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SOME POSSIBLE ASYMMETRY EFFECTS OF NUCLEAR MATTER IN RELATIVISTIC HEAVY ION COLLISIONS

by

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ABSTRACT

The asymmetry dependence of nuclear incompressibility and that of nuclear critical temperature are calculated based on a Thomas-Fermi model with Seyler-Blanchard interaction. It is found that the asymmetry effects are big enough to allow for checking the existence of these effects in relativistic heavy-ion collision experiments.

Key-words: Nuclear equation of state; Relativistic heavy ion collisions.

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The properties of nuclear matter play a very important role in two research fields – in the relativistic heavy ion collisions as well as in the neutron star and supernova studies. But there is a difference concerning to the asymmetry of nuclear matter. The asymmetry dependent equation of state of nuclear matter is used in the neutron star and supernova studies[1] as the Coulomb interaction as well as the weak process $p + e^- \rightarrow n + \nu_e$ are important in the nuclear astrophysical context, while the asymmetry of nuclear matter is used to be neglected in the heavy ion collisions[2] as these processes can be considered as essentially under the influence of the strong interaction. This is true for the ultra relativistic collisions where the nuclear matter is very strongly excited and therefore the nuclear processes can be safely considered as charge--independente one, but it must be considered carefully for the collisions where the energy is not so high and therefore the Coulomb interaction as well as the Pauli blocking effect still play important roles. In the later case, an asymmetry dependence of the equation of state of nuclear matter will be resulted from the Pauli blocking effect[3,4,5,6]. Thus the problems are what asymmetry effects there are in the relativistic heavy ion collisions, and whether these asymmetry effects are big enough for a practical measurement. The purpose of this letter is to discuss these problems based on an asymmetry dependent equation of state of nuclear matter which is proposed by the Thomas-Fermi statistical model with Seyler-Blanchard momentum-dependent interaction[3,4]. In what follows, we will sketch this equation of state at first, and then we will discuss the calculated asymmetry dependences of the nuclear incompressibility $K(\delta)$, of the nuclear phase transition temperature $T(\delta)$, and of the critical temperature $T_c(\delta)$, where the asymmetry of nuclear matter is defined as $\delta = (n_n-n_p)/n$, where the n_n, n_p, and $n = n_n+n_p$ are the number densities of neutrons, protons, and nucleons of nuclear matter, respectively.

For the nucleon system with Seyler-Blanchard interaction, the Thomas-Fermi model gives the energy per nucleon u and the entropy per nucleon s as[4]

$$u = \frac{1}{n} \sum_\tau n_\tau \left[T \frac{\mathcal{F}_{3/2}(\eta_\tau)}{\mathcal{F}_{1/2}(\eta_\tau)} - \frac{1}{2} T_D \nu'_\tau\right] , \tag{1}$$

$$s = \frac{1}{n} \sum_\tau n_\tau \left[\frac{5}{3} \frac{\mathcal{F}_{3/2}(\eta_\tau)}{\mathcal{F}_{1/2}(\eta_\tau)} - \eta_\tau\right] . \tag{2}$$

where T is the temperature, n_τ is the density of nucleons with isospin τ, $T_D = b^2/2m$, m is the nucleon mass, b is the momentum parameter in the Seyler-Blanchard potential, $\mathcal{F}_\alpha(\eta)$ is the Fermi integral[7,8], and

$$\eta_\tau = (\mu_\tau - T_D\nu^0_\tau)/T , \tag{3}$$

where μ_τ is the chemical potential of nucleons with isospin τ, $\nu_\tau = \nu^0_\tau + \nu'_\tau$ is the dimensionless single-particle potential (in unit of T_D) at nucleon energy T_D ,

$$\nu'_\tau = \frac{3}{2} \left[\alpha\theta_\tau^{3/2} \mathcal{F}_{1/2}(\eta_\tau) + \beta\theta_{-\tau}^{3/2} \mathcal{F}_{1/2}(\eta_{-\tau})\right] , \tag{4}$$

$$\nu_\tau = \frac{3}{2}\left[\alpha\theta_\tau^{5/2}\,\mathcal{F}_{3/2}(\eta_\tau) + \beta\theta_{-\tau}^{5/2}\,\mathcal{F}_{3/2}(\eta_{-\tau})\right] , \tag{5}$$

where α and β are the strength parameters in Seyler-Blanchard potential, $t = T/T_D$, and $\theta_\tau = t/(1+\nu')$.

Having the thermodynamic functions u and s, it is easy to derive the free energy per nucleon f and the pressure p,

$$f = \frac{T_D}{n}\sum_\tau n_\tau \left\{t\left[\eta_\tau - \frac{2}{3}\frac{\mathcal{F}_{3/2}(\eta_\tau)}{\mathcal{F}_{1/2}(\eta_\tau)}\right] - \frac{1}{2}\nu'_\tau\right\} , \tag{6}$$

$$p = T_D\sum_\tau n_\tau\left[\nu_\tau^0 + \frac{1}{2}\nu'_\tau + \frac{2}{3}t\frac{\mathcal{F}_{3/2}(\eta_\tau)}{\mathcal{F}_{1/2}(\eta_\tau)}\right] . \tag{7}$$

The isothermal incompressibility coefficient K_t and the isentropic incompressibility coefficient K_s are defined, respectively, as

$$K_t = 9\left(\frac{\partial p}{\partial n}\right)_T , \tag{8}$$

$$K_s = 9\left(\frac{\partial p}{\partial n}\right)_S . \tag{9}$$

The parameters used here are as follows:

$$\begin{aligned} &\alpha = 2.59861 , \quad \beta = 3.79175 , \\ &b = 409.456\text{MeV/c} , \quad T_D = 89.27977\text{MeV} , \end{aligned} \tag{10}$$

which are determined with the liquid drop model parameters a_1 = 16.1MeV, J = 34MeV, r_0 = 1.159fm, and the Yukawa range of a = 0.557fm given by von Groote[9,10]. The numerical calculations involved the Fermi integral $\mathcal{F}_\alpha(\eta)$ which are given by the approximation formulas, such as found by Lattimer et al.[1]. The thermostatic properties of the asymmetric nuclear matter, especially the phase, the phase equilibrium, and the phase stability of asymmetric nuclear matter, based on this equation of state at zero as well as low temperature, have been discussed elsewhere[3,4,7] in detail, and what we will give here are some possible observable asymmetry effects from the experimental measurement point of view.

Figures 1 and 2 show the isothermal and isentropic incompressibilities $K_t(T,\delta)$ and $K_s(T,\delta)$, respectively, as functions of nuclear asymmetry δ for given temperature T. It can be seen that the incompressibilities K_t and K_s decrease with both the temperature T as well as the asymmetry δ monotonically, where the asymmetry δ plays a role in somewhat similar to that of the temperature T, and the reason for this similarity comes from the Pauli blocking effect — the higher asymmetry δ corresponds to the more dilute filling of the single-nucleon energy level which is equivalent to the higher temperature. Vinas et al.[5] have given also a result of $K_t(T,\delta)$ by a Hartree-Fock calculation with Skyrme interaction. Their result is similar to ours qualitatively although is different quantitatively. For example, their calculation yields $K_t(0,0)$ = 218MeV, $K_t(0,0{\cdot}2)$ = 203MeV, and $K_t(10,0)$ = 81MeV, while our results are 306MeV, 286MeV, and 171MeV, respectively.

Figure 3 shows the liquid-gas phase transition temperature of nuclear matter as the function of nucleon number density n/n_0 for given asymmetry δ, where $n_0 = 0.153\text{fm}^{-3}$ is the normal zero-temperature number density. Figure 4 shows the critical temperature of nuclear matter as a function of asymmetry δ (solid curve). In this figure, the Lattimer, Pethick, and Ravenhall's result based on the Thomas-Fermi model with Skyrme interaction[1] is given for comparison (dashed curve). It can be seen from both of these figures that the asymmetry effect in the transition temperature and especially in the critical temperature is obvious. For example, the critical temperature decreases for about 2MeV as the asymmetry δ increases from 0 to 0.3 which is near to the neutron drip point[3,4]. It is worthwhile to note that our result is much bigger than that of Lattimer et al. which is only about 0.5MeV.

We are encouraged by above results, as all of these asymmetry effects are big enough for experimental test. Firstly, there have been experimental analyses[11,12,13,14] which, even though some of them is argued, are declared to be able to determine the nuclear incompressibility and even the nuclear equation of state. Secondly, the critical temperature of finite nuclear system is declared to be determined experimentally based on a model-dependent theoretical analysis[15,16,17]. In the meanwhile, one believes that there should be some way to correlate the critical temperature of finite nuclear system to that of infinite nuclear matter. The problem arisen is that the nuclear matter considered in the analysis of these experiments is assumed to be symmetric, but on the other hand, our calculation shows that the asymmetry dependence of nuclear incompressibility as well as of nuclear matter critical temperature could not be neglected in these analyses. Therefore, it will be very interesting to check whether do there are these asymmetry effects in experiments. The biggest asymmetry effect is expected by measuring the ratio of $(^{238}U+^{238}U)/(^{40}Ca+^{40}Ca)$ in relativistic heavy ion collisions. It is estimated to be around 0.9 for the incompressibility whereas is around 0.95 for the nuclear critical temperature in our calculation.

It is worthwhile to note that these asymmetry effects are smaller in the calculation with Skyrme interactions than that of ours with the momentum-dependent Seyler-Blanchard interaction. As the importance of momentum-dependent interaction for the extraction of the nuclear equation of state from high-energy heavy ion collisions is emphasized[18], it should be very interesting to investigate these asymmetry effects both in the theories as well as in the experiments, carefully.

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Figure Captions

Fig. 1: The isothermal incompressibility $K_t(T,\delta)$ as a function of nuclear asymmetry δ for given temperature T.

Fig. 2: The isentropic incompressibility $K_s(T,\delta)$ as a function of nuclear asymmetry δ for given temperature T.

Fig. 3: The nuclear liquid-gas phase transition temperature T as the function of nucleon number density n/n_0 for given asymmetry δ.

Fig. 4: The critical temperature of nuclear matter T_c as a function of asymmetry δ . The solid curve is calculated in this work. The dashed curve is calculated using the formula given in Ref. 1, which is based on the Thomas-Fermi model with Skyrme interaction.

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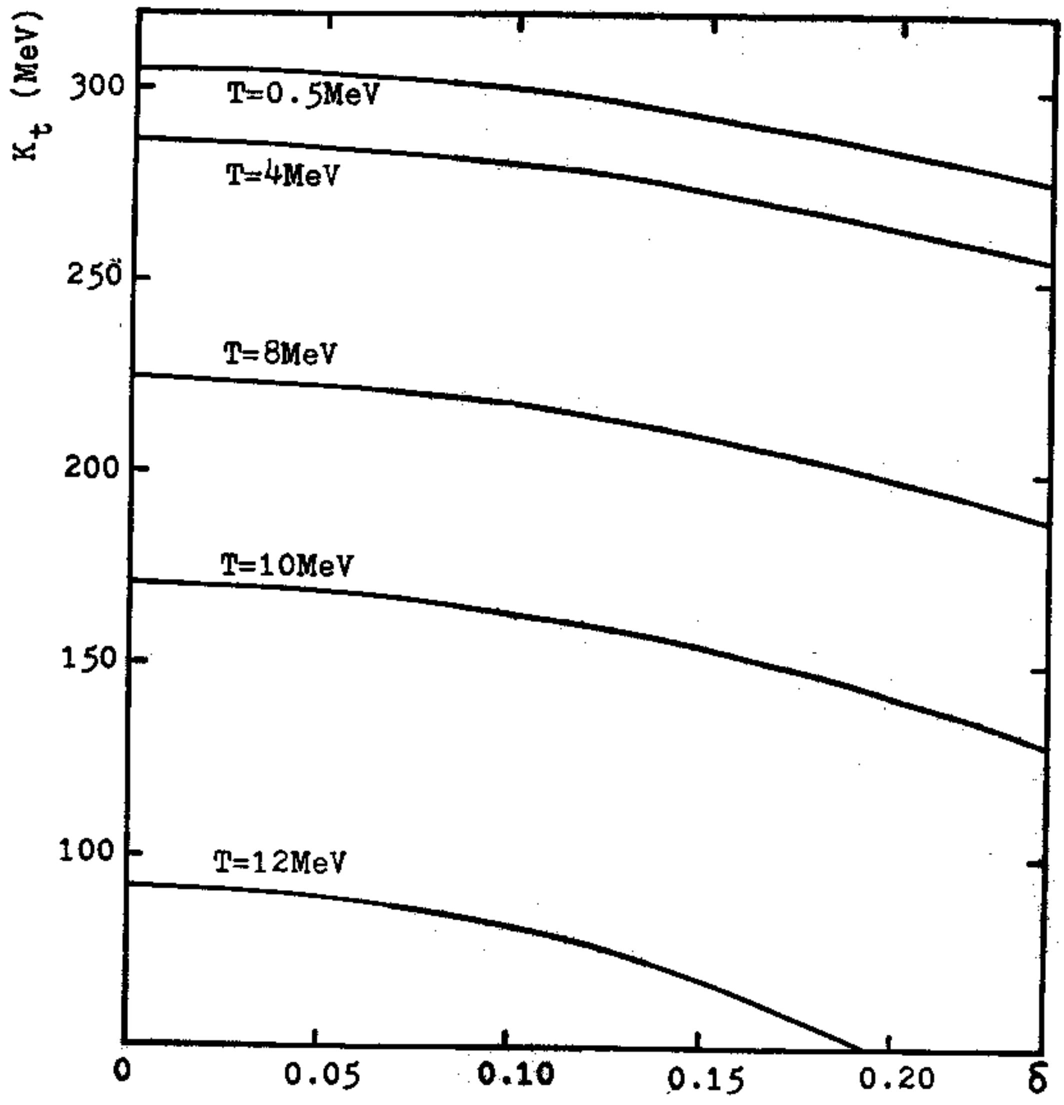

Fig. 1:

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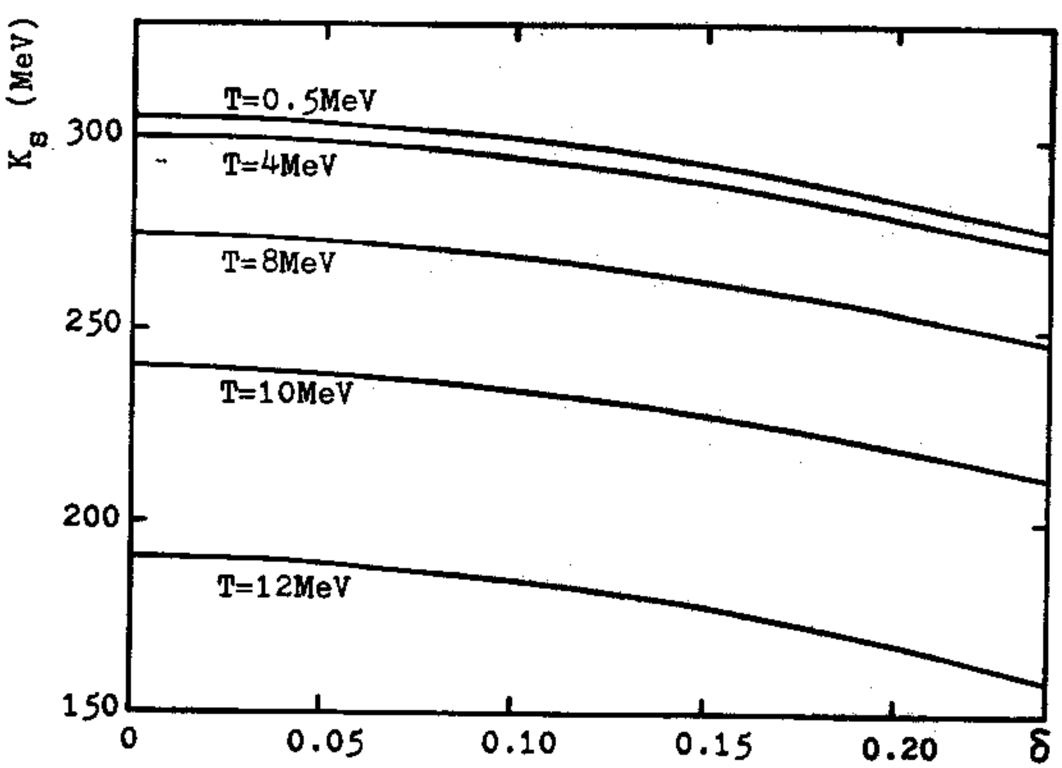

Fig.2:

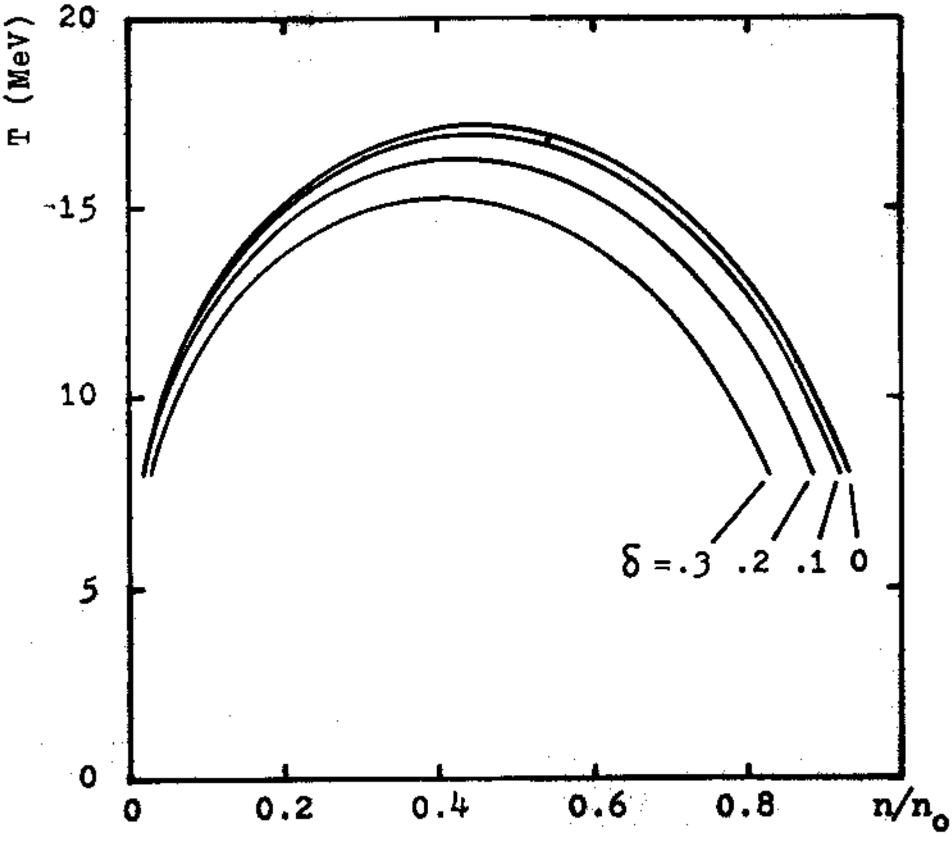

Fig.3:

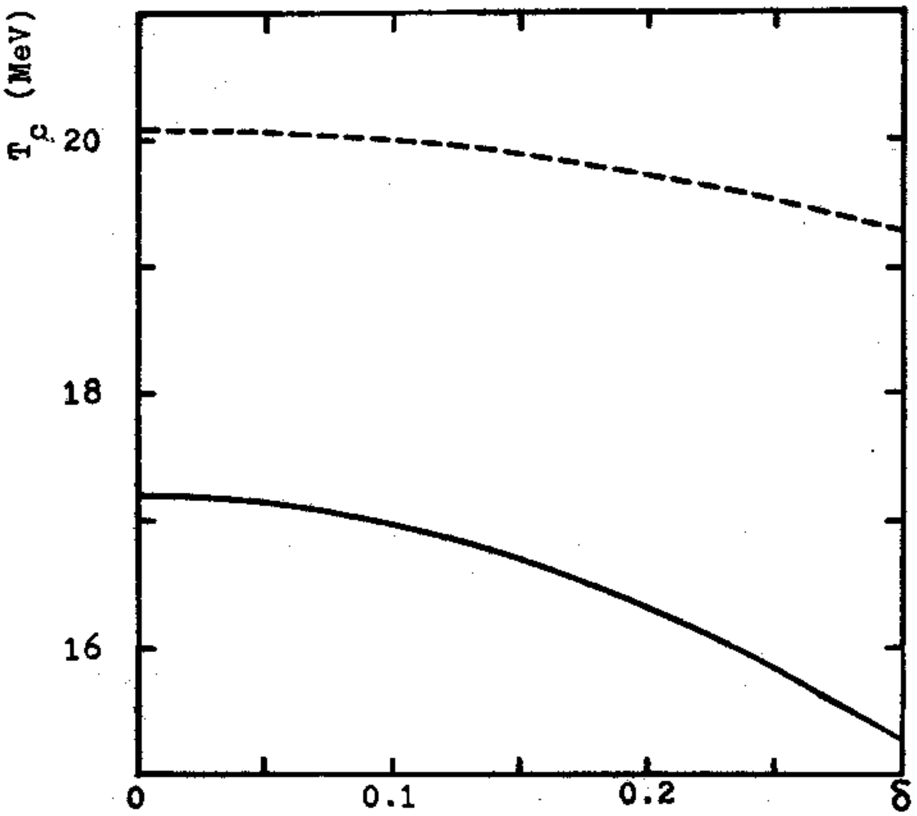

Fig.4:

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