Chiral nuclear thermodynamics

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Chiral perturbation theory and nuclear matter

- Nuclear matter: low-density and low-temperature phase of QCD.
- Effective field theory incorporating spontaneous and explicit chiral symmetry breaking: **Chiral Perturbation Theory**.
- Active degrees of freedom: **pions**, **nucleons** and $\Delta(\mathbf{1232})$**-isobars**.
- Calculation up to 3-loop order in the free energy density.
- In-medium ChPT: finite density effects. For example at $T = 0$:
  - Ground state: $|0\rangle$ (non-perturbative vacuum) $\Longrightarrow$ $|\phi_0\rangle$ (filled Fermi sea)
  - In-medium nucleon propagator:

$$S_F(p) = (\not{p} + M_N)\left[\frac{i}{p^2 - M_N^2 + i\epsilon} - 2\pi\,\delta(p^2 - M_N^2)\,\theta(k_F - |\mathbf{p}|)\,\theta(p_0)\right]$$

Chiral expansion for nuclear matter

Hierarchy of scales

Long and intermediate distances

Explicit 1π- and 2π-exchange dynamics:

- 2-body terms from N-N interaction.
- 3-body terms incl. Pauli-blocking effects on 2-body terms.

Short-distance physics

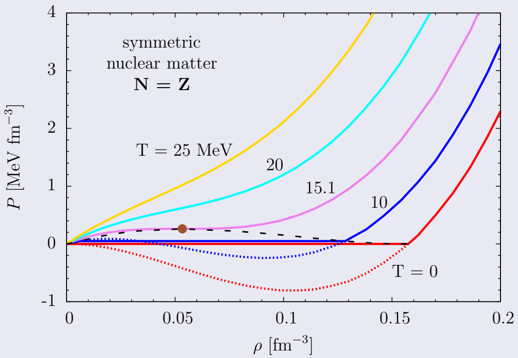
Contact terms tuned to reproduce selected properties of nuclear matter:

- Energy minimum: $E/A \simeq -16$ MeV.
- Asymmetry energy: $A(\rho_0) \simeq 34$ MeV.

- M. Lutz, B. Friman, Ch. Appel, *Phys. Lett.* B 474 (2000) 7
- N. Kaiser, S. Fritsch, W. Weise, *Nucl. Phys.* A 697 (2002) 255
- S. Fritsch, N. Kaiser, W. Weise, *Phys. Lett.* B 545 (2002) 73
- S. Fritsch, N. Kaiser, W. Weise, *Nucl. Phys.* A 750 (2005) 259

Isospin-symmetric nuclear matter

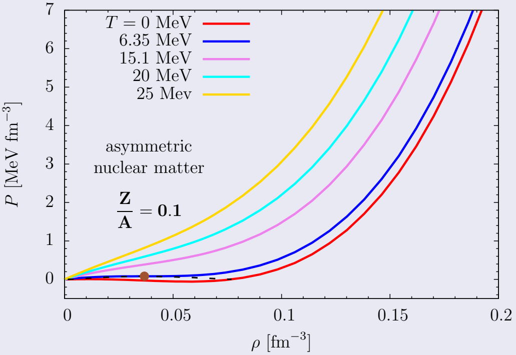
EoS at proton fraction 0.5



- First order liquid-gas phase transition: $T_C \simeq 15.1$ MeV.
- At $T = 0$ compressibility $K(\rho_0) \simeq 300$ MeV.

Isospin-asymmetric nuclear matter

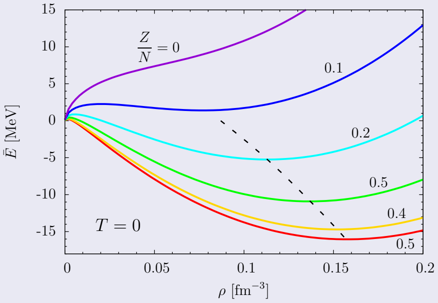
EoS at proton fraction 0.1



- First order liquid-gas phase transition: $T_C \simeq 6.3$ MeV.
- Energy and pressure at a given density increase in comparison to the symmetric case.

Evolution of saturation point

Energy per particle at T = 0

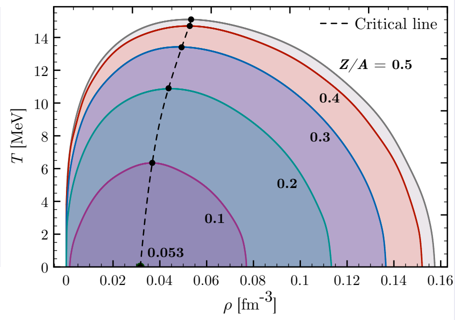


Proton fraction	*Saturation point*	
x_n	ρ_0 [fm^{-3}]	e_0 [MeV]
0.5	0.157	-16.03
0.4	0.152	-14.69
0.3	0.137	-10.9
0.2	0.113	-5.24
0.12	0.087	0

- For proton fractions $\lesssim$ 0.12 nuclear matter is unbound.

Phase diagram of nuclear matter

Temperature - density diagram

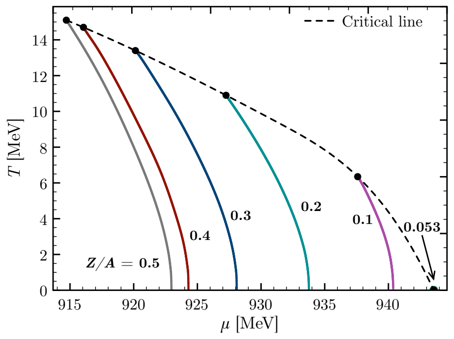


Liquid-gas transition region:

- Gradually smaller with increasing asymmetry.
- Vanishes at proton fraction $\simeq 0.05$.

Phase diagram of nuclear matter

Temperature - baryon chemical potential diagram



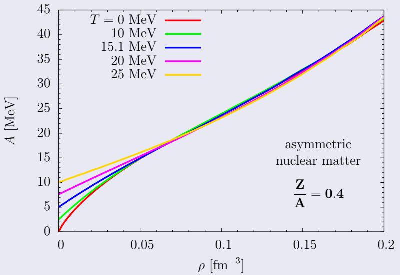
Liquid-gas transition region:

- Gradually smaller with increasing asymmetry.
- Vanishes at proton fraction $\simeq 0.05$.

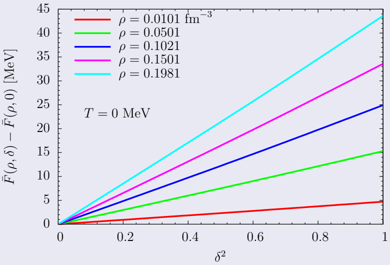
Asymmetry free energy

- Isospin-asymmetry parameter: $\delta = \dfrac{\rho_n - \rho_p}{\rho_n + \rho_p}$.
- Parabolic law: $\bar{F}(\rho, T, \delta) = \bar{F}(\rho, T, 0) + \delta^2 A(\rho, T) + \mathcal{O}(\delta^4)$.

Asymmetry free energy $\delta = 0.2$



Parabolic law at $T = 0$



The scalar quark condensate

- Chiral condensate is order parameter of the chiral phase transition:

$\langle \bar{q}q \rangle = 0$	**chiral symmetry** (Wigner-Weyl realization)
$\langle \bar{q}q \rangle \neq 0$	**spontaneously broken chiral symmetry** (Nambu-Goldstone realization)

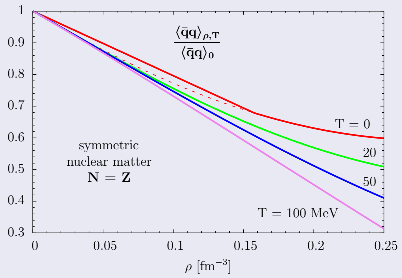
- By Hellmann-Feynman Theorem in-medium condensate is

$$\frac{\langle \bar{q}q \rangle (\rho, T)}{\langle \bar{q}q \rangle_0} = 1 - \frac{\rho}{f_\pi^2} \left[\frac{\sigma_N}{m_\pi^2} \frac{\partial}{\partial M} + \frac{\partial}{\partial m_\pi^2} \right] \bar{F}(\rho, T)$$

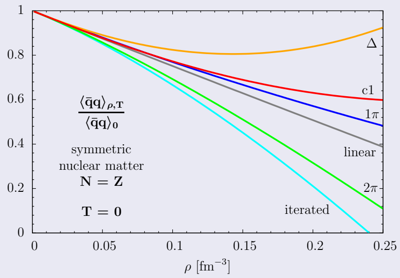
- N. Kaiser, P. de Homont, W. Weise, Phys. Rev. C 77 (2008)

Chiral condensate

Condensate at $m_\pi = 135$ MeV



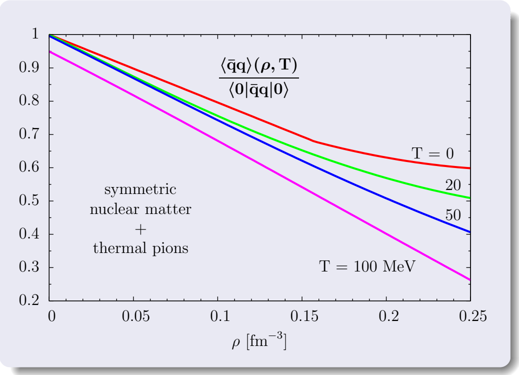
Contributions at $T = 0$



- Linear behaviour: trace of the liquid-gas phase transition.
- Net result of interactions:
  counteract reduction of condensate due to linear density term.
- **Crucial**: Δ-isobar contribution stabilizes the condensate!

Chiral condensate with thermal pions

- We add the contribution of the thermal pions to the chiral condensate †:



No indication of first order chiral phase transition for $\rho \lesssim 2\,\rho_0$ and $T \lesssim 100$ MeV

† N. Kaiser, Phys. Rev. C 59, 2945 (1999)

Summary

- Thermodynamic properties of nuclear matter and chiral condensate from in-medium ChPT at 3-loop order.
- Long-range correlations due to 1π- and 2π-exchange treated explicitly; short-distance dynamics encoded in contact terms.
- **Evolution of liquid-gas phase transition region and binding energy** with increasing asymmetry.
- **No indication of chiral symmetry restoration in nuclear matter** for

$$\rho \lesssim 2\,\rho_0 \text{ and } T \lesssim 100 \text{ MeV.}$$