Relativistic Nuclear Model With Point-Couplings Constrained by QCD and Chiral Symmetry ◇

P. Finelli [a,b], N. Kaiser, D. Vretenar [c], and W. Weise

[a] ECT*, I-38050 Villazzano (Trento), Italy

[b] Physics Department, University of Bologna, and INFN - Bologna, I-40126 Bologna, Italy

[c] Physics Department, Faculty of Science, University of Zagreb, 10 000 Zagreb, Croatia

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 point couplings of nucleons. Their strengths are determined by explicit contributions from chiral one- and two-pion exchange and by QCD sum rule constraints for the Lorentz scalar and vector nucleon self-energies that arise through the changes of the scalar quark condensate and the quark density at finite baryon density. In comparison to purely phenomenological mean-field approaches, the built-in QCD sum rule constraints and the explicit treatment of (multi-)pion exchange dynamics restrict the freedom in adjusting parameters and the functional form of density dependent couplings. It is shown that chiral two-pion exchange between nucleons plays a prominent role for nuclear binding and saturation, whereas the strong Lorentz 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:

$$\mathcal{L} = \mathcal{L}_{\rm free} + \mathcal{L}_{\rm 4N} + \mathcal{L}_{\rm der} + \mathcal{L}_{\rm em}, \tag{1}$$

with the four individual terms specified as follows:

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

This Lagrangian (1)-(5) is understood to be formally used in the mean-field Hartree approximation, with effects from pionic fluctuations encoded in the 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:

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

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

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

The following table displays the calculated binding energies per nucleon and the charge radii of the closed shell nuclei ^{16}O and ^{40}Ca in comparison with experimental data (given 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 single-particle energies of neutrons and protons are also well reproduced for these nuclei, in comparison to the corresponding experimental levels as shown in Fig. 1.

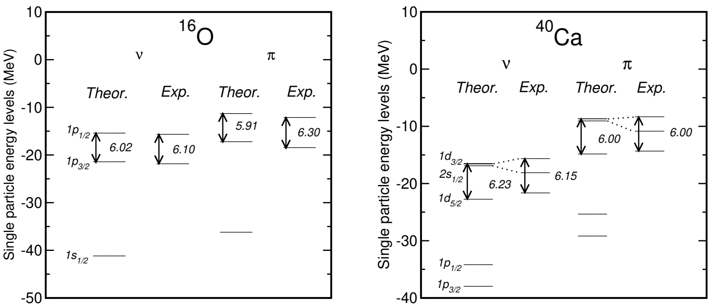

Fig. 1: Neutron and proton single-particle energies for the closed shell nuclei ^{16}O (left) and ^{40}Ca (right)

In summary, we have demonstrated that an approach to nuclear many-body 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.

References

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◇ Work supported in part by BMBF and GSI