Nuclear Theory – Nuclear astrophysics

J.W. Holt

Introduction:

The structure, phases, and dynamics of nuclear matter are crucial to understand stellar explosions, the origin of the elements, patterns in observed gravitational waves, and the composition of the densest observable matter in the universe. The appropriate tool to study strongly interacting matter at the typical scales relevant in nuclear astrophysics (well below the scale of chiral symmetry breaking $\Lambda_\chi \approx 1$ GeV) is chiral effective field theory [1-3]. In recent years, chiral effective field theory has become a cornerstone of the modern approach to nuclear many-body dynamics that provides a systematic framework for describing realistic microphysics, such as multi-pion exchange processes and three-body forces, within a well-defined organizational hierarchy. The long and intermediate-range parts of the nuclear potential result from one- and two-pion exchange processes, while short-distance dynamics, not resolved at the wavelengths corresponding to typical nuclear Fermi momenta, are introduced as contact interactions between nucleons. Chiral effective field theory is unique in its multichannel methods for quantifying uncertainties and especially in its ability to estimate the importance of missing physics.

Microscopic global optical potential with quantified uncertainties

Large-scale numerical simulations are essential for identifying the astrophysical site of the r-process, the primary candidates being the wind-driven ejecta from accretion disks surrounding binary neutron-star mergers or collapsars as well as the neutrino-driven winds of core-collapse supernovae. Neutron-capture rates on exotic neutron-rich isotopes are particularly important during the non-equilibrium freeze-out phase of r-process nucleosynthesis, but direct experimental studies at rare-isotope facilities remain unfeasible. The large uncertainties in these capture rates, due in part to difficulties in extrapolating phenomenological optical model potentials far from the valley of stability, limit the precision of predicted heavy-element abundances. Previously we have computed proton-nucleus and neutron-nucleus optical potentials [4,5] by combining the improved local density approximation [6] with chiral effective field theory calculations of the nucleon self-energy in homogeneous nuclear matter. Proton and neutron differential elastic scattering cross sections on calcium isotopes were found to be in good agreement with experimental data for projectile energies up to 150 MeV.

Recently, we have constructed [7] from chiral effective field theory two- and three-body forces a microscopic global nucleon-nucleus optical potential with quantified uncertainties. We started from the nuclear matter approach [8], in which the nucleon self-energy in infinite homogeneous matter at varying density and isospin asymmetry is used to construct nucleon-nucleus optical potentials by matching to the isoscalar and isovector densities of the target isotopes by way of the improved local density approximation. This was performed for proton and neutron projectiles on 1800 target nuclei in the mass range $12 < A < 242$ and for energies between $0\ \text{MeV} < E < 200\ \text{MeV}$. We then constructed a global optical potential parametrization that depends smoothly on the projectile energy as well as the target nucleus mass number and isospin asymmetry. This was then repeated for five different chiral interactions from which a covariance analysis of the parameters entering in the global optical potential could be used to create a continuous distribution of optical potentials. This enabled the propagation of statistical uncertainties within the model. In Fig. 1 we show the predicted neutron elastic differential scattering cross section distributions for a range of isotopes and energies from the microscopic global optical potential of Ref. [7] compared to experimental data.

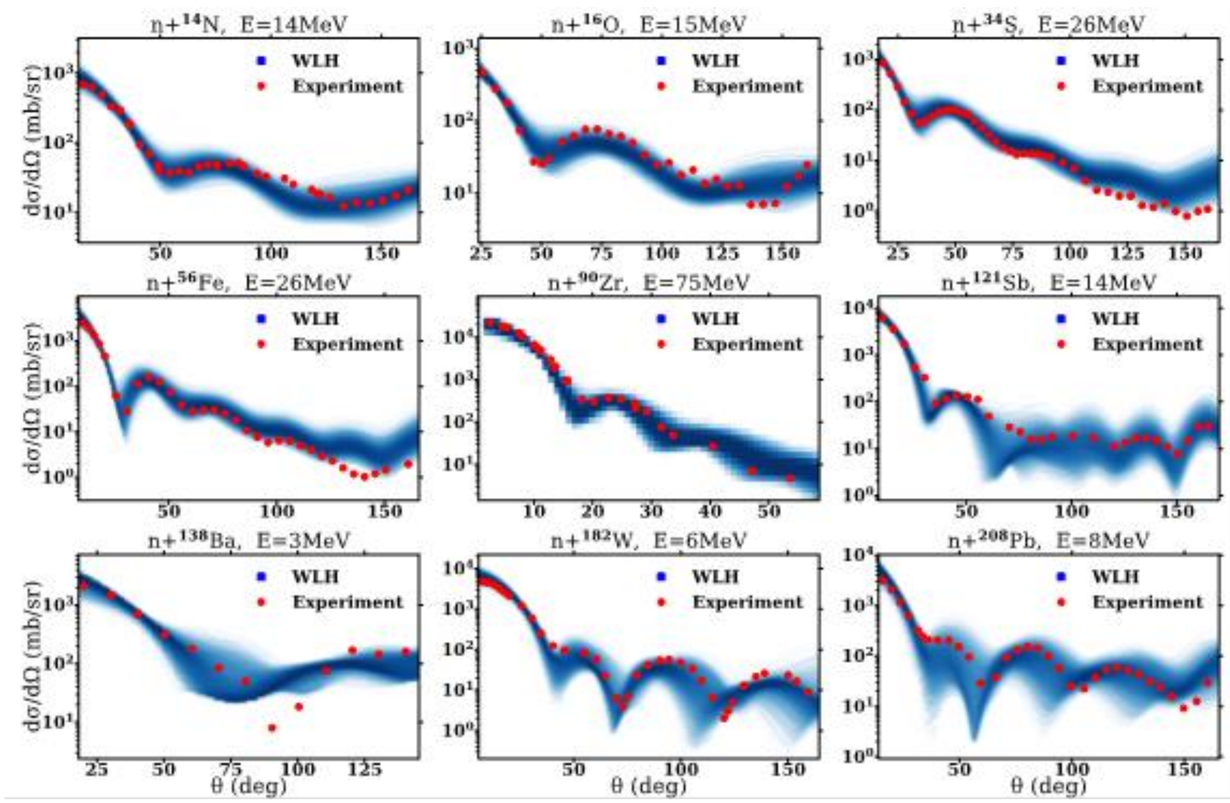

Fig. 1. Neutron elastic differential scattering cross sections from the microscopic global optical potential with quantified uncertainties of Ref. [WHI21] (blue) compared to experimental data (red dots).

Normalizing flows for efficient Monte Carlo importance sampling of many-body perturbation theory diagrams

Normalizing flows are a class of machine learning models used to construct a complex probability distribution through a bijective mapping of a simple base distribution. In recent work [9], we have demonstrated that normalizing flows are particularly well suited as a Monte Carlo integration framework for quantum many-body calculations that require the repeated evaluation of high-dimensional integrals across smoothly varying integrands and integration regions. As an example, the calculation of the finite-temperature nuclear equation of state could be precisely evaluated using normalizing flows, which resulted in a speedup factor of 100 compared to current state-of-the-art Monte Carlo importance sampling algorithms, such as VEGAS [10]. We also showed that a normalizing flow model trained on one target integrand can be used to efficiently calculate related integrals when the temperature, density, or even the nuclear force is varied. In Fig. 2 we show a comparison between the relative uncertainty $\sigma/\Omega^{(2)}$ in the evaluation of the second-order perturbation theory contribution to the grand canonical partition function $\Omega^{(2)}$ of symmetric nuclear matter using normalizing flow importance sampling (nflow) and VEGAS importance sampling. The left panel demonstrates that normalizing flows can achieve a better sampling efficiency (for the accumulated total uncertainty σ_t over many iterations or the batch uncertainty σ_b with 5000 drawn samples per batch) over VEGAS. The right panel demonstrates that normalizing flow models can achieve the same improvement over VEGAS without further training when the temperature, density, and choice of nuclear force (either a one-boson-exchange "OBE" interaction or the next-to-leading-order chiral pion-exchange interaction "χNLO,π") is varied.

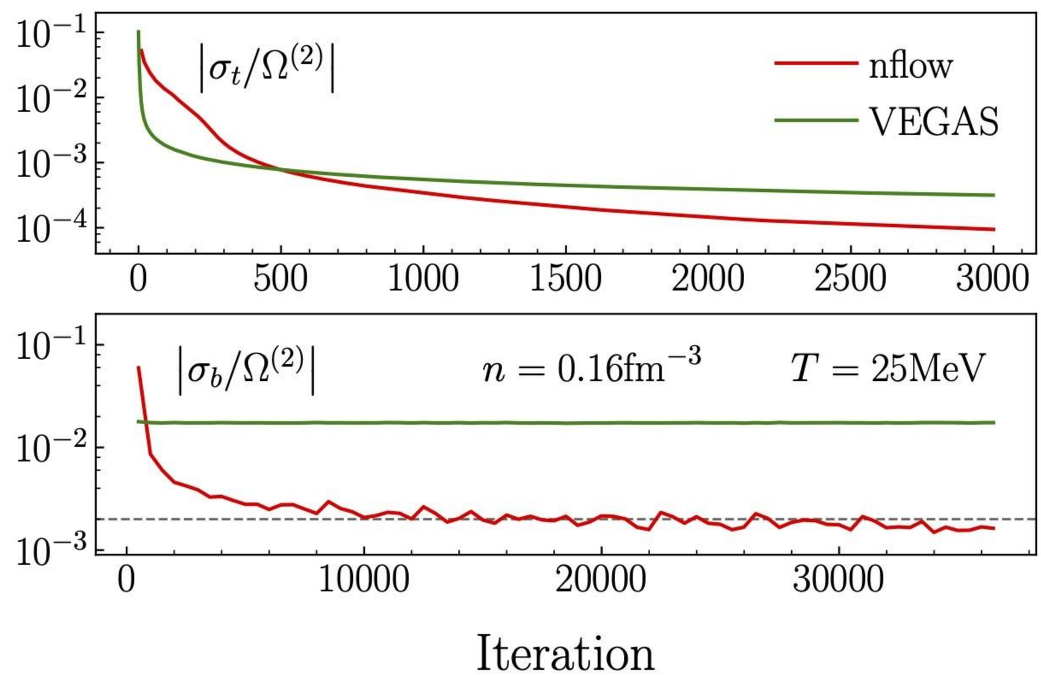

Fig. 2. Top: Comparison of the total relative uncertainty $\boldsymbol{\sigma_t/\Omega^{(2)}}$ in the calculation of the second-order grand canonical partition function of nuclear matter as a function of accumulated samples (5000 samples/iteration) for normalizing flow importance sampling and VEGAS importance sampling. Bottom: Same as top except for the batch relative uncertainty $\boldsymbol{\sigma_b/\Omega^{(2)}}$ with 5000 samples/batch.

[1] S. Weinberg, Physica A **96**, 327 (1979).
[2] E. Epelbaum, H.-W. Hammer and U.-G. Meissner, Rev. Mod. Phys. **81**, 1773 (2009).
[3] R. Machleidt and D. R. Entem, Phys. Rept. **503**, 1 (2011).
[4] T. R. Whitehead, Y. Lim, and J. W. Holt, Phys. Rev. C **100**, 014601 (2019).
[5] T. R. Whitehead, Y. Lim, and J. W. Holt, Phys. Rev. C **101**, 064613 (2020).
[6] J. P. Jeukenne, A. and Lejeune and C. Mahaux, Phys. Rev. C 16, 80 (1977).
[7] T. R. Whitehead, Y. Lim, and J. W. Holt, Phys. Rev. Lett. **127**, 182502 (2021).
[8] J. P. Jeukenne, A. Lejeune, and C. Mahaux, Phys. Rep. **25**, 83 (1976).
[9] J. Brady, P. Wen, and J.W. Holt, Phys. Rev. Lett. **127**, 062701 (2021).
[10] G.P. Lepage, J. Comp. Phys. **27**, 192 (1978).