Relativistic Nuclear Density Functional Constrained by QCD and Chiral Symmetry ◊

P. Finelli, N. Kaiser, D. Vretenar [a], and W. Weise
[a] Physics Department, Faculty of Science, University of Zagreb, 10 000 Zagreb, Croatia

A new relativistic energy density functional has been derived in [1], where the many-body dynamics is constrained by in-medium QCD sum rules [2] and chiral symmetry [3]. The basic assumptions at the origin of our approach are:

1. Large scalar and vector fields of approximately equal magnitude and opposite sign, arising from the in-medium changes of the chiral condensate and the quark density, act as background fields (BG). They are parametrized by local four-point interactions with constant couplings G_i^{BG} $(i = S, V)$.

2. In-medium chiral pion-nucleon dynamics, calculated according to the rules of chiral perturbation theory, is consistently encoded in density dependent couplings $G_i^{\pi}(\rho)$ $(i = S, V, TS, TV)$ and D_i^{π} $(i = S, V)$.

Inspired by the success of Density Functional Theory (DFT) [4], we have identified the following pattern in the expression of the energy ground-state[1]:

$$\mathcal{E}_0[\rho] = \mathcal{E}_{\rm kin}[\rho] + \mathcal{E}_{\rm BG}[\rho] + \mathcal{E}_{\pi}[\rho] + \mathcal{E}_{\rm coul}[\rho] \; , \qquad (1)$$

where $\mathcal{E}_{\rm kin}$ is the kinetic energy of the free system and

$$\begin{aligned} \mathcal{E}_{\rm BG}[\rho] &= \frac{1}{2}\int d^3x \; [G_S^{BG}\rho_S^2 + G_V^{BG}\rho^2] \; , & (2) \\ \mathcal{E}_{\pi}[\rho] &= \frac{1}{2}\Big\{\int d^3x \; [G_S^{\pi}(\rho)\rho_S^2 + G_V^{\pi}(\rho)\rho^2] \\ &\quad + \int d^3x \; [G_{TS}^{\pi}(\rho)\rho_{S3}^2 + G_{TV}^{\pi}(\rho)\rho_3^2] \\ &\quad - \int d^3x \; [D_S^{\pi}(\vec\nabla\rho_S)^2 + D_V^{\pi}(\vec\nabla\rho)^2]\Big\} \; , & (3) \\ \mathcal{E}_{coul}[\hat\rho] &= \int d^3x \; A^0 e\frac{1+\tau_3}{2}\rho \; . & (4) \end{aligned}$$

The overall structure of $\mathcal{E}_0$ is reminiscent of what is commonly introduced for relativistic atomic systems, where $\mathcal{E}_\pi$ plays the role of the exchange correlation term ($\mathcal{E}_{exc}$) and $\mathcal{E}_{BG}$ is the nuclear counterpart of the usual Hartree term. The philosophy behind DFT [4] is to isolate the (in principle) tractable dominant contribution from the many-body correlations. The success relies, of course, on whether approximations for the exchange correlation term could be found. Calculations performed in Ref. [3] are a good starting point. Minimization of the ground-state energy with respect to orbital wavefunctions leads to our "Kohn-Sham" equations of motion:

$$[-i\beta\boldsymbol{\alpha}\cdot\boldsymbol{\nabla} + M_N + \gamma_0\Sigma_V^0 + \Sigma_S]\psi_k = \epsilon_k\psi_k \; , \qquad (5)$$

where Σ_V^0 and Σ_S are respectively the vector and scalar potentials. This approach has been tested in the analysis of symmetric and asymmetric nuclear matter and in bulk properties of finite nuclei. As an example we show in Fig. 1 binding energies and isotope shifts predictions along the Pb isotope chain. The agreement with experimental data is indeed very good. Our "QCD-inspired" model is a first step towards estabilishing connections between the structure of finite nuclei and underlying principles of low-energy QCD. Work supported in part by BMBF, GSI and MURST.

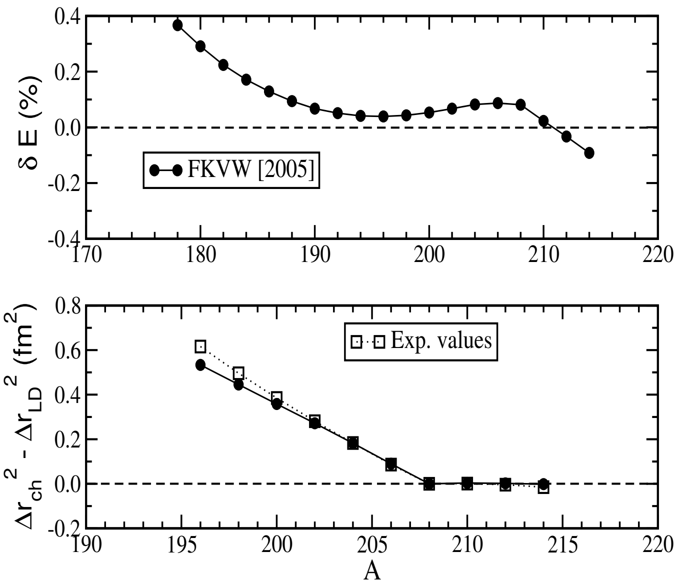

Fig. 1: The deviations of the theoretical masses and the isotope shifts of Pb isotopes from the empirical values, in comparison with phenomenological approaches [5].

References

[1] P. Finelli, N. Kaiser, D. Vretenar and W. Weise, Eur. Phys. J. **A17** (2003) 573 Nucl. Phys. **A735** (2004) 449
[2] T.D. Cohen, R.J.+Furnstahl and D.K. Griegel, Phys. Rev. Lett. **67** (1992) 1507 X. Jin, M. Nielsen, T.D. Cohen, R.J. Furnstahl and D.K. Griegel, Phys. Rev **.** (C49) 1994464
[3] N. Kaiser, S. Fritsch, and W. Weise, Nucl. Phys. **A697** (2002) 255 [nucl-th/0406038]
[4] R.M. Dreizler and E.K.U. Gross, Density Functional theory, Spinger-Verlag, 1990 R.M. Dreizler, Lect.Notes Phys. **620** (2003) 123
[5] G.A. Lalazissis, J. Konig and P. Ring, Phys.Rev. **C55** (1997) 540 T. Niksic, D. Vretenar, P. Finelli and P. Ring, Phys.Rev. **C66** (2002) 024306

◊ Supported in part by DFG, MURTS and BMBF.
[1] for notation and details we refer the reader to [1]