Unified treatment of sub-saturation stellar matter at zero and finite temperature

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Modelization of sub-saturated matter at T=0

our method: minimisation of ϵ_B at fixed (ρ_B, Y_e)

$$\mathcal{D}(A,\delta,\rho_g,y_g,V_{WS}) = \epsilon_{HM}(\rho_g,y_g) + E^e(A,\delta,\rho_g,y_g)/V_{WS} - \alpha\rho_g\left(\rho_0 - A/V_{WS}\right) + \alpha\rho_0\left(\rho_B - A/V_{WS}\right) - \beta y_g\left(\rho_0 - A/V_{WS}\right) + \beta\rho_0\left(\rho_B(1-2y_p) - A\delta/V_{WS}\right)$$

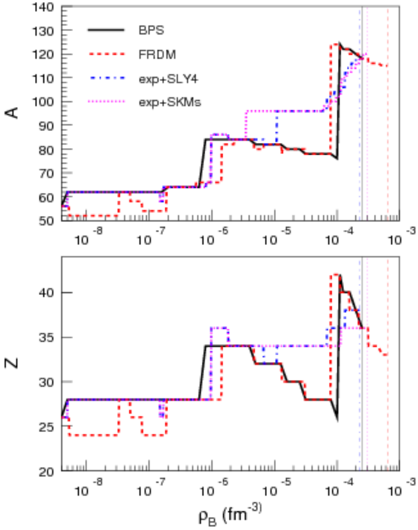
$$\rho_{Bp(n)} = \frac{A(1\mp\delta)}{2V_{WS}}; \quad \rho_{Bn(p)} = \rho_g\left(1 - \frac{A}{\rho_0 V_{WS}}\right) + \frac{A(1\pm\delta)}{2V_{WS}}$$

$$\frac{\partial(E^{nuc}/A)}{\partial A}|_\delta = 0$$

$$\frac{1}{A}\frac{\partial E^e}{\partial\delta}|_A \pm \frac{1}{1\mp\delta}\frac{\partial E^e}{\partial A}|_\delta = \pm\mu_g\frac{1}{1\mp\delta}\left(1 - \frac{\rho_g}{\rho_0}\right) + \mu_g\frac{\rho_g\rho_0'}{\rho_0^2}$$

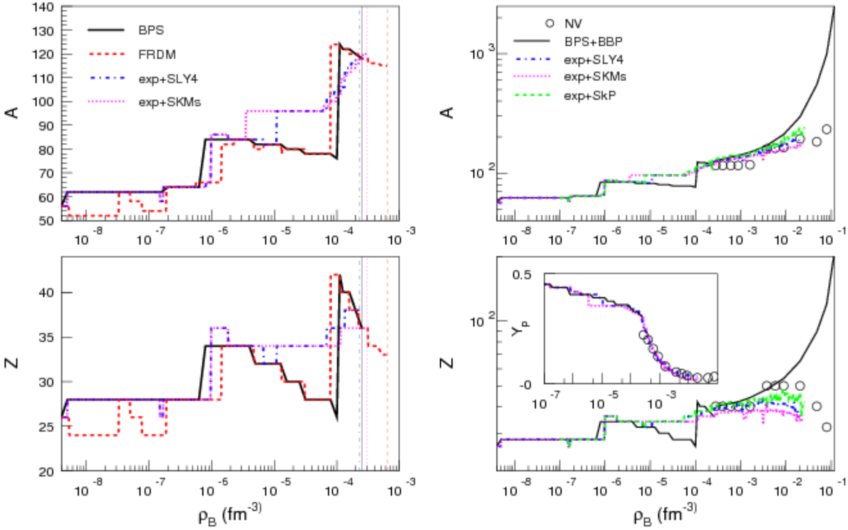
- similar to BBP'71

Crust structure at T=0



perfect agreem. with BPS'71
if M_{exp} are used

Crust structure at T=0



perfect agreem. with BPS'71 if M_{exp} are used

BBP predicts large clusters because of low K eff. int. and in-med. eff.

SNA at finite T

minimization under constraints of free energy density:

$$F_{WS} = F^e_\beta(A,\delta,\rho_g,y_g) - TV_{WS} lnz^{HM}_\beta(\rho_g,y_g) - TV_{WS} lnz^{el}_\beta(\rho_p) + \delta F_{surf},$$

Leads to:

$$\rho_B = \rho_g + \frac{A}{V_{WS}}\left(1-\frac{\rho_g}{\rho_0(\delta)}\right);\ Y_p\rho_B = \rho_{pg} + \frac{Z}{V_{WS}}\left(1-\frac{\rho_{pg}}{\rho_0^p(\delta)}\right);$$

$$\frac{\partial E^e}{\partial A}|_{\delta,\rho_g,y_g} = \mu_B\frac{\rho_0-\rho_g}{\rho_0} + \mu_3\frac{\rho_0\delta - y_g}{\rho_0} + \frac{3T}{2A}\frac{\rho_0 V_{WS}}{\rho_0 V_{WS}-A} + T\frac{\partial \ln c_\beta}{\partial A}|_{\delta,\rho_g,y_g}$$

$$\frac{\partial E^e}{\partial \delta}|_{A,\rho_g,y_g} = \mu_3 A + \frac{\rho_0' A}{\rho_0}(\mu_B\frac{\rho_g}{\rho_0} + \mu_3\frac{y_g}{\rho_0}) + \frac{3}{2}T\frac{\rho_g}{\rho_0}\frac{\rho_0'\rho_0 V_{WS}}{(\rho_0-\rho_g)(\rho_0 V_{WS}-A)} + T\frac{\partial \ln c_\beta}{\partial \delta}|_{A,\rho_g,y_g}$$

$$\frac{\partial(F^0_\beta/A)}{\partial A}|_{\delta,V_{WS}} = 0$$

similar to LS

no skin effects, no bubbles, no phase transitions

SNA to NSE

consider a large volume $V \to \infty$ which contains a number $n \to \infty$ of different WS cell and introduce two Langrange multipliers to fix ρ_B and ρ_i
$F_{tot}(k) = -TV \ln z_\beta^{HM}(k) - TV \ln z_{beta}^{el} + \sum_i n_i^{(k)} F_\beta^{(k)}(i)$
$F_\beta^e(i) = E^e(A, \delta, \rho_g, y_g, \rho_e) - T \ln V - T \ln c_\beta - \frac{3}{2} T A_e$

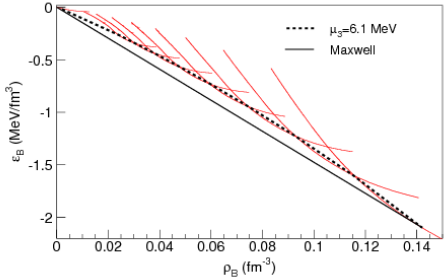
.....

$Z^{cl}_{\beta,\mu_B,\mu_3} = \prod_i \exp \omega_{\beta,\mu_B,\mu_3}(i)$
with $\omega_{\beta,\mu_B,\mu_3}(i) = \exp -\beta \left(F_\beta^e(A, \delta, \rho_g, y_g, \rho_e) - \mu_B A_e \mu_3 I_e \right)$

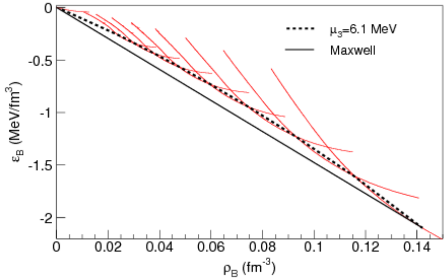
formulation similar to other NSE except that e-clusters are used

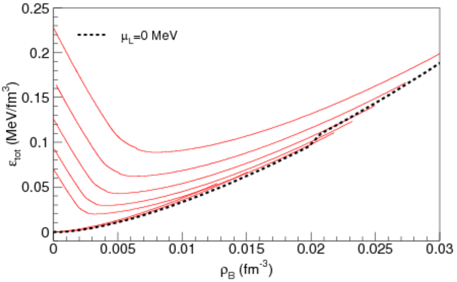
- results look *qualitatively* similar to those of other NSE
- (so far) no *quantitative* comparison with LS (help!)

Phase transitions in the crust?



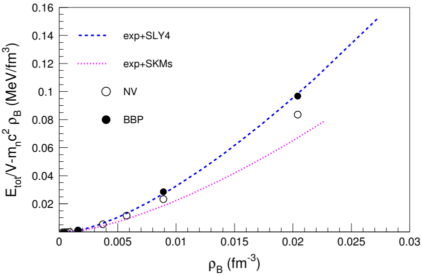
Phase transitions in the crust?

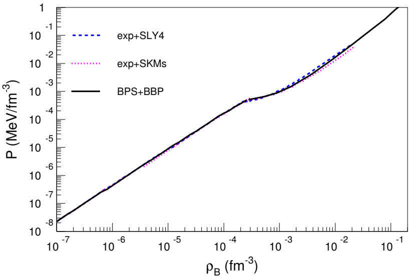




$E_{tot}/V(\rho)$ is convex; star matter is stable

EOS


0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.005
0.01
0.015
0.02
0.025
0.03
exp+SLY4
exp+SKMs
NV
BBP
$E_{tot}/V-m_n c^2 \rho_B$ (MeV/fm^3)
ρ_B (fm^{-3})


1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
exp+SLY4
exp+SKMs
BPS+BBP
P (MeV/fm^{-3})
ρ_B (fm^{-3})

Conclusions

- unitary model for T=0 and T finite
- suitable to contribute to Compose
    - relation between nucleonic and starmatter EOSs
    - crust structure impact on $M(R)$
    - etc.

Modelization of sub-saturated matter at T=0

Historical overview:

- variational methods

- external crust

  Baym, Pethick, Sutherland, ApJ 170, 299 (1971);

  Roca-Maza, Piekarewicz, PRC78 025807 (2008)

- internal crust

  Baym, Bethe, Pethick, NPA175, 225 (1971)

- Hartree-Fock

  Negele, Vautherin, NPA207, 298 (1973)

- Extended Thomas-Fermi

  Pearson, Chamel, Goriely, Ducoin, PRC85, 065803 (2012)