Meson-nucleus bound states in QMC model

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Introduction

Experimental and theoretical studies have demonstrated that substantial attractive potential causes in-medium mass drops for hadrons within nuclear matter, created during heavy ion collision experiments. Under recoil-less kinematics, this may lead to form meson-nucleus bound states, where a meson is trapped inside a nucleus. Experimental programs at J-PARC-E29, $\bar{\text{P}}$ANDA@FAIR, and JLab have included the investigations on bound states. A precise measurement of the binding energies (BEs) of such states offers significant insights into the strongly interacting systems. This work explores the probable formations of $K, \bar{K}, D, \bar{D}, B, \bar{B}$ meson-nuclear bound states with the nuclei, ^{16}O, ^{40}Ca, ^{90}Zr, ^{197}Au, and ^{208}Pb, using potentials computed from the quark meson coupling (QMC) model.

QMC Model

The model relies on a mean-field description of non-overlapping nucleon bags bound by self-consistent interactions of scalar (σ, δ) and vector (ω, ρ) mesons with (anti)quarks inside the bags, which is further extended with the realization of Born-Oppenheimer approximation, to explore the properties of nuclei [1]. In the case of nuclei, Coulomb interaction between protons plays a crucial role and is thus introduced by the electromagnetic 4-potential A_μ. Within the mean-field approximation, nucleons are moving independently in the mesonic mean-field potentials $V_\sigma(r) = g_\sigma(\sigma(r))\sigma(r)$, $V_\delta(r) = g_\delta(\delta(r))\delta^3(r)$, $V_\omega(r) = g_\omega\omega_0(r)$, $V_\rho(r) = g_\rho\rho_0^3(r)$ and $V_c(r) = eA_0(r)$, where the boson fields are treated classically, i.e., $\langle\sigma\rangle \equiv \sigma, \langle\delta^a\rangle \equiv \delta^{a3}\delta^a, \langle\omega_\mu\rangle \equiv \delta^{\mu 0}\,\omega_\mu, \langle\rho^a_\mu\rangle \equiv \delta^{\mu0}\delta^{a3}\rho^a_\mu, \langle A_\mu\rangle \equiv \delta^{\mu 0}\,A_\mu$ and satisfy Dirac eq. obtained within the model,

$$(\frac{d}{dr} + \frac{\kappa}{r})G_\alpha(r) = [m^*_N(r) - V(r) + \epsilon_\alpha]F_\alpha(r)$$
$$(\frac{d}{dr} - \frac{\kappa}{r})F_\alpha(r) = [m^*_N(r) + V(r) - \epsilon_\alpha]G_\alpha(r)$$

where $m^*_N(r) = m_N - V_\sigma(r) - \tau^3 V_\delta(r)/2$, $V(r) = V_\omega(r) + \tau^3 V_\rho(r)/2 + (1+\tau^3)V_c(r)/2$ and $G_\alpha(F_\alpha)$ is the upper(lower) component of Dirac nucleon spinor[2], with α as single particle quantum number. Behaviors of the mean fields within a static, spherical nucleus are obtained through their equations of motion,

$$(-\frac{d^2}{dr^2} - \frac{2}{r}\frac{d}{dr} + m^2_M)M(r) \;=\; \mathcal{J}_M(r),$$

where m_M=$\{m_\sigma, m_\delta, m_\omega, m_\rho\, m_c \;=\; 0\}$ and the source terms are, $\mathcal{J}_M(r)$

$$= \begin{cases} g_\sigma \left[\rho^s_p(r)\left(-\frac{\partial m^*_p(r)}{\partial\sigma}\right) + \rho^s_n(r)\left(-\frac{\partial m^*_n(r)}{\partial\sigma}\right)\right] \\ \frac{g_\delta}{2}\left[\rho^s_p(r)\left(-\frac{\partial m^*_p(r)}{\partial\delta^3}\right) + \rho^s_n(r)\left(-\frac{\partial m^*_n(r)}{\partial\delta^3}\right)\right] \\ g_\omega\left[\rho_p(r) + \rho_n(r)\right] \\ \frac{g_\rho}{2}\left[\rho_p(r) - \rho_n(r)\right] \\ e\rho_p(r) \end{cases}$$

with the nucleon($i = p, n$) densities defined as,

$$\rho^s_i(r) = \sum_i^{Z \text{ or, N}} \frac{(2j_i+1)}{4\pi r^2}(|G_i(r)|^2 - |F_i(r)|^2)$$
$$\rho_i(r) = \sum_i^{Z \text{ or, N}} \frac{(2j_i+1)}{4\pi r^2}(|G_i(r)|^2 + |F_i(r)|^2)$$

and the in-medium masses of the hadrons take the following form within the model,

$$m^\star_h(\sigma, \delta^3) = \frac{\sum_f n_{fh}\Omega^\star_{fh} - Z_h}{R^\star_h} + \frac{4}{3}\pi R^{\star 3}_h B,$$

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with $\Omega_{fh} = \sqrt{x_{fh}^{\star 2} + (R_h^\star m_{fh}^\star)^2}$ with $m_{fh}^\star = m_{fh}^0 - V_\sigma^q - (\tau_f^3) V_\delta^q/2$, are effective light quark masses. However, for heavy quarks(Q), $m_Q^\star = m_Q$. Details of the parameters can be found in ref.[2]. The potentials experienced by the pseudoscalar mesons (P) while they are produced inside the nucleus are,

$$V_s^P(r) = m_P^\star(r) - m_P,$$
$$V_v^{K^-,D^-,B^-}(r) = \frac{1}{3}V_\omega(r) - \frac{1}{2}V_\rho(r) - A(r),$$
$$V_v^{\bar{K}^0,\bar{D}^0,\bar{B}^0}(r) = \frac{1}{3}V_\omega(r) + \frac{1}{2}V_\rho(r),$$
$$V_v^{K^0,D^0,B^0}(r) = -(\frac{1}{3}V_\omega(r) + \frac{1}{2}V_\rho(r)).$$

With a careful inspection of the potentials and their BEs, obtained from the relativistic Klein-Gordon (K-G) equation,

$$\left[\nabla^2 + [\epsilon_P - m_P - V_v^P(r)]^2 - m_P^{\star 2}(r)\right]\Phi_P(r) = 0,$$

a naive idea of the existence of P-mesic bound states can be drawn. Here, $\nabla^2 = \frac{d^2}{dr^2} - \frac{l(l+1)}{r^2}$, $\Phi_P(r)$ is the wave function and ϵ_P is the binding energy for the state.

Results and Discussions

Using the parameters, $g_\sigma = 6.26$, $g_\omega = 8.17$, $g_\delta = 18.63$, $g_\rho = 9.33$, $m_\sigma = 418$ MeV, $m_\omega = 778$ MeV, $m_\delta = 1000$ MeV and $m_\rho = 770$ MeV, the mean-field potentials are solved iteratively for various nuclei. For the obtained meson-nucleus potentials, BEs of the states are calculated through the K-G equation. The

TABLE I: BEs (MeV) for $B^- - {}^{208}$Pb states, considering different conditions of interactions within the nuclei. '×' refers to unbound states and $\tilde{V}_\omega = 1.96 \times V_\omega$ is phenomenologically suggested more repulsive ω-coupling [1].

	$B^-(V_\omega, V_c)$	$B^-(V_\omega)$	$B^-(\tilde{V}_\omega, V_c)$	$B^-(\tilde{V}_\omega)$
$1s$	-33.31	-9.61	-17.58	×
$1p$	-32.73	-9.30	-17.49	×

results are presented for B^- meson in Table - I, indicating Coulomb interaction provides more attractive potentials to negatively charged mesons within the nucleus. Furthermore, the opposite ω interaction for P^0 and $\bar{P}^0$

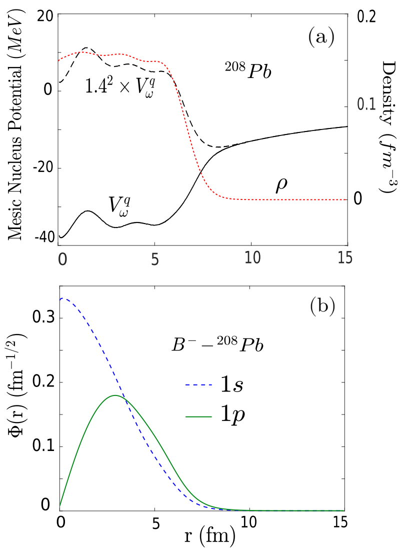

FIG. 1: Behavior of the (a)$B^- - {}^{208}$Pb potentials where the dotted line represents the baryon density distributions in ^{208}Pb and (b) ground state wave functions of $B^- - {}^{208}$Pb bound state.

leads to a significant difference in their BEs, revealing the influence of vector mean field. Whereas, a comparison between BEs of $\bar{P}^0$ with P^- meson states without Coulomb interaction unveils the contribution of ρ field. In certain cases, the exclusive contribution of the δ meson can lead to the formation of a light-bound state among a few mesons. Our results indicate that bound state formations are more permissible with heavier mesons, even when the potentials are comparable, reflecting the scalar interaction strengths of these mesons within nuclei. Due to the constituents of B mesons, they can form more strongly bound states with nuclei. As illustrated in Fig.1, in such structures, the meson is much closer to the nuclei, allowing to probe smaller variations in the nuclear matter properties.

References

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