

SPIN ORDERED PHASE TRANSITIONS IN NEUTRON MATTER UNDER THE PRESENCE OF A STRONG MAGNETIC FIELD

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In dense neutron matter under the presence of a strong magnetic field, considered in the model with the Skyrme effective interaction, there are possible two types of spin ordered states. In one of them the majority of neutron spins are aligned opposite to magnetic field (thermodynamically preferable state), and in other one the majority of spins are aligned along the field (metastable state). The equation of state, incompressibility modulus and velocity of sound are determined in each case with the aim to find the peculiarities allowing to distinguish between two spin ordered phases.

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1. INTRODUCTION

Magnetars are strongly magnetized neutron stars [1] with emissions powered by the dissipation of magnetic energy. Magnetars are thought to give the origin to the extremely powerful short-duration γ -ray bursts [2, 3]. The magnetic field strength at the surface of a magnetar is about of 10^{14} - 10^{15} G [4, 5]. Such huge magnetic fields can be inferred from observations of magnetar periods and spin-down rates, or from hydrogen spectral lines. In the interior of a magnetar the magnetic field strength may be even larger, reaching values of about 10^{18} G [6, 7]. Under such circumstances, the issue of interest is the behavior of neutron star matter in a strong magnetic field [6, 7, 8, 9].

In the recent study [9], neutron star matter was approximated by pure neutron matter in a model with the effective nuclear forces. It was shown that the behavior of spin polarization of neutron matter in the high density region in a strong magnetic field crucially depends on whether neutron matter develops a spontaneous spin polarization (in the absence of a magnetic field) at several times nuclear matter saturation density, or the appearance of a spontaneous polarization is not allowed at the relevant densities (or delayed to much higher densities). The first case is usual for the Skyrme forces [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21], while the second one is characteristic for the realistic nucleon-nucleon (NN) interaction [22, 23, 24, 25, 26, 27, 28]. In the former case, a ferromagnetic transition to a totally spin polarized

state occurs while in the latter case a ferromagnetic transition is excluded at all relevant densities and the spin polarization remains quite low even in the high density region. If a spontaneous ferromagnetic transition is allowed, it was shown in the subsequent model consideration with the Skyrme effective forces [29] that the self-consistent equations for the spin polarization parameter at nonzero magnetic field have not only solutions corresponding to negative spin polarization (with the majority of neutron spins oriented opposite to the direction of the magnetic field) but, because of the strong spin-dependent medium correlations in the high-density region, also the solutions with positive spin polarization. In the last case, the formation of a metastable state with the majority of neutron spins oriented along the magnetic field is possible in the high-density interior of a neutron star.

In the present study, we provide the zero-temperature calculations of the equation of state (EoS), incompressibility modulus and sound velocity for neutron matter in a strong magnetic field with the aim to find the peculiarities allowing to distinguish between two possible spin ordered states - the stable one with negative spin polarization and the metastable one with positive spin polarization. It will be shown that in the thermodynamically stable state the incompressibility modulus and the speed of sound are characterized by the appearance of the well-defined maximum just around the density at which the ferromagnetic (FM) phase transition sets in. Contrarily to that, such features are missing in the metastable state. Besides, all calculated quanti-

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ties behave differently under changing magnetic field in stable and metastable states.

At this point, it is worthy to note that we consider thermodynamic properties of spin polarized states in neutron matter in a strong magnetic field up to the high density region relevant for astrophysics. Nevertheless, we take into account the nucleon degrees of freedom only, although other degrees of freedom, such as pions, hyperons, kaons, or quarks could be important at such high densities.

2. BASIC EQUATIONS

Here we only outline the basic equations necessary for further calculations, and a more detailed description of a Fermi-liquid approach to neutron matter in a strong magnetic field can be found in our earlier work [29]. The normal (nonsuperfluid) states of neutron matter are described by the normal distribution function of neutrons $f_{\kappa_1\kappa_2} = \text{Tr} \varrho a_{\kappa_2}^\dagger a_{\kappa_1}$, where $\kappa \equiv (\mathbf{p}, \sigma)$, \mathbf{p} is momentum, σ is the projection of spin on the third axis, and ϱ is the density matrix of the system [18, 19, 21]. Further it will be assumed that the third axis is directed along the external magnetic field \mathbf{H} . The self-consistent matrix equation for determining the distribution function f follows from the minimum condition of the thermodynamic potential [30] and is

$$f = \{\exp(Y_0\varepsilon + Y_4) + 1\}^{-1} \equiv \{\exp(Y_0\xi) + 1\}^{-1}. \quad (1)$$

Here the single particle energy ε and the quantity Y_4 are matrices in the space of κ variables, with $Y_{4\kappa_1\kappa_2} = Y_4\delta_{\kappa_1\kappa_2}$, $Y_0 = 1/T$, and $Y_4 = -\mu_0/T$ being the Lagrange multipliers, μ_0 being the chemical potential of neutrons, and T the temperature. Given the possibility for alignment of neutron spins along or oppositely to the magnetic field \mathbf{H} , the normal distribution function of neutrons and single particle energy can be expanded in the Pauli matrices σ_i in spin space

$$\begin{aligned} f(\mathbf{p}) &= f_0(\mathbf{p})\sigma_0 + f_3(\mathbf{p})\sigma_3, \\ \varepsilon(\mathbf{p}) &= \varepsilon_0(\mathbf{p})\sigma_0 + \varepsilon_3(\mathbf{p})\sigma_3. \end{aligned} \quad (2)$$

Using Eqs. (1) and (2), one can express evidently the distribution functions f_0, f_3 in terms of the quantities ε :

$$\begin{aligned} f_0 &= \frac{1}{2}\{n(\omega_+) + n(\omega_-)\}, \\ f_3 &= \frac{1}{2}\{n(\omega_+) - n(\omega_-)\}. \end{aligned} \quad (3)$$

Here $n(\omega) = \{\exp(Y_0\omega) + 1\}^{-1}$ and

$$\begin{aligned} \omega_\pm &= \xi_0 \pm \xi_3, \\ \xi_0 &= \varepsilon_0 - \mu_0, \quad \xi_3 = \varepsilon_3. \end{aligned} \quad (4)$$

As follows from the structure of the distribution functions f , the quantities ω_\pm play the role of the quasiparticle spectrum and correspond to neutrons

with spin up and spin down. The distribution functions f should satisfy the normalization conditions

$$\frac{2}{\mathcal{V}} \sum_{\mathbf{p}} f_0(\mathbf{p}) = \varrho, \quad (5)$$

$$\frac{2}{\mathcal{V}} \sum_{\mathbf{p}} f_3(\mathbf{p}) = \varrho_\uparrow - \varrho_\downarrow \equiv \Delta\varrho. \quad (6)$$

Here $\varrho = \varrho_\uparrow + \varrho_\downarrow$ is the total density of neutron matter, ϱ_\uparrow and ϱ_\downarrow are the neutron number densities with spin up and spin down, respectively. The quantity $\Delta\varrho$ may be regarded as the neutron spin order parameter. The spin ordering in neutron matter can also be characterized by the neutron spin polarization parameter

$$\Pi = \frac{\varrho_\uparrow - \varrho_\downarrow}{\varrho} \equiv \frac{\Delta\varrho}{\varrho}.$$

The spin order parameter determines the magnetization of the system $M = \mu_n\Delta\varrho$, μ_n being the neutron magnetic moment. The magnetization may contribute to the internal magnetic field $B = H + 4\pi M$. However, we will assume, analogously to Refs. [7, 9], that the contribution of the magnetization to the magnetic field B remains small for all relevant densities and magnetic field strengths, and hence, $B \approx H$. This assumption holds true due to the tiny value of the neutron magnetic moment $\mu_n = -1.9130427(5)\mu_N \approx -6.031 \cdot 10^{-18}$ MeV/G [31] (μ_N being the nuclear magneton) and is confirmed numerically in a subsequent integration of the self-consistent equations.

In order to get the self-consistent equations for the components of the single particle energy, one has to set the energy functional of the system. In view of the above approximation, it reads [19]

$$\begin{aligned} E(f) &= E_0(f, H) + E_{int}(f) + E_{field}, \\ E_0(f, H) &= 2 \sum_{\mathbf{p}} \varepsilon_0(\mathbf{p})f_0(\mathbf{p}) - 2\mu_n H \sum_{\mathbf{p}} f_3(\mathbf{p}), \\ E_{int}(f) &= \sum_{\mathbf{p}} \{\tilde{\varepsilon}_0(\mathbf{p})f_0(\mathbf{p}) + \tilde{\varepsilon}_3(\mathbf{p})f_3(\mathbf{p})\}, \\ E_{field} &= \frac{H^2}{8\pi} \mathcal{V}, \end{aligned} \quad (7)$$

where

$$\tilde{\varepsilon}_0(\mathbf{p}) = \frac{1}{2\mathcal{V}} \sum_{\mathbf{q}} U_0^n(\mathbf{k})f_0(\mathbf{q}), \quad \mathbf{k} = \frac{\mathbf{p} - \mathbf{q}}{2}, \quad (8)$$

$$\tilde{\varepsilon}_3(\mathbf{p}) = \frac{1}{2\mathcal{V}} \sum_{\mathbf{q}} U_1^n(\mathbf{k})f_3(\mathbf{q}). \quad (9)$$

Here $\varepsilon_0(\mathbf{p}) = \frac{\mathbf{p}^2}{2m_0}$ is the free single particle spectrum, m_0 is the bare mass of a neutron, $U_0^n(\mathbf{k}), U_1^n(\mathbf{k})$ are the normal Fermi liquid (FL) amplitudes, and $\tilde{\varepsilon}_0, \tilde{\varepsilon}_3$ are the FL corrections to the free single particle spectrum. Note that the field contribution E_{field} , being the energy of the magnetic field in the absence of matter, leads only to the constant shift of the total energy and, by this reason, can be omitted. Using

Eq. (7), one can get the self-consistent equations in the form [19]

$$\xi_0(\mathbf{p}) = \varepsilon_0(\mathbf{p}) + \tilde{\varepsilon}_0(\mathbf{p}) - \mu_0, \quad (10)$$

$$\xi_3(\mathbf{p}) = -\mu_n H + \tilde{\varepsilon}_3(\mathbf{p}). \quad (11)$$

To obtain numerical results, we utilize the effective Skyrme interaction [32]. Expressions for the normal FL amplitudes in terms of the Skyrme force parameters were written in Refs. [30, 33]. Thus, using expressions (3) for the distribution functions f , we obtain the self-consistent equations (10), (11) for the components of the single-particle energy $\xi_0(\mathbf{p})$ and $\xi_3(\mathbf{p})$, which should be solved jointly with the normalization conditions (5), (6). Further we do not take into account the effective tensor forces, which lead to coupling of the momentum and spin degrees of freedom, and, correspondingly, to anisotropy in the momentum dependence of FL amplitudes with respect to the spin quantization axis.

If the self-consistent equations have a few branches of the solutions, it is necessary to compare the corresponding energies (at zero temperature) in order to decide which solution is thermodynamically preferable. The energy per neutron, E/A , can be directly calculated from Eq. (7). The equation of state (EoS) of neutron matter in a strong magnetic field then can be obtained from the equation

$$P = \varrho^2 \frac{\partial (e/\varrho)}{\partial \varrho}, \quad (12)$$

where $e = \varrho(mc^2 + E/A)$ is the energy density, which includes also the rest energy term. The incompressibility modulus, $K = 9 \frac{\partial P}{\partial \varrho}$, according to Eq. (12), reads

$$K = 9\varrho^2 \frac{\partial^2 (E/A)}{\partial \varrho^2} + 18 \frac{P}{\varrho}. \quad (13)$$

The speed of sound, $v_s = c \sqrt{\frac{\partial P}{\partial e}}$, can be related to the incompressibility modulus by the equation

$$v_s = c \sqrt{\frac{K}{9(mc^2 + \frac{E}{A} + \frac{P}{\varrho})}}. \quad (14)$$

3. EOS OF DENSE NEUTRON MATTER IN A STRONG MAGNETIC FIELD

The self-consistent equations were analyzed at zero temperature in Ref. [29] for the magnetic field strengths up to $H_{max} \sim 10^{18}$ G, allowed by a scalar virial theorem [34], in the model consideration with SLy4 and SLy7 Skyrme effective forces [35]. It was shown that a thermodynamically stable branch of solutions for the spin polarization parameter as a function of density corresponds to negative spin polarization when the majority of neutron spins are oriented opposite to the direction of the magnetic field. Besides, beginning from some threshold density $\varrho_{th} \sim 4\varrho_0$, being slightly dependent on the magnetic field strength, the state with positive spin polarization can also be realized as a metastable state

in neutron matter (cf. branches Π_1 and Π_3 in Fig. 2 of Ref. [29]). This conclusion was based on the comparison of the free energies of two states which turn out to be very close to each other [29, 36]. However, as it will be shown later, additional constraints, such as, e.g., stability of the system with respect to the density fluctuations, will define more accurately the density range admissible for the state with positive spin polarization.

In this work, the previous study [29] will be extended by calculating the EoS of dense neutron matter in a strong magnetic field for various branches of solutions of the self-consistent equations. Each possible state should match the constraint $K > 0$ for allowable densities and magnetic field strengths being the condition of the mechanical stability of the system. Besides, in the high-density region, the velocity of sound should not exceed the speed of light in the vacuum, $v_s < c$. Note that further the contribution of the magnetic field pressure to the total pressure will be omitted because in the magnetic fields up to 10^{18} G the magnetic field pressure is still small compared to the matter pressure in the high-density region of interest.

First, we present the results of determining the zero-temperature EoS of neutron matter in a strong magnetic field at the density region where both stable and metastable spin ordered states can be realized. Because the results of calculations with SLy4 and SLy7 Skyrme forces are very close, here we present the obtained dependences only for the SLy7 Skyrme interaction. Fig. 1 shows the pressure of neutron matter as a function of density for two branches of spin polarization, stable Π_1 and metastable Π_3 , corresponding to negative and positive polarizations, respectively (the branch Π_2 with positive spin polarization considered in Ref. [29] has the considerably larger energy per neutron as compared to the previous ones).

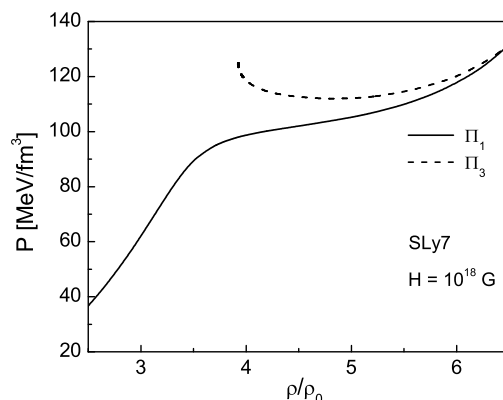


Fig. 1. Pressure vs. density for the branches Π_1 (stable) and Π_3 (metastable) of spin polarization in neutron matter with the Skyrme SLy7 interaction at $H = 10^{18}$ G

For the branch Π_1 , the pressure is the increasing function of the density for all relevant densities, and, hence, the incompressibility coefficient is always

positive. However, for the branch Π_3 , beginning from the threshold density $\rho_{th} \approx 3.92\rho_0$ up to the density $\rho_c \approx 4.85\rho_0$ (at $H = 10^{18}$ G), the pressure decreases with the density. Hence, in this density range the incompressibility coefficient is negative and the metastable state characterized by the branch Π_3 of positive spin polarization cannot appear at these densities. However, beyond the critical density ρ_c , the metastable state with positive spin polarization is allowed by the criterion $K > 0$. Note that the EoS for the metastable state of neutron matter in a strong magnetic field is stiffer than that for the thermodynamically equilibrium state. Fig. 2 shows the pressure of neutron matter as a function of the magnetic field strength for the branches Π_1 and Π_3 of spin polarization at $\rho = 5\rho_0$. It is seen that the dependence of the EoS for stable and metastable branches is different: for the branch Π_1 the EoS becomes softer with the magnetic field while for the branch Π_3 stiffer.

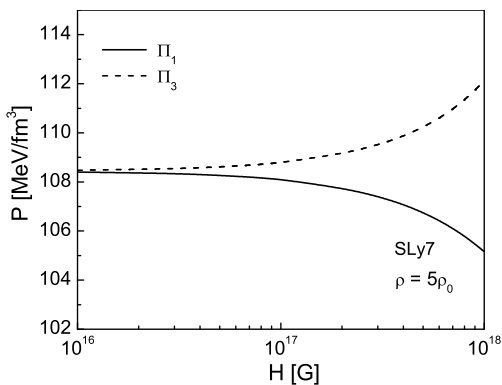


Fig. 2. Pressure vs. magnetic field strength for the branches Π_1 and Π_3 of spin polarization in neutron matter with the Skyrme *SLy7* interaction at $\rho = 5\rho_0$

These calculations show that the impact of the magnetic field on the EoS remains small up to the field strengths of about 10^{17} G.

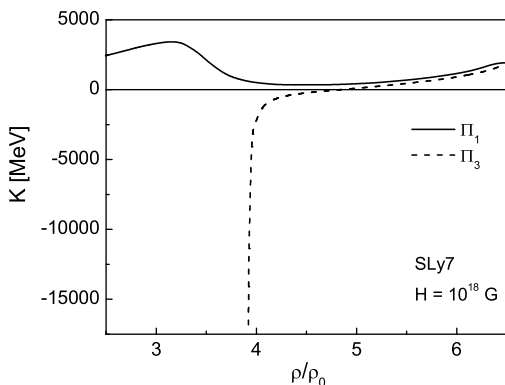


Fig. 3. Same as in Fig. 1, but for the incompressibility modulus of neutron matter in a strong magnetic field

Fig. 3 shows the zero-temperature incompressibility modulus of neutron matter in a strong magnetic field as a function of density for the branches Π_1 and Π_3 of spin polarization. For the branch Π_3 , the incompressibility modulus monotonously increases with the den-

sity and changes sign from negative to positive at the critical density ρ_c , marking the stability range with respect to density fluctuations at densities beyond ρ_c . As a consequence, if the metastable state with positive spin polarization can be realized in the high-density region of neutron matter in a strong magnetic field, under decreasing density (going from the interior to the outer regions of a magnetar) it changes at the critical density ρ_c to a thermodynamically stable state with negative spin polarization.

For the branch Π_1 , the behavior of incompressibility modulus is nonmonotone. The most important peculiarity is that just around the density ($\rho_{tr} \approx 3.16\rho_0$ at $H = 10^{18}$ G) at which the magnitude of the spin polarization parameter for the branch Π_1 begins rapidly to increase (cf. Fig. 2 of Ref. [29]), the increasing behavior of the incompressibility modulus with the density changes on the decreasing one. Because the density ρ_{tr} can be regarded as the density at which a ferromagnetic state sets in, this qualitative feature in the behavior of the incompressibility modulus can be used as the characteristic of the density-driven FM phase transition in neutron matter possessing equilibrium spin polarization. The incompressibility modulus decreases till the density about $4\rho_0$ at which the spin polarization parameter is well developed and gets about two third of its strength. Then there is the plateau in the density dependence of incompressibility modulus till the density about $5\rho_0$ beyond which the incompressibility modulus begins gradually to increase. Note that the noticeable decrease of the incompressibility modulus around the density of the transition to the ferromagnetic state was mentioned also in Ref. [37], although the total incompressibility modulus was not explicitly shown there, but only that for the spin-up and spin-down neutron components in the state with equilibrium spin polarization. Besides, in Refs. [9, 37], there were no any calculations related to the metastable branch of spin polarization because this branch itself was missed in these studies.

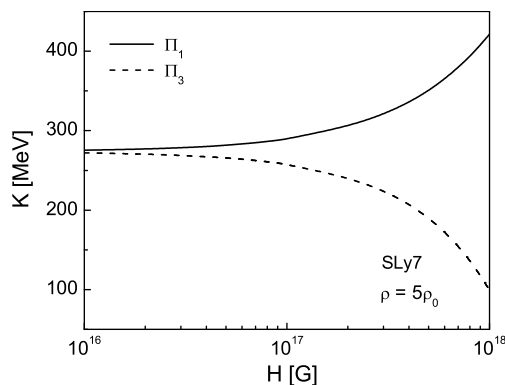


Fig. 4. Incompressibility modulus vs. magnetic field strength for the branches Π_1 and Π_3 of spin polarization in neutron matter with the Skyrme *SLy7* interaction at $\rho = 5\rho_0$

Fig. 4 shows the incompressibility modulus of neutron matter as a function of the magnetic field strength

for the branches Π_1 and Π_3 of spin polarization at the density $\varrho = 5\varrho_0$. For the branch Π_1 , the incompressibility modulus increases with the magnetic field strength while for the branch Π_3 it decreases. It follows from these calculations that the impact of the magnetic field on the incompressibility modulus remains mild up to the field strengths of about 10^{17} G. Fig. 5 shows the sound velocity in neutron matter under the presence of a strong magnetic field as a function of density for the branches Π_1 and Π_3 of spin polarization. For the branch Π_3 , Eq. (14) automatically guarantees the fulfillment of the condition $K > 0$ (for all relevant densities $E/A > 0$).

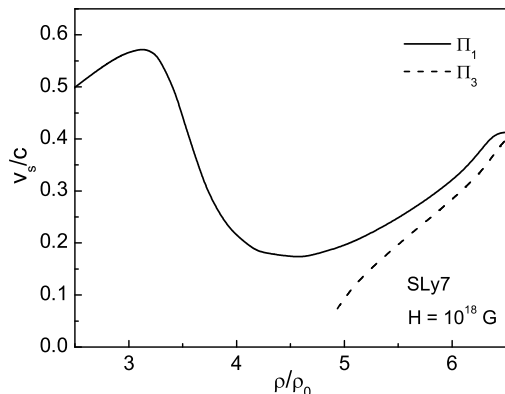


Fig. 5. Same as in Fig. 1, but for the sound velocity in neutron matter under the presence of a strong magnetic field

It is seen that for both branches at the relevant densities the superluminous regime doesn't occur. While for the branch Π_3 the sound velocity monotonously increases with the density, for the branch Π_1 it has non-monotone behavior. In fact, near the transition density ϱ_{tr} the sound velocity in a thermodynamically stable state has a clear peak structure considerably decreasing at the densities where the ferromagnetic phase sets in. This feature, together with the presence of the maximum in the density dependence of the incompressibility modulus, can be used for the identification of the density-driven FM phase transition in neutron matter possessing equilibrium spin polarization. On the other hand, the incompressibility modulus and the speed of sound monotonously increase with density in the metastable state with positive spin polarization, and hence, these features can be used for distinguishing between the thermodynamically stable (negative spin polarization) and metastable (positive spin polarization) states in neutron matter under the presence of a strong magnetic field. Fig. 6 shows the sound velocity in neutron matter as a function of the magnetic field strength for the branches Π_1 and Π_3 of spin polarization at the density $\varrho = 5\varrho_0$. For the branch Π_1 , the sound velocity increases with the magnetic field strength while for the branch Π_3 it decreases. These trends are quite similar to those in the behavior of the incompressibility modulus $K(H)$ for the branches Π_1 and Π_3 .

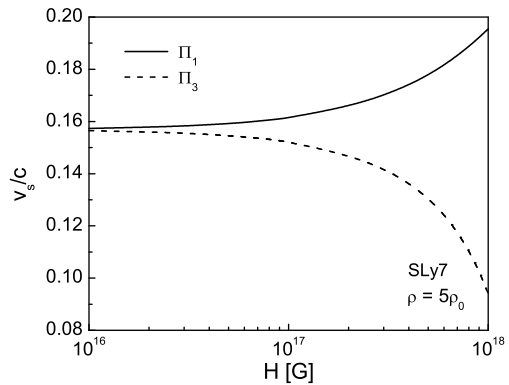


Fig. 6. Same as in Fig. 4 but for the sound velocity in neutron matter under the presence of a strong magnetic field

4. CONCLUSIONS

In dense neutron matter under the presence of a strong magnetic field, considered in the model with the Skyrme effective interaction, there are possible two types of spin ordered states: the one with the majority of neutron spins aligned opposite to magnetic field (thermodynamically preferable state), and the other one with the majority of spins aligned along the field (metastable state). The equation of state, incompressibility modulus and velocity of sound have been determined in each case for SLy7 Skyrme force with the aim to find the peculiarities allowing to distinguish between two spin ordered phases.

For the stable state with the branch Π_1 of negative spin polarization, the EoS is softer than that for metastable state with the branch Π_3 of positive spin polarization. The condition of the positiveness of the incompressibility modulus, $K > 0$, is satisfied for all relevant densities and magnetic field strengths for the stable branch Π_1 . However, for the branch Π_3 , although formally the solutions of the self-consistent equations exist at densities larger than some threshold one, ϱ_{th} , the condition $K > 0$ is satisfied only at the densities larger than the critical one, ϱ_c (e.g., for $H = 10^{18}$ G, $\varrho_{th} \approx 3.92\varrho_0$ and $\varrho_c \approx 4.85\varrho_0$). As a consequence, if the metastable state with positive spin polarization can be realized in the high-density region of neutron matter in a strong magnetic field, under decreasing density (going from the interior to the outer regions of a magnetar) it changes at the critical density ϱ_c to a thermodynamically stable state with negative spin polarization.

For the thermodynamically stable branch Π_1 , the incompressibility modulus and the speed of sound are characterized by the appearance of the well-defined maximum just around the density at which the ferromagnetic phase sets in. The last qualitative features can be used for the identification of the density-driven FM phase transition in neutron matter, possessing equilibrium spin polarization, under the presence of a strong magnetic field. Contrarily to the previous case, for the branch Π_3 of positive spin polarization, the incompressibility modulus and the speed of sound monotonously increase with density that can

be used to distinguish between two different spin ordered phases.

The dependence of all calculated quantities on the magnetic field strength H turns out to be different for two spin ordered phases. For the thermodynamically stable branch Π_1 , the incompressibility modulus and sound velocity increase with H while the pressure decreases. The exactly opposite tendency has been found for the branch Π_3 of positive spin polarization that also allows one to differentiate between spin polarized states with opposite polarizations in neutron matter under the presence of a strong magnetic field.

As yet one problem for consideration, it would be interesting to study the role of finite temperature effects on the EoS, incompressibility modulus and speed of sound in dense neutron matter in a strong magnetic field. As has been shown already, these effects can lead to a number of nontrivial features such as, e.g., unusual behavior of the entropy in various spin ordered systems [36, 38, 39, 40].

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ФАЗОВЫЕ ПЕРЕХОДЫ С УПОРЯДОЧЕНИЕМ СПИНОВ В НЕЙТРОННОЙ МАТЕРИИ ПРИ НАЛИЧИИ СИЛЬНОГО МАГНИТНОГО ПОЛЯ

А.А. Исаев, Дж. Янг

В плотной нейтронной материи при наличии сильного магнитного поля в модели с эффективным взаимодействием Скирма возможны два типа спиновупорядоченных состояний. В одном из них большинство нейтронных спинов ориентировано противоположно магнитному полю (термодинамически предпочтительное состояние), в другом – по полю (метастабильное состояние). В каждом случае определены: уравнение состояния, модуль несжимаемости и скорость звука с целью найти особенности, позволяющие отличить эти спиновупорядоченные фазы.

ФАЗОВІ ПЕРЕХОДИ З УПОРЯДКУВАННЯМ СПІНІВ У НЕЙТРОННІЙ МАТЕРІЇ ЗА НАЯВНІСТЮ СИЛЬНОГО МАГНІТНОГО ПОЛЯ

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У густій нейтронній матерії за наявності сильного магнітного поля в моделі з ефективною взаємодією Скирма можливі два типи спіновпорядкованих станів. В одному з них більшість спінів орієнтовані протилежно магнітному полю (термодинамічно кращий стан), в іншому – вздовж поля. У кожному випадку визначені: рівняння стану, модуль нестисловості та швидкість звуку з метою знайти особливості, що дозволяють відрізнити ці спіновпорядковані стани.