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THERMAL COMPRESSION MODULUS OF POLARIZED NEUTRON MATTER *

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ABSTRACT

We applied the equation of state for pure polarized neutron matter at finite temperature, calculated previously, to calculate the compression modulus. The compression modulus of pure neutron matter at zero temperature is very large and reflects the stiffness of the equation of state. It has a little temperature dependence. Introducing the spin excess parameter in the equation of state calculations is important because it has a significant effect on the compression modulus.

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One hopes that the information on the equation of state of dense nuclear matter can be extracted from the experimental data. This knowledge is essential for understanding neutron star structure and for the onset of possible transition from hadron matter to the quark–gluon plasma. Recent studies on high energy heavy ion collisions [1)–7)] have shown that particle production, in the form of pions and kaons, provides information on the kinetic energy available in the high-density stage of the reaction. This idea was used [1)–7)] to identify the equation of state (EOS) of nuclear matter at extremely high densities $\rho_0 < \rho < 4\rho_0$, where ρ_0 is the normal nuclear matter density at saturation, and temperatures $T < 100$ Mev. Stock and co-workers [1)–3)] applied the Vlasov–Vehling–Vhlenbeck approach to extract the EOS from the pion yield distribution. They obtained for both relatively light [1)–3)] and heavy nuclei [7)] a very stiff EOS. The value of the compression modulus they used is $K_0 = 380$ Mev. Cusson *et al.* [6)] applied the time-dependent Dirac equation with relativistic mean field dynamics for relatively light nuclei and they obtained a very stiff EOS ($K_0 = 550$ Mev). It was believed that [8),9)] with the inclusion of a momentum dependence term in the interaction, relatively soft EOS ($K_0 < 200$ Mev) the general features of high energy heavy ion collision can be reproduced. Soft EOS plus momentum dependence could not [10)] reproduce a sufficient sideways flow in the high energy heavy ion collision.

It was noticed by Brown [11)] that the isotope shift is a good clue to determine the nuclear compression modulus. Sagawa *et al.* [12)] studied the isotope shift of Pb taking into account giant monopole and quadrupole resonance by a perturbative method. They used three parameter sets of Skyrme interactions namely: SGI, SGII and SIII. They obtained for the compression moduli $K_0 = 269$ Mev, 217 Mev and 365 Mev, respectively.

Co' and Speth [13)] used Landau's Fermi–liquid theory to extract the EOS from the charge distribution differences between isotopes of heavy mass nuclei. They argue that presently this is the only reliable way to extract the EOS since the data relate to the inner part of the nucleus. Their analysis indicated that K_0 should be larger than the commonly accepted value [14)] $K_0 = 210 \pm 30$ Mev with a preference for $K_0 \simeq 350$ Mev.

Van der Woude *et al.* [15)] argue that the scaling model provides a reliable method to extract the EOS from the excitation energy of giant monopole resonance. They used heavy and light mass nuclei, taking into account surface effects explicitly, in the fitting procedure. Their analysis gave for the compression modulus $K_0 \simeq 270$ Mev.

Cavedon *et al.* [16)] determined the ground state charge densities of $^{204,206-208}Pb$ by elastic–electron scattering. The shape of the density difference $^{207}Pb - {}^{208}Pb$ is sensitive to the nuclear compression modulus at zero temperature. The observed fluctuations are reproduced best by a density–dependent force having a compression modulus $K_0 = 228$ Mev.

Several attempts have been done to extract the EOS from neutron star masses [17)–21)] and from supernovae explosions [22)]. The most accurately measured masses of neutron stars are in general agreement with a value 1.4 M_S, where M_S is the mass of the sun. Therefore, if a nuclear EOS is to be raiable it must support a neutron star mass of at least 1.44 M_S [10)].

Glendenning [17] has argued that the observed neutron star masses set a relatively large lower limit to the compression modulus of nuclear matter. He solved the relativistic mean field theory equations and found that the values of the compression modulus $K_0 \leq 200$ Mev are incompatible with the observed neutron star masses.

Prakash and Ainsworth [18], using a linear σ model, found results consistent with Glendenning. Prakash, Ainsworth and Lattimer [19] used a parameterization form of the EOS consistent with the empirical nuclear matter properties and causality. The observed neutron star masses are consistent with $K_0 < 140$ Mev. Müther *et al.* [20] used the relativistic Brueckner–Hartree-Fock approach. They obtained maximum masses of the order of 2.4 M_S using the compression modulus $K_0 \simeq 200$ Mev. Wiringa *et al.* [21] have calculated a series of potential model with $K_0 \simeq 200$ Mev and the maximum masses are in excess of 2 M_S.

Baron, Cooperstein and Kahana [22] studied the shock–explosive mechanism for generating type II supernovae. To obtain a prompt explosion, the compression modulus must have values $K_0 < 180$ Mev.

The above discussion shows that it is a point of interest to study the compression modulus as a function of density and temperature. In a previous work [23], we studied the compression modulus of thermal and polarized nuclear matter. In the present work we study the compression modulus of thermal and polarized netron matter.

For neutron matter calculations we applied [24] the Thomas–Fermi model using the Seyler–Blanchard two body interaction in its modified form [25] for asymmetric polarized nuclear matter. The energy per neutron for polarized neutron matter is given by [24]

$$F = F_v + \frac{1}{2} x^2 F_x$$

where $F_v (F_x)$ is the volume (spin excess) energy, and x is the spin excess parameter $\left(x = \frac{N\uparrow - N\downarrow}{N\downarrow + N\uparrow} \right)$. The dependence of the energy on temperature is given, using the T^2 approximation, as

$$F_v = F_v^0 + F_v^t T^2, \qquad \text{and}$$
$$F_x = F_x^0 + F_x^t T^2$$

where $F_v^0 (F_x^0)$ is the volume (spin excess) energy at $T = 0$ Mev.

The compression modulus for pure polarized neutron matter in the same approximation is given by

$$K = K_v + \frac{1}{2} x^2 K_x ,$$

where

$$K_v = K_v^0 + K_v^t T^2, \qquad \text{and}$$
$$K_x = K_x^0 + K_x^t T^2 .$$

Table 1 gives the resulting values for the compression modulus at the considered values of temperatures at $x = 0$. Our value for the volume compression modulus at $\rho = \rho_0$ ($T = 0$ Mev and $x = 0$) is in reasonable agreement with that of Müther *et al.* [20], where they got for pure neutron matter $K_v^0 = 420$ Mev. The larger values for K at high density in the present calculations reflect the stiffness of the EOS. It must be noticed that the Seyler–Blanchard two body interaction parameters used in our calculations are fitted [25] to give the compression modulus of symmetric nuclear matter the value $K_0 = 220$ Mev at $\rho = \rho_0$. It is found that [23] K_0 decreases with increasing neutrons. Table 1 shows that there is a small decrease in K with increasing temperatures. This decreasing becomes negligeable at high densities.

Table 2 shows the effect of the spin excess parameter (x) on the compression modulus. There is a significant decrease in K with increasing x (a factor of $\approx \frac{1}{2}$). The effect of the spin excess parameter on the EOS of pure neutron matter is more important than temperature. So, in studying neutron star structure and stability, it is important to introduce the spin excess parameter.

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Table 1

The compression modulus as a function of density (ρ/ρ_0) at different values of temperatures (T(Mev)) the units of K is Mev ($x = 0$).

T \ ρ/ρ_0	1	2	3	4
0	541	1845	3683	6009
2	540	1840	3682	6008
4	535	1831	3680	6007
6	527	1826	3676	6004
8	515	1818	3670	5999
10	501	1809	3663	5993

Table 2

The same as in Table 1 but at different values of the spin excess parameter (x) at $T = 0$ Mev.

x \ ρ/ρ_0	1	2	3	4
0.2	524	1782	3579	5843
0.4	473	1623	3269	5345
0.6	388	1358	2753	4515
0.8	268	988	2030	3352