Clustering in Dilute Matter and Equation of State

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Nuclear Astrophysics Virtual Institute

Dilute Matter in Nature

- astrophysical objects
  - crust of neutron stars and neutron star mergers
  - core-collapse supernovae
- laboratory experiments
  - expanding matter in heavy-ion collisions
  - surface of atomic nuclei

Similar Conditions but Different Systems

- nuclear matter: only strongly interacting particles
  - no electromagnetic interaction, no charge neutrality
  - densities below nuclear saturation density
    $\Rightarrow$ 'non-congruent' liquid-gas phase transition
- stellar matter: hadrons and leptons
  - strong and electromagnetic interaction, charge neutrality
  - formation of inhomogeneous matter
    $\Rightarrow$ new particle species (clusters/nuclei), 'pasta' phases
  - lattice formation at low temperatures
    $\Rightarrow$ phase transition: liquid/gas $\leftrightarrow$ solid

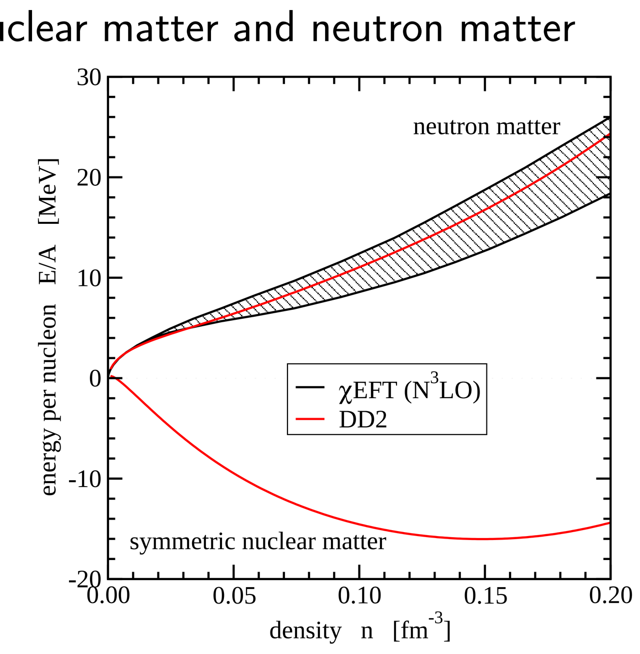
Interacting Many-Body Systems

- correlations essential
- assuming equilibrium conditions $\Rightarrow$ equation of state (EoS)
  $\Rightarrow$ thermodynamic properties and chemical composition

Generalized Relativistic Density Functional (gRDF)

- grand canonical approach
  extension of phenomenological relativistic mean-field models with density-dependent meson-nucleon couplings
  $\Rightarrow$ grand canonical potential density $\omega(T, \{\mu_i\})$
- model features
  - extended set of constituents
    baryons (n, p, hyperons, ...), leptons, photons,
    light nuclei (^{2}H,^{3}H, ^{3}He, ^{4}He), heavy nuclei ($^{A_i}Z_i$, $A_i > 4$)
    – experimental binding energies:
    AME2012 (M. Wang et al., Chinese Phys. 36 (2012) 1603)
    – extension up to neutron/proton driplines:
    DZ10 predictions (J. Duflo, A.P. Zuker, Phys. Rev. C 52 (1995) R23)
    $\Rightarrow$ 16744 nuclei with $N \leq 184$, $Z \leq 184$
  - nucleon-nucleon scattering correlations considered
    $\Rightarrow$ correct low-density limit: virial EoS
  - medium modifications of composite particles
    $\Rightarrow$ mass shifts, internal excitations
  - particles and antiparticles included
  - thermodynamically consistent approach
    $\Rightarrow$ "rearrangement" contributions
  - Coulomb correlations with correct limits
    $\Rightarrow$ phase transition to crystal
  - phonons in solid phase (modified Debye model)
  - quasiparticles with scalar potential S_i and vector potential V_i
  - model parameters from fit to properties of finite nuclei
    $\Rightarrow$ nuclear matter parameters
    $\Rightarrow$ EoS of symmetric nuclear matter and neutron matter

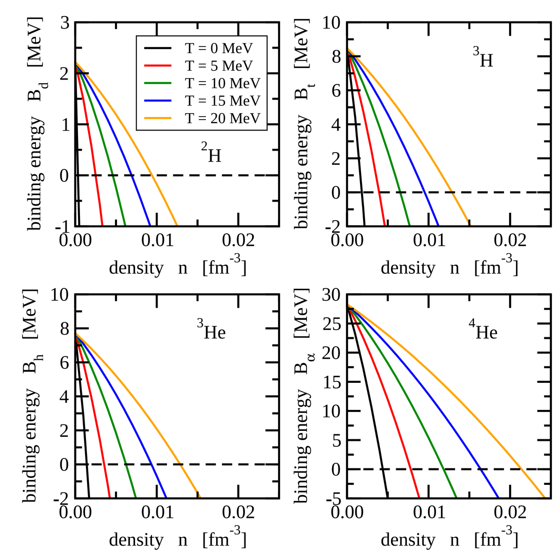
$n_{\text{sat}} = 0.149$ fm^{-3}
$a_V = 16.02$ MeV
$K = 242.7$ MeV
$J = 31.67$ MeV
$L = 55.04$ MeV

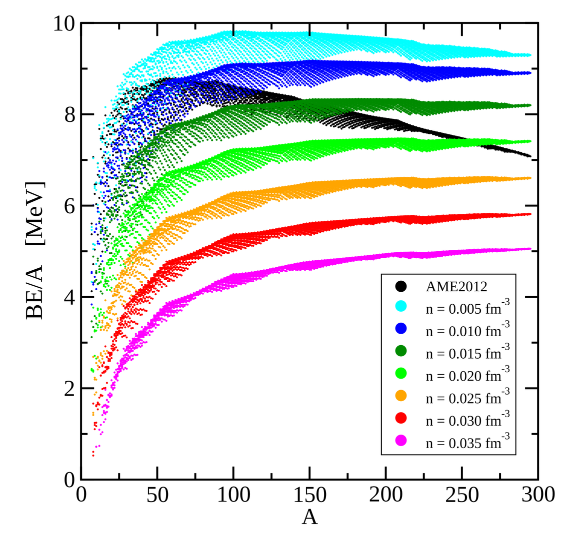


$\Rightarrow$ consistent with results from chiral effective field theory
(I. Tews et al., Phys. Rev. Lett 110 (2013) 032504,
T. Krüger et al., Phys. Rev. C 88 (2013) 025802)

Cluster Mass Shifts

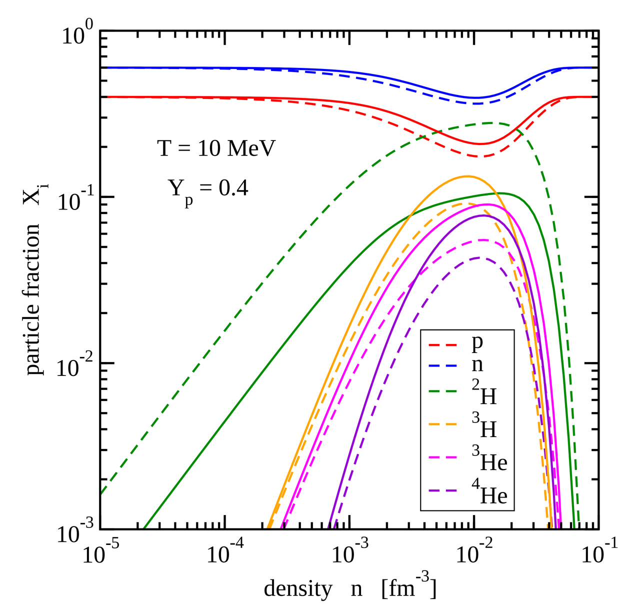
- concept applies to composite particles
  - light nuclei/scattering correlations:
    from solution of in-medium Schrödinger equation with realistic nucleon-nucleon potentials
  - heavy nuclei:
    from spherical Wigner-Seitz cell calculations in extended Thomas-Fermi approximation with gRDF functional
  - replaces conventional excluded-volume mechanism





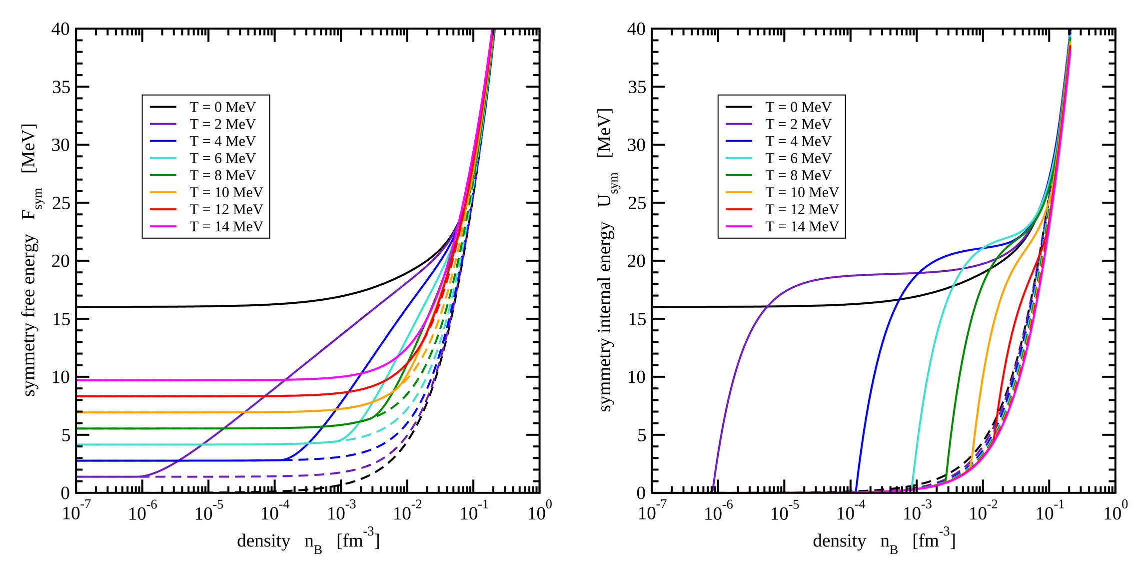
Chemical Composition of Stellar Matter

- mass number fractions
  $X_i = A_i \frac{n_i}{n_B}$ $\quad n_B = \sum_i A_i n_i$
- low densities: two-body correlations most important
- high densities: dissolution of clusters $\Rightarrow$ Mott effect
- continuum correlations (dashed/full lines: without/with continuum)
  $\Rightarrow$ correct low-density limit



Symmetry Energy and Neutron Skins

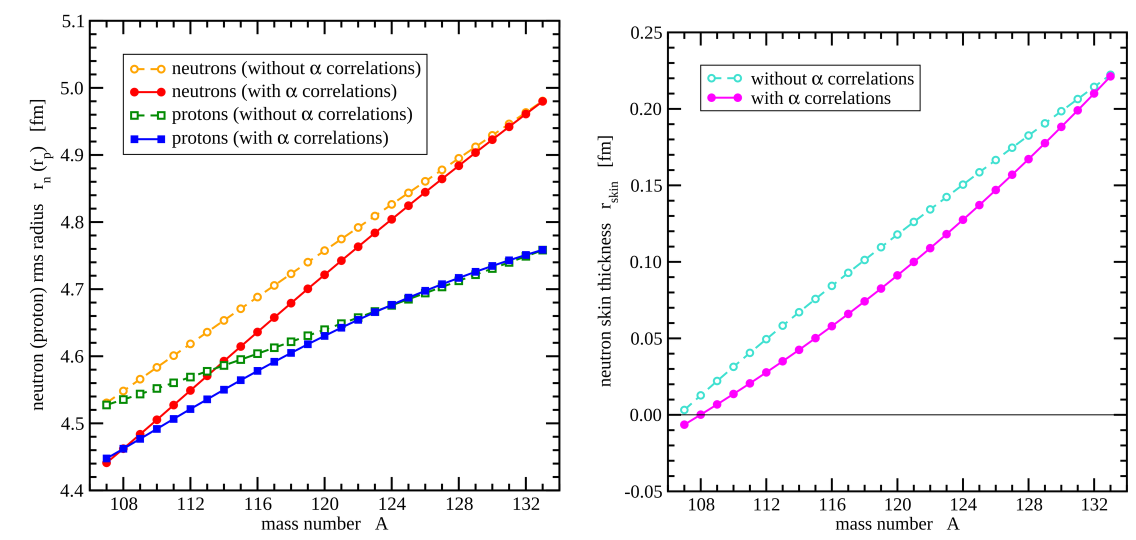
- nuclear matter: liquid-gas phase transition
  $\Rightarrow$ increase of low-density symmetry energies
  (dashed/full lines: without/with phase transition)



- correlation: neutron skin thickness $r_{\text{skin}} = r_n - r_p$
  $\Leftrightarrow$ stiffness of neutron matter EoS
  $\Leftrightarrow$ slope parameter L of symmetry energy
- $r_{\text{skin}} \leftrightarrow L$ correlation from mean-field calculations of nuclei
  $\Rightarrow$ effects of clustering on surface on neutron skin thickness?
- finite-temperature gRDF calculations
  $\Rightarrow$ enhanced probability of clusters at nuclear surface
- entension to zero temperature:
  only α-particles relevant, density distribution from wave function in WKB approximation
- modification of original DD2 parametrization
  - change from Hartree to Thomas-Fermi approximation
    $\Rightarrow$ rescaling of σ meson mass and coupling
    (no effect on nuclear matter properties)
  - variation of isovector interaction (DD2^{+++}, ..., DD2^{--}),
    $\Rightarrow$ dependence of neutron skin thickness r_{skin} on slope coefficient L

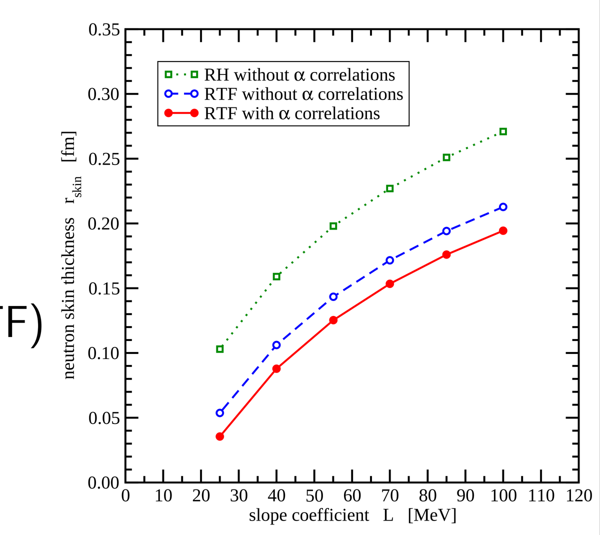
Neutron Skin of Sn Nuclei

- variation of r_n, r_p and r_{skin} with neutron excess



Neutron Skin of ^{208}Pb

- correlation $r_{\text{skin}} \leftrightarrow L$
  (not linear since no complete refit of parameters, only isovector interaction)
- relativistic Hartree (RH) vs. relativistic Thomas-Fermi (RTF)
- with α clusters: reduction of neutron skin thickness
  $\Rightarrow$ change of $r_{\text{skin}} \leftrightarrow L$ correlation



Conclusions

- correlations in many-body systems
  $\Rightarrow$ change of chemical composition, appearance of clusters
  $\Rightarrow$ modification of thermodynamic properties
  $\Rightarrow$ increase of low-density symmetry energy
  $\Rightarrow$ reduction of neutron skin thickness
- main applications of gRDF approach:
  - EoS of stellar matter $\Rightarrow$ astrophysical simulations

References

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