Phi-meson--nuclear bound states


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ϕ-meson–nucleus bound state energies and absorption widths are calculated for seven selected nuclei by solving the Klein-Gordon equation with complex optical potentials. Essential input for the calculations, namely the medium-modified K and $\overline{K}$ meson masses, as well as the density distributions in nuclei, are obtained from the quark-meson coupling model. 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.

I. 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. In part this has been related to their imputed potential to carry information on the partial restoration of chiral symmetry [1–3]. In 2007 the KEK-E325 collaboration reported a 3.4% mass reduction of the ϕ-meson [4] and an in-medium decay width of $\approx$ 14.5 MeV at normal nuclear matter density. These conslusions were based upon the measurement of the invariant mass spectra of e^+e^- pairs in 12 GeV p+A reactions, whith copper and carbon being used as targets [4].

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 [5–9], without observing any mass shift. It is therefore evident that the search for evidence of a light vector meson mass shift in nuclear matter is indeed a complicated issue and further experimental efforts are required in order to understand the phenomenon better. Indeed, the J-PARC E16 collaboration [10, 11] intends to perform a more systematic study for the mass shift of vector mesons with higher statistics than the abovementioned 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, 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, the E29 collaboration at J-PARC has recently put forward a proposal [14, 15] to study the in-medium mass modification of the ϕ-meson via the possible formation of ϕ-nucleus bound states [16, 17] using the primary reaction $\overline{p}p \to \phi\phi$. Furthermore, there is also a proposal at JLab, following the 12 GeV upgrade, to study the binding of ϕ (and η) to ^{4}He [18]. This new experimental approach [11, 16–18] for the measurement of the ϕ meson mass shift in nuclei, will produce a slowly moving ϕ-meson [11, 16–18], where the maximum nuclear matter effect can be probed. In this way, one may indeed anticipate the formation of a ϕ-nucleus bound state, where the ϕ-meson is trapped inside the nucleus.

Meson-nucleus systems bound by attractive strong interactions are very interesting objects (see Refs. [19, 20] and references therein). 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) [11, 17, 22–31]. 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 [1–3] but the structure of finite nuclei as well [12, 13].

The 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, the strength of which is expected to be of the same order as that of the mass shift. 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 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. [4] 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.

An initial calculation of possible ϕ-nucleus bound states was carried out in Ref. [32] for a few nuclei. However, the theoretical potential on which this study was based [33] was too weak, with only two bound states being found. In order to remedy this, the real part of the potential was scaled, without any theoretical basis, so as to simulate a 3% mass reduction of the ϕ-meson, that is, approximately equal to that reported in Ref. [4]. This (scaled) potential was mainly used to study the sensitivity of the formation spectra to the potential strength [33]. Here, it was found that, as expected, whether or not the formation of the ϕ-meson bound state is possible depends on the strength of the attractive potential between the ϕ-meson and the nucleus.

In previous work [34] 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 self-energy, with the in-medium K and $\overline{K}$ masses explicitly calculated by the quark-meson coupling (QMC) model [35]. Here we extend our previous initial study [34] to seven selected nuclei, showing details of the calculated nuclear potential and computing the ϕ-nucleus bound state energies and absorption widths by solving the Klein-Gordon equation. The nuclear density distributions for heavy nuclei studied (except for ^{4}He), as well as the medium modification of the K and $\overline{K}$ masses, are explicitly calculated using the QMC model [36].

This paper is organized as follows. In Section II we briefly discuss the computation and present results for the mass shift and decay width of the ϕ-meson in infinite (symmetric) nuclear matter. Using the results of Section II, together with the density profiles of the nuclei to be studied, in Section III we present results for the real and imaginary parts of the scalar ϕ-nucleus potentials, as well as the corresponding bound state energies and absorption widths. Finally, Section IV is devoted to a summary and discussion.

II. ϕ-MESON SELF-ENERGY IN INFINITE NUCLEAR MATTER

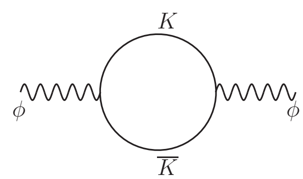

FIG. 1: $K\overline{K}$-loop contribution to the ϕ-meson self-energy.

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. Therefore, one expects that a significant fraction of the density dependence of the ϕ-meson self-energy in nuclear matter might arise from the in-medium modification of the $K\overline{K}$-loop in the ϕ-self-energy intermediate state.

Here we use the effective Lagrangian approach of Ref. [37] and briefly review the computation of the ϕ-meson self-energy in vacuum and in nuclear matter [34]. The lowest-order interaction Lagrangian in the $\phi K\overline{K}$ coupling constant g_ϕ, without the term in g_ϕ^2 arising from the covariant derivative involving the ϕ-meson [37, 38] (or "the gauge term"), is given by

$$\mathcal{L}_{\phi K\overline{K}} = \mathrm{i} g_\phi \phi^\mu \left[\overline{K}(\partial_\mu K) - (\partial_\mu \overline{K})K\right], \tag{1}$$

where we use the convention $K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}$ and $\overline{K} = \begin{pmatrix} K^- & \overline{K}^0 \end{pmatrix}$ for the isospin doublets. For more detailed discussions on the interaction Lagrangian with the covariant derivative involving the ϕ-meson see Ref. [34]. The scalar self-energy for the ϕ-meson, $\Pi_\phi(p)$, is computed from Eq. (1) by evaluating the $K\overline{K}$ loop in Fig. 1. For a ϕ-meson at rest the scalar self-energy is given by

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

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 $g_\phi = 4.539$ is the coupling constant, which we determined [34] from 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 (4.266 MeV) [39].

The integral in Eq. (2) is divergent but it will be regulated using a phenomenological form factor, with cutoff parameter Λ_K, as in Refs. [34, 40]. The sensitivity of the results to the cutoff value is analyzed below. The mass

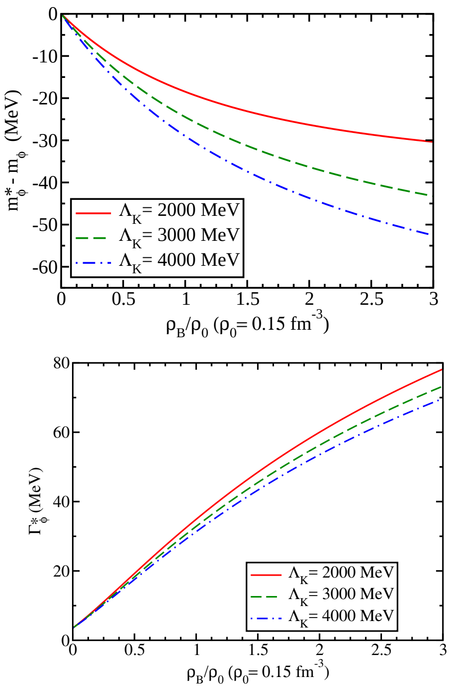

FIG. 2: ϕ-meson mass shift (upper panel) and decay width (lower panel) in symmetric nuclear matter for three values of the cutoff parameter Λ_K.

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 in Ref. [34] from

$$m_\phi^2 = \left(m_\phi^0\right)^2 + \Re\Pi_\phi(m_\phi^2), \qquad (3)$$

$$\Gamma_\phi = -\frac{1}{m_\phi}\Im\Pi_\phi(m_\phi^2). \qquad (4)$$

The nuclear density dependence of the ϕ-meson mass and decay width is driven by the intermediate state kaon and antikaon interactions with the nuclear medium. This effect enters through m^*_K in the kaon propagators in Eq. (2). The in-medium mass, m^*_K, is calculated within the QMC model [34], 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. [35, 41, 42]. 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 Hartree approximation [34]. We also recall that, to calculate the in-medium $K\overline{K}$-loop contributions to the ϕ-meson self-energy, 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 [35, 41, 42].

In Fig. 2, we present the ϕ-meson mass shift (upper panel) and decay width (lower 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: it increases rapidly with increasing nuclear matter density, up to a factor of ~ 20 enhancement for the largest value of ρ_B. At normal nuclear matter density, ρ_0, we see that the negative kaon and antikaon mass shift of 13% [34] 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. These results support 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-nucleus bound state formation experimentally. We explore this further in the following section.

III. ϕ-NUCLEAR BOUND STATES

In this section we 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 [36]. For ^{4}He, we use the parametrization for the density distribution obtained in Ref. [43]. Then, using a local density approximation we calculate the ϕ-meson complex potentials for a nucleus A, which can be written as

$$V_{\phi A}(r) = U_\phi(r) - \frac{\mathrm{i}}{2}W_\phi(r), \qquad (5)$$

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 $W_\phi(r) =$

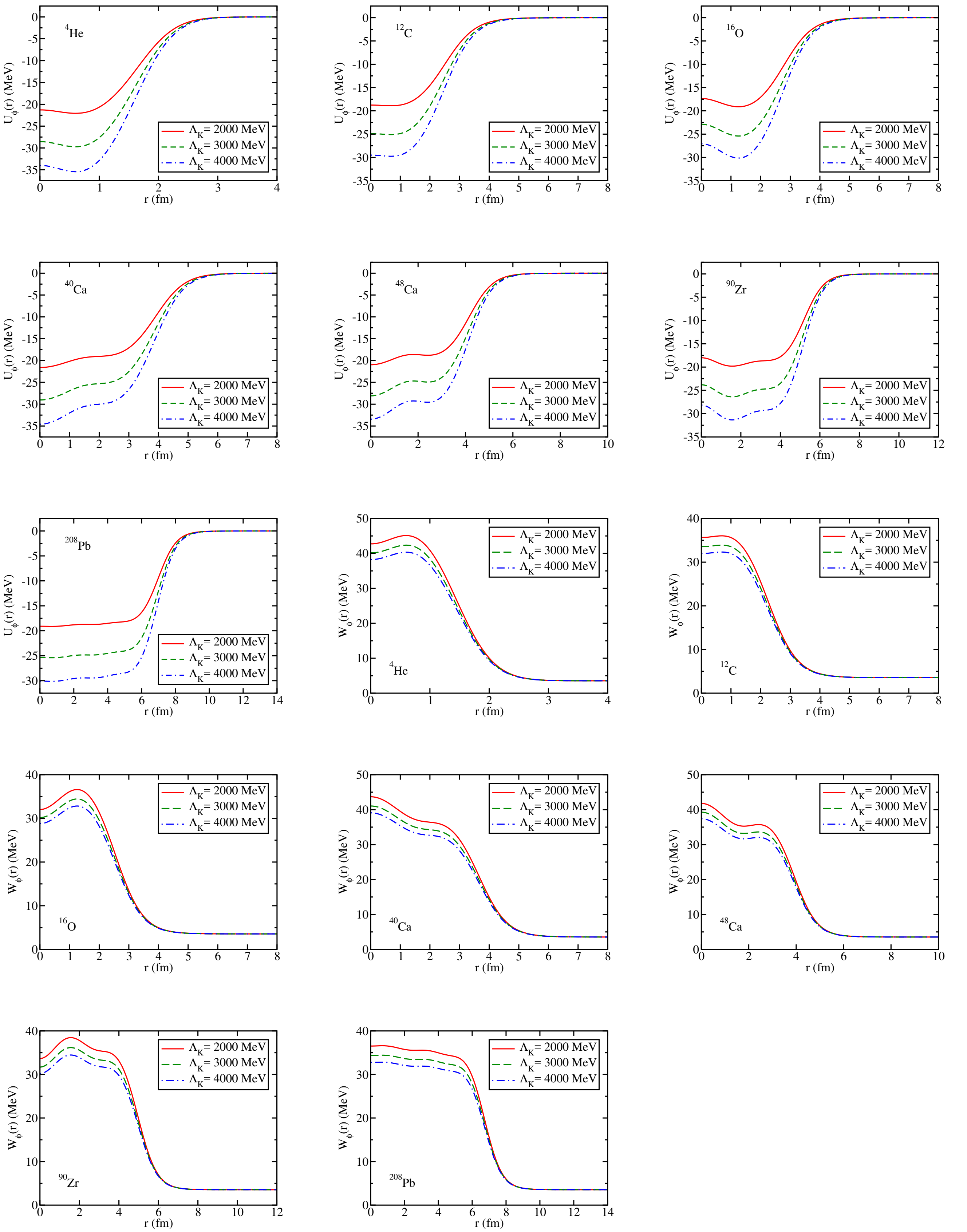

FIG. 3: Real ($U_\phi(r)$) and imaginary ($W_\phi(r)$) parts of the ϕ-meson-nucleus potentials in seven nuclei selected, for three values of the cutoff parameter Λ_K.

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

In Figure 3 we present the ϕ-meson potentials calculated for the seven nuclei selected, for three values of the cutoff parameter Λ_K, $2000, 3000$ and 4000 MeV. One can see that the depth of the real part of the potential, $U_\phi(r)$, 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. In addition, one can see that the imaginary part does not vary much with different values of Λ_K. These observations may well have consequences for the feasibility of experimental observation of the expected bound states.

		$\Lambda_K = 2000$		$\Lambda_K = 3000$		$\Lambda_K = 4000$	
		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
$^{40}_\phi$Ca	1s	-9.7 (-11.1)	16.5	-15.9 (-16.7)	16.2	-20.5 (-21.2)	15.8
	1p	-1.0 (-3.5)	12.9	-6.3 (-7.8)	13.3	-10.4 (-11.4)	13.3
	1d	n (n)	n	n (n)	n	n (-1.4)	n
$^{48}_\phi$Ca	1s	-10.5 (-11.6)	16.5	-16.5 (-17.2)	16.0	-21.1 (-21.6)	15.6
	1p	-2.5 (-4.6)	13.6	-7.9 (-9.2)	13.7	-12.0 (-12.9)	13.6
	1d	n (n)	n	n (-0.8)	n	-2.1 (-3.6)	11.1
$^{90}_\phi$Zr	1s	-12.9 (-13.6)	17.1	-19.0 (-19.5)	16.4	-23.6 (-24.0)	15.8
	1p	-7.1 (-8.4)	15.5	-12.8 (-13.6)	15.2	-17.2 (-17.8)	14.8
	1d	-0.2 (-2.5)	13.4	-5.6 (-6.9)	13.5	-9.7 (-10.6)	13.4
	2s	n (-1.4)	n	-3.4 (-5.1)	12.6	-7.4 (-8.5)	12.7
	2p	n (n)	n	n (n)	n	n (-1.1)	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 I: ϕ-nucleus single-particle energies, E, and half widths, $\Gamma/2$, obtained with and without the imaginary part of the potential, 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 brackets, $\Gamma = 0$ for all nuclei. "n" indicates that no bound state is found. All quantities are given in MeV.

Using the ϕ-meson potentials obtained in this manner, we next calculate the ϕ-meson–nuclear bound state energies and absorption widths for the seven nuclei selected. Before proceeding, a few comments on the use of Eq. (6) 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 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

$$\left(-\nabla^2 + \mu^2 + 2\mu V(\vec{r})\right)\phi(\vec{r}) = \mathcal{E}^2 \phi(\vec{r}), \tag{6}$$

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. (5). We solve the Klein-Gordon equation using the momentum space methods developed in Ref. [44]. Here, Eq. (6) is first converted to momentum space representation via a Fourier transform, followed by a partial wave-decomposition of the Fourier-transformed potential. Then, for a given value of angular momentum, the eigenvalues of the resulting equation are found by the inverse iteration eigenvalue algorithm. The calculated bound state energies (E) and 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 I for three values of the cutoff parameter Λ_K, with and without the imaginary part of the potential, $W_\phi(r)$.

We first discuss the case in which the imaginary part of the ϕ-nucleus potential, $W_\phi(r)$, is set to zero. The results are listed inside brackets in Table I. From the values shown in brackets, we see that the ϕ-meson is expected to form bound states with all the seven nuclei selected, for all values of the cutoff parameter $\Lambda_K = 2000, 3000$ and 4000 MeV. (For the variation in the potential depths due to the Λ_K values, see Fig. 3.) However, 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, the situation changes appreciably. From the results presented in Table I we note that, for the largest value of the cutoff parameter $\Lambda_K = 4000$ MeV which yields the deepest attractive potentials, the ϕ-meson is expected to form bound states in all the nuclei selected, including the lightest ^{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 [11, 16–18].

We here comment that we have also solved the Schröedinger equation with the potential Eq. (5) with and without its imaginary part for the single-particle energies and widths, and compared with those given in Table I. The results found in both cases are essentially the same.

IV. SUMMARY AND DISCUSSION

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, with the inclusion of the $K\overline{K}$ meson 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–nuclear complex potentials, 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 the 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 seven 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-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.

Acknowledgements

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