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Constructing nuclear functionals for neutron stars and nucleosynthesis applications

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Describing all different neutron star layers within a unified framework is a challenge in view of the very wide range of densities encountered. The description of massive pulsars such as J1614-2230 and J0740+662 [1], for example, brings the requirement of a stiff neutron matter equation of state in order to balance the strong gravity field of these compact objects. Additionally, the description of the rapid neutron-capture process (or r-process) nucleosynthesis taking place in neutron-star mergers requires detailed knowledge of nuclear reactions and radioactive decays (hence of the nuclear-structure properties, in particular nuclear masses) for a few thousand exotic neutron-rich nuclei. The challenge for nuclear theory is then the construction of a model that accurately describes: (i) masses of neutron-rich nuclei present in the crust of neutron stars, and (ii) masses of all the neutron-rich potentially produced during the r-process nucleosynthesis, together with (iii) a stiff enough neutron matter equation of state to explain the most massive observed pulsars.
A new family of microscopic nuclear energy density functionals and associated nuclear mass models have been recently proposed [2]. The Brussels-Skyrme-on-a-Grid (BSkG) functionals have the advantage of being based on the concept of utmost symmetry breaking for exotic nuclear configuration, allowing for exotic shapes like for instance triaxial or octupole deformation during the adjustment process. To compensate for the increase in computational cost, machine learning techniques were employed to optimize the parameter adjustment.
We show in this contribution the latest parametrization BSkG3, which greatly improves the infinite nuclear matter properties of BSkG functionals. To do so, we follow the procedure of Ref. [3] and use an extended form of the Skyrme functional to ensure a stiff enough neutron-matter equation of state at high densities. This new functional BSkG3 is consistent with observations of heavy pulsars. Furthermore, we include a pairing interaction designed to match the 1S0 pairing gaps in infinite nuclear matter deduced from ab-initio calculations. The latter is particularly important for a reliable description of superfluids in neutron stars. Both improvements, combined with our state-of-the-art description of atomic nuclei and simultaneous accurate description of many different observables, including in particular nuclear masses for thousands of nuclei, make BSkG3 a tool of choice for applications in nuclear structure and astrophysics.

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[2] G. Scamps et al., Eur. Phys. J. A 57, 333 (2021); W. Ryssens et al., Eur. Phys. J. A 58, 246 (2022).
[3] N. Chamel, S. Goriely and J. M. Pearson, Phys. Rev. C 80, 065804 (2009).

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