We present $\Phi$– and $J/\Psi$–nuclear bound state energies and absorption widths for some selected nuclei, using potentials in the local density approximation computed from an effective Lagrangian approach combined with the quark-meson coupling model. Our results suggest that these mesons should form bound states with all the nuclei considered provided that these mesons are produced in nearly recoil-less kinematics.

**KEYWORDS:** vector mesons, nuclear matter, vector meson mass shift, nuclear bound states

1. Introduction

The properties of vector mesons at finite baryon density, such as its mass and decay width, have attracted considerable experimental and theoretical interest over the last few decades [1], in part due to their potential to carry information on the partial restoration of chiral symmetry and the possible role of QCD van der Waals forces in the binding of quarkonia to nuclei [2]. However, an experimentally unified consensus has not yet been reached for the $\phi$ meson [3] and further studies need to be done [4, 5]. The study of, for example, the $\phi$–nucleus bound states [4, 5] is expected to provide information on the $\phi$ properties at finite density, since a downward mass shift of the $\phi$ in a nucleus is directly connected with the existence of an attractive potential between the $\phi$ and the nucleus where it has been produced. Various authors predict a small downward shift of the in-medium $\phi$ mass and a large broadening of its decay width [6] at normal nuclear matter density. In Ref. [7] we computed the $\phi$ mass shift and decay width in nuclear matter by evaluating the $K\bar{K}$ loop contribution to the $\phi$ self-energy, with the in-medium $K$ and $\bar{K}$ masses calculated using the quark-meson coupling (QMC) model [8]. This study was extended in Ref. [9] by computing the $\phi$–nucleus bound state energies and absorption with complex potentials. The Results for $^{197}$Au nucleus are presented for the first time. Furthermore, we also update results for the $J/\Psi$ vector meson, adding also the $^{197}$Au nucleus for the first time.
2. \textit{Φ}-meson in nuclear matter and \textit{Φ}-meson–nucleus bound states

We compute the $\phi$ self-energy $\Pi_\phi$ in vacuum and in nuclear matter [7] using an effective Lagrangian approach, considering only the $\phi K\bar{K}$ vertex [7], since we expect that a large fraction of the density dependence of $\Pi_\phi$ arises from the in-medium modification of the $K\bar{K}$ intermediate state,

$$\mathcal{L}_{\phi K\bar{K}} = ig_\phi \phi^\mu \{ \overline{K} (\partial_\mu K) - (\partial_\mu \overline{K}) K \}, \quad (1)$$

where $K$ and $\overline{K}$ are isospin doublets and $\phi^\mu$ is the $\phi$ meson vector field. The contribution from Eq. (1) to $\Pi_\phi(p)$ is given by

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

where $D_K(q) = 1/(q^2 - m_K^2 + i\epsilon)$ is the kaon propagator; $p = (p^0 = m_\phi, \vec{0})$ for a $\phi$ at rest, $m_\phi$ its mass; $m_K (= m_\pi)$ the kaon mass; and $g_\phi = 4.539$ [7] the coupling constant. The integral in Eq. (2) is divergent and will be regulated using a dipole form factor, with cutoff parameter $\Lambda_K$ [7]. The dependence of our results on the value of $\Lambda_K$ is studied below. The mass and decay width of the $\phi$ in vacuum ($m_\phi$ and $\Gamma_\phi$), as well as in nuclear matter ($m_\phi^*$ and $\Gamma_\phi^*$), are determined [7] from

$$m_\phi^2 = (m_\phi^0)^2 + \text{Re} \Pi_\phi(m_\phi^2), \quad \Gamma_\phi = - (1/m_\phi) \text{Im} \Pi_\phi(m_\phi^2). \quad (3)$$

The density dependence of the $\phi$ mass and decay width is driven by the interactions the $K\bar{K}$ intermediate state with the nuclear medium, which we calculate in the QMC model [8, 10]. In Figure 1 (left panel) we present the in-medium kaon Lorentz scalar mass as a function of the nuclear matter density, at normal nuclear matter density $\rho_0 = 0.15$ fm$^{-3} m_K^*$ has decreased by 13%. In Figure 1 we present the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig1.pdf}
\caption{Left panel: In-medium kaon mass; center and right panels: $\phi$ mass shift and decay width.}
\end{figure}

$\phi$ mass shift (center panel) and decay width (right panel) as a function of the nuclear matter density, $\rho_B$, for three values of $\Lambda_K$. For the largest value of $\rho_B$, the downward mass shift turns out to be a few percent at most for all $\Lambda_K$. On the other hand, $\Gamma_\phi^*$ depends strongly on the nuclear density, increasing by up to a factor of $\approx 20$ for the largest value of $\rho_B$. These results open the experimental possibility to study the binding and absorption of the $\phi$ in nuclei.

We now investigate the situation where the $\phi$ meson is “placed” inside a nucleus [9]. The nuclear density distributions for all nuclei but $^4$He are obtained in the QMC model [11]. For $^4$He we use Ref. [12]. Using a local density approximation the $\phi$–nucleus potentials for a nucleus $A$ is given by

$$V_{\phi A}(r) = U_\phi(r) - (i/2) W_\phi(r), \quad (4)$$

$$\text{where} \quad U_\phi(r) = \int d^3x \rho(x) \phi^\mu \sigma^\mu \phi(x)$$

$$\text{and} \quad W_\phi(r) = \frac{1}{2} \int d^3x \rho(x) \phi^\mu \sigma^\mu \phi(x).$$

The $\phi$–nucleus effective interaction is then

$$V_{\phi A}(r) = \rho A \cdot \frac{1}{N} \sum_{\alpha B} \left[ \rho A \cdot \rho B \cdot \frac{\phi^\mu B}{\rho A} \cdot \phi^\alpha B \right] \cdot \sigma^\mu \sigma^\alpha.$$
Fig. 2. Real $U_\phi(r)$ and imaginary $W_\phi(r)$ parts of the $\phi$–nucleus potentials for various nuclei.

where $r$ is the distance from the center of the nucleus and $U_\phi(r) = m^*_\phi(\rho_B^A(r)) - m_\phi$ and $W_\phi(r) = \Gamma_\phi(\rho_B^A(r))$ are, respectively, the $\phi$ mass shift and decay width inside nucleus $A$, with $\rho_B^A(r)$ the baryon density distribution of nucleus $A$. In Figure 2 we show the $\phi$ potentials for some selected nuclei. We note that the results for $^{197}$Au nucleus are presented here for the first time. One can see that the depth of $U_\phi(r)$ is sensitive to $\Lambda_K$, but $W_\phi(r)$ is not. Using these complex potentials, we calculate the $\phi$ single-particle energies and absorption widths for various nuclei, considering the situation where the $\phi$ is produced at rest. Then, under this condition, solving the Proca equation becomes equivalent to solving the Klein-Gordon equation

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

where $\mu$ is the reduced mass of the system in vacuum, and $V(r)$ is given by Eq. (4). The calculated bound state energies ($E$) and absorption widths ($\Gamma$) [9], related to the complex eigenvalue $\mathcal{E}$ by $E =$
The table below, Table I, provides a comparison between the results for the bound states in the original studies [13] and the updated results for the new studies. The table includes information about the nuclear-bound states, where the vector meson self-energy has a significant impact.

### Table I

| \( n \) | \( \Lambda_K = 2000 \) | \( \Lambda_K = 3000 \) | \( \Lambda_K = 4000 \) |
|---|---|---|---|
| \( \phi \) | \( E \) | \( E \) | \( E \) |
| \( ^3\text{He} \) | 1s | \(-0.8\) | \(-1.4\) | \(-3.2\) | 8.3 |
| \( ^{14}\text{C} \) | 1s | \(-2.1\) | \(-4.2\) | 10.6 | \(-6.4\) | 11.1 | \(-9.8\) | 11.2 |
| \( ^{16}\text{O} \) | 1s | \(-4.0\) | \(-5.9\) | 12.5 | \(-8.9\) | \(-10.0\) | 12.5 | \(-12.6\) | 13.4 | 12.4 |
| | 1p | \( n\) | \( n\) | \( n\) | \( n\) | \( n\) | \( n\) | \( n\) | \(-1.5\) | \n |
| \( ^{197}\text{Au} \) | 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 | \(-1.3\) | \n | \(-3.9\) | \(-5.3\) | 13.0 | \(-7.9\) | \(-8.8\) | 12.9 |
| | 2d | \n | \n | \n | \n | \n | \n | \n | \n |
| \( ^{208}\text{Pb} \) | 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 | \(-1.9\) | \n | \(-4.8\) | \(-6.1\) | 13.5 | \(-8.9\) | \(-9.8\) | 13.4 |
| | 2d | \n | \n | \n | \n | \n | \n | \n | \n |

Re \( E - \mu \) and \( \Gamma = -2 \text{Im} E \), respectively, are given in Table I with and without \( W_\phi(r) \). When \( W_\phi(r) = 0 \) the \( \phi \) is expected to form bound states with all the nuclei studied (values in parenthesis). However, \( E \) is dependent on \( \Lambda_K \), increasing with it. For \( W_\phi(r) \neq 0 \) the situation changes considerably. Whether or not the bound states can be observed experimentally is sensitive to the value of \( \Lambda_K \). However, for the largest value of \( \Lambda_K \), which yields the deepest potentials, the \( \phi \) is expected to form bound states with all the nuclei studied. However, 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 \( W_\phi(r) = 0 \). This feature is obvious for the \( ^4\text{He} \) nucleus, making it especially relevant to the future experiments, planned at J-PARC and JLab using light and medium-heavy nuclei [4, 5].

### 3. Nuclear-bound J/Ψ

Following the same procedure as in the \( \phi \) meson case, here we update results for the J/Ψ-nuclear bound states, considering only the lightest intermediate state in the J/Ψ self-energy, namely the \( \Delta \bar{\Delta} \) loop. In the original studies [13], the J/Ψ self-energy intermediate states involved the \( D, \Delta, \bar{D}, \Delta^* \), and \( \Delta^0 \) mesons. However, it turned out that the J/Ψ self-energy has larger contributions from the loops involving the \( D^\ast \) and \( \Delta^\ast \) mesons, which is unexpected; see Krein et al in Ref. [1] for details on the issues involved. In Table I, right panel, we present our updated results for the J/Ψ-nuclear bound states, adding also the \( ^{197}\text{Au} \) nucleus for the first time. We note that we have set the strong interaction width of the J/Ψ to zero [13], and therefore the J/Ψ potentials are real for all nuclei. From these results, we expect that the J/Ψ meson will form nuclear bound states for nearly all the nuclei considered, but some cases for \( ^4\text{He} \), and that the signal for the formation should be experimentally very clear, provided that the J/Ψ meson is produced in recoilless kinematics. Thus, it will be possible to search for the bound states in a \( ^{208}\text{Pb} \) nucleus at JLab after the 12 GeV upgrade.

### 4. Summary

We have presented results for the \( \phi \)- and J/Ψ-nuclear bound states, where the vector meson potentials in nuclei have been obtained in the local density approximation from the vector meson self-energy in nuclear matter. The in-medium \( K \) and \( D \) masses as well as the the nuclear density distributions for all nuclei but \( ^4\text{He} \) are obtained in the QMC model. From our results, we expect that the \( \phi \) and J/Ψ vector mesons should form bound states for all five nuclei studied, provided that these...
vector mesons are produced in (nearly) recoilless kinematics.

References

[1] R. S. Hayano and T. Hatsuda, Rev. Mod. Phys. 82, 2949 (2010); S. Leupold, V. Metag and U. Mosel, Int. J. Mod. Phys. E 19, 147 (2010); A. Hosaka, T. Hyodo, K. Sudo, Y. Yamaguchi and S. Yasui, Prog. Part. Nucl. Phys. 96, 88 (2017); G. Krein, A. W. Thomas and K. Tsushima, Prog. Part. Nucl. Phys. 100, 161 (2018) V. Metag, M. Nonaka and E. Y. Paryev, Prog. Part. Nucl. Phys. 97, 199 (2017).

[2] T. Appelquist and W. Fischler, Phys. Lett. 77B, 405 (1978); S. J. Brodsky, I. A. Schmidt and G. F. de Teramond, Phys. Rev. Lett. 64, 1011 (1990); M. E. Luke, A. V. Manohar and M. J. Savage, Phys. Lett. B 288, 355 (1992); H. Gao, T. S. H. Lee and V. Marinov, Phys. Rev. C 63, 022201 (2001); S. R. Beane, E. Chang, S. D. Cohen, W. Detmold, H.-W. Lin, K. Orginos, A. Parreoo and M. J. Savage, Phys. Rev. D 91, no. 11, 114503 (2015); H. Gao, H. Huang, T. Liu, J. Ping, F. Wang and Z. Zhao, Phys. Rev. C 95, no. 5, 055202 (2017).

[3] D. Kawama et al., PoS Hadron 2013, 178 (2013); D. Kawama et al., JPS Conf. Proc. 1, C01074 (2014); Y. Morino et al., JPS Conf. Proc. 8, 022009 (2015); T. Ishikawa et al., Phys. Lett. B 608, 215 (2005); R. Muto et al., Phys. Rev. Lett. 98, 042501 (2007); T. Mibe et al., Phys. Rev. C 76, 052202 (2007); X. Qian et al., Phys. Lett. B 680, 417 (2009); M. H. Wood et al., Phys. Rev. Lett. 105, 112301 (2010); A. Polyanskiy et al., Phys. Lett. B 695, 74 (2011).

[4] H. Ohnishi et al., Acta Phys. Polon. B 45, 819 (2014); P. Buhler et al. 2010 http://j-parc.jp/researcher/Hadron/en/pac_0907/pdf/Ohnishi.pdf; P. Buhler et al. 2010 http://j-parc.jp/researcher/Hadron/en/pac_1007/pdf/KEK_J-PARC-PAC2010-02.pdf

[5] M. Paolone et al. 2014 https://www.jlab.org/exp_prog/PACpage/PAC42/PAC42_FINAL_Report.pdf.

[6] C. M. Ko, P. Levai, X. J. Qiu and C. T. Li, Phys. Rev. C 45, 1400 (1992); T. Hatsuda and S. H. Lee, Phys. Rev. C 46, no. 1, R34 (1992); F. Klingl, T. Waas and W. Weise, Phys. Lett. B 431, 254 (1998); E. Oset and A. Ramos, Nucl. Phys. A 679 (2001) 616; D. Cabrera and M. J. Vicente Vacas, Phys. Rev. C 67, 045203 (2003); P. Gubler and W. Weise, Phys. Lett. B 751, 396 (2015); D. Cabrera, A. N. Hiller Blin and M. J. Vicente Vacas, Phys. Rev. C 95, no. 1, 015201 (2017).

[7] J. J. Cobos-Martínez, K. Tsushima, G. Krein and A. W. Thomas, Phys. Lett. B 771, 113 (2017).

[8] K. Tsushima, K. Saito, A. W. Thomas and S. V. Wright, Phys. Lett. B 429, 239 (1998) Erratum: Phys. Lett. B 436, 453 (1998).

[9] J. J. Cobos-Martínez, K. Tsushima, G. Krein and A. W. Thomas, Phys. Rev. C 96, no. 3, 035201 (2017).

[10] K. Saito, K. Tsushima and A. W. Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007).

[11] K. Saito, K. Tsushima and A. W. Thomas, Nucl. Phys. A 609, 339 (1996).

[12] K. Saito, K. Tsushima and A. W. Thomas, Phys. Rev. C 56, 566 (1997).

[13] G. Krein, A. W. Thomas and K. Tsushima, Phys. Lett. B 697, 136 (2011); K. Tsushima, D. H. Lu, G. Krein and A. W. Thomas, Phys. Rev. C 83, 065208 (2011).

[14] J. J. Cobos-Martínez, K. Tsushima, G. Krein and A. W. Thomas, “ηc- and J/Ψ–nucleus bound states”, in preparation.