Relativistic nuclear model with point-couplings constrained by QCD and chiral symmetry

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We have derived a microscopic relativistic point-coupling model of nuclear many-body dynamics constrained by in-medium QCD sum rules and chiral symmetry [1]. The effective Lagrangian is characterized by density dependent coupling strengths, determined by chiral one- and two-pion exchange and by QCD sum rule constraints for the large isoscalar nucleon self-energies that arise through changes of the quark condensate and the quark density at finite baryon density. In comparison with purely phenomenological mean-field approaches, the built-in QCD constraints and the explicit treatment of pion exchange restrict the freedom in adjusting parameters and functional forms of density dependent couplings. It is shown that chiral (two-pion exchange) fluctuations play a prominent role for nuclear binding and saturation, whereas strong scalar and vector fields of about equal magnitude and opposite sign, induced by changes of the QCD vacuum in the presence of baryonic matter, generate the large effective spin-orbit potential in finite nuclei.

The model is defined by the Lagrangian density

$$\mathcal{L} = \mathcal{L}_{\rm free} + \mathcal{L}_{\rm 4f} + \mathcal{L}_{\rm der} + \mathcal{L}_{\rm em}, \qquad (1)$$

with the four terms specified as follows:

$$\begin{aligned}
\mathcal{L}_{\rm free} &= \bar{\psi}(i\gamma_\mu\partial^\mu - M)\psi\ , & (2)\\
\mathcal{L}_{\rm 4f} &= -\frac{1}{2}\, G_S(\hat{\rho})(\bar{\psi}\psi)(\bar{\psi}\psi) \\
&\quad -\frac{1}{2}\, G_V(\hat{\rho})(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi) + \dots\ , & (3)\\
\mathcal{L}_{\rm der} &= -\frac{1}{2}\, D_S(\hat{\rho})(\partial_\nu\bar{\psi}\psi)(\partial^\nu\bar{\psi}\psi) \\
&\quad -\frac{1}{2}\, D_V(\hat{\rho})(\partial_\nu\bar{\psi}\gamma_\mu\psi)(\partial^\nu\bar{\psi}\gamma^\mu\psi) + \ \dots\ , & (4)\\
\mathcal{L}_{\rm em} &= eA^\mu\bar{\psi}\frac{1+\tau_3}{2}\gamma_\mu\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\ . & (5)
\end{aligned}$$

This Lagrangian (1)-(5) is understood to be formally used in the mean-field approximation, with fluctuations encoded in density-dependent couplings $G_i(\hat{\rho})$ and $D_i(\hat{\rho})$. Combining effects from in-medium QCD condensates [2], where the ratio of scalar and vector nucleon self-energies at the leading order is:

$$\frac{\Sigma_S^{(0)}}{\Sigma_V^{(0)}} = \frac{G_S^{(0)}\rho_s}{G_V^{(0)}\rho} = -\frac{\sigma_N}{4(m_u+m_d)}\frac{\rho_s}{\rho} \simeq -1\ , \qquad (6)$$

and pionic fluctuations encoded in $G_{S,V}^{(\pi)}$, determined within in-medium Chiral Perturbation Theory [3], the strength parameters of the isoscalar four-fermion interaction terms in the Lagrangian (1) are:

$$G_{S,V}(\rho) = G_{S,V}^{(0)} + G_{S,V}^{(\pi)}(\rho)\ . \qquad (7)$$

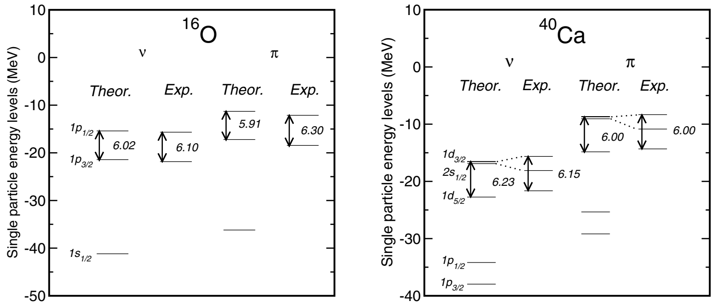

Figure 1: Neutron and proton single-particle energies for ^{16}O (left) and ^{40}Ca (right)

The following table displays the calculated binding energies per nucleon and charge radii of ^{16}O and ^{40}Ca in comparison with experimental data (in brackets).

	E/A (exp) (MeV)	r_c (exp) (fm^{-3})
^{16}O	8.027 (7.976)	2.735 (2.730)
^{40}Ca	8.508 (8.551)	3.470 (3.485)

The neutron and proton single-particle energies are reproduced, respectively, in comparison with the corresponding experimental levels in Fig. 1.

We have demonstrated that an approach to nuclear dynamics, constrained by the chiral symmetry breaking pattern and the condensate structure of low-energy QCD, can describe properties of finite nuclei, at a quantitative level comparable with the best phenomenological relativistic and non-relativistic mean-field models. This is a promising result which opens perspectives of bridging the gap between basic features of low-energy, non perturbative QCD and the rich nuclear phenomenology.

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References

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