Light clusters in dilute nuclear matter

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Describing the clusters in matter

Our approach:

- describes matter as a mixture of quasiparticles (lifetime $\rightarrow \infty$)
- binding energies depend on temperature and density
- formation of deuteron and alpha condensates
- mean-field contribution (effective masses) from a Skyrme model

Output:

- Equation of state of symmetric and isospin asymmetric matter
- Composition of matter
- Critical temperatures for condensations
- Medium modified binding energies

Physical relevance:

Composition of matter could affect neutrino interactions and formation of supernova signal at the neutrinosphere

Key equations

Equilibrium Thermodynamics of light nuclei:

The thermodynamic potential and densities

$$\Omega(\mu_n, \mu_p, T) = \sum_\alpha \Omega_\alpha(\mu_\alpha, T) \quad (1)$$

$$\frac{\partial \Omega_\alpha}{\partial \mu_\alpha} = i g_\alpha \int \frac{d\omega d^3p}{(2\pi)^4} G_\alpha^<(\omega, \vec{p}) \to \boxed{g_\alpha \int \frac{d\omega d^3p}{(2\pi)^4} S_\alpha(\omega, \vec{p}) f_{F/B}(\omega) = n_\alpha .} \quad (2)$$

where the spectral functions are

$$S_\alpha(\omega, \vec{p}) = \frac{\Gamma_\alpha(\omega, \vec{p})}{[\omega - E_\alpha(\omega, \vec{p})]^2 + \Gamma_\alpha^2(\omega, \vec{p})/4} \simeq 2\pi\delta\left(\omega - E_\alpha(\omega, \vec{p})\right) . \quad (3)$$

The single particle spectrum of individual nucleus is given by

$$\boxed{E_\alpha(\omega, \vec{p}) = \frac{p^2}{2Am} + B_\alpha + \mathrm{Re}\Sigma_\alpha(\omega, \vec{p}) - \mu_\alpha ,} \quad (4)$$

Key equations

Equilibrium Thermodynamics of light nuclei:

The pressure and entropy are computed from

$$P = -\frac{\Omega}{V}, \qquad S = -\frac{\partial \Omega}{\partial T}, \qquad etc\ldots \tag{5}$$

The electrons (neutrinos and anti-neutrinos) contribute

$$\Omega_e = -g_e T \int \frac{d^3k}{(2\pi)^3} \ln\left[f^{-1}\left(-E_e(k) + \mu_e\right)\right], \tag{6}$$

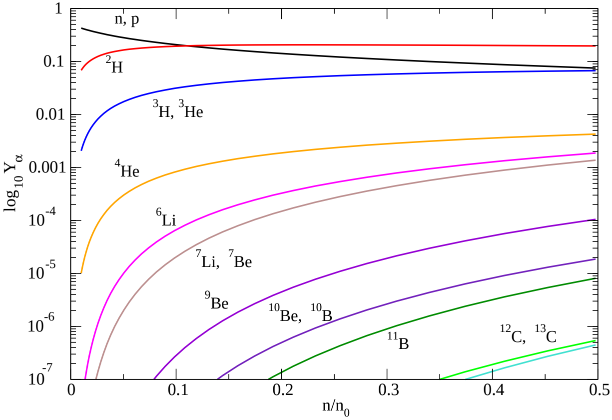
where the charge neutrality and conservations of charges (baryonic/electric)

$$\boxed{n_e - \sum_\alpha Z n_\alpha = 0, \quad \mu_\alpha = (A - Z)\mu_n + Z\mu_p.} \tag{7}$$

I. Density independent binding energies

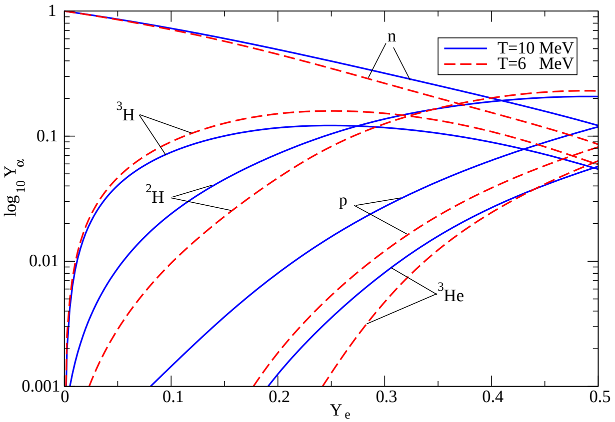
Phys. Rev C 80, 015805, 2009

Symmetrical matter. Composition at $T = 10$ MeV



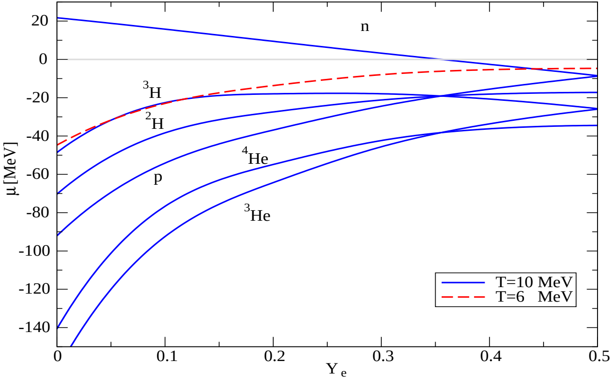
- $Y_\alpha = n_\alpha / n$ - fractional densities of species
- Isospin symmetrical nuclear matter, including all stable nuclei with $A \leq 13$.

Asymmetrical matter. Composition at $T = 10$ and 6 MeV



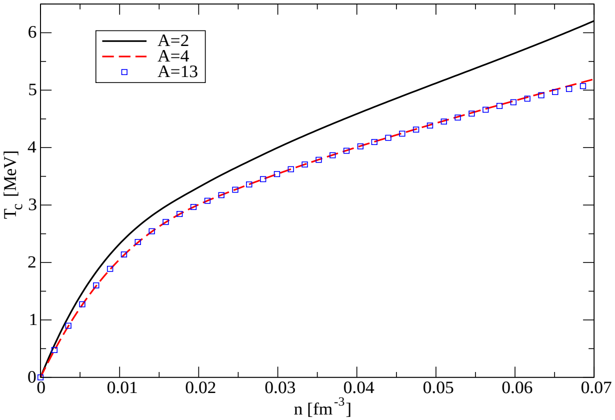
- Isospin asymmetrical nuclear matter, including all stable nuclei with $A \leq 4$.

Signals of deuteron condensation



- Monitoring the chemical potentials for signs of condensation, composition with $A \leq 4$.

Critical temperature of deuteron condensation



- Symmetrical nuclear matter, including all stable nuclei with $A \leq 4$ and $A \leq 13$.

II. Density dependent binding energies

Phys. Rev. C 73, 035803, 2006.

Computing the two-body bound states

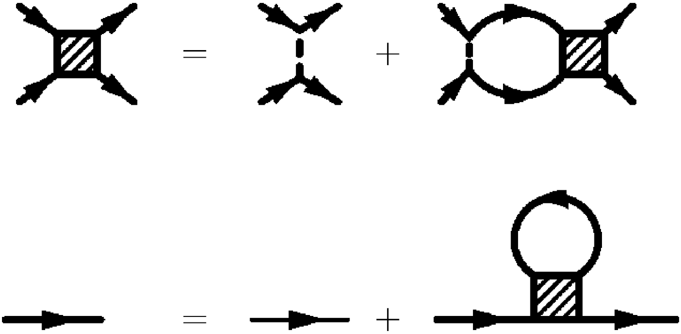


Figure: Coupled equations for the T-matrix (upper line) and the self-energy (lower line). The T-matrix is represented by the square, the bare interaction V by a vertical dashed line, the solid lines correspond to single-particle Green's functions.

Computing the three-body bound states

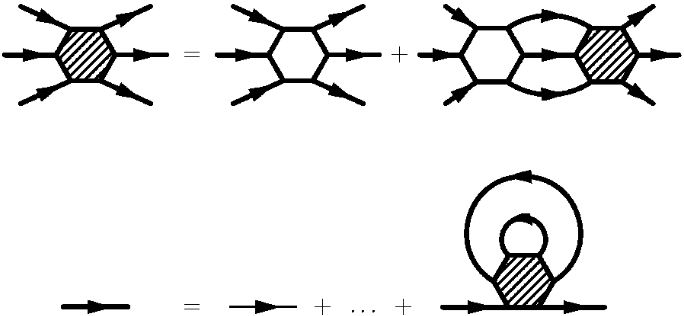
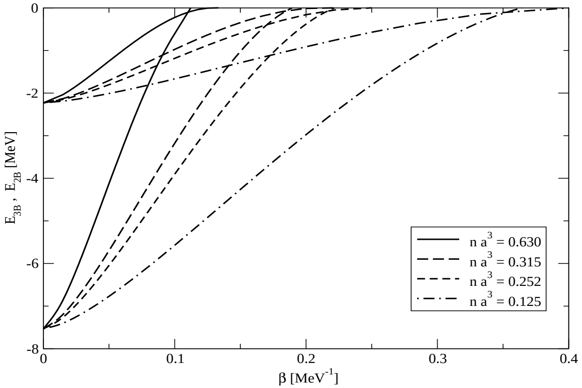
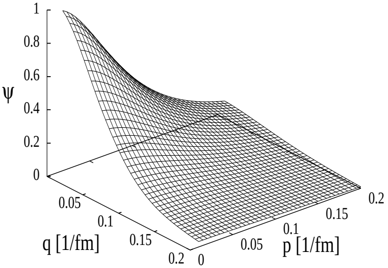


Figure: Coupled integral equations for the three-body $\mathcal{T}$-matrix (first line) and the single particle propagator (second line). The shaded vertex stands for the amplitude $T^{(i)}$, the empty vertex stands for a channel T_{kj} matrix. The second line shows the Dyson equation for the single particle Green's function including the contribution from three-body scattering. The dots stand for the contribution from the two-body scattering shown in Fig 2.

Background dependent binding energies of triton in nuclear matter

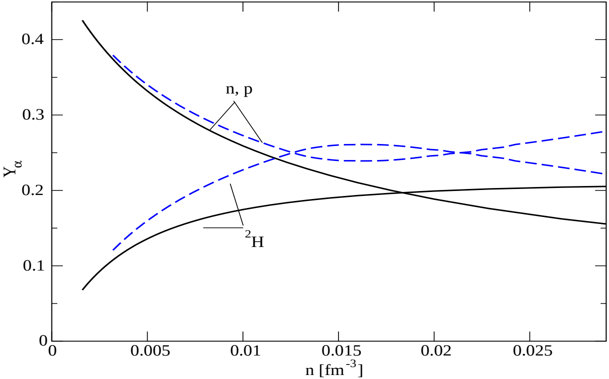


The ratio $\eta = E_{3B}(T)/E_{2B}(T)$ is independent of temperature.



Squeezing the wave function in the momentum space: signal of a quantum phase transition to the unbound state.

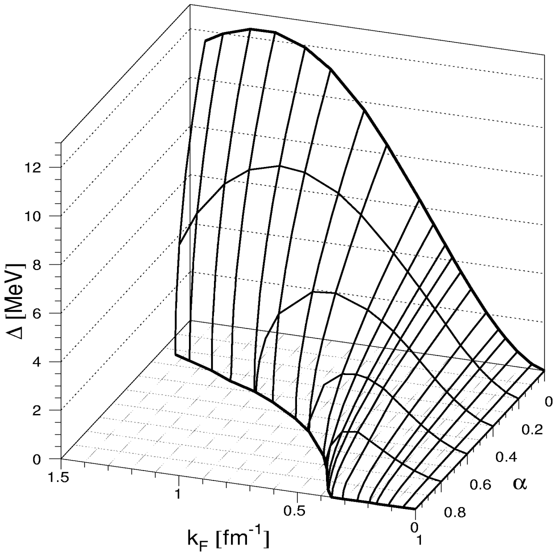
Modifications of binding energies



- Deuteron abundances in symmetrical nuclear matter. Correct asymptotic state at high densities corresponds to a Fermi liquid.

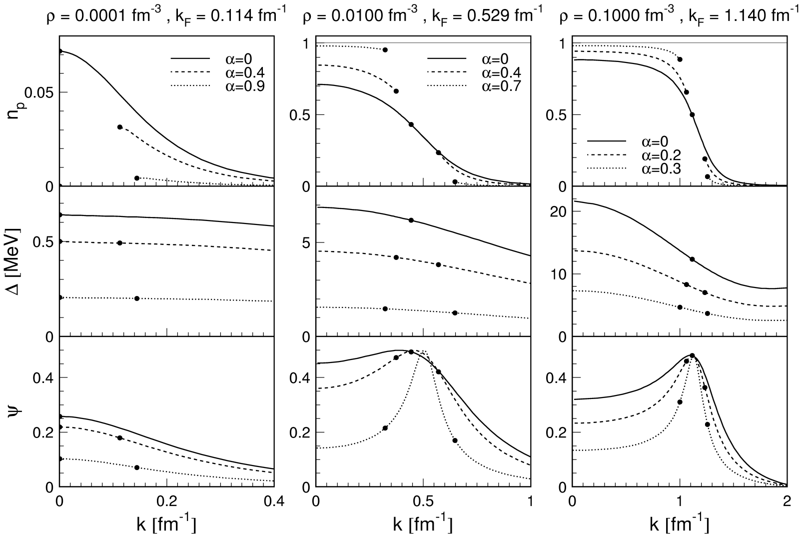
III. Condensates

Deuteron condensation under isospin asymmetry



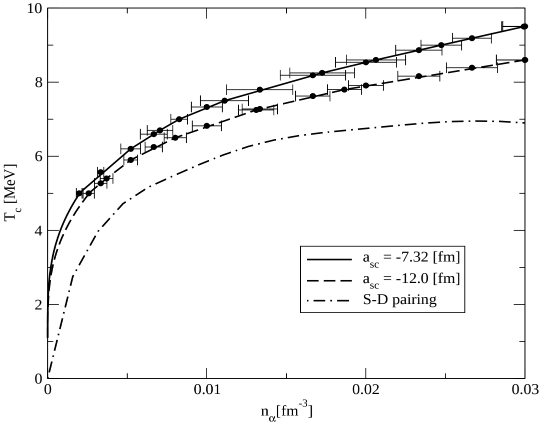
Pairing gap in the 3S1-3D1 channel as a function of fermi momentum and asymmetry.

BCS-BEC crossover in asymmetrical nuclear matter



BCS-BEC from right to left. Upper panel: proton occupations, middle - gap, lower - wave function.

Alpha condensation



Critical temperature from 3d lattice Monte-Carlo calculations [Nucl. Phys. A766:97-106, 2006].

Key points:

- Light clusters can influence of physics of supernova envelopes, including EOS, neutrino cross-sections, etc.,
- Medium modifications of small cluster binding energies can be computed from first principles.
- Condensates are important at temperatures $\sim$MeV.