ISSN 1063-7788, Physics of Atomic Nuclei, 2019, Vol. 82, No. 4, pp. 402–407.

NUCLEI
Theory

Neutron Star Matter and Baryonic Interactions

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Received December 25, 2018; revised December 25, 2018; accepted December 25, 2018

Abstract—The properties of neutron-star matter up to the appearance of hyperons are calculated with the aid of Skyrme potentials. The conditions for the appearance of Λ hyperons in matter and values of the density at the point of their appearance are analyzed for various parametrizations of nucleon—nucleon and hyperon—nucleon interactions. The dependence of the results on the magnitude of density-dependent forces, the degree of nonlocality, the behavior of the symmetry energy, and incompressibility of nuclear matter is examined.

DOI: 10.1134/S1063778819030098

1. INTRODUCTION

The presence of hyperons in the interior of neutron stars is a question that has been a subject of discussions since the publication of the articles of Ambartsumyan and Saakyan [1] and Cameron [2]. Interest in it was quickened by the discovery [3—5] of massive neutron stars (of mass about two Sun's masses). It is well known that the appearance of hyperons entails softening of the equation of state for neutron stars. Soft equations of state lead to inability of the matter of a heavy neutron star to withstand gravitational compression. As a result, the maximum mass of a neutron star for soft equations of state turns out to be substantially less than two Sun's masses. Various ways to overcome this contradiction were proposed in a number of theoretical studies (see, for example, [6—8]), but it has not yet been explained conclusively.

Investigations into this issue led to revealing that there are substantial uncertainties in the calculation of the equation of state for neutron stars. First, available information about nucleon systems comes basically from the properties of atomic nuclei, which are systems of inner density not exceeding $\rho_0 \sim 0.17$ fm^{-3} that are close to isospin-symmetric systems (N/Z is not more than 1.5). In neutron-star theory, one has to deal with matter whose density is several times as high as ρ_0 and where the number of neutrons, N, is many times greater than the number of protons, Z. Incompressibility is one of the most important features of neutron-star matter. So far, however, it could not be determined reliably even for symmetric systems, to say nothing of highly neutron-rich systems. The symmetry energy of nuclear matter is likely to be even more important feature, whose value is rather well known at densities of $\rho \sim \rho_0$. The behavior of the symmetry energy at higher densities is currently of considerable interest not only in connection with neutron-star problems but also in connection with the physics of relativistic heavy-ion collisions, but it remains unknown even at a qualitative level [9].

Further uncertainties are associated with the inclusion of hyperons. Data on hypernuclei is the main source of information about hyperon interactions. To date, the Λ-hyperon binding energy of 28 to 30 MeV in nuclear matter has been determined to a rather high degree of precision. Data concerning Σ and Ξ hyperons are also available [10], but they are substantially less precise. In particular, the data obtained experimentally in [11] are indicative of Σ—nucleus repulsion. This questioned the appearance of Σ hyperons in neutron stars, which was thought to be obvious, for example, in [12]. The absence of Σ hyperons facilitates the appearance of Ξ hyperons, which are heavier, at not very high densities. However, all these data also refer to $\rho \sim \rho_0$, and their extrapolation to the region of higher densities is nontrivial.

The authors of [13] took a fresh look at the role of the symmetry energy of nuclear matter. They used a large number of parametrizations of a Skyrme type equation of state for nonstrange nuclear matter, paying particular attention to the density dependence predicted by these parametrizations for the symmetry energy. Some parametrizations predict a monotonic growth of the symmetry energy with density; in others, the symmetry energy reaches a maximum at some value of $\rho > \rho_0$, whereupon it begins decreasing. It was shown that, in the first case, the fractions of protons and neutrons in neutron-star matter

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gradually approach each other, in agreement with a large number of earlier studies, but, in the second case, protons may disappear at high densities, with the result that matter becomes purely neutron matter.

In the same article, it was indicated that a nonmonotonic behavior of the symmetry energy (presence of a maximum) may be an obstacle to the appearance of hyperons, but the hyperon—nucleon interaction was not taken there into account—only the Λ-hyperon mass was included.

It should be noted that a nonmonotonic behavior of the symmetry energy was confirmed to some extent in analyzing heavy-ion collisions [9], but definitive conclusions have not yet been drawn on the subject.

In the present study, we examine conditions for the appearance of Λ-hyperons in neutron-star matter and their interplay with the equation of state for nuclear matter. In contrast to what was done in [13], we take fully into account available information about the Λ—nucleus interaction and analyze its properties that have an effect on the conditions for the appearance of hyperons.

2. SKYRME INTERACTION AND ITS PARAMETRIZATION

In order to calculate the equation of state for neutron-star matter—both in the case where this matter incorporates nucleons and leptons exclusively and in the case where it additionally includes hyperons—one uses most frequently relativistic mean-field theory, which is a rather simple and powerful method that makes it possible to describe multicomponent baryon systems in terms of a comparatively small number of free parameters. In the present study, we apply a nonrelativistic approach based on Skyrme potentials and used repeatedly in studying neutron stars (see, for example, [13–15]).

The method that relies of Skyrme potentials has a number of drawbacks in relation to relativistic theories. First, the nonrelativistic approach leads to a violation of casuality (superluminosity) at high densities. Second, it requires introducing, for a multicomponent system, a significant number of parameters, of which many are difficult to determine phenomenologically at the present time.

However, the versatility of the Skyrme parametrization of interaction in nucleon matter is the most important for our purposes. It is well known that, in calculations, Λ hyperons mostly arise at moderately small densities of $2\rho_0$ to $3\rho_0$, in which case relativistic effects are hardly operative. Since only conditions for the appearance of Λ hyperons are under study here, we do not consider the region of high densities. We do not address here the cases of other (Σ and Ξ) hyperons either; therefore, it is legitimate to rely on well established properties of the Λ—nucleus interaction, whose parametrization has a solid phenomenological basis.

It is important to note that different Skyrme parametrizations may lead to either a monotonic or a nonmonotonic density dependence of the symmetry energy. We emphasize that the most widespread version of relativistic mean-field theory (that is, $\sigma\omega\rho$ model) predicts unambiguously a monotonic behavior of the symmetry energy.

A general form of the Skyrme effective nucleon—nucleon interaction is well known [16]. Here, we use the SkI3 [17] and SLy230a [14] parameter sets, which we believe to be quite realistic; for extreme cases, we consider the SV parametrization [18], which involves no density dependence, and the T5 interaction [19], which is purely local. We give particular attention to the SkX parametrization [20], which, in contrast to the other ones, predicts a nonmonotonic density dependence of the symmetry energy of nuclear matter. Some features of nuclear matter that were calculated by employing the aforementioned parametrizations are given in Table 1.

An explicit expression for the equation of state for nuclear matter within an approach that relies on Skyrme forces can be found, for example, in [14]. Figure 1 shows the equation of state calculated for nuclear matter with the parameter values from the SLy230a set at various values of the proton population $Y_p = Z/(N+Z)$. The minima on these curves correspond to the saturation state.

It is convenient to choose the parameters of the Skyrme hyperon—nucleon interaction in the form [22]

$$a_0 = t_0^{\Lambda}\left(1 + x_0/2\right), \quad a_1 = \frac{1}{4}\left(t_1^{\Lambda} + t_2^{\Lambda}\right), \tag{1}$$
$$a_2 = \frac{1}{8}(3t_1^{\Lambda} - t_2^{\Lambda}), \quad a_3 = \frac{1}{4}t_3^{\Lambda}\left(1 + x_3/2\right),$$

where t_0^{Λ}, x_0, t_1^{Λ}, t_2^{Λ}, t_3^{Λ}, x_3, and α are standard parameters of the Skyrme potential. The Λ-hyperon binding energy in nucleon matter, D_{Λ}, is the asymptotic value of the hyperon binding energy in a finite nucleus, B_{Λ}, for its mass number tending to infinity, $A \to \infty$, and, at zero hyperon density, appears to be the sign-reversed Λ-hyperon chemical potential; that is,

$$D_{\Lambda} = -a_0\rho_N - a_1\tau_N - \frac{3}{2}a_3\rho_N^{1+\alpha}, \tag{2}$$

where ρ_N and τ_N are, respectively, the nucleon density and the nucleon kinetic energy in the nucleus [16]. Table 2 gives the values of the parameters in the ΛN interactions used in the present study and the values of $D_{\Lambda}(\rho_0)$, where ρ_0 is the saturation density. The YMR [23], SLL4′ [24], and LYI [25]

Table 1. Properties of symmetric nuclear matter for the parametrizations used here the nucleon–nucleon interaction (the quoted results were calculated at $\rho = \rho_0$, where ρ_0 is the saturation density; E/A is the energy per nucleon, a_s is the symmetry energy, K is the incompressibility parameter, and m^*/m is the effective nucleon mass)

	ρ_0, fm^{-3}	$E/A(\rho_0)$, MeV	$a_s(\rho_0)$, MeV	$K(\rho_0)$, MeV	m^*/m
SV [18]	0.1551	−16.048	32.824	305.675	0.383
SkI3 [17]	0.1577	−15.980	34.833	258.179	0.577
SLy230a [14]	0.1600	−15.988	31.986	229.874	0.697
SkO [21]	0.1604	−15.835	31.970	223.326	0.896
T5 [19]	0.1640	−15.997	37.004	201.681	1.000
SkX [20]	0.1554	−16.051	31.098	271.045	0.993

parametrizations lead to the best agreement with experimental data on Λ hypernuclei and are therefore quite realistic. We have also used the following parameter sets obtained earlier for the Skyrme potential: SKSH1 [26], which does not involve the density dependence of the interaction; YBZ2 [27], which features the strongest density dependence; and YBZ6 [27], which corresponds to an especially strong nonlocality. These parametrizations also permit describing experimental data quite satisfactorily.

3. CONDITIONS PER THE APPEARANCE OF HYPERONS

Within the approach used in the present study, we can calculate the population and density dependences of various features of the system being considered. In neutron-star matter, the equilibrium conditions should hold for the chemical potentials, and this makes it possible to obtain the population Y_p as a function of the density ρ from the chemical-equilibrium equations. For matter consisting of nucleons, electrons, and muons, these equations have the form

$$\begin{cases} \mu_n = \mu_p + \mu_e, \\ \mu_e = \mu_\mu, \end{cases} \tag{3}$$

where μ_i is the chemical potential for particles of sort i. For the sake of convenience, we define μ_i in such a way that the chemical potentials for leptons include their rest energy, while the baryon chemical potentials do not include its counterpart. Figure 2 shows examples of the calculation of the chemical potentials versus the density for the SLy230a parametrization.

Let us introduce $D_\Lambda^{\rm cr}$ as the hyperon critical energy in nucleon matter:

$$D_\Lambda^{\rm cr} = m_\Lambda - m_n - \mu_n(\rho). \tag{4}$$

This quantity depends only on the properties of the nucleon–nucleon interaction. In matter consisting of nucleons and leptons, hyperons appear at the density for which the following relation holds:

$$D_\Lambda^{\rm cr} = D_\Lambda = -\mu_\Lambda. \tag{5}$$

Figure 3 shows the density dependences of (a) $D_\Lambda^{\rm cr}(\rho)$ and (b) the symmetry energy $a_s(\rho)$ for various parametrizations of the nucleon–nucleon interaction. These two quantities exhibit a distinct correlation: if the symmetry energy grows fast with density, then $D_\Lambda^{\rm cr}$ decreases fast, and vice versa. In the first case, hyperons may arise earlier. The SkX parametrization deserves particular attention; for it, the behavior not only of $D_\Lambda^{\rm cr}$ but also of the symmetry energy differs substantially from their behavior for the other parametrizations.

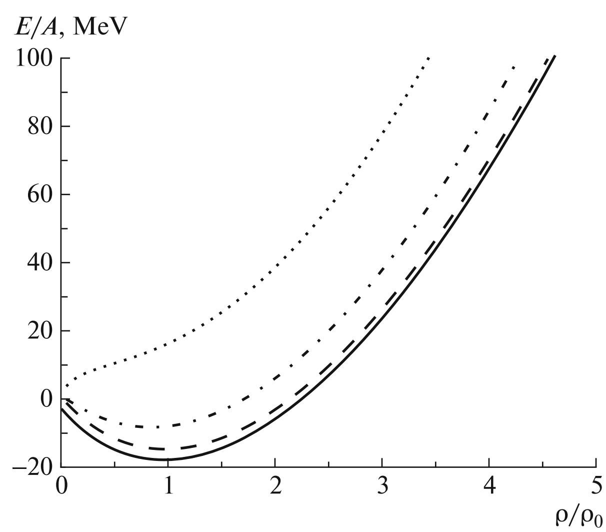

Fig. 1. Energy per nucleon, E/A, of nuclear matter as a function of the density ρ/ρ_0 for the SLy230a parametrization at the proton populations of (solid curve) $Y_p = 0.5$, (dashed curve) $Y_p = 0.4$, (dash-dotted curve) $Y_p = 0.25$, and (dotted curve) $Y_p = 0$.

Table 2. Parameters a_0, a_1, a_3, and α of the ΛN interactions used and the Λ-hyperon energy D_Λ in nucleon matter at the saturation density ρ_0

	a_0, MeV fm^3	a_1, MeV fm^5	a_3, MeV fm$^{3+3\alpha}$	α	$D_\Lambda(\rho_0)$, MeV
SKSH1 [26]	−176.5	2.075	0	–	27.5
YBZ2 [27]	−375.2	26.25	750	1	26.8
YBZ6 [27]	−352.3	45.00	500	1	29.4
YMR [23]	−1056	26.25	703	1/8	30.2
LYI [25]	−465.2	16.25	326	1/3	29.1
SLL4′ [24]	−326.0	20.50	470	1	30.6

4. POINT OF THE APPEARANCE OF HYPERONS

Figure 4 shows the density dependences of D_Λ and $D_\Lambda^{\rm cr}$ for all of the interactions in nucleon matter that are considered in the present study. Hyperons appear at the density corresponding to the point of intersection of these dependences. The order of the graphs is such that, upon going over from Fig. 4*a* to Fig. 4*f*, the curve representing $D_\Lambda^{\rm cr}$ moves rightward to the region of higher density values. In the case of employing the first two parametrizations of the nucleon–nucleon interaction, SV and SkI3, hyperons appear even at moderately low densities for all of the ΛN interactions used. For the SLy230a and SkO parametrizations, the point of the appearance of hyperons is shifted rightward. Moreover, the curves for the YBZ2 potential, which features a a strong density dependence, do not intersect—that is, hyperons do not arise. For the

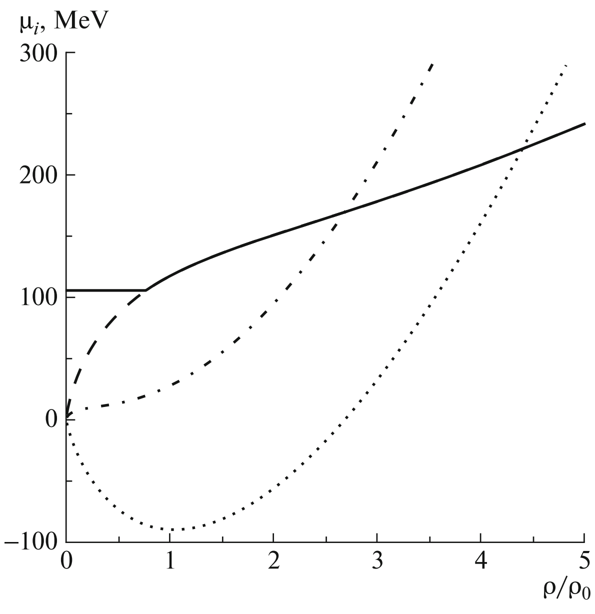

Fig. 2. Chemical potential μ_i for various components of matter as a function of the density ρ/ρ_0 for the SLy230a parametrization in the case of the $npe\mu$ composition of matter: (solid curve) chemical potential for muons, μ_μ; (dashed curve) chemical potential for electrons, μ_e; (dash-dotted curve) chemical potential for neutrons, μ_n; (dotted curve) chemical potential for protons, μ_p.

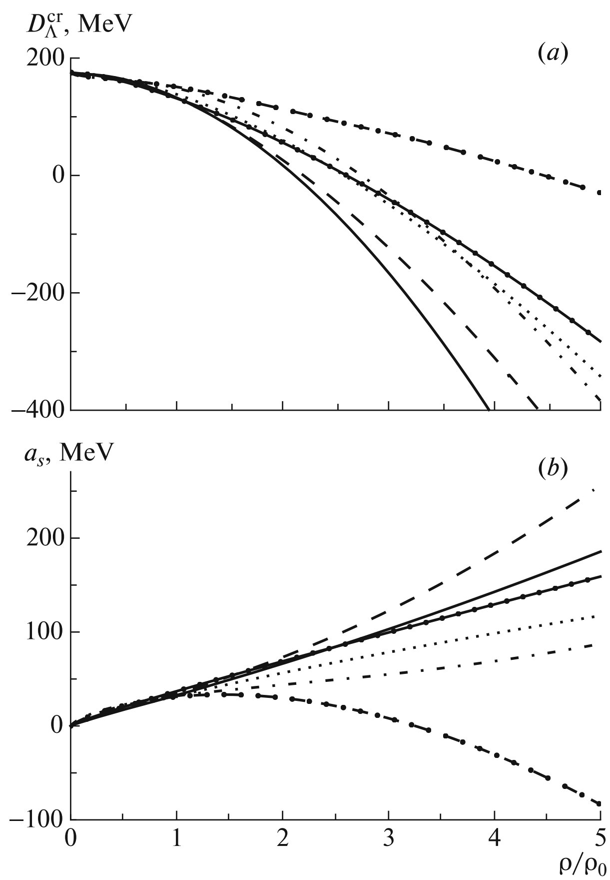

Fig. 3. (*a*) Hyperon critical energy $D_\Lambda^{\rm cr}$ in nuclear matter and (*b*) symmetry energy a_s versus the density ρ/ρ_0 for the (solid curve) SV, (dashed curve) SkI3, (dash-dotted curve) SLy230a, (dotted curve) SkO, (solid curve going through dots) T5, and (dashed curve going through dots) SkX parametrizations of the nucleon–nucleon interaction.

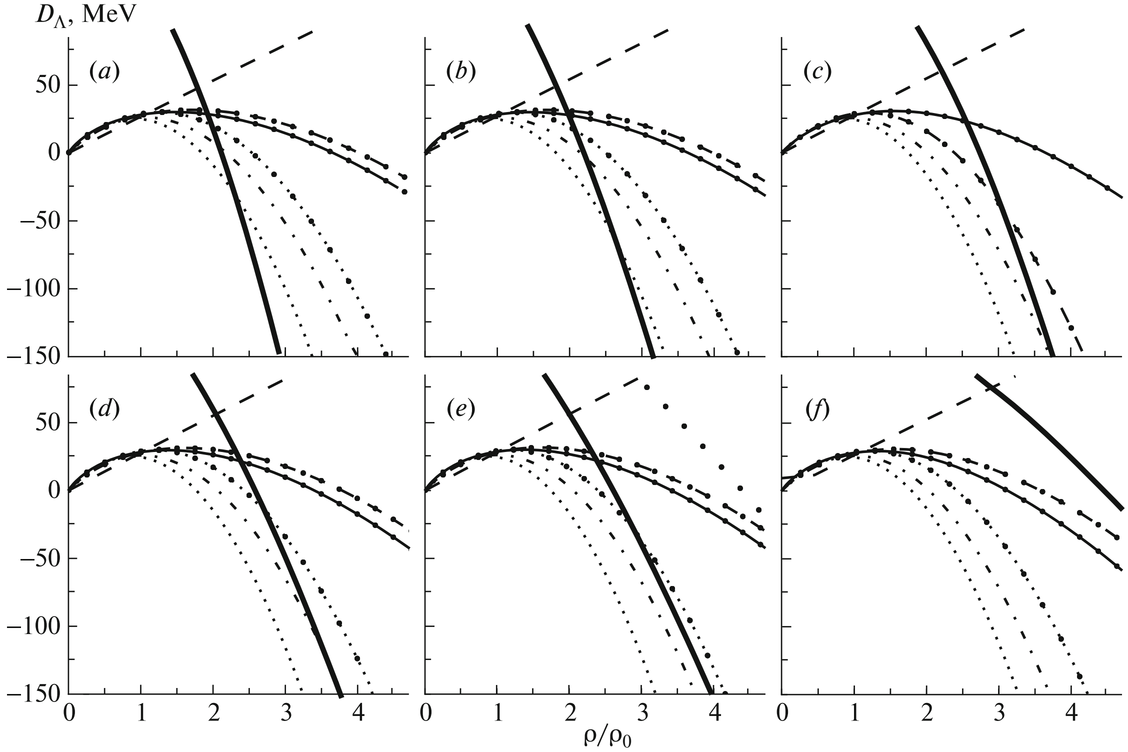

Fig. 4. Dependences of D_Λ and $D_\Lambda^{\rm cr}$ on the density ρ/ρ_0 for all parametrizations used in the present study for the nucleon–nucleon interaction: (*a*) SV, (*b*) SkI3, (*c*) SLy230a, (*d*) SkO, (*e*) T5, and (*f*) SkX. All panels give the (thick solid curve) critical Λ-hyperon energy $D_\Lambda^{\rm cr}$ and the Λ-hyperon energy D_Λ in nucleon matter for the (dashed curve) SKSH1, (dotted curve) YBZ2, (dash-dotted curve) YBZ6, (solid curve going through dots) YMR, (dashed curve going through dots) LYI, and (dotted curve going through thick dots) SLL4 parametrizations of the NN interaction.

T5 potential, we found even two hyperon–nucleon interactions for which hyperons do not appear. Finally, it turned out that, for the SkX potential, only if the hyperon–nucleon interaction is independent of the density do hyperons appear in the region of nuclear-matter densities that is considered here. Table 3 gives the values of the baryon-matter density at the point of the appearance of Λ hyperons for all combinations of the interactions being considered. We note that, in the absence of the density dependence either in the nucleon–nucleon of in the hyperon–nucleon interaction, hyperons appear always. In typical cases, the point of the appearance of hyperons lies in the range between $1.8\rho_0$ and $3.2\rho_0$, which complies with applicability region of our approach; in order to illustrate an overall picture, however, we show a broader density interval in the figures on display.

Table 3. Dimensionless densities ρ/ρ_0 at which Λ hyperons appear (the uppermost row and the leftmost column indicate the parametrizations used for, respectively, the NN and ΛN interactions)

	SV	SkI3	SLy230a	SkO	T5	SkX
SKSH1	1.8	1.8	2.2	2.0	2.0	2.9
YBZ2	2.2	2.5	–	–	–	–
YBZ6	2.0	2.1	3.6	3.2	–	–
YMR	1.9	2.0	2.6	2.4	2.4	–
LYI	1.9	2.0	2.6	2.3	2.3	6.5
SLL4′	2.0	2.1	3.0	2.7	2.9	–

5. CONCLUSIONS

We have analyzed conditions for the appearance of Λ hyperons in neutron-star matter, paying particular attention to the role of various properties of both nucleon–nucleon and hyperon–nucleon interaction. The appearance of hyperons is hindered in the case of a strong density dependence of the hyperon–nucleon interaction or its strong nonlocality. On the contrary, a weak density dependence of the nucleon–nucleon and/or the hyperon–nucleon interaction facilitates the appearance of hyperons at comparatively low densities. A nonmonotonic character of the symmetry energy of nuclear matter as a function of the density does not favor the appearance of hyperons, but they may arise for some hyperon–nucleon interactions. At the same time, we have not found any correlation between the point of the appearance of hyperons and the incompressibility of nuclear matter.

The question of whether hyperons are present in neutron-star matter is of great importance in view of the fact that massive neutron stars do indeed exist. Our present study have shown which properties of the interaction should be established more reliably in order to answer this question.

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