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Nuclear physics inputs for neutron stars and nucleosynthesis simulations

Describing matter at the extreme conditions present in neutron stars (NS) within a unified framework is challenging in view of the wide range of densities encountered. On the other hand, nucleosynthesis simulations of rapid neutron-capture processes (or r-process) require detailed knowledge of nuclear reactions and radioactive decay (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 nuclei 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.
We will present the new family of microscopic nuclear energy density functionals (EDFs) [1] developed at IAA, which aims to provide accurate nuclear physics inputs to astrophysical applications, and progress in the above topics. The Brussels-Skyrme-on-a-Grid (BSkG) are parameterizations of the Skyrme EDF with the advantage of being based on the powerful concept of symmetry breaking, allowing for exotic shapes such as triaxial and octupole deformation during the adjustment process. To compensate for the increase in computational cost, machine learning techniques are employed to optimize the parameter adjustment. The latest BSkG3 [2] greatly improves the infinite nuclear matter properties (INM) of BSkG parametrizations. Compared to its predecessors, BSkG3 offers a more realistic description of matter at the extreme densities relevant to NS and is consistent with observations of heavy pulsars, a condition that is not reached in most of the Skyrme forces. Furthermore, we include a pairing treatment designed to match the 1S0 pairing gaps in INM deduced from ab-initio calculations. The latter is particularly important for a reliable description of superfluids in NS. Quantitatively, the model offers lowered root-mean-square deviations on 2457 masses (0.631 MeV), and an unmatched accuracy with respect to 45 primary fission barriers of actinide nuclei (0.33 MeV). Reconciling the complexity of NS with those of atomic nuclei establishes BSkG3 as a tool of choice for applications in nuclear astrophysics.
The next step is to improve the nuclear inputs to NS merger simulations. We will also present our efforts to add constraints at finite temperature INM properties in the fit protocol. For that we explore an alternative form for the Skyrme EDF that could tackle more INM properties, while keeping a high quality description of nuclear structure properties.

[1] G. Scamps et al., Eur. Phys. J. A 57, 333 (2021); W. Ryssens et al., Eur. Phys. J. A 58, 246 (2022).
[2] G. Grams, et al, Accepted to Eur. Phys. J.. arXiv: 2307.14276 (2023).

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