He, making it especially relevant to the future experiments, planned at J-PARC and JLab using light and medium-heavy nuclei.

Summary and Conclusions II

- We have calculated the ϕ-meson–nucleus bound state energies and absorption widths for various nuclei.
- The ϕ-meson–nuclear potentials were calculated using a local density approximation (ϕ-meson mass shift and decay in nuclear matter and nuclei)
- The nuclear density distributions, as well as the in-medium K and $\overline{K}$ meson masses, were consistently calculated by employing the QMC model
- We expect that the ϕ-meson should form bound states for all seven nuclei selected, 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 difficult to identify experimentally
- Therefore, the feasibility of observation of the ϕ-meson–nucleus bound states needs further investigation, including explicit reaction cross section estimates