The Equation of state of hot nuclear matter

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We have carried out calculations of the equation of state (EOS) of hot nuclear matter, using the semi classical extended Thomas-Fermi approximation for the internal kinetic energy of nucleons and the potential energy due to the Skyrme effective nucleon-nucleon interaction. We have paid special attention to the derivation of the stiffness coefficients, such as the incompressibility coefficient $K(\rho_0)$ and the isospin symmetry coefficient $C_{\mathrm{sym}}(\rho_0)$. We point out that the use of the Skyrme interaction with parameters adjusted to reproduce the ground state properties of nuclei within the mean-field model is a reasonable approximation for our purposes. In fact, the effective interaction is modified only slightly (by a few percent) in a wide temperature range, $T = 0 \div 20$ MeV. Here, we present results of numerical calculations of the incompressibility coefficient $K(\rho_0)$ and the symmetry energy coefficient $C_{\mathrm{sym}}(\rho_0)$ for the SkM*, Sly203b and the more modern KDE0v1 Skyrme interactions.

In Table I we give the values of the Skyrme parameters for the SkM*, KDE0v1 and Sly230b interactions and the corresponding physical quantities of symmetric nuclear matter at saturation density, ρ_{eq}. Note that, in general, the transport coefficients $K,$ and C_{sym}, are temperature dependent. This can be seen, in a transparent way, by normalizing the density ρ_0 to the equilibrium density $\rho_{\mathrm{eq}}(T)$ and using the dimensionless ratio $\rho_0/\rho_{\mathrm{eq}}(T)$ as a variable. To avoid any misunderstanding, we point out that the particle density ρ_0 is an independent variable which is fixed by the Lagrange multiplier ξ in the variational Euler-Lagrange equation. In the case of $\xi = 0$ and zero temperature $T = 0$, the variational equation provides the actual equilibrium state with the saturation density $\rho_0 = \rho_{\mathrm{eq}}(T = 0)$. In a heated system at $T \neq 0$ and below the phase separation point, the equilibrium density $\rho_{\mathrm{eq}}(T)$ is derived by the equilibrium condition for the pressure $P(\rho, T) = 0$, where $P(\rho, T) = \rho^2 \partial F(\rho, T)/\partial\rho$ and $F(\rho, T)$ is the free energy. For higher temperatures above the point of the phase separation, the value of $\rho_{\mathrm{eq}}(T)$ is obtained from the interphase equilibrium condition. The temperature dependence of the equilibrium density $\rho_{\mathrm{eq}}(T)$ can be approximated as $\rho_{\mathrm{eq}}(T) = \rho_{\mathrm{eq}}(T = 0)(1 - 1.6 \cdot 10^{-3} T^2)$, where the temperature T is taken in MeV. In Figs. 1 and 2, we show the density dependence of the incompressibility, K, and the symmetry energy coefficient, C_{sym}, respectively, for different temperatures T for three sets of Skyrme forces, SkM*, KDE0v1 and Sly230b.

As seen from Fig.1, the instability regime where $K < 0$ is shifted to higher values of the ratio $\rho_0/\rho_{\mathrm{eq}}(T)$ with increasing temperature T. The stable mode disappears at the critical temperature $T_{\mathrm{crit}} = 14 \div 15$ MeV, where $K = 0$ at $\rho_0/\rho_{\mathrm{eq}}(T) = 1$, see Table I.

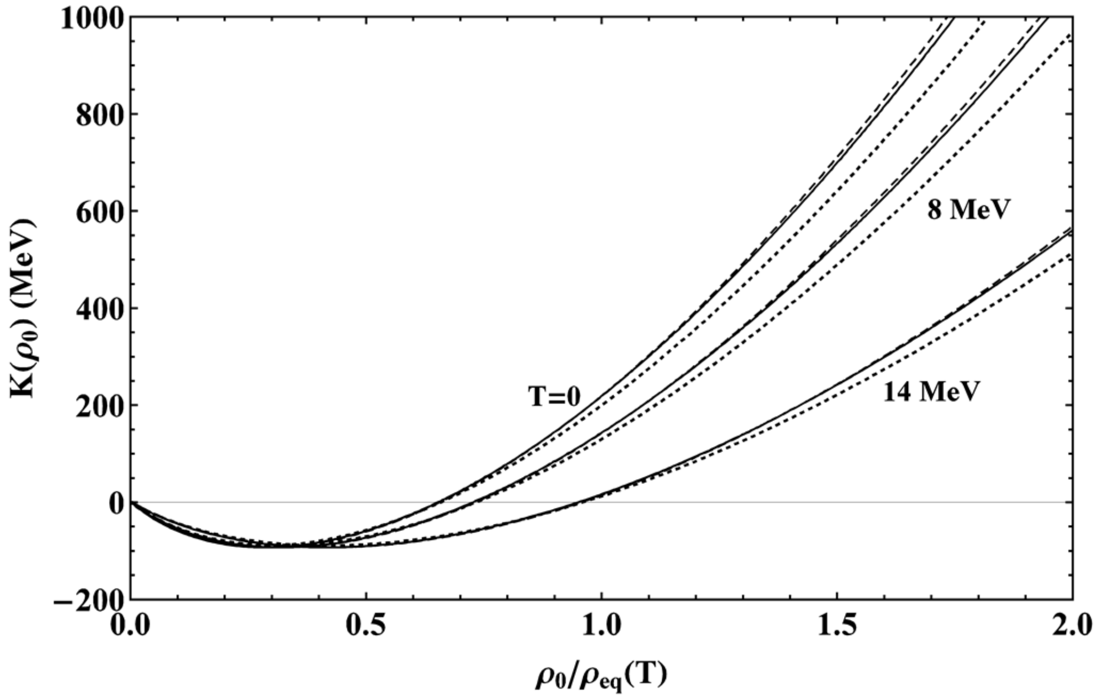

FIG. 1. The density dependence of the incompressibility coefficient $\boldsymbol{K(\rho_0)}$ for different temperatures $\boldsymbol{T=0}$, $\boldsymbol{8}$ and $\boldsymbol{14}$ MeV (shown) calculated for Skyrme interactions SkM* (dotted lines), KDE0v1 (solid lines) and SLy230b (dashed lines).

Table 1. Values of the Skyrme parameters and the corresponding physical quantities of nuclear matter for the SkM*, KDE0v1 and Sly230b interactions.

Parameters	SkM^*	$KDE0v1$	$Sly230b$
$t_0\ (MeV \cdot fm^3)$	-2645.00	-2553.0843	-2488.91
$t_1\ (MeV \cdot fm^5)$	410.00	411.6963	486.82
$t_2\ (MeV \cdot fm^5)$	-135.00	-419.8712	-546.39
$t_3\ (MeV \cdot fm^{3(1+\nu)})$	15595.00	14603.6069	13777.0
x_0	0.0900	0.6483	0.8340
x_1	0.0000	-0.3472	-0.3438
x_2	0.0000	-0.9268	-1.0
x_3	0.0000	0.9475	1.3539
$W_0\ (MeV \cdot fm^5)$	130.00	124.4100	122.69
ν	0.16667	0.1673	0.166667
E/A	15.78	16.23	15.972
$K\ (MeV)$	216.7	227.54	229.90
$\rho_{\text{eq}}(fm^{-3})$	0.160	0.165	0.160
m^*/m	0.79	0.74	0.695
$C_{\text{sym}}(MeV)$	30.03	34.58	32.01
$L(MeV)$	45.78	54.69	45.97
κ	0.53	0.23	0.25
$T_{\text{crit}}(MeV)$	14.62	14.74	14.67

Fig. 2 shows that the dependence of symmetry energy coefficient, $C_{\text{sym}}(\rho_0)$, on the particle density ρ_0 is strongly sensitive to the choice of the Skyrme interactions. In contrast to the behavior of the incompressibility coefficient $K(\rho_0)$ in Fig. 1, the ρ-dependence of the symmetry energy coefficient $C_{\text{sym}}(\rho_0)$ is completely different for the SkM* than for KDE0v1 and the Sly230b interactions. In the case of SkM* interaction, the symmetry energy coefficient $C_{\text{sym}}(\rho_0)$ is a non-monotonic function of the density and it becomes negative in a superdense nuclear matter. In this case, the symmetry energy coefficient $C_{\text{sym}}(T)$ and thereby the isospin stability of Fermi liquid decreases with temperature for the dilute regime at $\rho_0/\rho_{\text{eq}}(T) \lesssim 1$. This behavior is reversed for the super dense regime at $\rho_0/\rho_{\text{eq}}(T) \gtrsim 2$. For the KDE0v1 and Sly230b interactions, the symmetry energy coefficient $C_{\text{sym}}(\rho_0)$ is an increasing function of particle density and the nuclear matter does not reach the instability regime. Thus, the density dependence of the symmetry energy coefficient $C_{\text{sym}}(\rho_0)$ and the occurrence of the isospin instability are sensitive to the Skyrme interaction parametrization.

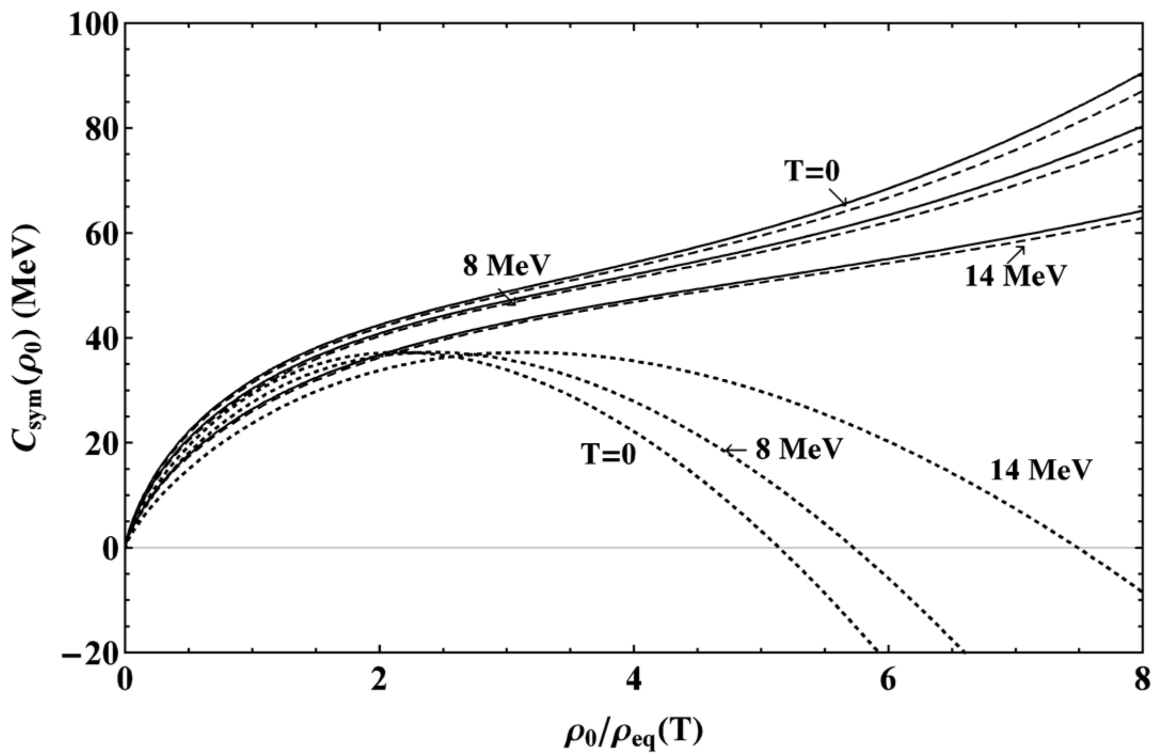

FIG. 2. The same as in Fig. 1, but for symmetry energy coefficient $\boldsymbol{C}_{\text{sym}}$.

[1] V.M. Kolomietz and S. Shlomo, Phys. Rev. C **95**, 054614 (2017).