Ferromagnetic instabilities in neutron matter at finite temperature

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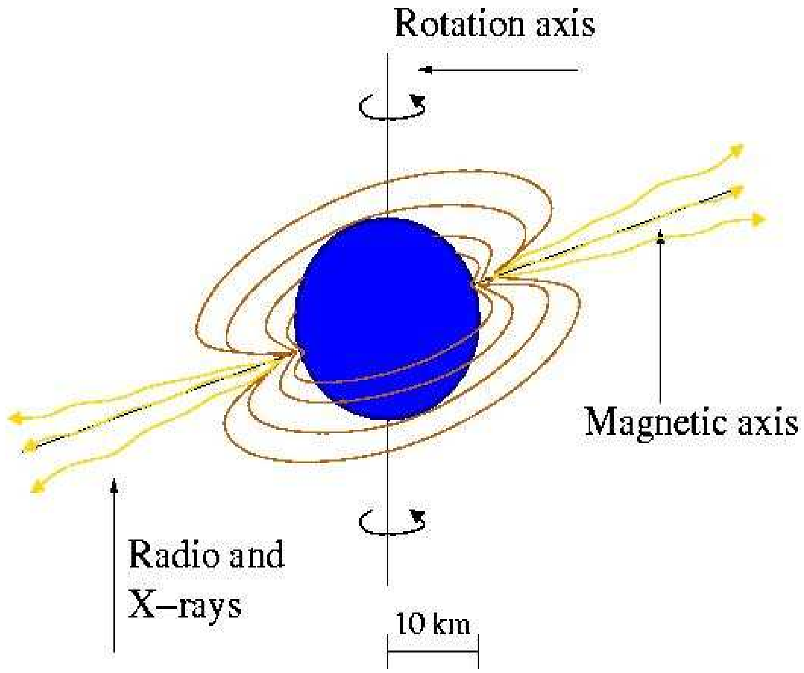
GSI



Pulsars are believed to be rapidly rotating NS with strong surface Magnetic Fields

Origin of the M.F. ?

- Magnetic flux conservation
- Dynamo mechanism
- Ferromagnetic state

Magnetic properties of dense matter !!

Pure Neutron matter

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Nuclear matter

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Skyrme interaction

$$V(r_1,r_2) = t_0(1+x_0P^\sigma)\delta(r) + \frac{1}{6}t_3(1+x_3P^\sigma)[\rho(R)]^\alpha + \frac{1}{2}t_1(1+x_1P^\sigma)(k'^2\delta(r)+\delta(r)k^2)$$
$$+ t_2(1+x_2P^\sigma)\, k'.\delta(r)k + iW_0(\sigma_1+\sigma_2).[k' \times \delta(r)k]$$

$$\frac{E}{A} = \frac{\hbar^2}{2m}\frac{1}{\rho}(\tau_\uparrow+\tau_\downarrow) + \frac{1}{4\rho}2t_2(1+x_2)(\tau_\uparrow\rho_\uparrow+\tau_\downarrow\rho_\downarrow)$$
$$+\frac{1}{4\rho}(t_1(1-x_1)+t_2(1+x_2))(\tau_\uparrow\rho_\downarrow+\tau_\downarrow\rho_\uparrow) + \frac{1}{\rho}[t_0(1-x_0)+\frac{1}{6}t_3(1-x_3)]\rho_\uparrow\rho_\downarrow$$

$$\frac{S}{A} = \sum_\sigma \frac{5}{3}\frac{1}{\rho}\frac{1}{4\pi^2}\left(\frac{2m^*_\sigma}{\hbar^2}\right)^{3/2} J_{3/2}(\eta_\sigma) - \eta_\sigma$$

$$\tau_\sigma = \frac{g}{4\pi^2}\left(\frac{2m^*_\sigma T}{h^2}\right)^{5/2} J_{3/2}(\eta_\sigma)$$

$$\frac{F}{A} = \frac{E}{A} - T\frac{S}{A}$$

$$\varepsilon_\sigma(k) = \frac{\hbar^2 k^2}{2m} + U_\sigma(k)$$

$$\varepsilon_\sigma(k) = \frac{\hbar^2 k^2}{2m^*_\sigma} + \overline{U}_\sigma$$

$$\frac{m^*_\sigma}{m} = \left(1+\frac{2m}{\hbar^2}a_\sigma\right)^{-1}$$

$$a_\sigma = \frac{1}{4}\left[2t_2(1+x_2)\rho_\sigma + (t_1(1-x_1)+t_2(1+x_2))\,\rho_{-\sigma}\right]$$

BHF approximation

$$G_{\sigma_1\sigma_2\sigma_3\sigma_4} = V_{\sigma_1\sigma_2\sigma_3\sigma_4} + \sum_{\sigma_5\sigma_6} V_{\sigma_1\sigma_2\sigma_5\sigma_6} \left(\frac{Q_{\sigma_5\sigma_6}}{E}\right) G_{\sigma_5\sigma_6\sigma_3\sigma_4}$$

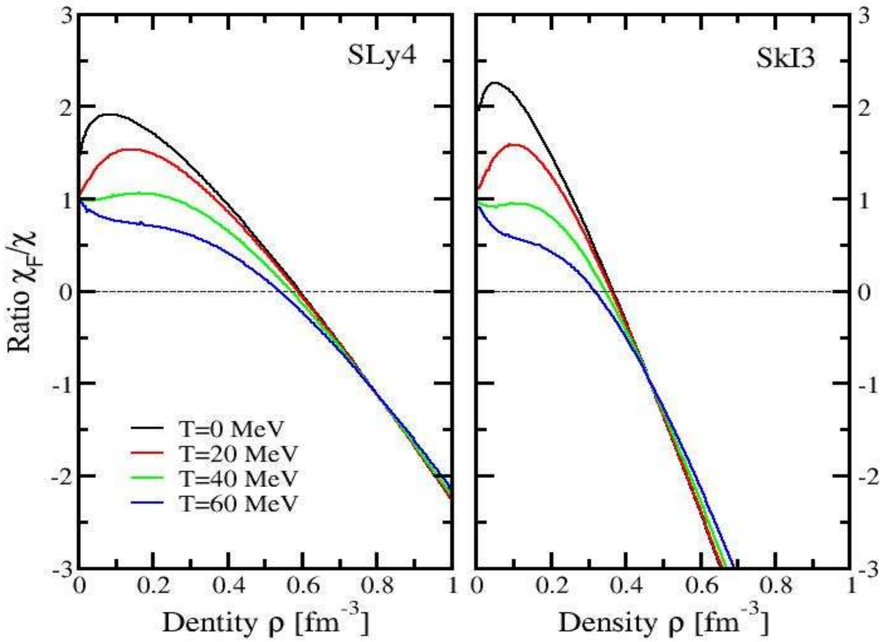
$$U_\sigma(k) = \sum_{\sigma' k'} f_{\sigma'}(k',T) < kk' | G_{\sigma\sigma'\sigma\sigma'} | kk' >_A$$

$$\frac{E}{A} = \frac{1}{A}\sum_{\sigma k} f_\sigma(k,T)\left(\frac{\hbar^2 k^2}{2m} + \frac{1}{2}U_\sigma(k)\right)$$

$$\frac{S}{A} = -\frac{1}{A}\sum_{\sigma k}\Big(f_\sigma(k,T)\ln\left(f_\sigma(k,T)\right) + \left(1-f_\sigma(k,T)\right)\ln\left(1-f_\sigma(k,T)\right)\Big)$$

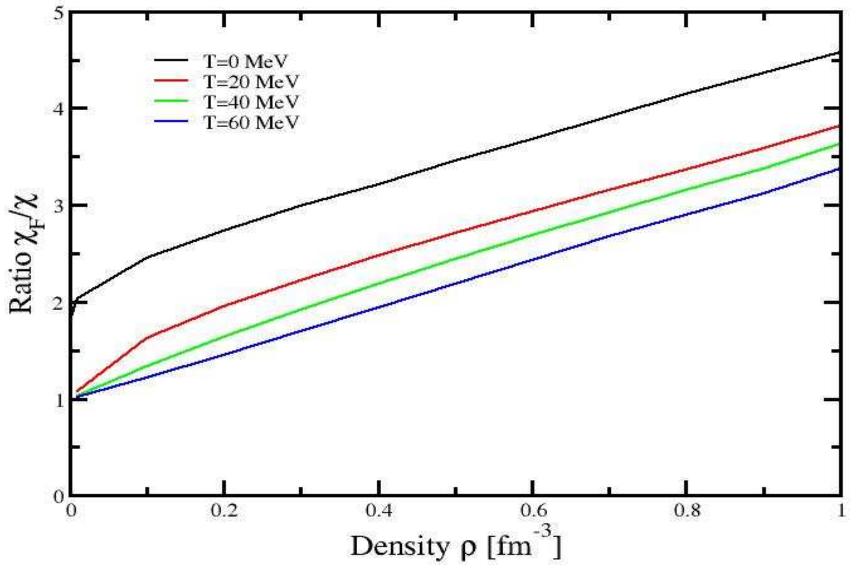
$$\frac{F}{A} = \frac{E}{A} - T\frac{S}{A}$$

Magnetic Susceptibility

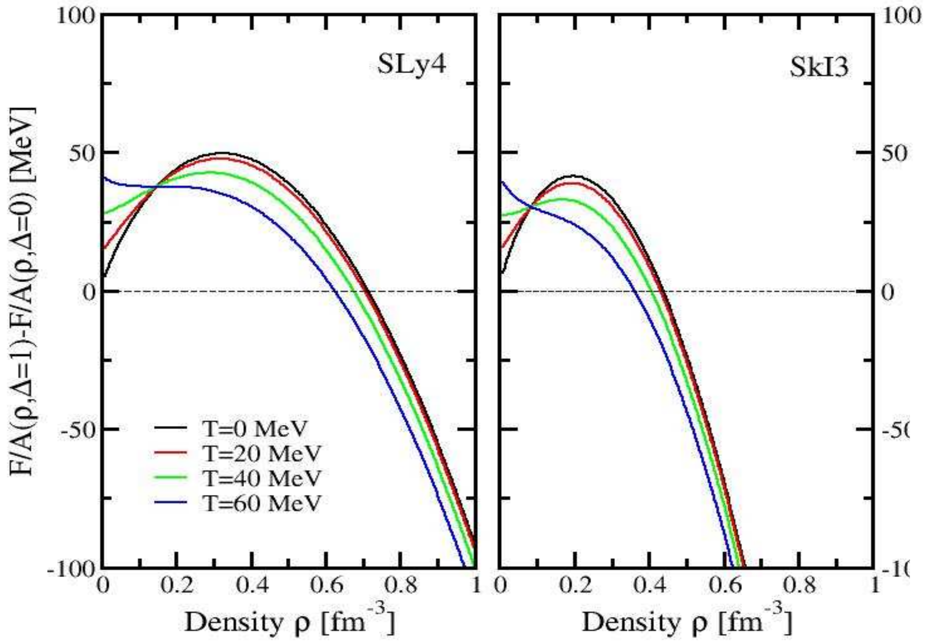


Skyrme

BHF (AV18)

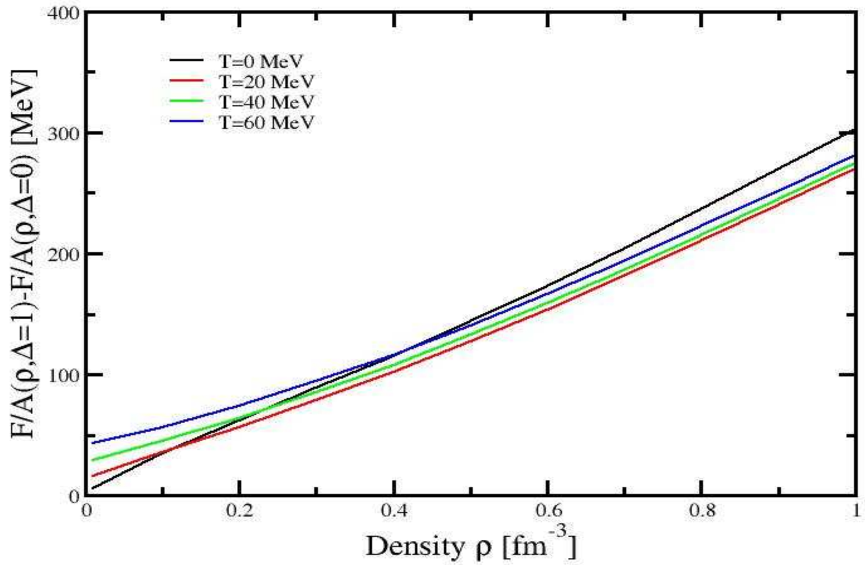


Free energy per particle

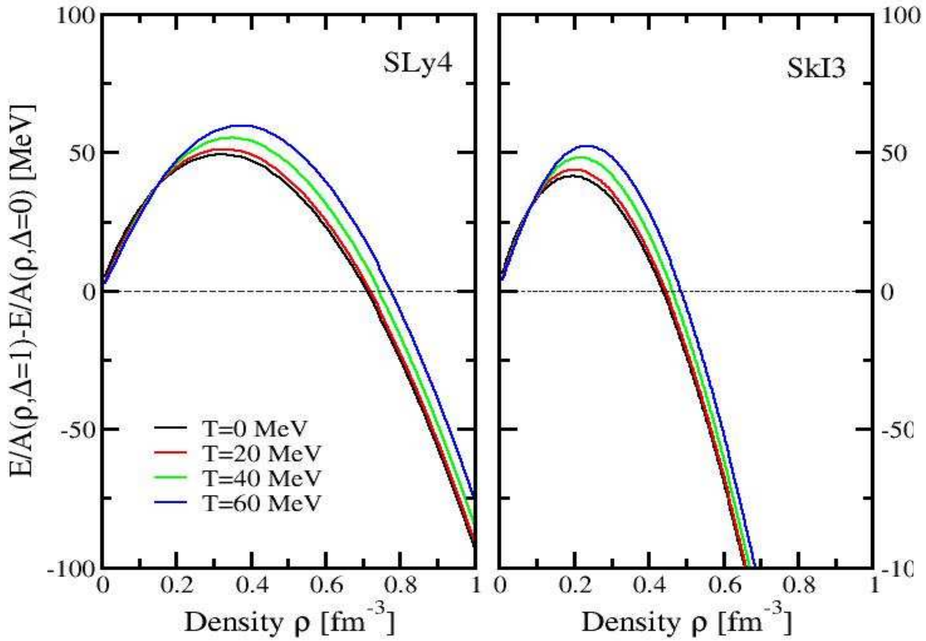


Skyrme

BHF (AV18)

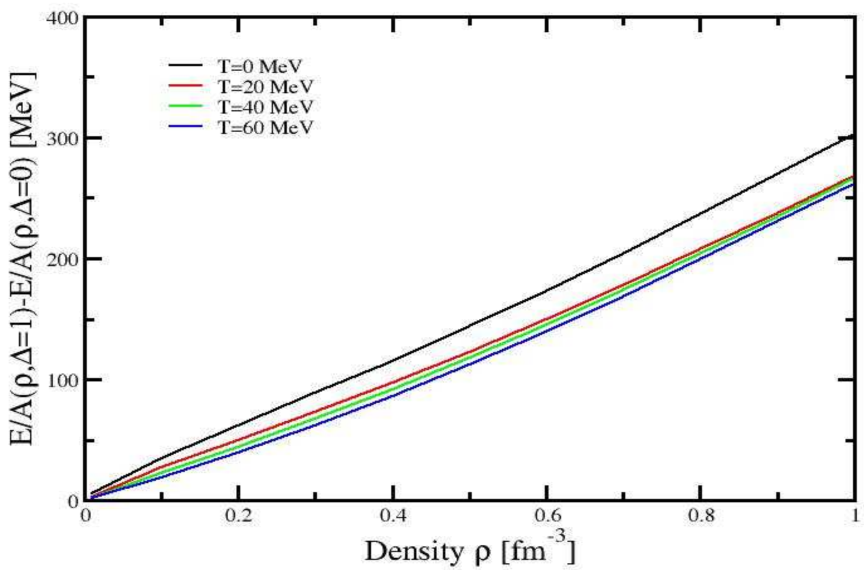


Energy per particle

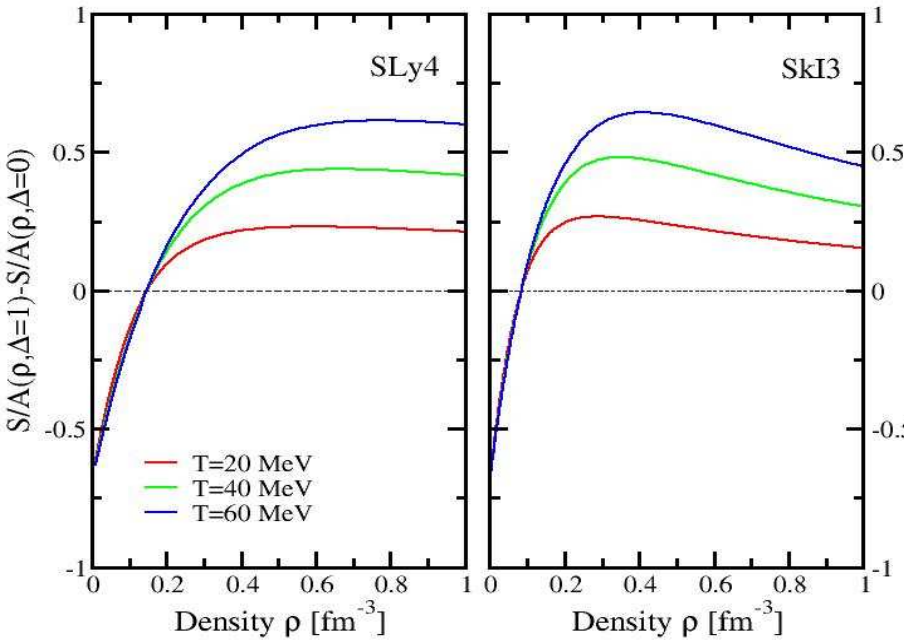


Skyrme

BHF (AV18)

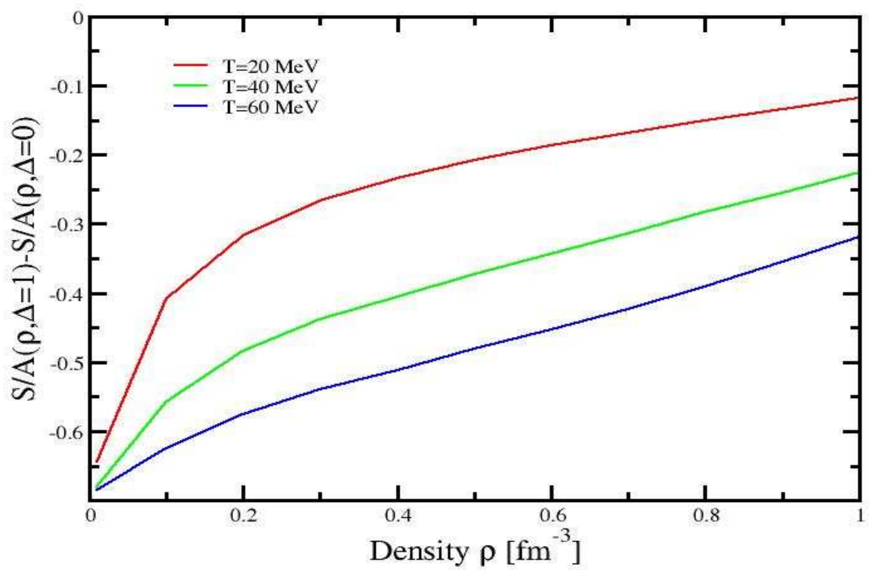


Entropy per particle

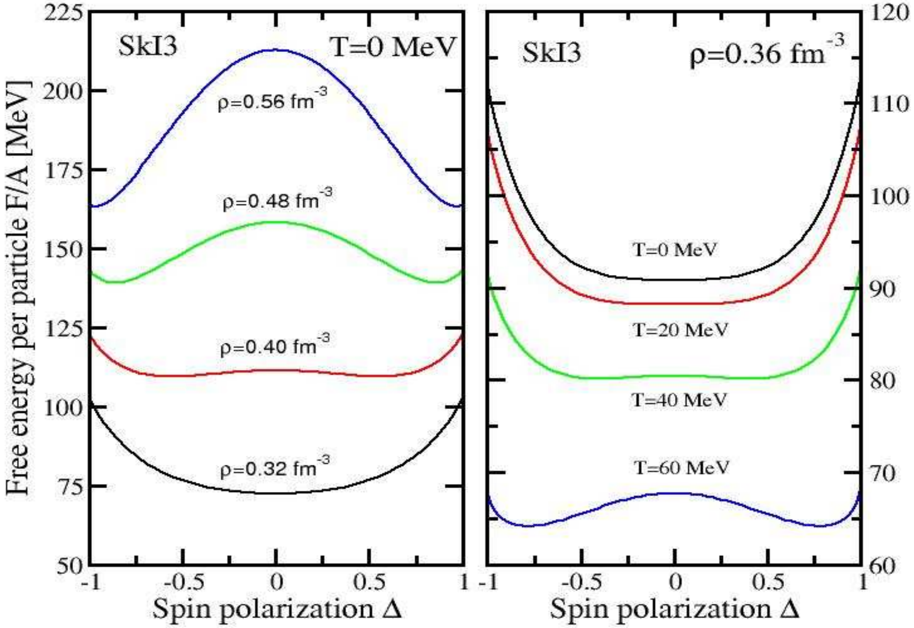


Skyrme

BHF (AV18)

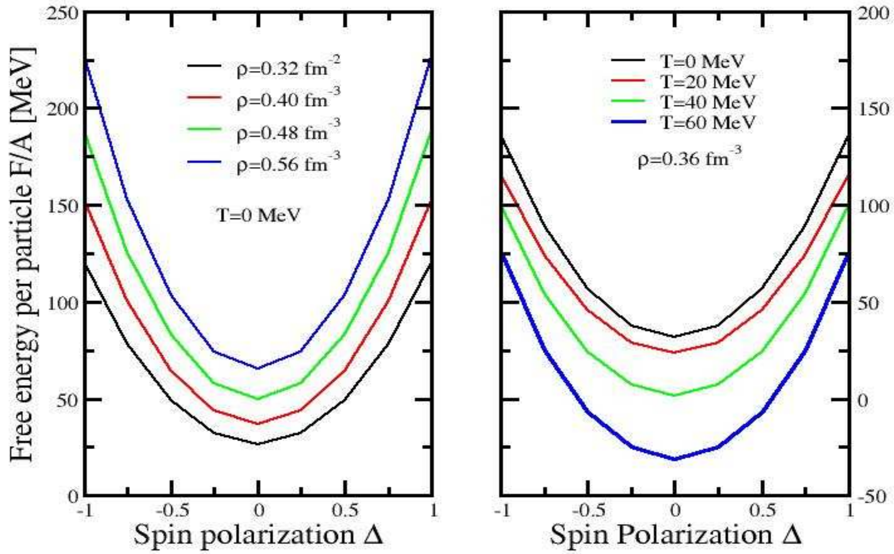


Free energy versus polarization

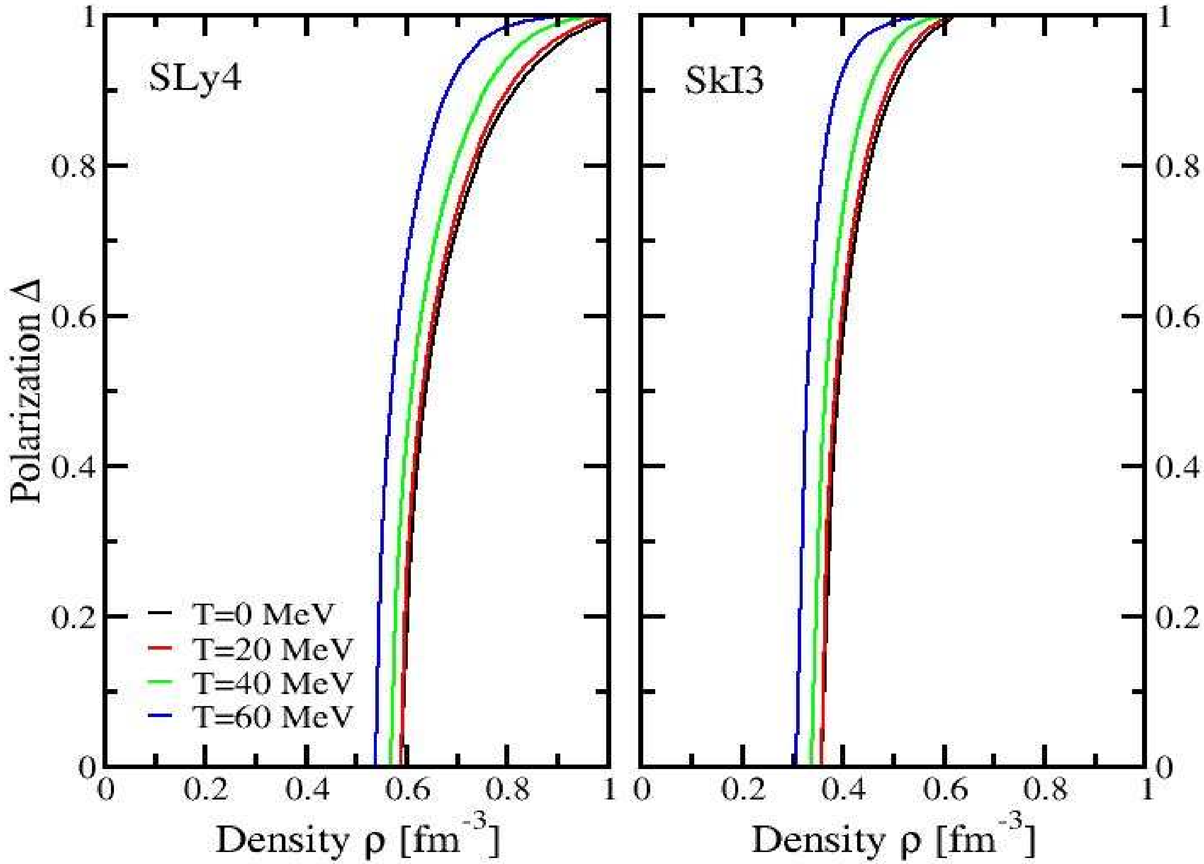


Skyrme

BHF (AV18)

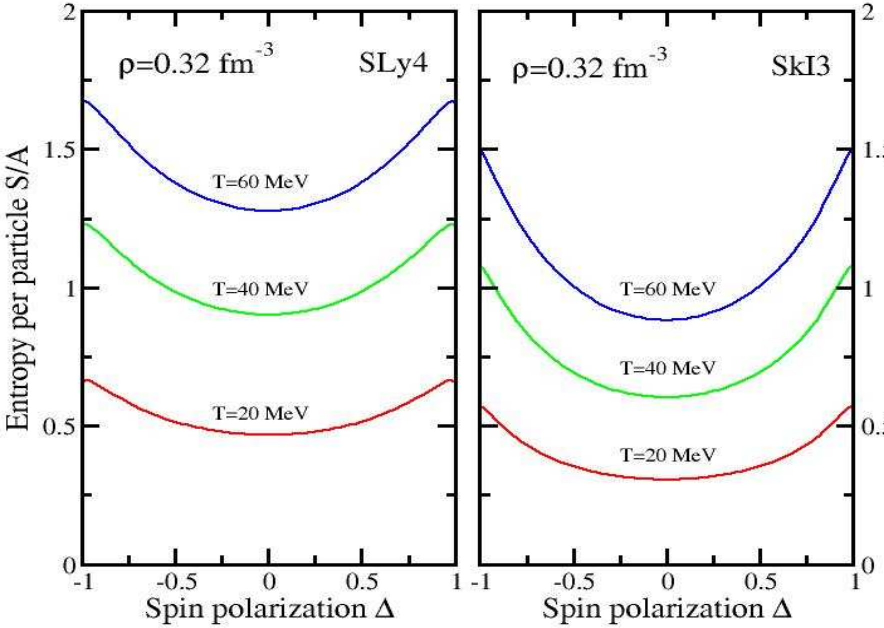


Equilibrium polarization



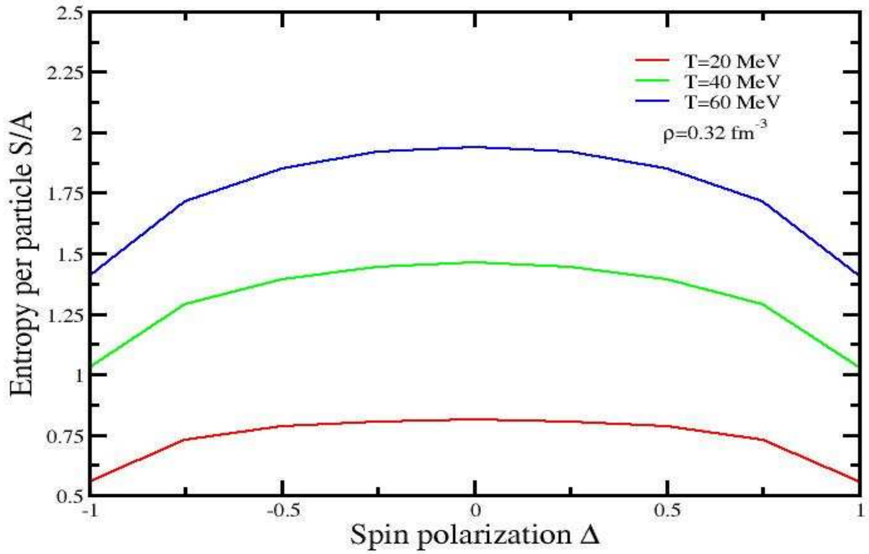
Clearly for BHF $\Delta_{equilibrium} = 0$ at any density

Entropy versus polarization



Skyrme

BHF (AV18)



Entropy and effective mass

Classical limit: $\frac{\rho\lambda^3}{g} \longrightarrow 0$

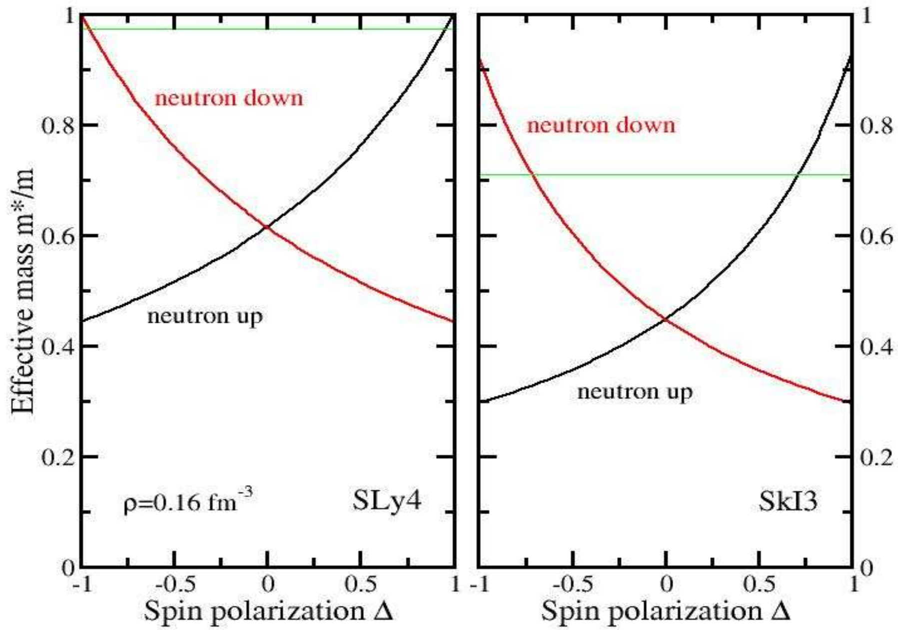
$$\Delta(S/A)_{cla} = -\ln 2 + \frac{3}{2}\ln\left(\frac{m^*(\rho,\Delta=1)}{m^*(\rho,\Delta=0)}\right)$$

Degenerate limit: $\frac{T}{\varepsilon_F} << 1$

$$\Delta(S/A)_{deg} = \frac{\pi^2 T m^*(\rho,\Delta=0)}{\hbar^2 (6\pi^2\rho)^{2/3}} \left(\frac{m^*(\rho,\Delta=1)}{m^*(\rho,\Delta=0)} - 2^{2/3}\right)$$

Imposing $\Delta(S/A)_{cla} < 0$, $\Delta(S/A)_{deg} < 0$

$$\frac{1+\frac{2m}{\hbar^2}\frac{\rho}{8}[t_1(1-x_1)+3t_2(1+x_2)]}{1+\frac{2m}{\hbar^2}\frac{\rho}{4}2t_2(1+x_2)} < 2^{2/3}$$



Summary & Conclusions

1-. Properties of spin polarized neutron matter have been studied at zero and finite temperature using Skyrme-like (SLy4, SkI3) interactions and compared with BHF calculations with realistic (AV18) interactions.

2-. Whereas Skyrme-like interactions show a ferromagnetic transition for densities around (2-4) ρ_0, BHF calculations exclude such instability, at least up to $6\rho_0$ for any temperature.

3-. We found that the critical density at which ferromagnetism takes place decreases with temperature. This unexpected behaviour is due to an anomalous behaviour of the entropy, which becomes larger for the polarized phase above a certain density. This fact is a consequence of the dependence of the entropy on the effective mass of the neutrons with different third spin component. A new constraint on the parameters of the Skyrme force is derived to avoid such a behaviour.

Magnetic susceptibility: Response of a system to a magnetic field

$$\frac{1}{\chi} = \frac{\partial H}{\partial M} \quad \text{with} \quad M = \mu\,(\rho_\uparrow - \rho_\downarrow) = \mu\rho\Delta$$

$$H = \rho\,\frac{\partial (F/A)}{\partial M}$$

$$\frac{1}{\chi} = \frac{1}{\mu^2\rho}\,\frac{\partial^2 (F/A)}{\partial \Delta^2}$$

Stability against spin fluctuations if $\frac{1}{\chi} > 0$