Vol. 40 (2009) *ACTA PHYSICA POLONICA B* No 3

APPLICATIONS OF IN-MEDIUM CHIRAL DYNAMICS TO NUCLEAR STRUCTURE*

P. Finelli

Department of Physics, University of Bologna and INFN
Via Irnerio 46, 40126 Bologna, Italy
paolo.finelli@bo.infn.it

(Received November 12, 2008)

A relativistic nuclear energy density functional is developed, guided by two important features that establish connections with chiral dynamics and the symmetry breaking pattern of low-energy QCD: (*i*) strong scalar and vector fields related to in-medium changes of QCD vacuum condensates; (*ii*) the long- and intermediate-range interactions generated by one- and two-pion exchange, derived from in-medium chiral perturbation theory, with explicit inclusion of $\Delta(1232)$ excitations. Applications are presented for the description of ground-state properties.

PACS numbers: 21.10.Dr, 21.60.Jz

One of the most complete and accurate description of structure phenomena in finite nuclei is currently provided by self-consistent non-relativistic and relativistic mean-field approaches. They represent an approximate implementation of Kohn–Sham density functional theory (DFT) [1]. The DFT provides a description of the nuclear many-body problem in terms of an energy density functional $E[\rho]$. A major goal of nuclear structure theory is to build an energy density functional which is universal, in the sense that the same functional is used for all nuclei with the same set of parameters. This framework should then provide a reliable microscopic description of infinite nuclear and neutron matter, ground-state properties of bound nuclei, rotational spectra and low-energy vibrations.

In order to formulate a microscopic nuclear energy density functional, one must be able to systematically calculate the exchange-correlation part

* Presented at the Zakopane Conference on Nuclear Physics, September 1–7, 2008, Zakopane, Poland.

of the energy functional, $E_{\rm xc}[\rho]$, starting from the relevant active degrees of freedom at low energy. In principle, the *exact* $E_{\rm xc}$ includes all kind of many-body effects; the usefulness of DFT crucially depends on our ability to construct accurate approximations to the exact exchange-correlation energy. The natural microscopic framework is chiral effective field theory [2]. It is based on the separation of scales between long-range pion–nucleon dynamics, described explicitly, and short-distance interactions not resolved in detail at low energies.

Our approach to the nuclear energy density functional, emphasizing links with low-energy QCD and its symmetry breaking pattern, has been introduced in Refs. [3,4] and it is based on the two following sources of interaction:

1. Short-range dynamics

The nuclear ground state is characterized by strong scalar $U_{\rm S}$ and vector $U_{\rm V}$ mean fields which have their origin in the in-medium changes of the scalar quark condensate (the chiral condensate) and of the quark density. They can be calculated by QCD sum rules techniques [5] to obtain, at leading order,

$$U_{\rm S} = -\frac{\sigma_N M_N}{m_\pi^2 f_\pi^2}\rho_{\rm S}\,, \tag{1}$$

$$U_{\rm V} = \frac{4(m_u+m_d)M_N}{m_\pi^2 f_\pi^2}\rho\,, \tag{2}$$

where $\sigma_N = \langle N|m_q\,\bar{q}q|N\rangle$ is the nucleon sigma term ($\simeq$ 50 MeV), m_π the pion mass (138 MeV), M_N the nucleon mass (939 MeV), $m_{u,d}$ the quark masses ($\simeq$ 5 MeV), f_π the pion decay constant (92.4 MeV) and ρ and $\rho_{\rm S}$ are the baryon and the scalar density, respectively. The resulting $U_{\rm S}$ and $U_{\rm V}$ are individually of the order of 300–400 MeV in magnitude. Their ratio

$$\frac{U_{\rm S}}{U_{\rm V}} = -\frac{\sigma_N}{4(m_u+m_d)}\frac{\rho_{\rm S}}{\rho} \tag{3}$$

is close to -1. As a result, in the single-nucleon Dirac equation there is an almost complete cancellation in the central potential ($\sim U_{\rm V}+U_{\rm S}$), giving a negligible contribution to the binding of the system, but, at the same time, a large contribution to the spin-orbit potential

$$V_{\rm LS} \sim \frac{1}{2M_N^2}\frac{1}{r}\left(\frac{\partial}{\partial r}(U_{\rm V}-U_{\rm S})\right)\boldsymbol{l}\cdot\boldsymbol{s}\,. \tag{4}$$

2. Medium- and long-range correlations induced by pion-exchange dynamics

Nuclear binding and saturation arise primarily from chiral (pionic) fluctuations in combination with Pauli blocking effects and three-nucleon ($3N$) interactions, superimposed on the condensate background fields and calculated according to the rules of in-medium chiral perturbation theory (ChPT). The starting point is the description of nuclear matter based on the chiral effective Lagrangian with pions and nucleons with the inclusion of explicit $\Delta(1232)$ degrees of freedom [6]. The relevant *small* scales are the Fermi momentum $k_{\rm F}$, the pion mass m_π and the $\Delta - N$ mass difference $\Delta \equiv M_\Delta - M_N \simeq 2.1 m_\pi$, all of which are well separated from the characteristic scale of spontaneous chiral symmetry breaking, $4\pi f_\pi \simeq 1.16$ GeV. The calculations have been performed to three-loop order in the energy density. They incorporate the one-pion exchange Fock term, iterated one-pion exchange and irreducible two-pion exchange, including one or two intermediate Δ's. The resulting nuclear matter equation of state is given as an expansion in powers of the Fermi momentum $k_{\rm F}$. The expansion coefficients are functions of $k_{\rm F}/m_\pi$ and Δ/m_π, the dimensionless ratios of the relevant small scales. Divergent momentum space loop integrals are regularized by introducing subtraction constants in the spectral representations of these terms (the only free parameters a chiral approach). They encode short-distance dynamics not resolved in detail at the characteristic momentum scale $k_{\rm F} \ll 4\pi f_\pi$. The finite parts of the energy density, written in closed form as functions of $k_{\rm F}/m_\pi$ and Δ/m_π, represent long and intermediate range (chiral) dynamics with input fixed entirely in the πN sector.

3. A mean field approach for finite nuclei

The relativistic density functional describing the ground-state energy of the system can be written as a sum of four distinct terms:

$$E_{\rm free}[\hat\rho] = \int d^3r \; \langle\phi_0|\bar\psi[-i\boldsymbol{\gamma}\cdot\boldsymbol{\nabla} + M_N]\psi|\phi_0\rangle\,, \tag{5}$$

$$E_{\rm H}[\hat\rho] = \tfrac{1}{2}\int d^3r \; \{\langle\phi_0|G_{\rm S}^{(0)}(\bar\psi\psi)^2|\phi_0\rangle + \langle\phi_0|G_{\rm V}^{(0)}(\bar\psi\gamma_\mu\psi)^2|\phi_0\rangle\}\,, \tag{6}$$

$$\begin{aligned} E_\pi[\hat\rho] = \tfrac{1}{2}\int d^3r \; \Big\{&\langle\phi_0|G_{\rm S}^{(\pi)}(\hat\rho)(\bar\psi\psi)^2|\phi_0\rangle + \langle\phi_0|G_{\rm V}^{(\pi)}(\hat\rho)(\bar\psi\gamma_\mu\psi)^2|\phi_0\rangle \\ &+\langle\phi_0|G_{\rm TS}^{(\pi)}(\hat\rho)(\bar\psi\vec\tau\psi)^2|\phi_0\rangle + \langle\phi_0|G_{\rm TV}^{(\pi)}(\hat\rho)(\bar\psi\gamma_\mu\vec\tau\psi)^2|\phi_0\rangle \\ &-\langle\phi_0|D_{\rm S}^{(\pi)}[\boldsymbol{\nabla}(\bar\psi\psi)]^2|\phi_0\rangle\Big\}\,, \end{aligned} \tag{7}$$

$$E_{\rm coul}[\hat\rho] = \tfrac{1}{2}\int d^3r \; \langle\phi_0|A^\mu e\bar\psi\frac{1+\tau_3}{2}\gamma_\mu\psi|\phi_0\rangle\,, \tag{8}$$

where $|\phi_0\rangle$ denotes the nuclear ground state. Here $E_{\rm free}$ is the energy of the free (relativistic) nucleons including their rest mass. $E_{\rm H}$ is a Hartree-type contribution representing strong scalar and vector mean fields, later to be connected with the leading terms of the corresponding nucleon self-energies deduced from in-medium QCD sum rules. Furthermore, E_π is the part of the energy generated by chiral $\pi N\Delta$-dynamics, including a derivative (surface) term, with all pieces explicitly derived in Ref. [6]. The couplings are

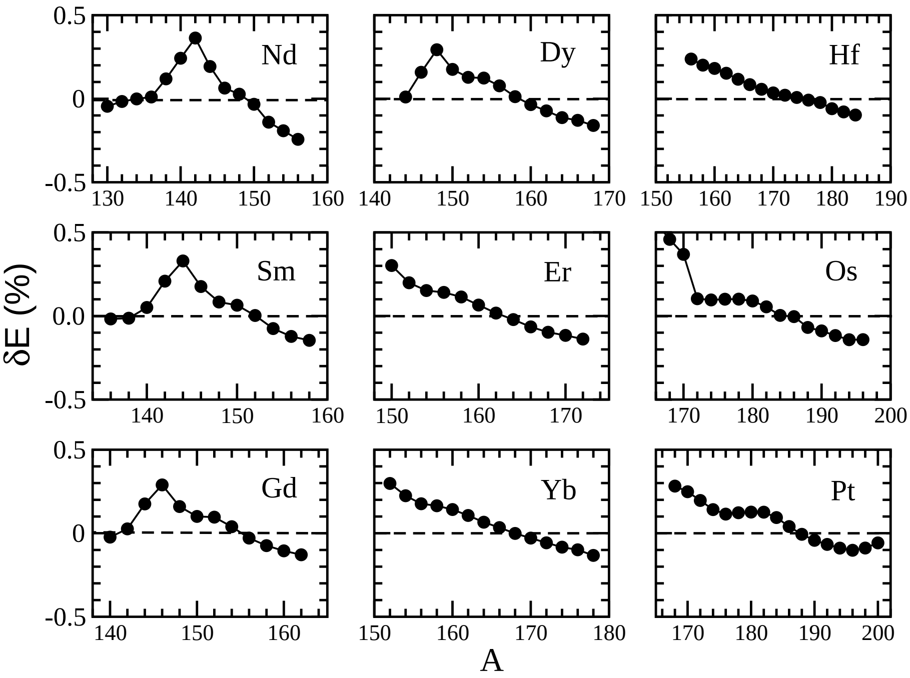

Fig. 1. The deviations (in percent) of the calculated binding energies from the experimental values of Nd, Sm, Gd, Dy, Er, Yb, Hf, Os, and Pt isotopes. We used the Gogny interaction in the pairing channel.

decomposed into density independent parts $G_i^{(0)}$ which arise from strong isoscalar-scalar and vector background fields, and density dependent parts $G_i^{(\pi)}(\hat{\rho})$ generated (regularized) by one- and two-pion exchange dynamics. It is assumed that only pionic processes contribute to the isovector channels. $D_{\rm S}^{(\pi)}$ is a surface term and can be estimated within the chiral approach [6]. There are 7 free parameters ($G_{\rm S}^{(0)}$,$G_{\rm V}^{(0)}$, two isoscalar and two isovector contact terms in the contact couplings $G_i^{(\pi)}(\hat{\rho})$ and the surface term $D_{\rm S}^{(\pi)}$) that have to be adjusted in order to reproduce ground-state properties of closed shell nuclei. To demonstrate that chiral effective field theory provides a consistent microscopic framework for finite nuclei description, we show in Fig. 1 a large set of calculations for isotope chains of deformed nuclei. Good agreement is found over the entire region of deformed nuclei. The maximum deviation of the calculated binding energies from data is below 0.5% for all isotopes.

I would like to thank my collaborators Dario Vretenar, Norbert Kaiser and Wolfram Weise. This work has been supported by MIUR and INFN.

REFERENCES

[1] R.M. Dreizler, E.K.U. Gross, *Density Functional Theory*, Spinger, 1990.
[2] S. Scherer, M.R. Schindler, `hep-ph/0505265`.
[3] P. Finelli, N. Kaiser, D. Vretenar, W. Weise, *Nucl. Phys.* **A735**, 449 (2004).
[4] P. Finelli, N. Kaiser, D. Vretenar, W. Weise, *Nucl. Phys.* **A770**, 1 (2006).
[5] T.D. Cohen *et al.*, *Prog. Part. Nucl. Phys.* **35**, 221 (1995).
[6] S. Fritsch, N. Kaiser, W. Weise, *Nucl. Phys.* **A750**, 259 (2005).