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To cite this article: J J Cobos-Martínez *et al* 2017 *J. Phys.: Conf. Ser.* **912** 012009

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

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Abstract.
    The work presented at this workshop is divided into two parts. In the first part, the
mass and decay width of the ϕ-meson in cold nuclear matter are computed in an effective
Lagrangian approach. The medium dependence of these properties are obtained by evaluating
kaon-antikaon loop contributions to the ϕ-meson self-energy, employing medium-modified kaon
masses calculated using the quark-meson coupling model. The loop integral is regularized with
a dipole form factor, and the sensitivity of the results to the choice of cutoff mass in the form
factor is investigated. At normal nuclear matter density, we find a downward shift of the ϕ mass
by a few percent, while the decay width is enhanced by an order of magnitude. Our results
support the literature which suggest that one should observe a small downward mass shift and
a large broadening of the decay width. In the second part, we present ϕ-meson–nucleus bound
state energies and absorption widths for four selected nuclei, calculated by solving the Klein-
Gordon equation with complex optical potentials. The attractive potential for the ϕ-meson in
the nuclear medium originates from the in-medium enhanced $K\overline{K}$ loop in the ϕ-meson self-
energy. The results suggest that the ϕ-meson should form bound states with all the nuclei
considered. However, the identification of the signal for these predicted bound states will need
careful investigation because of their sizable absorption widths.

1. Introduction
The properties of light vector mesons at finite baryon density, such as their masses and decay
widths, have attracted considerable experimental and theoretical interest over the last few
decades [1–5]. This has been in part due to their potential to carry information on the partial
restoration of chiral symmetry, and the possible role of QCD of van der Waals forces in the
binding of quarkonia to nuclei. In particular, there is special interest on the ϕ-meson, the
main reasons being: i) despite its nearly pure $s\bar{s}$ content, the ϕ-meson does interact strongly
with a nucleus, composed predominantly of light u and d quarks, through the excitation of

[5] Speaker

below-threshold virtual kaon and anti-kaon states that might have their properties changed in medium [6–10]; (ii) the ϕN interaction in vacuum [11–14] and a possible in-medium mass shift of the ϕ are related to the strangeness content of the nucleon [15], which may have implications beyond the physics of the strong interaction [16–18]; (iii) medium modifications of ϕ-meson properties have been proposed [19] as a possible source for the anomalous nuclear mass number A-dependence observed in ϕ-meson production from nuclear targets [20]; (iv) furthermore, as the ϕ-meson is a nearly pure $s\bar{s}$ state and gluonic interactions are flavor blind, studying it serves to test theories of the multiple-gluon exchange interactions, including long range QCD van der Waals forces [21], which are believed to play a role in the binding of the J/Ψ and other exotic heavy-quarkonia to matter [22–33].

Heavy-ion collisions and photon- or proton-induced reactions on nuclear targets have been used to extract information on the in-medium properties of hadrons. Several experiments have focused on the light vector ρ, ω, and ϕ mesons, since their mean-free paths can be comparable with the size of a nucleus after being produced inside the nucleus. However, a unified consensus has not yet been reached among the different experiments—see Refs. [1–5] for comprehensive reviews on the current status.

For the ϕ-meson, although the precise values are different, a large in-medium broadening of its decay width has been reported by most of the experiments performed, while only a few of them find evidence for a substantial mass shift [20; 34–38]. In 2007 the KEK-E325 collaboration reported a 3.4% mass reduction of the ϕ-meson [34] and an in-medium decay width of ≈ 14.5 MeV at normal nuclear matter density $\rho_0 = 0.15$ fm^{-3}. These conclusions were based upon the measurement of the invariant mass spectra of e^+e^- pairs in 12 GeV p+A reactions, with copper and carbon being used as targets [34]. Even though this result may indicate a signal for partial restoration of chiral symmetry in nuclear matter, it is not possible to draw a definite conclusion solely from this. In fact, recently, a large in-medium ϕ-meson decay width (>30 MeV) has been extracted at various experimental facilities without observing any mass shift [20; 35–38],

It is therefore clear that the search for evidence of a light vector meson mass shift in nuclear matter is indeed a complicated issue and further experimental efforts [32; 39] are required in order to understand the phenomenon better. Indeed, the J-PARC E16 collaboration [32; 39] intends to perform a more systematic study for the mass shift of vector mesons with higher statistics than the above-mentioned experiment at KEK-E325.

However, either complementary or alternative experimental methods are desired. The study of the ϕ-meson–nucleus bound states is complementary to the invariant mass measurements, such as Ref. [34], where only a small fraction of the produced ϕ-mesons decay inside the nucleus and may be expected to provide extra information on the ϕ-meson properties at finite baryon density. Along these lines, and motivated by the 3.4% mass reduction reported by the KEK-E325 experiment [34], the E29 collaboration at J-PARC has recently put forward a proposal [40; 41] to study the in-medium mass modification of the ϕ-meson via the possible formation of ϕ-meson– nucleus bound states [31; 42]. Furthermore, there is also a proposal at JLab, following the 12 GeV upgrade, to study the binding of ϕ and η mesons to ^{4}He [43]. This new experimental approach [31; 32; 42; 43] for the measurement of the ϕ-meson mass shift in nuclei, will produce a slowly moving ϕ-meson [31; 32; 42; 43], where the maximum nuclear matter effect can be probed. In this way, one may indeed anticipate the formation of a ϕ-meson–nucleus bound state, where the ϕ-meson is trapped inside the nucleus.

Meson-nucleus systems bound by attractive strong interactions are very interesting objects [4; 5]. First, they are strongly interacting exotic many-body systems and to study them serves, for example, to understand better the multi-gluon exchange interactions, including QCD "van der Waals" forces [21], which are believed to play a role in the binding of the J/Ψ and other exotic heavy-quarkonia to matter (a nucleus) [22–33]. Second, they provide unique laboratories for the study of hadron properties at finite density, which may not only lead to a deeper understanding

of the strong interaction [1–5] but of the structure of finite nuclei as well [44; 45].

A downward mass shift of the ϕ-meson in a nucleus is directly connected with the possible existence of an attractive potential between the ϕ-meson and the nucleus where it has been produced, the strength of which is expected to be of the same order as that of the mass shift.

Concerning the theoretical evaluation of the ϕ-meson mass shift, various authors predict a downward shift of the in-medium ϕ-meson mass and a broadening of its decay width, many of them focusing on the self-energy of the ϕ-meson due to the kaon-antikaon loop. Ko et al. [46] used a density-dependent kaon mass determined from chiral perturbation theory and found that at normal nuclear matter density, ρ_0, the ϕ-meson mass decreases very little, by at most 2%, and a $\Gamma_\phi \approx 25$ MeV width which broadens drastically for large densities. Hatsuda and Lee calculated the in-medium ϕ-meson mass based on the QCD sum rule approach [47; 48], and predict a 1.5%-3% decrease at ρ_0. Other investigations also predict a small downward mass shift and a large broadening of the ϕ-meson width at ρ_0: Ref. [49] reports a negative mass shift of $< 1\%$ and a decay width of 45 MeV; Ref. [50] predicts a decay width of 22 MeV but does not report a result on the mass shift; and Ref. [51] gives a rather small negative mass shift of $\approx 0.81\%$ and a decay width of 30 MeV. More recently, Ref. [52] reported a downward mass shift of $< 2\%$ and a large broadening width of 45 MeV at ρ_0; and finally, in Ref. [53], extending the work of Refs. [50; 51], the authors reported a negative mass shift of 3.4% and a large decay width of 70 MeV at ρ_0. The reason for these differences may lie in the different approaches used to estimate the kaon-antikaon loop contributions to the ϕ-meson self-energy and this might have consequences for the formation of ϕ-meson–nucleus bound states.

From a practical point of view, the important question is whether this attraction, if it exists, is sufficient to bind the ϕ-meson to a nucleus. A simple argument can be given as follows. One knows that for an attractive spherical well of radius R and depth V_0, the condition for the existence of a nonrelativistic s-wave bound state of a particle of mass m is $V_0 > \frac{\pi^2 \hbar^2}{8mR^2}$. Using $m = m_\phi^*$, where m_ϕ^* is the ϕ-meson mass at normal nuclear matter density found in Ref. [34] and $R = 5$ fm (the radius of a heavy nucleus), one obtains $V_0 > 2$ 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. Real nuclei, however, have a surface and this estimate can be quite misleading [4]. A full calculation using realistic density profiles of nuclei is required for a more reliable estimate.

The work presented at this workshop was carried out in collaboration with professors K. Tushima, G. Krein, and A. W. Thomas and has been published in Refs. [54; 55]. In Ref. [54] we studied the ϕ-meson mass shift and decay width in nuclear matter, based on an effective Lagrangian approach, by evaluating the $K\overline{K}$ loop contribution in the ϕ-meson self-energy, with the in-medium K and $\overline{K}$ masses explicitly calculated by the quark-meson coupling (QMC) model [56]. This initial study has been extended in Ref. [54] to some selected nuclei by computing the ϕ-meson–nucleus bound complex potential in the local density approximation and solving the Klein-Gordon equation in order to obtain the bound state energies and absorption widths. The nuclear density distributions for all nuclei studied, except for ^{4}He, are explicitly calculated using the QMC model [57].

2. ϕ-meson mass and decay width in nuclear matter

The ϕ-meson property modifications in nuclear matter, such as its mass and decay width, are strongly correlated to its coupling to the $K\overline{K}$ channel, which is the dominant decay channel in vacuum. Thus, one expects that a significant fraction of the density dependence of the ϕ-meson self-energy in nuclear matter arises from the in-medium modification of the $K\overline{K}$ intermediate state in the ϕ-meson self-energy.

We briefly review the computation [54] of the ϕ-meson self-energy in vacuum and in nuclear matter using an effective Lagrangian approach [58]. The interaction Lagrangian $\mathcal{L}_{\text{Int}}$ involves

$\phi K\overline{K}$ and $\phi\phi K\overline{K}$ couplings dictated by a local gauge symmetry principle:

$$\mathcal{L}_{\text{Int}} = \mathcal{L}_{\phi K\overline{K}} + \mathcal{L}_{\phi\phi K\overline{K}}, \tag{1}$$

where (we use the convention $K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}$, $\overline{K} = \begin{pmatrix} K^- & \overline{K}^0 \end{pmatrix}$ for isospin doublets)

$$\mathcal{L}_{\phi K\overline{K}} = \mathrm{i}g_\phi \phi^\mu \left[\overline{K}(\partial_\mu K) - (\partial_\mu \overline{K})K \right], \tag{2}$$

$$\mathcal{L}_{\phi\phi K\overline{K}} = g_\phi^2 \phi^\mu \phi_\mu \overline{K}K. \tag{3}$$

We note that the use of the effective interaction Lagrangian of Eq. (1) without the term given in Eq. (3) may be considered as being motivated by the hidden gauge approach in which there are no four-point vertices, such as Eq. (3), that involve two pseudoscalar mesons and two vector mesons [59; 60]. This is in contrast to the approach of using the minimal substitution to introduce vector mesons as gauge particles where such four-point vertices do appear. However, these two methods have been shown to be consistent if both the vector and axial vector mesons are included [61–64]. Therefore, we present results with and without such an interaction [54; 55]. We consider first the contribution from the $\phi K\overline{K}$ coupling, given by Eq. (2), to the scalar part of the ϕ-meson self-energy, $\Pi_\phi(p)$.

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

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

where $D_K(q) = \left(q^2 - m_K^2 + \mathrm{i}\epsilon\right)^{-1}$ is the kaon propagator; $p = (p^0 = m_\phi, \vec{0})$ is the ϕ-meson four-momentum vector at rest, with m_ϕ the ϕ-meson mass; $m_K(= m_{\overline{K}})$ is the kaon mass; and g_ϕ is the coupling constant. When $m_\phi < 2m_K$ the self-energy $\Pi_\phi(p)$ is real. However, when $m_\phi > 2m_K$, which is the case here, $\Pi_\phi(p)$ acquires an imaginary part.

The integral in Eq. (4) is divergent but it will be regulated using a phenomenological form factor, with cutoff parameter Λ_K, as in Refs. [54; 65]. The sensitivity of the results to the cutoff value is analyzed below.

The mass and decay width of the ϕ-meson in vacuum (m_ϕ and Γ_ϕ), as well as in nuclear matter (m_ϕ^* and Γ_ϕ^*), are determined self-consistently [54] from

$$m_\phi^2 = \left(m_\phi^0\right)^2 + \mathrm{Re}\,\Pi_\phi(m_\phi^2), \tag{5}$$

$$\Gamma_\phi = -\frac{1}{m_\phi}\mathrm{Im}\,\Pi_\phi(m_\phi^2). \tag{6}$$

The coupling constant g_ϕ is determined [54] from Eqs. (4) and (6), and the experimental value for the $\phi \to K\overline{K}$ decay width in vacuum, corresponding to the branching ratio of 83.1% of the total decay width [66].

The nuclear density dependence of the ϕ-meson mass and decay width is driven by the intermediate $K\overline{K}$ state interactions with the nuclear medium. This effect enters through m_K^* in the kaon propagators in Eq. (4). The in-medium mass m_K^* is calculated within the QMC model [54], which has proven to be very successful in studying the properties of hadrons in nuclear matter and finite nuclei. For a more complete discussion of the model see Refs. [6; 56; 67]. Here we just make a few necessary comments. In order to calculate the in-medium properties of K and $\overline{K}$, we consider infinitely large, uniformly symmetric, spin-isospin-saturated nuclear matter in its rest frame, where all the scalar and vector mean field potentials, which are responsible for the nuclear many-body interactions, become constant in the Hartree approximation [54]. In

Figure 1 (left panel) we present the resulting in-medium kaon Lorentz scalar mass (=antikaon Lorentz scalar mass), calculated using the QMC model, as a function of the baryon density. The kaon effective mass at normal nuclear matter density $\rho_0 = 0.15$ fm^{-3} has decreased by about 13%. We also recall, in connection with the calculation of the in-medium $K\overline{K}$ loop contributions to the ϕ-meson self-energy, that the isoscalar-vector ω mean field potentials arise both for the kaon and antikaon. However, they have opposite signs and cancel each other. Equivalently, they can be eliminated by a variable shift in the loop calculation [6; 56; 67] of the ϕ-meson self-energy, and therefore we do not show them here.
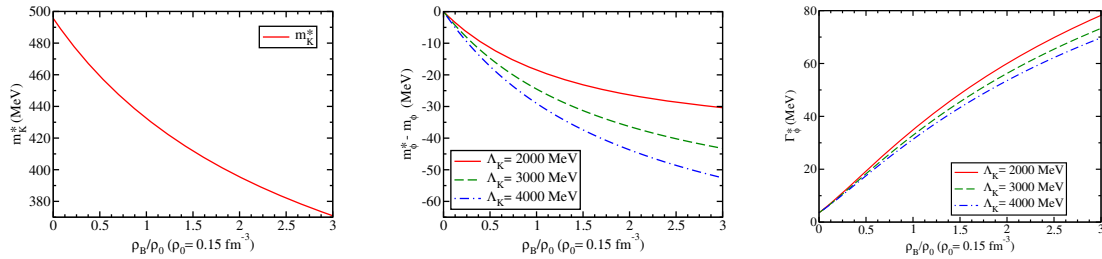

Figure 1. Left panel: In-medium kaon mass (=antikaon) Lorentz scalar mass m_K^*; centre and right panels: ϕ-meson mass shift and decay width, respectively, in symmetric nuclear matter for three values of the cutoff parameter Λ_K.

In Figure 1, we present the ϕ-meson mass shift (centre panel) and decay width (right panel) as a function of the nuclear matter density, ρ_B, for three values of the cutoff parameter Λ_K. As can be seen, the effect of the in-medium kaon and antikaon mass change yields a negative mass shift for the ϕ-meson. This is because the reduction in the kaon and antikaon masses enhances the $K\overline{K}$ loop contribution in nuclear matter relative to that in vacuum. For the largest value of the nuclear matter density, the downward mass shift turns out to be a few percent at most for all values of Λ_K. On the other hand, we see that Γ_ϕ^* is very sensitive to the change in the kaon and antikaon masses, increasing rapidly with increasing nuclear matter density, up to a factor of ~ 20 enhancement for the largest value of ρ_B. In Table 1 we present the values for m_ϕ^* and Γ_ϕ^* at normal nuclear matter density ρ_0. We see that the negative kaon and antikaon mass shift of 13% [54] induces a downward mass shift of the ϕ-meson of just $\approx 2\%$, while the broadening of the ϕ-meson decay width is an order-of-magnitude larger than its vacuum value.

In Ref. [54] we evaluated the impact of adding the $\phi\phi K\overline{K}$ interaction of Eq. (3) on the in-medium ϕ-meson mass and decay width. We found that one still gets a downward shift of the in-medium ϕ-meson mass as well as a significant broadening of the decay width when this interaction is added. In both cases, though, the absolute values are slightly different from those shown in Figure 1. In Table 1 we present the values for m_ϕ^* and Γ_ϕ^* at ρ_0 obtained by adding the gauged Lagrangian of Eq. (3). In both cases, for the mass and decay width in nuclear matter, the effect of adding Eq. (3) can be compensated by the use of a larger cutoff Λ_K.

The results described above support those which suggest that one should observe a small downward mass shift and a large broadening of the decay width of the ϕ-meson in a nuclear medium. Furthermore, they open experimental possibilities for studying the binding and absorption of ϕ-meson in nuclei. Although the mass shift found in this study may be large enough to bind the ϕ-meson to a nucleus, the broadening of its decay width will make it difficult to observe a signal for the ϕ-meson–nucleus bound state formation experimentally. We explore this further in the second part of this talk.

	$\Lambda_K = 2000$	$\Lambda_K = 3000$	$\Lambda_K = 4000$
m_ϕ^*	1000.9 (1009.5)	994.9 (1004.3)	990.4 (1000.6)
Γ_ϕ^*	34.8 (37.8)	32.8 (36.0)	31.3 (34.7)

Table 1. ϕ-meson mass and width at normal nuclear matter density ρ_0 with and without the gauged Lagrangian of Eq. (3). The values in parentheses were computed by adding the gauged Lagrangian of Eq. (3). All quantities are given in MeV.
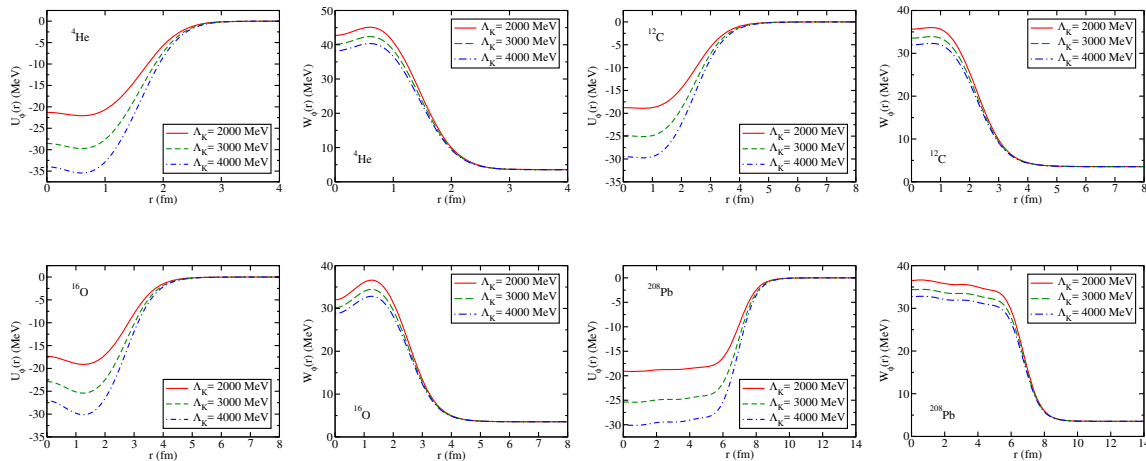

Figure 2. Real $[U_\phi(r)]$ and imaginary $[W_\phi(r)]$ parts of the ϕ-meson-nucleus potentials in the nuclei ^{12}C, ^{16}O, ^{40}Ca , and ^{208}Pb, for three values of the cutoff parameter Λ_K.

3. ϕ-meson–nuclear bound states

In this part we discuss the situation where the ϕ-meson is placed in a nucleus. The nuclear density distributions for the nuclei ^{12}C, ^{16}O, ^{40}Ca , and ^{208}Pb are obtained using the QMC model [57]. For ^{4}He, we use the parametrization for the density distribution obtained in Ref. [68]. Then, using a local density approximation we calculate the ϕ-meson complex potentials for a nucleus A, which can be written as

$$V_{\phi A}(r) = U_\phi(r) - \frac{\mathrm{i}}{2} W_\phi(r), \tag{7}$$

where r is the distance from the center of the nucleus and $U_\phi(r) = \Delta m_\phi(\rho_B(r)) \equiv m_\phi^*(\rho_B(r)) - m_\phi$, and $W_\phi(r) = \Gamma_\phi(\rho_B(r))$ are, respectively, the ϕ-meson mass shift and decay width in a nucleus A, with $\rho_B(r)$ the baryon density distribution for the particular nucleus.

Figure 2 shows the ϕ-meson potentials calculated for the selected nuclei, for three values of the cutoff parameter Λ_K. One can see that the depth of the real part of the potential is sensitive to the cutoff parameter, varying from -20 MeV to -35 MeV for ^{4}He and from -20 MeV to -30 MeV for ^{208}Pb. On the other hand, one can see that the imaginary part does not vary much with Λ_K. These latter observations may well have consequences for the feasibility of experimental observation of the expected bound states.

Using the ϕ-meson potentials obtained in this manner, we next calculate the ϕ-meson–nucleus bound state energies and absorption widths for the selected nuclei. Before proceeding, a few comments on the use of Eq. (8) are in order. 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

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

Table 2. ϕ-meson–nucleus single-particle energies, E, and half widths, $\Gamma/2$, obtained with and without the imaginary part of the potential of Eq. (7), for three values of the cutoff parameter Λ_K. When only the real part is included, where the corresponding single-particle energy E is given inside parenthesis, $\Gamma = 0$ for all nuclei. "n" indicates that no bound state is found. All quantities are given in MeV.

wave function ψ^μ_ϕ. After imposing the Lorentz condition, $\partial_\mu \psi^\mu_\phi = 0$, to solve the Proca equation becomes equivalent to solving the Klein-Gordon equation

$$\left(-\nabla^2 + \mu^2 + 2\mu V(\vec{r})\right) \phi(\vec{r}) = \mathcal{E}^2 \phi(\vec{r}), \tag{8}$$

where $\mu = m_\phi m_A / (m_\phi + m_A)$ is the reduced mass of the ϕ-meson-nucleus system with m_ϕ (m_A) the mass of the ϕ-meson (nucleus A) in vacuum, and $V(\vec{r})$ is the complex ϕ-meson-nucleus potential of Eq. (7). We solve the Klein-Gordon equation using the momentum space methods [69]. The calculated bound state energies (E) and absorption widths (Γ), which are related to the complex energy eigenvalue $\mathcal{E}$ by $E = \Re\mathcal{E} - \mu$ and $\Gamma = -2\Im\mathcal{E}$, are listed in Table 2 for three values of the cutoff parameter Λ_K, with and without the imaginary part of the potential.

We first discuss the case in which the imaginary part of the ϕ-meson–nucleus potential is set to zero. The results are given within parentheses in Table 2. From the values shown, we see that the ϕ-meson is expected to form bound states with all the nuclei selected, for all values of the cutoff parameter Λ_K. The bound state energy is obviously dependent on Λ_K, increasing as Λ_K increases. Next, we discuss the results obtained when the imaginary part of the potential is included. Adding the absorptive part of the potential changes the situation appreciably. From the results presented in Table 2 we note that for the largest value of the cutoff parameter Λ_K, which yields the deepest attractive potentials (see Figure 2), the ϕ-meson is expected to form bound states with all the selected nuclei, including the lightest one, the ^{4}He nucleus. However, in this case, whether or not the bound states can be observed experimentally is sensitive to the value of the cutoff parameter Λ_K. One also observes that the width of the bound state is insensitive to the values of Λ_K for all nuclei. Furthermore, since the so-called dispersive effect of the absorptive potential is repulsive, the bound states disappear completely in some cases, even though they were found when the absorptive part was set to zero. This feature is obvious for the ^{4}He nucleus, making it especially relevant to the future experiments, planned at J-PARC and JLab using light and medium-heavy nuclei [31; 32; 42; 43].

4. Summary and discussion
We have calculated the ϕ-meson mass and width in nuclear matter within an effective Lagrangian approach up to three times of normal nuclear matter density. Essential to our results are the in-medium kaon masses, which are 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. At normal nuclear matter density, allowing for a very large variation of the cutoff parameter Λ_K, although we have found a sizable negative mass shift of 13% in the kaon mass, this induces only a few percent downward shift of the ϕ-meson mass. On the other hand, it induces an order-of-magnitude broadening of the decay width.

We have also calculated the ϕ-meson–nucleus bound state energies and absorption widths for various nuclei. The ϕ-meson–nucleus potentials were calculated using a local density approximation, with the inclusion of the $K\overline{K}$ loop in the ϕ-meson self-energy. The nuclear density distributions, as well as the in-medium K and $\overline{K}$ meson masses, were consistently calculated by employing the quark-meson coupling model. Using the ϕ-meson–nucleus complex potentials found, we have solved the Klein-Gordon equation in momentum space, and obtained ϕ-meson–nucleus bound state energies and absorption widths.

Furthermore, we have studied the sensitivity of our results to the cutoff parameter Λ_K in the form factor at the $\phi K\overline{K}$ vertex appearing in the ϕ-meson self-energy. We expect that the ϕ-meson should form bound states for all four nuclei selected, provided that the ϕ-meson is produced in (nearly) recoilless kinematics. This feature, is even more obvious in the (artificial) case where the absorptive part of the potential is ignored. Given the similarity of the binding energies and widths reported here, the signal for the formation of the ϕ-meson–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.

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