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ηN interactions in the nuclear medium. η-nuclear bound states

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Abstract. We report on our recent study of in-medium ηN interactions and η-nuclear quasi-bound states. The ηN scattering amplitudes considered in the calculations are constructed within coupled-channel models that incorporate the S_{11} $N^*(1535)$ resonance. The implications of self-consistent treatment and the role played by subthreshold dynamics are discussed.

1 Introduction

The ηN attraction generated by the $N^*(1535)$ resonance near threshold seems to be strong enough to allow binding of the η meson in nuclei. However, in-medium modifications and strong energy dependence of the ηN scattering amplitudes have to be carefully taken into account. This contribution briefly summarizes systematic treatment of energy dependence within self-consistent calculations of η quasi-bound states in selected nuclei (see [1–3] for more details).

2 Methodology

The ηN scattering amplitudes are highly model dependent as illustrated in Fig. 1 for meson-baryon interaction models GW [4], CS [5], M2 [6], and GR [7]. The ηN amplitudes differ below as well as above the ηN threshold, except perhaps common value $\mathrm{Im}F_{\eta N} \approx 0.2 - 0.3$ fm at threshold.

The in-medium amplitudes which serve as an input in our many-body self-consistent calculations are obtained from the free-space amplitudes GW and M2 by applying the multiple scattering approach [8] (see Ref. [2] for details). In the GR and CS models, the Pauli principle restricts integration domain in the Green's function which enters the underlying Lippmann-Schwinger equations [2].

The strong energy dependence of the ηN scattering amplitudes $F_{\eta N}(\sqrt{s})$ has to be treated self-consistently [1, 2]. The argument $\sqrt{s}$ in the scattering amplitudes is given by

$$\sqrt{s} = \sqrt{(\sqrt{s_{\mathrm{th}}} - B_\eta - B_N)^2 - (\vec{p}_\eta + \vec{p}_N)^2} \leq \sqrt{s_{\mathrm{th}}}, \tag{1}$$

where $\sqrt{s_{\mathrm{th}}} \equiv m_\eta + m_N$ and B_η and B_N are η and nucleon binding energies. In the nuclear medium (for $A \gg 1$ approximated by the lab system) the momentum dependent term causes additional downward energy shift, since $(\vec{p}_\eta + \vec{p}_N)^2 \neq 0$, which can be approximated as [2]

$$\delta\sqrt{s} \approx -B_N\frac{\rho}{\bar{\rho}} - \xi_N B_\eta\frac{\rho}{\rho_0} - \xi_N T_N(\frac{\rho}{\rho_0})^{2/3} - \xi_\eta\frac{\sqrt{s}}{\omega_\eta E_N}2\pi\mathrm{Re}\, F_{\eta N}(\sqrt{s},\rho)\rho\ , \tag{2}$$

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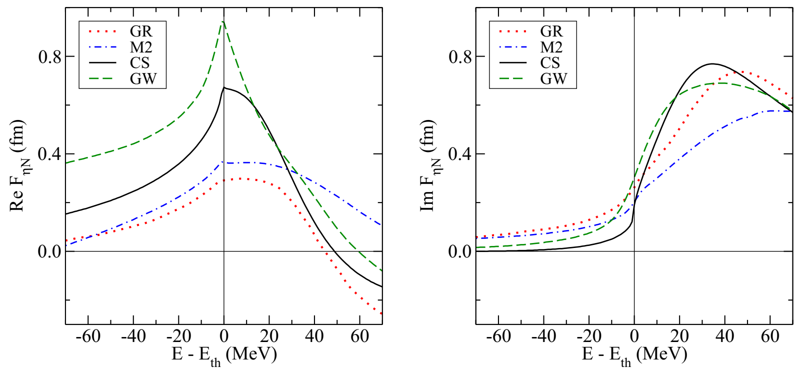

Figure 1. Energy dependence of the real (left panel) and imaginary (right panel) parts of the free ηN scattering amplitude in interaction models GW [4] (dashed), CS [5] (solid), M2 [6] (dot-dashed), and GR [7] (dotted). The vertical line denotes the ηN threshold.

where $\xi_{N(\eta)} = m_{N(\eta)}/(m_N + m_\eta)$, $T_N = 23.0$ MeV at ρ_0, $B_N \approx 8.5$ MeV is the average nucleon binding energy, and $\bar{\rho}$ is the average nuclear density. For attractive scattering amplitudes, all terms in Eq. 2 are negative definite, providing substantial downward energy shift. A variant of Eq. 2 was used in η-nuclear three- and four-body calculations (see Ref. [3] for details).

In few-body ηNN and ηNNN systems, the η-nuclear cluster wave functions were expanded in a hyperspherical basis and the ground-state binding energies were calculated variationally. For the NN interaction, the Minnesota central potential [9] and the Argonne AV4' potential [10] were used. The ηN interaction was described by energy dependent local ηN potentials that reproduce the ηN scattering amplitudes below threshold in considered interaction models [3].

The conversion widths were evaluated through the expression $\Gamma/2 \approx \langle \Psi_{g.s.}| - \mathrm{I}m V_{\eta N} |\Psi_{g.s.}\rangle$, where $V_{\eta N}$ sums overall pairwise ηN interactions [1].

The interaction of the η meson with the nuclear many-body system was described by the Klein–Gordon (KG) equation of the form

$$[\,\nabla^2 + \tilde{\omega}_\eta^2 - m_\eta^2 - \Pi_\eta(\omega_\eta, \rho)\,]\,\psi = 0\,, \tag{3}$$

where $\tilde{\omega}_\eta = \omega_\eta - \mathrm{i}\Gamma_\eta/2$ is complex energy of η, $\omega_\eta = m_\eta - B_\eta$, and Γ_η is the width of the η-nuclear bound state. The self-energy operator $\Pi_\eta(\sqrt{s}, \rho) \equiv 2\omega_\eta V_\eta = -(\sqrt{s}/E_N)\, 4\pi F_{\eta N}(\sqrt{s}, \rho)\rho$ was constructed self-consistently using the RMF density distributions in a core nucleus.

It is to be stressed that $\mathrm{Re}F_{\eta N}(\sqrt{s})$ and B_η appear as arguments in the expression for $\delta\sqrt{s}$ (Eq. 2), which in turn serves as an argument for $F_{\eta N}$ and thus for the self-energy Π_η. Therefore, a self-consistency scheme in terms of both Π_η and B_η is required in calculations.

3 Results

Our few-body calculations of the ηNN system found *no* bound states in the considered coupled-channel models. For ηNNN, a relatively broad and weakly bound state (with η separation energy below 1 MeV) was found for the Minesota NN potential and one particular variant of the ηN potential

[1] We found an error in normalization in Ref. [3], which made the calculated widths about factor of 2 larger.

that reproduced the GW scattering amplitudes (see Ref. [3] for details). *No* ηNNN bound states were found using more realistic NN interaction models.

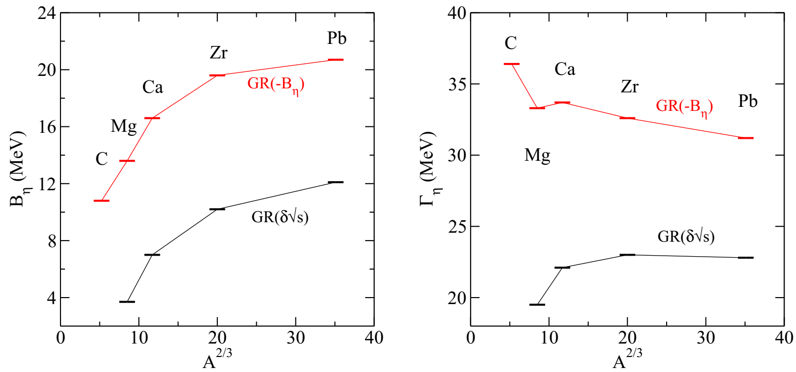

Figure 2. Binding energies (left) and widths (right) of the $1s$ η-nuclear states in selected nuclei calculated using the GR ηN scattering amplitude [7] with different procedures for subthreshold energy shift $\delta\sqrt{s}$.

Figure 2 illustrates the role of the energy dependence of ηN scattering amplitudes in self-consistent evaluations of η nuclear-states in many-body nuclear systems. A comparison is made for the in-medium GR amplitude: our self-consistency scheme based on $\delta\sqrt{s}$ of Eq. 2 (marked $\delta\sqrt{s}$) reduces considerably the GR binding energies and widths with respect to the original calculations of Ref. [7] that used the $\delta\sqrt{s} = -B_\eta$ procedure (marked $-B_\eta$). However, even the reduced GR widths are still quite high, suggesting that η-nuclear states will be extremely difficult to resolve if the GR model is the realistic one.

The model dependence of the ηN scattering amplitudes shown in Fig. 1 manifests itself in the calculations of η-nuclear states. Figure 3 presents binding energies B_η and widths Γ_η calculated for the $1s$ η-nuclear states in selected nuclei using the above ηN amplitudes.

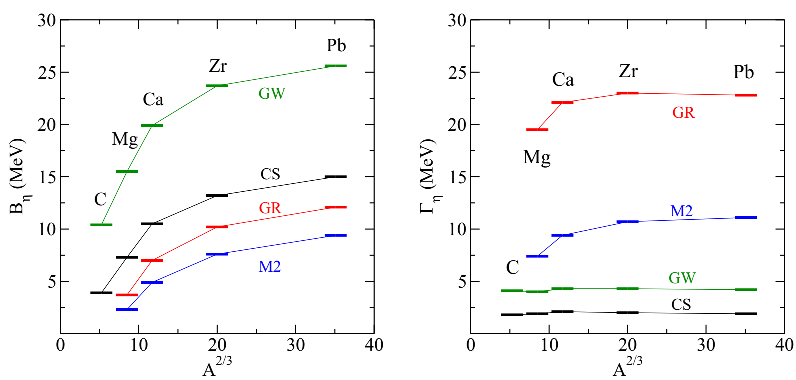

Figure 3. Binding energies (left) and widths (right) of $1s$ η-nuclear states in selected nuclei calculated self-consistently using the M2, GR, CS, and GW ηN scattering amplitudes (see text).

The left panel of Fig. 3 demonstrates that for each of the ηN amplitude models the binding energy increases with A and tends to saturate for large values of A. The hierarchy of the curves reflects the strength of $\mathrm{Re}F_{\eta N}(\sqrt{s})$ in the subthreshold region (see Fig. 1). The M2 amplitude is too weak to produce the $1s$ η bound state in ^{12}C. In contrast, $\mathrm{Re}F_{\eta N}(\sqrt{s})$ of the GW model is strong enough to bind η in ^{12}C and even in lighter nuclei, e.g., it predicts the $1s$ η bound state in ^{4}He with $B_\eta = 1.2$ MeV and $\Gamma_\eta = 2.3$ MeV (calculated using a static ^{4}He density).

The right panel shows substantial differences between the widths Γ_η calculated using the above mentioned models. The CS and GW models yield relatively small uniform widths of order 2 and 4 MeV, respectively. On the other hand, the GR and M2 models predict much larger widths which increase with A. This reflects partly the energy dependence of $\mathrm{Im}F_{\eta N}(\sqrt{s})$ in the subthreshold region and partly the difference in the in-medium renormalization stemming from $\mathrm{Re}F_{\eta N}(\sqrt{s})$. For instance, the large downward energy shift due to the subthreshold amplitude in the GW model (57 MeV at ρ_0) causes a particularly large reduction in the strength of the $\mathrm{Im}F_{\eta N}(\sqrt{s})$ input.

The widths calculated here do not include contributions from two-nucleon processes which are estimated to add a few MeV. We may therefore conclude that η-nuclear states could in principle be observed if the CS and GW models turn out to be realistic ones, provided a suitable production/formation reaction is found. Other models give either too large widths or are too weak to generate η-nuclear bound states in lighter nuclei.

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