Properties of Localized Protons in Neutron Star Matter at Finite Temperatures

Adam Szmagliński and Włodzimierz Wójcik
Institute of Physics, Cracow University of Technology, Poland

Abstract

We study properties of the proton component of neutron star matter for realistic nuclear models. Vanishing of the nuclear symmetry energy implies proton-neutron separation instability in dense nuclear matter [1]. Protons which forms admixture tend to be localized in potential wells corresponding to neutron matter inhomogeneities created by the protons in the neutron medium. To compare the energy of a normal phase of uniform density and a phase with localized protons we apply the Wigner-Seitz approximation and divide the system into cells, each of them enclosing a single localized proton [2,3]. The neutron density profile is obtained by solving the appropriate variational equation [4]. We performed our calculations at finite temperatures [5]. Though at higher temperature the rms radius of the localized proton probability distribution becomes smaller, the threshold density, above which the protons are localized is also smaller.

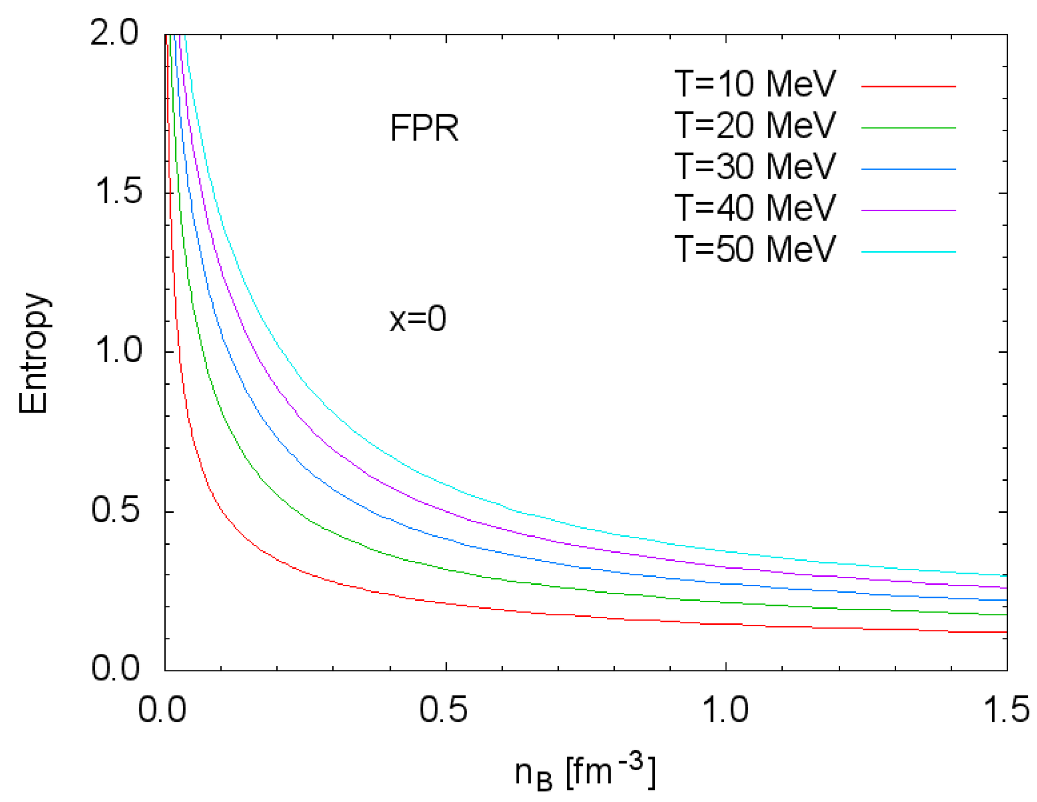

Figure 1: Entropy per baryon vs baryon number density at different temperatures for the Friedman-Pandharipande-Ravenhall model.

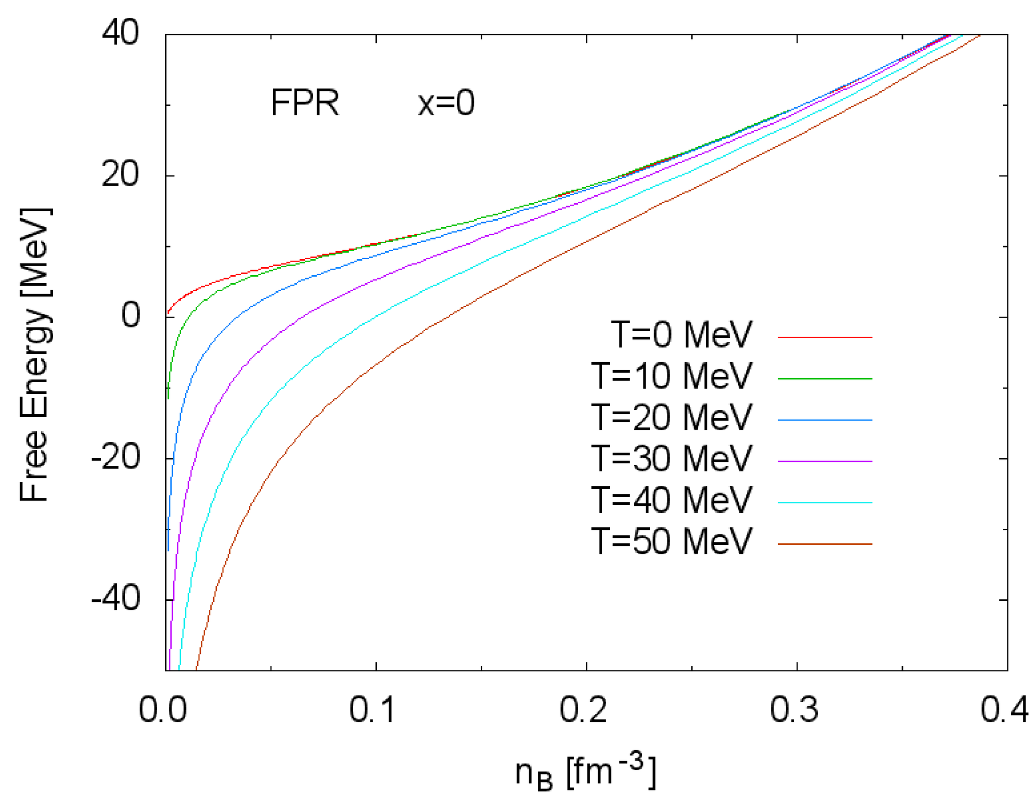

Figure 2: Free energy per baryon vs baryon number density at different temperatures for the Friedman-Pandharipande-Ravenhall model.

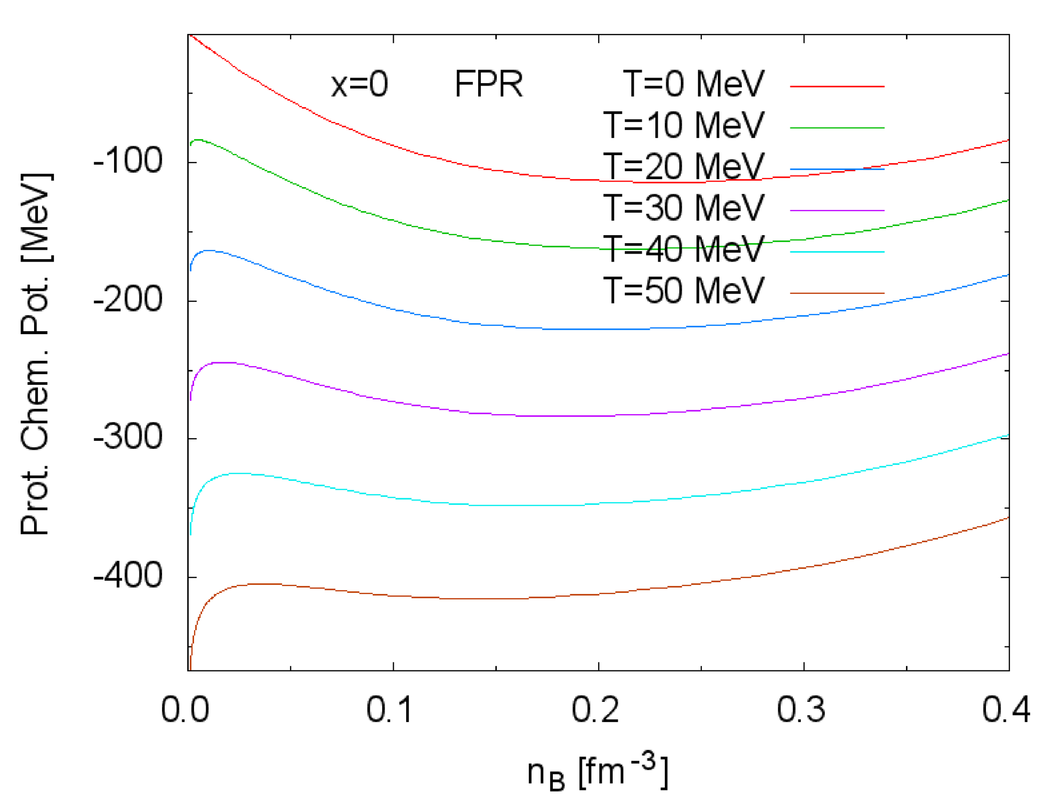

Figure 3: Proton chemical potential vs baryon number density at different temperatures for the Friedman-Pandharipande-Ravenhall model.

Protons are impurities in neutron star matter of a few per cent abundance.
Neutron background forms a potential well with neutron density distribution given by equation

$$\frac{d\mu_P(n_N(r))}{dn_N(r)}\Psi_P^*(r)\,\Psi_P(r)+\mu_N(n_N(r))+2B_N\frac{d^2n_N(r)}{dr^2}-\mu_N=0, \tag{1}$$

where $\mu_N(n_N(r))=\frac{d\varepsilon(n_N(r))}{dn_N(r)}$. At Fig. 4 we show induced neutron background shape.

Entropy per baryon (Fig. 1):

$$S_{N,P}=\frac{5}{3}\frac{1}{n_{N,P}}\frac{1}{4\pi^2}\left(2m^*_{N,P}T\right)^{3/2}J_{3/2}(\eta_{N,P})-\frac{1}{2}\eta_{N,P} \tag{2}$$

$\eta=\frac{\mu}{k_BT}$ can be derived from the baryon number density:

$$n_{N,P}=\frac{2}{(2\pi)^2}\left(2m^*_{N,P}T\right)^{3/2}J_{1/2}(\eta_{N,P}) \tag{3}$$

The Fermi integrals are used here:

$$J_\nu(\eta)=\int_0^\infty dx\,\frac{x^\nu}{1+e^{x-\eta}} \tag{4}$$

Kinetic energy density:

$$\tau_{N,P}=\frac{2}{(2\pi)^2}\left(2m^*_{N,P}T\right)^{5/2}J_{3/2}(\eta_{N,P}) \tag{5}$$

where Free energy per baryon (Fig. 2):

$$F=\left(\varepsilon(n_N,n_P,T)-T(n_NS_N+n_PS_P)\right)/n \tag{6}$$

Chemical potential (Fig. 3) (f is the free energy density here):

$$\mu_{N,P}=\frac{\partial f}{\partial n_{N,P}}=n\frac{\partial F}{\partial n_{N,P}}+F \tag{7}$$

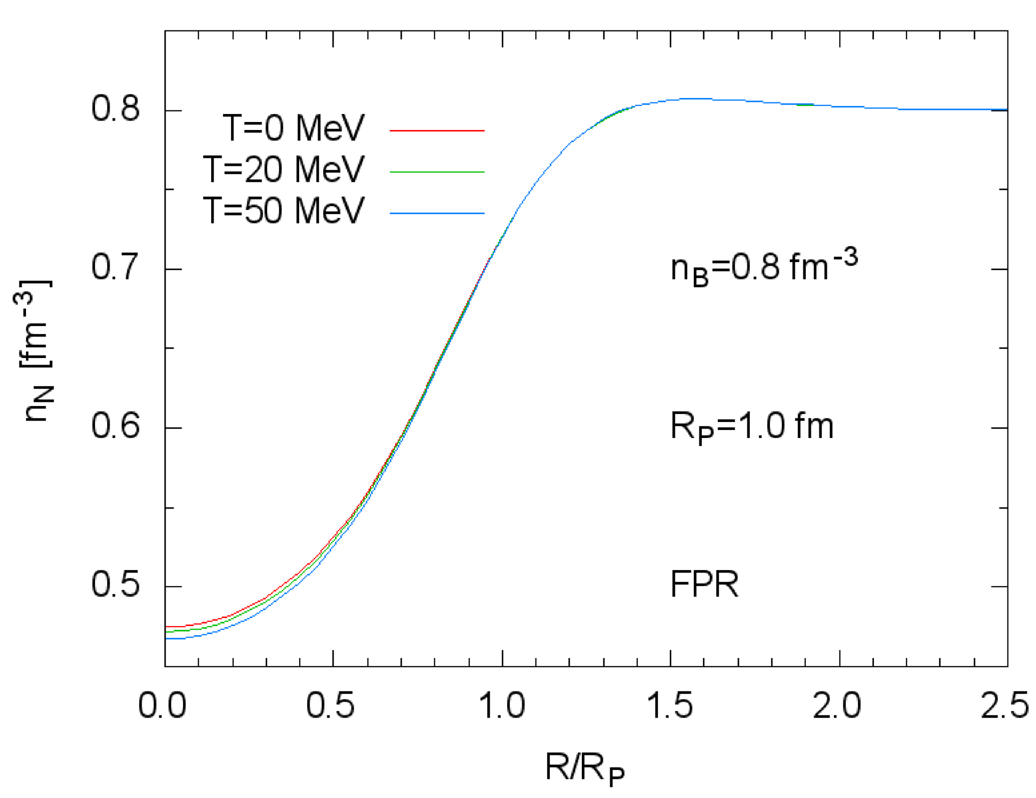

Figure 4: The neutron density distribution obtained from Eq.(1) at different temperatures for the Friedman-Pandharipande-Ravenhall model.

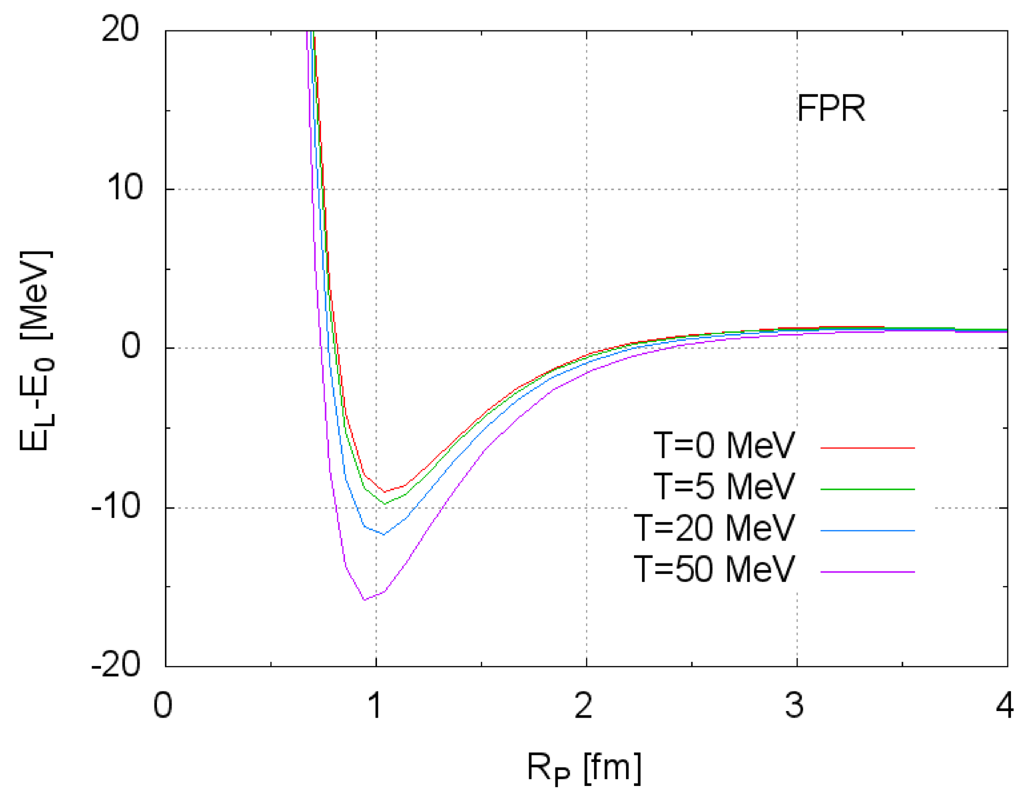

Figure 5: The energy difference $\Delta E=E_L-E_0$ as a function of the proton rms radius at different temperatures for the Friedman-Pandharipande-Ravenhall model.

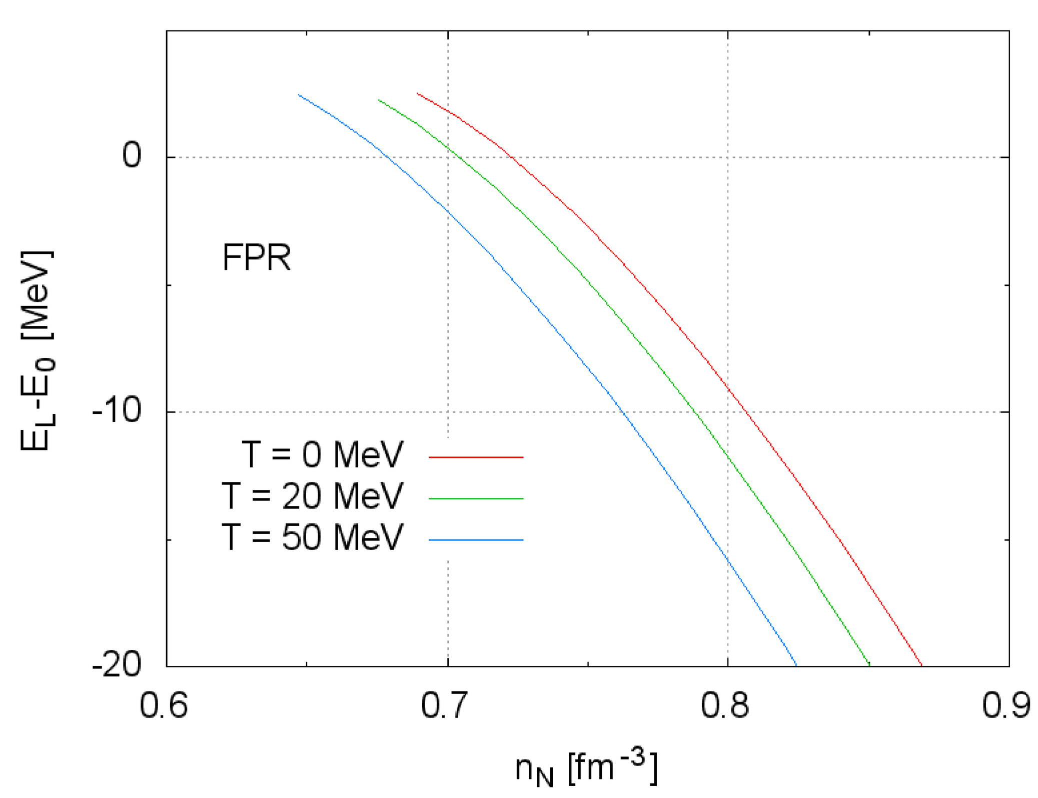

Figure 6: The minimum of the energy difference $\Delta E=E_L-E_0$ as a function of the neutron matter density at different temperatures for the Friedman-Pandharipande-Ravenhall model.

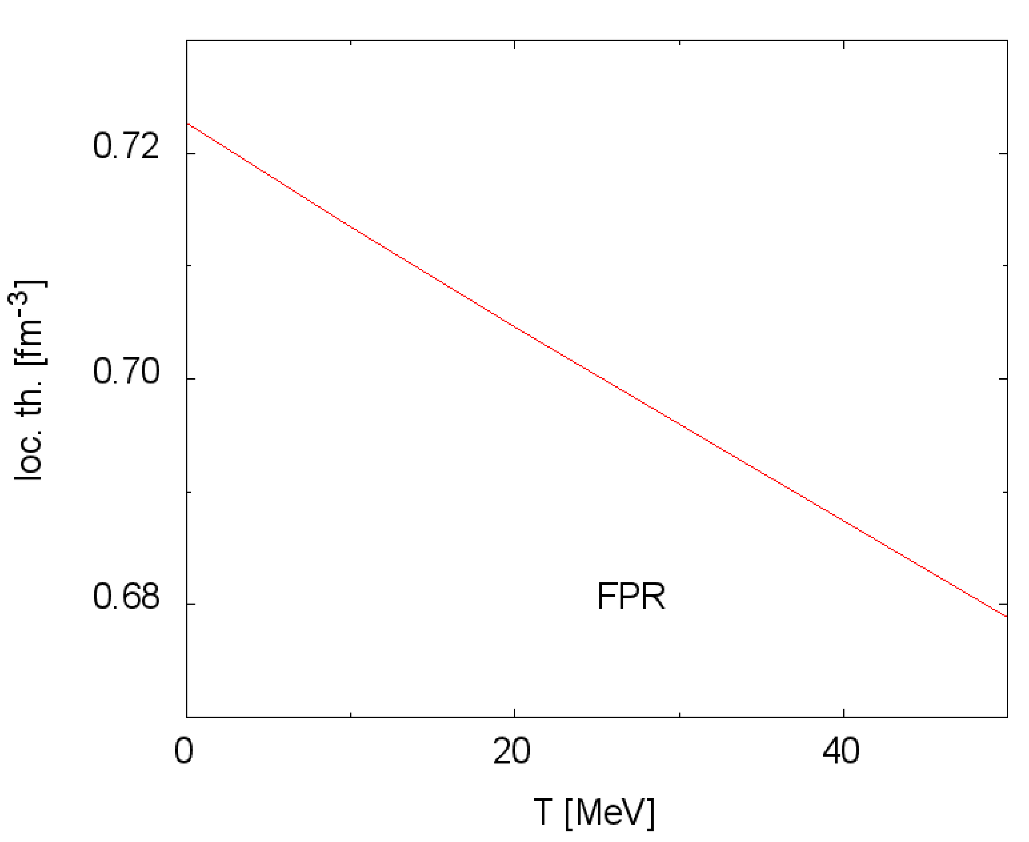

Figure 7: The threshold density above which the localization effect is predicted as a function of the temperature of neutron matter for the Friedman-Pandharipande-Ravenhall model.

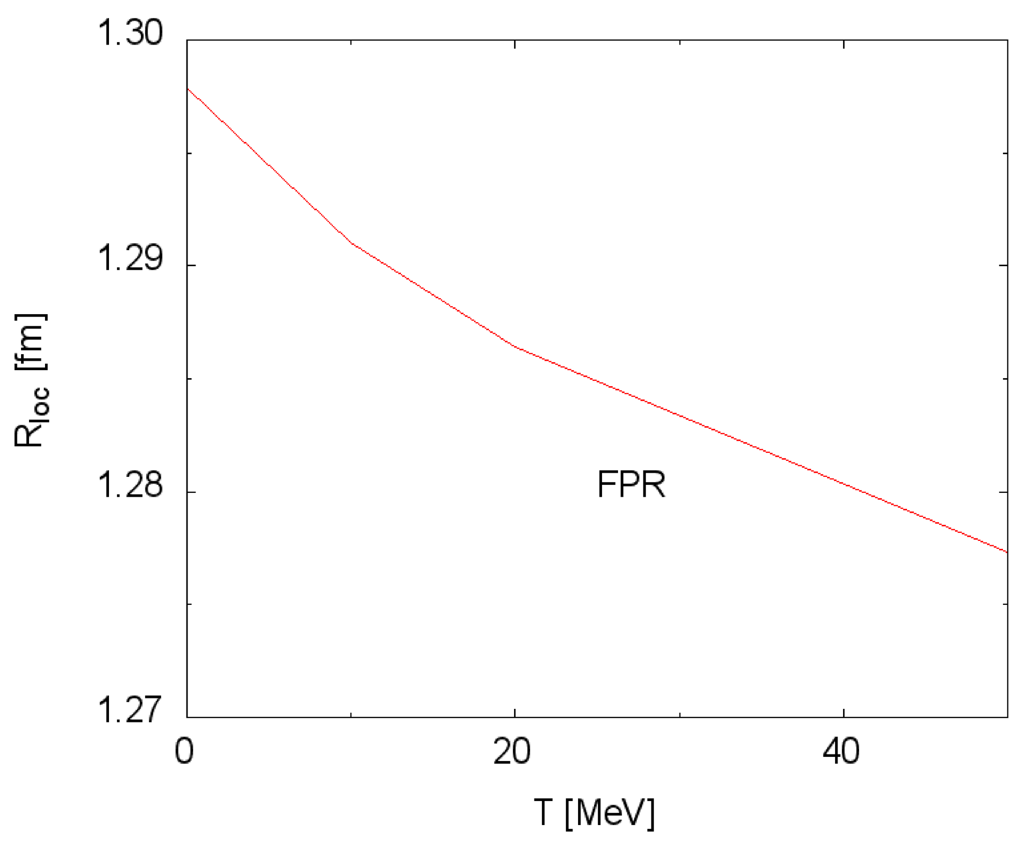

Figure 8: The rms radius of proton wave function corresponding to the threshold density above which the localization effect is predicted as a function of the temperature of neutron matter for the Friedman-Pandharipande-Ravenhall model.

Conclusions

At higher temperatures the localization of protons in the neutron star matter begins at lower densities and is stronger.

Bibliography

[1] M. Kutschera, Phys. Lett. **B340**, 1 (1994).
[2] M. Kutschera, W. Wójcik, Phys. Lett. **B223**, 11 (1989).
[3] M. Kutschera, W. Wójcik, Phys. Rev. **C47**, 1077 (1993).
[4] M. Kutschera, S. Stachniewicz, A. Szmagliński, W. Wójcik, Acta Phys. Pol. **B33**, 743 (2002).
[5] K. Strobel, F. Weber, M. K. Weigel, Z. Naturforsch., **54a**, 83, (1990).