IL NUOVO CIMENTO **47 C** (2024) 50
DOI 10.1393/ncc/i2024-24050-y

Colloquia: COMEX7

Nuclear energy density functionals constrained by collective nuclear excitations and parity violating electron scattering experiments

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received 31 October 2023

Summary. — Recent advancements, such as measurements of dipole polarizability and experiments involving parity-violating electron scattering on ^{48}Ca (CREX) and ^{208}Pb (PREX-II), have opened new perspectives for our understanding of nuclear energy density functionals (EDF). In particular, these advancements shed light on the isovector channel of the EDFs, which plays a pivotal role in determining properties related to symmetry energy and the thickness of the neutron skin in nuclei. Recently, a novel relativistic EDF DD-PCX has been developed based on point coupling interaction, adjusted using not only the ground state properties of nuclei but also the properties of isoscalar giant monopole resonance and the dipole polarizability in ^{208}Pb. The DD-PCX interaction describes well the nuclear ground state properties, including the thickness of the neutron skin, and provides reasonable descriptions of nuclear excited states. Furthermore, the symmetry energy and its slope are found to be consistent with previous studies. Moreover, by applying the relativistic EDF framework, the consequences of the CREX and PREX-II electron scattering data have been investigated for the symmetry energy of nuclear matter and the isovector properties of finite nuclei, such as neutron skin thickness and dipole polarizability. The weak-charge form factors extracted from the CREX and PREX-II experiments have been directly used to optimize the relativistic density-dependent point coupling EDFs. Notably, the EDF derived from the CREX data yields substantially smaller values for parameters associated with symmetry energy, neutron skin thickness, and dipole polarizability for both ^{48}Ca and ^{208}Pb, when compared to the EDF derived from the PREX-II data, as well as previously established EDFs. It has become evident that the CREX and PREX-II experiments have not yielded consistent constraints for the isovector sector of the EDFs. Consequently, further theoretical investigations and experimental studies are required to clarify these discrepancies.

1. – Introduction

Describing the isovector channel of energy density functionals (EDF) and understanding the associated density dependence of nuclear symmetry energy, a crucial aspect of

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the nuclear Equation of State (EOS), remains a longstanding and unresolved challenge in nuclear physics [1]. The primary difficulty stems from the fact that nuclear symmetry energy cannot be directly measured through experiments, necessitating the identification and implementation of relevant observables on finite nuclei to constrain its properties [1].

Observables such as the neutron skin thickness (ΔR_{np}) [2] and neutron star mass-radius relationships [3] have been employed to constrain the isovector channel of nuclear energy density functionals (EDF) and the parameters of nuclear EOS near the saturation density. Another crucial observable closely linked to the isovector properties of EDFs is the dipole polarizability (α_D), which is derived from the strength distributions of isovector dipole transitions in nuclei [4-6]. Recently, the dipole polarizability in ^{208}Pb has been directly incorporated into the χ^2 minimization procedure to adjust the model parameters of a relativistic EDF based on a density-dependent point-coupling interaction, referred to as DD-PCX [7]. The symmetry energy and related parameters are found to be consistent with the previous studies [1], and a reasonable description of nuclear properties and excitations are obtained using the DD-PCX functional.

Furthermore, experimental data from parity-violating electron scattering experiments on ^{48}Ca (CREX) [8] and ^{208}Pb (PREX-II) [9] offer novel insights into the neutron skin thickness within nuclei. These experiments enable the determination of the nuclear weak-charge form factor F_W through measurements of the parity-violating asymmetry A_{PV}. Notably, this form factor is closely associated with the density dependence of symmetry energy and the neutron skin thickness in nuclei, making it a valuable quantity for probing the isovector properties of EDFs [10]. Parity-violating electron scattering experiments provide precise and model-independent data for the nuclear weak-charge form factor F_W, making it a valuable resource for constraining EDFs [10, 11]. The CREX [8] and PREX-II [9] experiments reported the weak-charge form factors for ^{48}Ca as F_W(q=0.8733 fm^{-1})= 0.1304 ± 0.0052(stat)±0.0020(syst) and for ^{208}Pb as F_W(q=0.3978 fm^{-1})= 0.368± 0.013 (exp.), respectively. Analyses of the measured parity-violating asymmetry A_{PV} in ^{48}Ca and ^{208}Pb using EDFs have revealed difficulties in simultaneously describing A_{PV} in both nuclei [12, 13].

This proceedings paper presents an overview of recent advancements in constraining relativistic EDFs with density-dependent point couplings, utilizing recent data on dipole polarizability and nuclear weak-charge form factor F_W from CREX [8] and PREX-II [9] experiments, together with selected ground state properties of nuclei. The paper also discusses the implications of these experiments on dipole polarizability and parity-violating electron scattering experiments, on the properties of finite nuclei and nuclear matter, particularly focusing on symmetry energy and its slope near the saturation density.

2. – Methods

Theoretical framework employed in studies in refs. [7, 14] presented here, is based on the relativistic EDF with point coupling interaction with density dependent couplings [15]. The relativistic EDF has been successfuly employed in a variety of recent studies of nuclear ground state, excitation phenomena, and weak-interaction processes [16-28], as well as in the study of nuclear drip lines at finite temperature [29]. In the formulation given by the Lagrangian density, an effective interaction between nucleons is described with four fermion contact interaction terms, including isoscalar-scalar, isoscalar-vector, isovector-vector channels, supplemented with the electromagnetic field and derivative terms to account for the leading effects of finite-range interactions necessary to describe nuclear density distribution and radii. The relativistic Hartree-Bogoliubov (RHB) model

[15, 30, 31] is used to describe open-shell nuclei, including the pairing field formulated using separable pairing force, which also contains two parameters for the proton and neutron pairing strengths (G_p and G_n) [32].

The EDF parameterization DD-PCX, introduced in ref. [7], is determined by minimizing the χ^2 objective function, utilizing a set of observables related to nuclear ground state properties. These include binding energies (34 nuclei), charge radii (26 nuclei), and mean pairing gaps (15 nuclei). Additionally, two observables pertaining to collective excitations have been incorporated: the isoscalar giant monopole resonance (ISGMR) energy [33] (E_{ISGMR}) and dipole polarizability [6, 34] for ^{208}Pb. Recently, dipole polarizability has attracted considerable interest since it is strongly correlated with the neutron form factor, neutron skin thickness, and the properties of the symmetry energy of nuclear matter [4-6]. In the following study [14], the data from parity-violating experiments PREX-II and CREX were used in adjusting the EDFs. Therein, the RHB model was employed to constrain 12 model parameters through χ^2 minimization, using the same set of nuclear ground state properties as employed in the DD-PCX interaction. However, in this optimization, the most recent nuclear weak-charge form factors F_W from the CREX experiment (^{48}Ca) [8] and the PREX-II experiment (^{208}Pb) [9] were also included. This led to the optimization of two functionals: DDPC-CREX and DDPC-PREX, using ground state properties and weak-charge form factor data for ^{48}Ca and ^{208}Pb, respectively. Additionally, the functional DDPC-REX was established by incorporating weak-charge form factor data for both ^{48}Ca and ^{208}Pb. After the interactions were optimized, the statistical uncertainties of the model parameters were assessed through co-variance analysis [35].

3. – Results

The primary outcomes achieved through the recently developed DD-PCX functional can be found in ref. [7]. These results encompass computations of the nuclear binding energies, charge radii, neutron-skin thickness and dipole polarizability in nuclei not used in constraining the model parameters. It is demonstrated that collective nuclear excitations play a pivotal role in constraining the isovector sector of the EDFs and, consequently, the symmetry energy.

In fig. 1, we address the connection between the calculated value of α_D and difference between charge and weak form factors, denoted as $F_{ch} - F_W$. This exploration is carried out alongside corresponding experimental data, aiming to assess the consistency of various functionals in describing both quantities for different nuclei. The experimental data, along with their associated uncertainties, are represented as horizontal and vertical bands for α_D and $F_{ch} - F_W$, respectively. Notably, a strong correlation between α_D and $F_{ch} - F_W$ is evident for both ^{48}Ca and ^{208}Pb, encompassing a variety of point-coupling and meson-exchange functionals. This strong correlation is also obtained from the statistical covariance analysis of the newly optimized EDFs, which includes the coefficient of determination (CoD) and error ellipsoids between α_D and $F_{ch} - F_W$. The CoD numbers close to one and narrow error ellipsoids validate strong correlation between the two observables. For ^{48}Ca, only one newly introduced interaction, DDPC-REX, and the previously established DDPC (J=29 MeV) functional fall within the experimental limits for both α_D and $F_{ch} - F_W$ (CREX). The DDPC-CREX interaction yields a slightly smaller α_D value than the lower experimental limit, while the DDPC-PREX interaction results in α_D and $F_{ch} - F_W$ values significantly higher and beyond the experimental range. The DD-PCX interaction, which was fine-tuned to

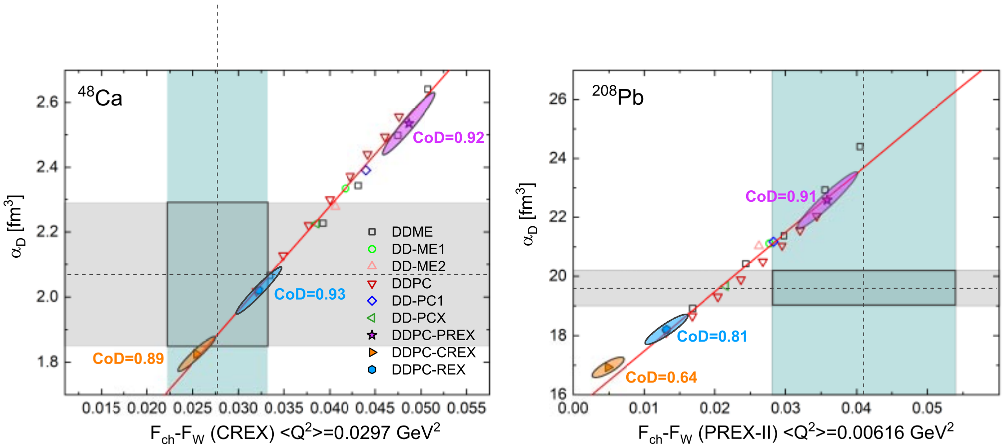

Fig. 1. – The dipole polarizability α_D of ^{48}Ca and ^{208}Pb as a function of the form factor difference $F_{ch} - F_W$. The CREX [8] and PREX-II [9] values are shown as vertical bands, while α_D values [6, 34, 37] are denoted by horizontal bands. The coefficient of determination (CoD) and error ellipsoids obtained from the statistical covariance analysis are also provided for the new EDFs. Figure is taken from ref. [14].

match the experimental dipole polarizability in ^{208}Pb, does not appear to be consistent with the $F_{ch} - F_W$ values from CREX. Furthermore, coupled cluster theory calculations for ^{48}Ca predict $1.92 \leq \alpha_D(^{48}Ca) \leq 2.38$ fm^3, aligning only with the predictions of the DDPC-REX interaction [36]. In the case of ^{208}Pb, none of the newly introduced or previously established functionals can simultaneously reproduce experimental values for both α_D and $F_{ch} - F_W$ (PREX-II). As expected, DDPC-PREX is consistent with the experimental form factors but significantly overestimates the values of α_D. On the other hand, DDPC-CREX and DDPC-REX underestimate both α_D and $F_{ch} - F_W$ values (PREX-II). Clearly, the functionals constrained using CREX and PREX-II data exhibit substantial tension when confronted with dipole polarizability studies. Another study involving calculations with non-relativistic functionals also demonstrated a strong correlation between the parity-violating asymmetry A_{PV} and $J\alpha_D$ [13]. Given that A_{PV} is directly linked to F_{ch} and F_W, this further corroborates the main conclusion regarding the tension between results based on the CREX and PREX-II experiments, aligning with our findings in ref. [14].

4. – Conclusion

The utilization of EDF methodologies has advanced to encompass a broader range of nuclear observables, extending beyond ground state properties and enabling the direct incorporation of these observables in constraining the EDF parameters. By incorporating dipole polarizability and the excitation energy of the Isoscalar Giant Monopole Resonance (ISGMR) into the χ^2 minimization process that led to the development of the relativistic DD-PCX functional, crucial characteristics such as the symmetry energy at saturation density and the incompressibility of nuclear matter are directly influenced by relevant experimental data. Eventually, the DD-PCX provides reasonable values for the symmetry energy and its slope, which is consistent with previous studies [1]. When the experimental data from CREX and PREX-II are employed, the DDPC-CREX functional yields notably smaller values for the symmetry energy and its slope at saturation density, as well as for the neutron skin thickness, in comparison to the results obtained with the DDPC-PREX functional. The existence of tension between the outcomes derived from weak form factors obtained through parity-violating electron scattering and their incongruence with the properties of symmetry energy derived from dipole polarizability necessitates further examination and consideration.

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This work is supported by the QuantiXLie Centre of Excellence, a project co-financed by the Croatian Government and European Union through the European Regional Development Fund, the Competitiveness and Cohesion Operational Programme (KK.01.1.1.01.0004). E.Y. acknowledges support from the Science and Technology Facilities Council (UK) through grant ST/Y000013/1.

REFERENCES

[1] Roca-Maza X. and Paar N., *Prog. Part. Nucl. Phys.*, **101** (2018) 96.
[2] Typel S. and Brown B. A., *Phys. Rev. C*, **64** (2001) 027302.
[3] Lattimer J. M. and Steiner A. W., *Eur. Phys. J. A*, **50** (2014) 40.
[4] Piekarewicz J., Agrawal B. K., Colò G., Nazarewicz W., Paar N., Reinhard P.-G., Roca-Maza X. and Vretenar D., *Phys. Rev. C*, **85** (2012) 041302.
[5] Roca-Maza X., Brenna M., Colò G., Centelles M., Viñas X., Agrawal B. K., Paar N., Vretenar D. and Piekarewicz J., *Phys. Rev. C*, **88** (2013) 024316.
[6] Roca-Maza X., Viñas X., Centelles M., Agrawal B. K., Colò G., Paar N., Piekarewicz J. and Vretenar D., *Phys. Rev. C*, **92** (2015) 064304.
[7] Yüksel E., Marketin T. and Paar N., *Phys. Rev. C*, **99** (2019) 034318.
[8] Adhikari D. *et al.*, *Phys. Rev. Lett.*, **129** (2022) 042501.
[9] Adhikari D. *et al.*, *Phys. Rev. Lett.*, **126** (2021) 172502.
[10] Reinhard P.-G., Piekarewicz J., Nazarewicz W., Agrawal B. K., Paar N. and Roca-Maza X., *Phys. Rev. C*, **88** (2013) 034325.
[11] Horowitz C. J., Pollock S. J., Souder P. A. and Michaels R., *Phys. Rev. C*, **63** (2001) 025501.
[12] Reinhard P.-G., Roca-Maza X. and Nazarewicz W., *Phys. Rev. Lett.*, **127** (2021) 232501.
[13] Reinhard P.-G., Roca-Maza X. and Nazarewicz W., *Phys. Rev. Lett.*, **129** (2022) 232501.
[14] Yüksel E. and Paar N., *Phys. Lett. B*, **836** (2023) 137622.
[15] Nikšić T., Paar N., Vretenar D. and Ring P., *Comput. Phys. Commun.*, **185** (2014) 1808.
[16] Vale D., Rauscher T. and Paar N., *J. Cosmol. Astropart. Phys.*, **2016** (2016) 007.
[17] Yüksel E., Paar N., Colò G., Khan E. and Niu Y. F., *Phys. Rev. C*, **101** (2020) 044305.
[18] Kružić G., Oishi T., Vale D. and Paar N., *Phys. Rev. C*, **102** (2020) 044315.
[19] Ravlić A., Yüksel E., Niu Y. F., Colò G., Khan E. and Paar N., *Phys. Rev. C*, **102** (2020) 065804.
[20] Yüksel E., Oishi T. and Paar N., *Universe*, **7** (2021) 71.
[21] Oishi T., Kružić G. and Paar N., *Eur. Phys. J. A*, **57** (2021) 180.
[22] Vale D., Niu Y. F. and Paar N., *Phys. Rev. C*, **103** (2021) 064307.
[23] Ravlić A., Yüksel E., Niu Y. F. and Paar N., *Phys. Rev. C*, **104** (2021) 054318.
[24] Ravlić A., Niu Y. F., Nikšić T., Paar N. and Ring P., *Phys. Rev. C*, **104** (2021) 064302.
[25] Giraud S. *et al.*, *Phys. Rev. C*, **105** (2022) 055801.
[26] Oishi T., Ravlić A. and Paar N., *Phys. Rev. C*, **105** (2022) 064309.

[27] Popara N., Ravlić A. and Paar N., *Phys. Rev. C*, **105** (2022) 064315.
[28] Kružić G., Oishi T. and Paar N., *Eur. Phys. J. A*, **59** (2023) 50.
[29] Ravlić A., Yüksel E., Nikšić T. and Paar N., *Nat. Commun.*, **14** (2023) 4834.
[30] Vretenar D., Afanasjev A., Lalazissis G. and Ring P., *Phys. Rep.*, **409** (2005) 101.
[31] Nikšić T., Vretenar D. and Ring P., *Phys. Rev. C*, **78** (2008) 034318.
[32] Tian Y., Ma Z.-y. and Ring P., *Phys. Rev. C*, **80** (2009) 024313.
[33] Patel D. *et al.*, *Phys. Lett. B*, **726** (2013) 178.
[34] Tamii A. *et al.*, *Phys. Rev. Lett.*, **107** (2011) 062502.
[35] Dobaczewski J., Nazarewicz W. and Reinhard P.-G., *J. Phys. G: Nucl. Part. Phys.*, **41** (2014) 074001.
[36] Simonis J., Bacca S. and Hagen G., *Eur. Phys. J. A*, **55** (2019) 241.
[37] Birkhan J. *et al.*, *Phys. Rev. Lett.*, **118** (2017) 252501.