Nuclear thermodynamic equation of state from chiral effective field theory

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The equation of state of neutron-rich matter from sub- to supra-nuclear densities directly influences neutron star structure and evolution, the dynamics of core-collapse supernovae, r-process nucleosynthesis, as well as features of gravitational waves produced during the late inspiral and post-merger phases of binary neutron star coalescence. The major challenge is to model the free energy $F(n, T, Y_p)$ of baryonic matter over approximately eight orders of magnitude in density ($n \sim 10^8 - 10^{15}$g/cm^3), temperatures up to $T \sim 5{\times}10^{11}\,K$, and proton fractions $Y_p \leq 0.6$. Under this range of conditions (well below the chiral symmetry breaking scale of $\Lambda_\chi \approx 1$ GeV) effective field theory methods [1-3] are expected to provide a suitable framework for the description of strongly interacting matter. In anticipation of new observational campaigns of neutron stars (e.g., NICER) and searches for gravitational waves from binary neutron star mergers (Advanced LIGO), present efforts in our research group are focused on reducing theoretical uncertainties in the nuclear thermodynamic equation of state and refining phenomenological energy density functionals by imposing microscopic constraints from chiral effective field theory (chiral EFT).

Microscopic many-body calculations based on chiral EFT are now able to provide reliable predictions for properties of the nuclear equation of state through a multi-channel analysis of theoretical uncertainties. In the past year we studied [4] in particular the relationship between the nuclear isospin asymmetry energy, S_v, and its slope parameter, L (as shown in Fig.1). Even the most conservative

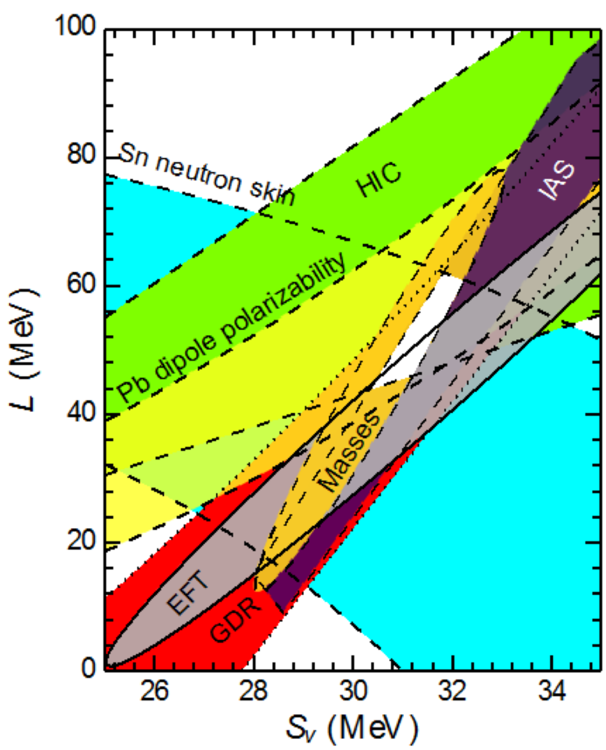

FIG. 1. Correlation between the nuclear symmetry energy, S_v, and its slope parameter, L, from chiral EFT (adapted from [4]).

theoretical uncertainty estimate on this correlation, shown as the "EFT" ellipse in Fig.1, yields a constraint on par with existing experimental investigations of the same quantity (shown as other bands in Fig. 1). This calculation utilized recent developments in perturbation theory [5] by our group that allowed for the inclusion of all third-order diagrams in the expansion of the nuclear equation of state.

More recently we have begun independent collaborations with Andrew Steiner and Shun Furusawa to develop new supernova equations of state that utilize the free energy of bulk nuclear matter obtained from chiral effective field theory in the Matsubara imaginary-time formalism. This expands on our previous finite-temperature studies [6-8] of the nuclear free energy for homogeneous nuclear and neutron matter. The free energy of bulk nuclear matter will be supplemented with a liquid-drop model formalism that accounts for the temperature- and composition-dependent surface energy. The inhomogeneous mixed phase of the supernova equation of state will then be constructed as in previous works [9,10].

Microscopic constraints on nuclear energy density functionals

The high-density ($\rho > 2\rho_0$) and high-temperature ($T > 50$ MeV) phase of nuclear matter plays only a small role in core-collapse supernovae. However, the construction of a universal equation of state suitable also for describing neutron star structure and binary neutron star mergers requires modeling in energy regimes beyond the scope of chiral effective field theory with coarse resolution nuclear potentials. This motivated our recent program to identify [11] existing energy density functionals and to construct new functionals [12] that are consistent with the low-energy constraints from effective field theory [4,6-8]. In Ref. [12] we derived new Skyrme interactions by fitting the bulk matter equation of state from chiral effective field theory as well as the binding energies of doubly magic nuclei, the latter to fix the density gradient coupling strengths. In the future, we plan to estimate the gradient terms microscopically from the density matrix expansion [13] at second order and via the static density-density response function.

Neutron star crusts constrained by chiral effective field theory

As a first application of the new Skyrme energy density functionals derived in Ref. [12], we computed properties of neutron star crusts, including the crust-core transition density and pressure, which have important implications for neutron star moments of inertia and the interpretation of pulsar glitches. We predicted a rather tight range in the transition density $0.084 \text{ fm}^{-3} < \rho_t < 0.094 \text{ fm}^{-3}$ by varying the microscopic force model and the treatment of surface contributions to the ground state energy in both the liquid-drop model and the Thomas-Fermi approximations. The full range of pasta phases was considered in both models and found to exist within a confined region in the inner crust of thickness 100m.

Nuclear dipole polarizability from mean-field models constrained by chiral EFT

The nuclear electric dipole polarizability has attracted much attention recently due to its strong correlation with neutron skin thicknesses and the density dependence of the nuclear isospin asymmetry energy. While ab initio many-body techniques have been used to investigate the dipole polarizability of medium-mass nuclei [14], only mean field theory methods can access the dipole response of heavy nuclei. We have recently computed [15] from new Skyrme mean field models constrained by chiral EFT the isovector dipole response of ^{48}Ca, ^{68}Ni, ^{120}Sn, and ^{208}Pb. The mean field models reproduce very well without additional fine tuning the peak positions of the giant dipole resonances in these nuclei as well as the associated dipole polarizabilities, which are proportional to an energy-weighted sum rule of the dipole response. The new Skyrme interactions are therefore useful for studying other isovector properties of atomic nuclei in regimes where ab initio many-body methods are not feasible.

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