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PROPERTIES OF NUCLEAR MATTER WITH AN EXCESS OF NEUTRONS, OF SPIN-UP NEUTRONS AND OF SPIN-UP PROTONS USING THE SKYRME INTERACTION *

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ABSTRACT

The binding energy of nuclear matter with an excess of neutrons, of spin-up neutrons, and of spin-up protons (characterized by the corresponding parameters, $\alpha_\tau = (N-Z/A)$, $\alpha_n = (N\uparrow - N\downarrow)/A$, and $\alpha_p = (Z\uparrow - Z\downarrow)/A$), contains three symmetry energies: the isospin symmetry energy ϵ_τ, the spin symmetry energy ϵ_σ, and spin-isospin symmetry energy $\epsilon_{\sigma\tau}$. General expressions for $\epsilon_\sigma, \epsilon_\tau$ and $\epsilon_{\sigma\tau}$ are given in the case of the Skyrme interaction.

These values are compared with previous results obtained by Dabrowski and Haensel (DH) with Brueckner-Gammel-Thaler, the Hamada-Johnston, and the Reid soft core nucleon-nucleon potentials.

The spin, isospin and spin-isospin dependent parts of the single-particle potential in nuclear matter are also calculated using the Skyrme interaction. The spin, isospin and spin-isospin incompressibility are calculated using the Skyrme interaction. The spin-spin part of the optical model potential is estimated. The results are compared with those of Dabrowski and Haensel (DH) and Hassan and Ramadan.

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I. INTRODUCTION

Much interest has been devoted recently to the calculation of the properties of nuclear matter using effective interactions. Lassey[1] has calculated the properties of nuclear matter and semi-infinite nuclear matter using several delta function interactions of the Skyrme type; Khanna and Barhai[2] have calculated the symmetry coefficient ϵ_τ and the isospin dependent part of the single-particle potential of nuclear matter using two effective interactions determined by them. Krewald et al.[3] have used a modified delta function interaction determined by Moszkowski[4] to calculate the properties of nuclear matter.

The ground-state energy of nuclear matter with an excess of neutrons, spin-up neutrons and spin-up protons was considered by Dabrowski and Haensel (DH)[5,6], and Dabrowski[7], using the K-matrix method and applying the Brueckner-Gammel-Thaler, Hamada-Johnston and Reid soft-core nucleon-nucleon potentials.

Hassan and Ramadan[8] used two versions of a velocity dependent effective potential of s-wave interaction[9,10] with one free parameter to calculate the binding energy of nuclear matter with an excess of neutrons, with spin-up neutrons and spin-up protons, contains three symmetry energies: the isospin ϵ_τ, the spin ϵ_σ and the spin-isospin symmetry energy $\epsilon_{\sigma\tau}$. They also calculated the spin, isospin and spin-isospin dependent parts of the single-particel potentials. They also estimated the spin-spin part of the optical model potential. In this work we use the Skyrme interaction defined by Refs.11-13. In Section II we give a description of the theory and method of calculation. Section III contains the results and discussion.

II. THEORY AND METHOD OF CALCULATION

The ground-state energy of nuclear matter with an excess of neutrons, of spin-up neutrons, and of spin-up protons are considered. The expression of the binding energy of nuclear matter (composed of $N\uparrow$ $(N\downarrow)$ neutrons with spin-up (down) and $Z\uparrow$ $(Z\downarrow)$ protons with spin-up (down), with corresponding Fermi momenta $K_n(\lambda_n)$ and $K_p(\lambda_p)$) can be written in the form

$$E/A = \epsilon_{vol.} + \tfrac{1}{2}\epsilon_\tau \alpha_\tau^2 + \tfrac{1}{2}\epsilon_\sigma(\alpha_n+\alpha_p)^2 + \tfrac{1}{2}\epsilon_{\sigma\tau}(\alpha_n-\alpha_p)^2 \quad ,$$

where

$$\alpha_\tau = (N\uparrow+N\downarrow-Z\uparrow-Z\downarrow)/A \quad ,$$
$$= (N-Z)/A \quad ,$$
$$\alpha_n = (N\uparrow-N\downarrow)/A \quad ,$$
$$\alpha_p = (Z\uparrow-Z\downarrow)/A \quad ,$$

ϵ_{vol} is the volume energy, ϵ_τ is the usual (isospin)symmetry energy, ϵ_σ is the measure of additional energy necessary to maintain a spin excess in the system, characterized by the spin-excess parameter $\alpha_\sigma = \alpha_n + \alpha_p$. Quantity ϵ_σ is referred to the spin symmetry energy, $\epsilon_{\sigma\tau}$ is the measure of additional energy necessary to maintain in the system an excess of spin-up neutrons and spin-down protons, characterized by the spin-isospin excess parameter $\alpha_{\sigma\tau} = \alpha_n - \alpha_p$. Quantity $\epsilon_{\sigma\tau}$ is henceforth referred to the spin-isospin symmetry energy.

Similarly[6], the single-particle potential $\bar{U}$ (for a neutron (proton) with momentum $\hbar m$ and with spin-up)can be written in the form

$$\bar{U}(m\uparrow^n_p) = U_o(m) \pm \tfrac{1}{4}\alpha_\tau U_\tau(m) + \tfrac{1}{4}(\alpha_n+\alpha_p)U_\sigma(m) \pm \tfrac{1}{4}(\alpha_n-\alpha_p)U_{\sigma\tau}(m) \quad ,$$

and the single-particle potential $\bar{U}$ [for a neutron (proton) with momentum $\hbar m$ and with spin-down] can be written in the form

$$\bar{U}(m\downarrow^n_p) = U_o(m) \pm \tfrac{1}{4}\alpha_\tau U_\tau(m) - \tfrac{1}{4}(\alpha_n+\alpha_p)U_\sigma(m) \mp \tfrac{1}{4}(\alpha_n-\alpha_p)U_{\sigma\tau}(m) \quad ,$$

where only linear terms are retained.

Using the Skyrme interaction defined by Ref.10, the two-body term in the form:

$$\langle\bar{k}|V_{12}|\bar{k}'\rangle = t_o(1+\chi_o P_\sigma)\delta(\bar{r}_1-\bar{r}_2) + \tfrac{1}{2}t_1[\delta(\bar{r}_1-\bar{r}_2)k^2+k'^2\delta(\bar{r}_1-\bar{r}_2)] + t_2\bar{k}'.\delta(\bar{r}_1-\bar{r}_2)\bar{k}$$
$$+ iw_o(\bar{\sigma}_1+\bar{\sigma}_2).\bar{k}'\delta(\bar{r}_1-\bar{r}_2)\bar{k} \quad ,$$

and the three-body term can be written in the form

$$\langle\bar{k}|V_{123}|\bar{k}'\rangle = (1/6)t_3\delta(\bar{r}_1-\bar{r}_2)\delta(\bar{r}_2-\bar{r}_3)[1+(1/2)P_\tau(12)P_\tau(23)-(3/2)P_\tau(12)]$$

We get,

$$\epsilon_{vol.} = (3/10)(\hbar^2k_f^2/M) + (1/4\pi^2)t_o k_f^3 + (3/40\pi^2)t_1 k_f^5 + (1/8\pi^2)t_2 k_f^5 + (1/36\pi^4)t_3 k_f^6 \quad ,$$

$$\epsilon_\tau = (1/3)(\hbar^2k_f^2/M) - (1/3\pi^2)(\tfrac{1}{2}t_o+t_o\chi_o)k_f^3 + (2/9\pi^2)t_2k_f^5 - (1/18\pi^4)t_3k_f^6 \quad ,$$

$$\epsilon_\sigma = (1/3)(\hbar^2k_f^2/M) - (1/3\pi^2)(\tfrac{1}{2}t_o-t_o\chi_o)k_f^3 + (2/9\pi^2)t_2k_f^5 - (1/18\pi^4)t_3k_f^6 \quad ,$$

$$\epsilon_{\sigma\tau} = (1/3)(\hbar^2k_f^2/M) - (1/6\pi^2)t_ok_f^3 + (2/9\pi^2)t_2k_f^5 - (1/18\pi^4)t_3k_f^6 \quad ,$$

$$U_o = (1/2\pi^2)t_ok_f^3 + (1/8\pi^2)t_1[(3/5)k_f^5+m^2k_f^3] + (1/8\pi^2)t_2[k_f^5+(5/3)m^2k_f^3] + (1/12\pi^4)t_3k_f^6 \quad ,$$

$$U_\tau = -(1/6\pi^2)t_o(1+2\chi_o)k_f^3 + (1/24\pi^2)(t_2-t_1)[k_f^5+m^2k_f^3] - (1/18\pi^4)t_3k_f^6 \quad ,$$

$$U_\sigma = -(1/6\pi^2)t_o(1-2\chi_o)k_f^3 + (1/24\pi^2)(t_2-t_1)[k_f^5+m^2k_f^3] - (1/18\pi^4)t_3k_f^6 \quad ,$$

$$U_{\sigma\tau} = -(1/6\pi^2)t_ok_f^3 + (1/24\pi^2)(t_2-t_1)[k_f^5+m^2k_f^3] - (1/18\pi^4)t_3k_f^6 \quad .$$

The spin-isospin and spin-isospin incompressibility are given by

$$K_{\tau,\sigma,\sigma\tau} = k_f^2 \frac{\partial^2 \epsilon_{\tau,\sigma,\sigma\tau}}{\partial k_f^2}$$

So we can write

$$K(\alpha_\tau,\alpha_n,\alpha_p) = K_{vol.} + \tfrac{1}{2}\alpha_\tau^2 K_\tau + \tfrac{1}{2}\alpha_\sigma^2 K_\sigma + \tfrac{1}{2}\alpha_{\sigma\tau}^2 K_{\sigma\tau} \quad ,$$

$$K_\tau = (2/3)(\hbar^2/M)k_f^2 - (2/\pi^2)[(t_o/2)+t_oX_o]k_f^3 + (40/9\pi^2)t_2k_f^5 - (5/3\pi^4)t_3k_f^6 \quad ,$$

$$K_\sigma = (2/3)(\hbar^2/M)k_f^2 - (2/\pi^2)[(t_o/2)-t_oX_o]k_f^3 + (40/9\pi^2)t_2k_f^5 - (5/3\pi^4)t_3k_f^6 \quad ,$$

$$K_{\sigma\tau} = (2/3)(\hbar^2/M)k_f^2 - (1/\pi^2)t_ok_f^3 + (40/9\pi^2)t_2k_f^5 - (5/3\pi^4)t_3k_f^6 \quad ,$$

III. RESULTS AND DISCUSSION

The spin,isospin and spin—isospin symmetry energies using Skyrme interactions are given in table (1). These interactions, lead to different equilibrium densities, i.e. different values of k_f. Our results are compared with those produced by others who used the Brueckner-Gammel -Thaler (BGT), Reid soft core (RSC) potentials[5] and K-matrix theory where the K-matrix depends on a single density[7]. All Skyrme interactions give similar values to the experimental symmetry energy, since they were originally fitted to give these values. The experimental values of the symmetry energies obtained by Green[14] and Cameron[15] are 61 and 63 MeV,respectively. Siemens[16] has obtained the value of 62 MeV. Using RSC potential. Brueckner, Coon and Dabrowski[17] obtained the value of 56 MeV. SK II, VG, and VY interactions give larger values than those obtained by others[18-20]. Brueckner and Gammel[21] found that the symmetry energy is very sensitive to the nature of the potential used. They concluded that the potentials which do not contain odd state forces give large symmetry energy. The repulsive singlet and the attractive triplet components usually reduce the symmetry energy. For ϵ_σ, all six sets of Skyrme interaction except SK V give smaller values compared with other calculations. The interactions SK I, III, and VI, which do not lead to a stable spin saturated[13] ground state of nuclear matter, give negative values for ϵ_σ.

For $\epsilon_{\sigma\tau}$, the values obtained using SK V are in agreement with others and with empirical values[28] while SK I, II, III, IV and VI give smaller values than those of DH and Hassan and Ramadan[8] The quantity $\sqrt{\epsilon_{\sigma\tau}/\epsilon_\tau}$ can be estimated experimentally according to Raphael, Überall and Werntz[22], the energies of the and [illegible] dipole L level in ^{16}O are 22.0 and 24.5 MeV and thus their ratio is 1.1 This value coincides with the ratio obtained by using SK V This result is obtained by DH. The value $\sqrt{\epsilon_{\sigma\tau}/\epsilon_\tau}$ is 0.97 for SK IV and Hassan and Ramadan[8]. We notice that SK I, III, and VI give negative values of $\epsilon_\sigma^{Pot.}$ and $\epsilon_{\sigma\tau}^{Pot.}$, while the other Skyrme sets and Hassan and Ramadan give positive values. This can be understand from the spin stability point of view[23,24]. SK IV and V give positive values of $\epsilon_\sigma^{Pot.}$ and $\epsilon_{\sigma\tau}^{Pot.}$ because they are characterized by the fact that they have the least value of the parameter t_3 and a positive value of the parameter t_2.

The spin, isospin, and the spin-isospin incompressibility calculated by VG and VY interactions[8] and the six sets of Skyrme interaction are shown in table (2). We noted that K_τ obtained by VG interaction agrees well with that calculated by Khanna and Barhai[18] (KB) and the values deduced by VY and SK V are larger than VG and KB. In general VG and VY give smaller values of K_σ and $K_{\sigma\tau}$ than SK V interaction, while the five sets of Skyrme interactions (I,II,III,IV and VI) give negative values for K_τ, K_σ and $K_{\sigma\tau}$.

The negative values obtained are easy to see if we consider the equations of incompressibilities which have the term containing the parameter t_3 with a negative sign. SK V has a positive value because it has the parameter $t_3 = 0$.

The spin isospin, and spin-isospin dependent parts of single-particle potential of nuclear matter using Skyrme interactions are given in table (1).

The values of U_τ obtained using SK I, II, III, and VI interactions agree well with those calculated by DH, VY,[8] KB[18] (U_{τ_1} = 158.5 MeV and U_{τ_2} = 102.6 MeV) and that by Green et al.[25] (U_τ = 120 MeV) but VG, SK IV and V give much smaller values than the other ones. The values of U_σ obtained using SK V agrees with the values obtained by DH, VG[8] and Dabrowski[7] but the other five Skyrme sets give smaller values. The value of $U_{\sigma\tau}$ obtained using VY interaction is in agreement with DH but smaller than the value obtained by Dabrowski[7] and all six sets of Skyrme and VG interactions disagree with DH results.

The spin-spin part of the optical model potential was estimated using the relation

$$U_{ss} = (U_{\sigma} \pm U_{\sigma\tau}) \begin{cases} (2I)^{-1} & \text{for } I=J=\ell+\frac{1}{2} \\ -2(I+1)^{-1} & \text{for } I=J=\ell-\frac{1}{2} \end{cases}$$

where we consider the case in which the total spin $\bar{I}$ of the nucleus in its ground state is equal to the spin $\bar{J}$ of a valence nucleon. The positive sign applies to the case when the scattered and the valence nucleon are like nucleon (both neutrons or both protons), and the negative sign applies to the opposite case.

Table (3) shows the experimental as well as the theoretical values of U_{ss} calculated by us using Skyrme interactions. DH and Hassan and Ramadan results for U_{ss} are shown for comparison in this table.

Since U_{σ} and $U_{\sigma\tau}$ are of a similar magnitude, we expect U_{ss} to be much bigger when the scattered and valence target nucleon are both protons or neutrons. This is produced by all the potentials except SK I, II, III and VI in the case of $^{27}AL_{-p}$, $^{55}CO_{-p}$ and $^{87}Rb_{-p}$ and SK IV, V, VG and VY[8] in the case of $^{89}Y_{-p}$. In case of $^{59}CO_{-n}$. Our results using Skyrme interactions are less than the experimental values but they are still better than those calculated by DH. $^{59}CO_{-n}$ is the only case in Table (3) of unlike valence and scattered nucleons. In the case of $^{27}AL_{-p}$, SK IV, V give identical results to DH and VY[8] and they record larger values than VG[8] and the experimental value. As for SK I, II, III and VI, they give small values compared with the experiment. In the case of $^{59}CO_{-p}$, the values of U_{ss} obtained using SKI, II, III, IV and VI give results similar to VG[8] and smaller than the experimental and DH calculations, but SK V agrees well with VY[8] which gives good results which coincide with DH and experiment. Satchler[26] gives U_{ss} = 12 MeV which agrees with SK I, II, III, IV and VI results. In the case of $^{89}Y_{-p}$, SK I and VI are in agreement with the experiment, and SK II, III, IV, V give similar values to VG but still smaller than the experimental though SK V agrees with VY and DH results. In the case of $^{87}Rb_{-p}$, SK V is approximately in agreement with VY, experiment and DH calculation but SK I, II, III, IV and VI give smaller values than experiment and DH but similar to VG.

The experimental values of U_{ss} for $^{85}Y_{-p}$ and $^{87}Rb_{-p}$ was discussed by Spencer[27] where he gave an estimate of U_{ss} = 124 $\pm$ 30 MeV. This estimate would be very nice except for two points:
First, the spin-spin term is assumed[17-21] to be of the surface type; second, there is a difference in sign which gives values in agreement with the experiment for $^{87}Rb_{-p}$ and have the same value for $^{89}Y_{-p}$ but of opposite sign. It was regrettable that the experimental values of U_{ss}, quoted in Table (3) for $^{59}CO_{-p}$, $^{27}AL_{-p}$, $^{85}Y_{-p}$, and $^{87}Rb_{-p}$ were based on the measurement of D parameter at one scattering angle only. Also the experimental values of U_{ss} quoted in table (3) for $^{59}CO_{-n}$ based on very extensive measurements of ($\sigma\uparrow\uparrow - \sigma\uparrow\downarrow$) concern the case of the unlike valence and scattered nucleons, where according to our results, only a small value of U_{ss} was expected.

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TABLE 1.

Potential	SK I	II	III	IV	V	VI	VG	VY	RSC (5)	RSC (5)	BGT (7)	Empirical value (28)
k_f	1.3						1.35	1.7	1.43	1.49	1.49	1.36
ϵ_τ	58.4	68.4	56.5	61.8	62.9	53.6	83.3	95.5	53.0 (7) 60.5	67.7	64.1	49.8
ϵ_σ	-29.5	9.3	-11.3	52.8	94.4	-41.8	66.9	95.5	65.0 (7) 74.1	84.0	64.9	62.9
$\epsilon_{\sigma\tau}$	14.5	38.8	18.8	57.3	78.7	5.9	75.1	95.5	86.6 (7) 73.0	81.7	76.6 (20) 92.5 (7)	71.7
U_τ	129.0	113.1	105.1	48.9	10.1	115.0	41.2	111.0	121.0	140.0	126.0	81.7
U_σ	-234.2	-117.2	-165.3	12.8	143.5	-265.8	16.1	111.0	178.0	105.2	129.0	134.6
$U_{\sigma\tau}$	-52.6	-2.1	-42.1	30.9	76.8	-75.4	59.5	111.0	171.0	197.6	175	169.7

TABLE 2.

Potential	SK I	II	III	IV	V	VI	VG	VY	KB[18]
k_f	1.3						1.35	1.7	1.35
K_τ	-816.0	-332.0	-791	-12.5	409.0	-1060.0	150.0	246.0	136.4
K_σ	-1343.0	-686.0	-1242.0	-67.0	598.0	-1629.0	162.0	246.0	-
$K_{\sigma\tau}$	-44.0	-509.0	-1016.0	-40.0	504.0	-1343.3	106.0	246.0	-

TABLE 3.

Target projectile	Energy	Valence proton config.	U_{ss} (exp.)	U_{ss}									
				Sk. I	II	III	IV	V	VI	VG	VY	BGT	RS1
$^{59}C_{o-n}$	0.3-1.0 1.0-8.0	$(1\ f_{7/2})^{-1}$	47-84 -(34-90)	-25.9	-16.4	-17.6	-2.6	9.5	-27.2	-6.2	zero	-7	1
$^{27}AL_{-p}$	18.0	$(1\ d_{5/2})^{-1}$	24^{+5}_{-8}	-57.4	-23.9	-33.9	8.7	44.1	-68.3	15.1	44.4	61	70
$^{59}C_{o-p}$	47.5	$(1\ f_{7/2})^{-1}$	42^{+21}_{-42}	-41.0	-17.0	-24.2	6.2	31.5	-48.8	10.8	31.7	43	50
$^{89}Y_{-p}$	~5	$(2\ P_{1/2})^{-1}$	124^{+30}_{-30}	95.6	39.8	56.5	-14.6	-73.4	113.8	-25.2	-74.0	-101	-116
$^{87}Rb_{-p}$		$(2\ P_{3/2})^{-1}$		-95.6	-39.8	-56.5	14.6	73.4	-113.8	25.2	74.0	101	116

TABLE CAPTIONS

Table 1. The spin, isospin and spin-isospin symmetry energies (in MeV), values of k_f (in F^{-1}) and the single-particle potential (S_{PP}) of the τ, σ and $\sigma\tau$ terms at the Fermi surface (in MeV) in nuclear matter using the six sets of Skyrme interaction, also the values obtained by DH and Hassan and Ramadan.

Table 2. The spin, isospin and spin-isospin incompressibility using VG, VY and the six sets of Skyrme interaction, also the values obtained by KB.

Table 3. Values of U_{ss} using the six sets of Skyrme interaction comparing with experimental estimates and also with DH calculations. All figures are in MeV.