FINITE TEMPERATURE EFFECTS ON SPIN POLARIZATION OF NEUTRON MATTER IN A STRONG MAGNETIC FIELD

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(Received August XXX, 2010; Accepted XXX)

ABSTRACT

Magnetars are neutron stars possessing magnetic field of about $10^{14}$-$10^{15}$ G at the surface. Thermodynamic properties of neutron star matter approximated by pure neutron matter are considered at finite temperature in strong magnetic fields up to $10^{18}$ G which could be relevant for the interior regions of magnetars. In the model with the Skyrme effective interaction, it is shown that a thermodynamically stable branch of solutions for the spin polarization parameter corresponds to the case when the majority of neutron spins are oriented opposite to the direction of the magnetic field (negative spin polarization). Besides, the self-consistent equations, beginning from some threshold density, have also two other branches of solutions corresponding to positive spin polarization. The influence of finite temperatures on spin polarization remains moderate in the Skyrme model up to temperatures relevant for protoneutron stars. In particular, the scenario with the metastable state characterized by positive spin polarization, considered at zero temperature in Phys. Rev. C 80, 065801 (2009), is preserved at finite temperatures as well. It is shown that above certain density the entropy for various branches of spin polarization in neutron matter with the Skyrme interaction in a strong magnetic field demonstrates the unusual behavior being larger than that of the nonpolarized state. By providing the corresponding low-temperature analysis, it is clarified that this unexpected behavior should be addressed to the dependence of the entropy of a spin polarized state on the effective masses of neutrons with spin up and spin down, and to a certain constraint on them which is violated in the respective density range.

Key words: Neutron star models, magnetar, neutron matter, Skyrme interaction, strong magnetic field, spin polarization, finite temperature

I. INTRODUCTION

Magnetars are strongly magnetized neutron stars (Duncan & Thompson 1992) with the magnetic field strength at the surface of about $10^{14}$-$10^{15}$ G (Thompson & Duncan 1996, Ibrahim et al. 2002). Such huge magnetic fields can be inferred from observations of magnetar periods and spin-down rates, or from hydrogen spectral lines. Among possible classes of various neutron stars, soft gamma-ray repeaters and anomalous X-ray pulsars are believed to be most probable candidates for these ultrastrong magnetized astrophysical bodies (Woods & Thompson 2006). Magnetars are relatively frequent objects in the Universe and comprise about 10% of the whole population of neutron stars (Kouveliotou et al. 1998). In the interior of a magnetar the magnetic field strength may be even larger, reaching values of about $10^{18}$ G (Chakrabarty, Bandyopadhyay & Pal 1997, Broderick, Prakash & Lattimer 2000). Therefore, magnetars provide a unique playground for studying properties of neutron star matter under extreme conditions of density and magnetic field strength (Chakrabarty, Bandyopadhyay & Pal 1997, Broderick, Prakash & Lattimer 2000, Cardall, Prakash & Lattimer 2001, Perez-Garcia 2008, Isayev & Yang 2009), which are inaccessible in the terrestrial laboratories.

In the recent study by Perez-Garcia (2008), neutron star matter was approximated by pure neutron matter in a model with the effective nuclear forces. It has been 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 (Rice 1969, Silverstein 1969, Østgaard 1970, Östgaard 1970, Viduarré, Navarro & Bernabeu 1984, Reddy et al. 1999, Akhiezer, Laskin & Peletminsky 1996, Marcos et al. 1991, Maruyama & Tatsumi 2001, Beraudo et al. 2004, Kutschera & Wojcik 1994, Isayev 2003, Isayev & Yang 2004a, Rios, Polls & Vidaña 2005, Isayev 2006), while the second one is characteristic for the realistic nucleon-nucleon (NN) interaction (Pandharipande, Garde & Srivastava 1972, Bäckmann & Källman 1973, Haensel 2001).
II. BASIC EQUATIONS

Here we present only the basic formulae necessary for further calculations, although more details concerning a Fermi-liquid approach to neutron matter in a strong magnetic field can be found in our earlier work (Isayev & Yang 2009). The normal (nonsuperfluid) states of neutron matter are described by the normal distribution function of neutrons \( f_\sigma = \text{Tr} a^+ \sigma a \), where \( \kappa \equiv (p, \sigma) \), \( p \) is momentum, \( \sigma \) is the projection of spin on the third axis, and \( \sigma \) is the density matrix of the system. Further it will be assumed that the third axis is directed along the external magnetic field \( H \). Given the possibility for alignment of neutron spins along or opposite to the magnetic field \( H \), the normal distribution function of neutrons and single particle energy can be expanded in the Pauli matrices \( \sigma_i \) in spin space

\[
\begin{align*}
\varepsilon(p) &= \varepsilon_0(p)\sigma_0 + \varepsilon_3(p)\sigma_3. \\
f(p) &= f_0(p)\sigma_0 + f_3(p)\sigma_3.
\end{align*}
\]

Expressions for the distribution functions \( f_0, f_3 \) in terms of the quantities \( \varepsilon \) read (Isayev 2003, Isayev & Yang 2004a)

\[
\begin{align*}
f_0 &= \frac{1}{2}(n(\omega_+) + n(\omega_-)), \\
f_3 &= \frac{1}{2}(n(\omega_+) - n(\omega_-)).
\end{align*}
\]

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

\[
\begin{align*}
\omega_\pm &= \xi_0 \pm \xi_3, \\
\xi_0 &= \varepsilon_0 - \mu_0, \quad \xi_3 = \varepsilon_3,
\end{align*}
\]

\( \mu_0 \) being the chemical potential of neutrons. The branches \( \omega_\pm \) of the quasiparticle spectrum correspond to neutrons with spin up and spin down.

The distribution functions \( f \) should satisfy the normalization conditions

\[
\begin{align*}
\frac{2}{V} \sum_p f_0(p) &= \varrho, \\
\frac{2}{V} \sum_p f_3(p) &= \varrho_\uparrow - \varrho_\downarrow \equiv \Delta \varrho.
\end{align*}
\]

Here \( \varrho = \varrho_\uparrow + \varrho_\downarrow \) is the total density of neutron matter, \( \varrho_\uparrow \) and \( \varrho_\downarrow \) 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. It determines the magnetization of the system \( M = \mu_\uparrow \Delta \varrho, \mu_\uparrow \) being the neutron magnetic moment. The magnetization may contribute to the internal magnetic field \( B = H + 4\pi M \). However, as we discussed earlier (Isayev & Yang 2009), and, analogously to the previous works (Perez-Garcia 2008, Broderick, Prakash & Lattimer 2000), we will assume that the contribution of the magnetization to the magnetic field \( B \) remains small for all relevant densities and magnetic field strengths, and, hence, \( B \approx H \).
The self-consistent equations for the components of the single-particle energy have the form (Isayev & Yang 2009)

\[ \xi_0(p) = \xi_0(p) + \xi_0(p) - \mu_0, \quad (6) \]
\[ \xi_3(p) = -\mu_0 H + \xi_3(p). \quad (7) \]

Here \( \xi_0(p) = \frac{p^2}{2m_0} \) is the free single particle spectrum, \( m_0 \) is the bare mass of a neutron, and \( \xi_0, \xi_3 \) are the Fermi liquid (FL) corrections to the free single particle spectrum, related to the normal FL amplitudes \( U_0^n(k), U_1^p(k) \) by formulas

\[ \xi_0(p) = \frac{1}{2\nu} \sum_q U_0^n(k) f_0(q), \quad k = \frac{p - q}{2}, \quad (8) \]
\[ \xi_3(p) = \frac{1}{2\nu} \sum_q U_1^p(k) f_3(q). \quad (9) \]

To obtain numerical results, we utilize the effective Skyrme interaction (Vautherin & Brink 1972). Expressions for the normal FL amplitudes in terms of the Skyrme force parameters were written by Akhiezer et al. 1997, Isayev & Yang 2006. Thus, using expressions (2) for the distribution functions \( f \), we obtain the self-consistent equations (6), (7) for the components of the single-particle energy \( \xi_0(p) \) and \( \xi_3(p) \), which should be solved jointly with the normalization conditions (4), (5).

Note that spin ordering in neutron matter can be characterized by the neutron spin polarization parameter

\[ \Pi = \frac{\theta_\uparrow - \theta_\downarrow}{\theta} = \frac{\Delta \theta}{\theta}. \]

The number densities of neutrons with spin up and spin down are related to the spin polarization parameter \( \Pi \) by formulas

\[ \theta_\uparrow = \frac{\theta}{2}(1 + \Pi), \quad \theta_\downarrow = \frac{\theta}{2}(1 - \Pi). \quad (10) \]

To examine the thermodynamic stability of different solutions of the self-consistent equations, it is necessary to compare the corresponding free energies \( F = E - TS \), where the energy functional \( E \) is characterized by two FL amplitudes \( U_0^n, U_1^p \) (Isayev & Yang 2006) and the entropy reads

\[ S = -\sum_p \sum_{\sigma = +, -} \{ n(\omega_\sigma) \ln n(\omega_\sigma) + \bar{n}(\omega_\sigma) \ln \bar{n}(\omega_\sigma)\}, \quad \bar{n}(\omega) = 1 - n(\omega). \quad (11) \]

III. SOLUTIONS OF SELF-CONSISTENT EQUATIONS AT FINITE \( T \). THERMODYNAMIC FUNCTIONS

The self-consistent equations were analyzed at zero temperature by Isayev & Yang 2009 for the magnetic field strengths up to \( H_{\text{max}} \sim 10^{18} \text{ G} \), allowed by a scalar virial theorem (Lai & Shapiro 1991), in the model consideration with SLy4 and SLy7 Skyrme effective forces (Chabanat et al. 1998). These Skyrme parametrizations were constrained originally to reproduce the results of microscopic neutron matter calculations (pressure-versus-density curve) and give neutron star models in a broad agreement with the observables such as the minimum rotation period, gravitational mass-radius relation, the binding energy, released in supernova collapse, etc. (Rikovska Stone et al. 2003). 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 dependent on the magnetic field strength, the state with positive spin polarization can be realized as a metastable state in the high-density region of neutron matter in the model with the Skyrme effective forces.

Here we study the impact of finite temperatures on spin polarization of neutron matter in a strong magnetic field. In particular, we are interested to learn whether the metastable state with positive spin polarization will survive at temperatures about several tens of MeV relevant for protoneutron stars. To that end, we directly find solutions of the self-consistent equations at nonzero temperature. 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 neutron spin polarization parameter as a function of density, normalized to the nuclear...
saturation density $\rho_0$ (for SLy7 force, $\rho_0 = 0.158 \text{ fm}^{-3}$), for a set of fixed values of the magnetic field strength at the temperature $T = 20 \text{ MeV}$. The branches of spontaneous polarization $\Pi_0^-, \Pi_0^+$, corresponding to the vanishing magnetic field, are shown by solid curves. As one can see, the obtained dependences qualitatively are similar to those obtained at zero temperature. The branches of spontaneous polarization are modified differently by the magnetic field: The branch $\Pi_1^-(\rho)$ turns to the branch $\Pi_1^+(\rho)$ with negative spin polarization while the branch $\Pi_0^-, \Pi_0^+$ splits into two branches, $\Pi_2^-(\rho)$ and $\Pi_3^-(\rho)$, corresponding to positive spin polarization. For the lower branch $\Pi_1^-(\rho)$, there are three characteristic density domains. At low densities $\rho \lesssim 0.5\rho_0$, the magnitude of the spin polarization parameter increases with decreasing density. At intermediate densities $0.5\rho_0 \leq \rho \lesssim 3\rho_0$, there is a plateau in the $\Pi_1^-(\rho)$ dependence, whose characteristic value depends on $H$ (at the given temperature). At densities $\rho \gtrsim 3\rho_0$, the absolute value of the spin polarization parameter increases with density and tends to unity. Note that in the low-density domain the possibility of the appearance of a "nuclear magnetic pasta" and its impact on the neutrino opacities in the protoneutron star early cooling stage should be explored in a more elaborated analysis as discussed in detail by Perez-Garcia (2008).

The upper branches $\Pi_2^+(\rho)$ and $\Pi_3^+(\rho)$, corresponding to positive spin polarization, appear stepwise at the same threshold density $\rho_{th}$ dependent on the magnetic field (at the given temperature) and being larger than the critical density of spontaneous spin instability in neutron matter. For the branch $\Pi_2^+(\rho)$, the spin polarization parameter decreases with density and tends to zero while for the branch $\Pi_3^+(\rho)$ it increases with density and approaches unity. Because of the negative value of the neutron magnetic moment, the magnetic field tends to orient the neutron spins opposite to the magnetic field direction. As a result, the spin polarization parameter for the branches $\Pi_2^+(\rho), \Pi_3^+(\rho)$ with positive spin polarization is smaller than that for the branch of spontaneous polarization $\Pi_1^-\Pi_0^+$, and, vice versa, the magnitude of the spin polarization parameter for the branch $\Pi_1^-\Pi_0^+$ with negative spin polarization is larger than the corresponding value for the branch of spontaneous polarization $\Pi_0^+$.

Thus, at densities larger than $\rho_{th}$, we have three branches of solutions: one of them, $\Pi_1^-(\rho)$, with negative spin polarization and two others, $\Pi_2^+(\rho)$ and $\Pi_3^+(\rho)$, with positive polarization. In order to clarify which branch is thermodynamically preferable we should compare the corresponding free energies. Fig. 2 shows the free energy per neutron as a function of density at $T = 20 \text{ MeV}$ and $H = 10^{18} \text{ G}$ for these three branches, compared with the free energy per neutron for a spontaneously polarized state (the branches $\Pi_0^\pm(\rho)$). It is seen that the state with the majority of neutron spins oriented opposite to the direction of the magnetic field (the branch $\Pi_1^-(\rho)$) has a lowest free energy. This result is intuitively clear, since magnetic field tends to direct the neutron spins opposite to $\mathbf{H}$, as mentioned earlier. However, the state, described by the branch $\Pi_3^+(\rho)$ with positive spin polarization, has the free energy very close to that of the thermodynamically stable state. This means that despite the presence of a strong magnetic field $H \sim 10^{18} \text{ G}$, the state with the majority of neutron spins directed along the magnetic field can be realized as a metastable state in the dense core of a neutron star in the model consideration with the Skyrme effective interaction. In this scenario, because such states exist only at densities $\rho \gtrsim 3\rho_0$, under decreasing density (going from the interior to the outer regions of a magnetar) a metastable state with positive spin polarization at the threshold density $\rho_{th}$ changes to a thermodynamically stable state with negative spin polarization.

An unexpected moment appears if we consider separately the entropy for various branches of spin polarization. Fig. 3 shows the difference between the entropy per neutron for the branches $\Pi_1^-\Pi_3^+$ and that of the nonpolarized state (with $\Pi = 0$ at $H = 0$) as a function of density at the fixed magnetic field strength $H = 10^{18} \text{ G}$ and different temperatures. Contrarily to the intuitively expected behavior, the entropy for the
Fig. 3.—(Color online) The entropy per neutron measured from its value in the nonpolarized state for the $\Pi_1$–$\Pi_3$ branches of spin polarization as a function of density at $H = 10^{18}$ G and different temperatures for the SLy7 interaction.

branch $\Pi_1$, beginning from a certain density weakly dependent on temperature (at the given magnetic field strength), is larger than the entropy of the nonpolarized state. Besides, the entropy for the branches $\Pi_2$ and $\Pi_3$ is larger than that for the nonpolarized state for all relevant densities. It looks like the spin polarized states described by the $\Pi_1$–$\Pi_3$ branches of spin polarization are less ordered than the nonpolarized state for the corresponding densities.

In order to understand qualitatively such an expected behavior, let us consider the low-temperature expansion for the entropy in terms of the effective masses of spin-up and spin-down neutrons. The density of entropy (11) can be written in the form

$$s = \frac{1}{\pi^2 \hbar^3} \sum_{\sigma=+,-} \sqrt{\frac{m_\sigma T^3}{2}} \times \left\{ \frac{5}{3} J_2(\eta_\sigma) - \eta_\sigma J_2(\eta_\sigma) \right\}, \eta_\sigma = \frac{\mu_\sigma}{T},$$

where

$$J_\nu(\eta) = \int_0^\infty \frac{x^\nu}{e^{x-\eta} + 1} dx$$

is Fermi-Dirac integral of the order $\nu$, $\mu_\sigma$ is the effective chemical potential of neutrons with spin up ($\sigma = +$) and spin down ($\sigma = -$), whose explicit expression was written by Isayev & Yang (2009). In the low-temperature limit, $\eta_\sigma \gg 1$, and, providing the corresponding expansion of Fermi-Dirac integrals in Eq. (12), one gets

$$s = \sum_{\sigma=+,-} s_\sigma, \quad s_\sigma = \frac{\pi^2}{2eF_\sigma} T, \quad (13)$$

where $\varepsilon_\sigma = \frac{\hbar^2 k_\sigma^2}{2m_\sigma}$ is the Fermi energy of neutrons with spin up and spin down, $k_\sigma = (6\pi^2 \rho_\sigma)^{1/3}$ being the respective Fermi momentum. The low-temperature expansion (13) is valid till $T/\varepsilon_{F\sigma} \ll 1$. Then, requiring for the difference between the entropies of spin polarized and nonpolarized states to be negative, one gets the constraint on the effective masses $m_{n\uparrow}$ and $m_{n\downarrow}$ of neutrons with spin up and spin down in a spin polarized state:

$$D \equiv \frac{m_{n\uparrow}}{m_n}(1 + \Pi)^\frac{3}{2} + \frac{m_{n\downarrow}}{m_n}(1 - \Pi)^\frac{3}{2} < 0, \quad (14)$$

Here $m_n$ is the effective mass of a neutron in nonpolarized neutron matter (Isayev & Yang 2004a),

$$h^2 \frac{2}{m_n} = \frac{\hbar^2}{2m_0} + \frac{\varepsilon_{F\uparrow}}{3}[t_1(1 - x_1) + 3t_2(1 + x_2)], \quad (15)$$

and expressions for the effective masses $m_{n\uparrow}, m_{n\downarrow}$ read (Isayev & Yang 2009)

$$h^2 \frac{2}{m_{n\uparrow}} = \frac{\hbar^2}{2m_0} + \frac{\varepsilon_{F\uparrow}}{2} t_2(1 + x_2) + \frac{\varepsilon_{F\downarrow}}{4} [t_1(1 - x_1) + t_2(1 + x_2)]. \quad (16)$$

In Eqs. (15), (16), $t_i$ and $x_i$ are some phenomenological parameters, specifying a given parametrization of the Skyrme interaction. According to Eq. (10), the number densities of neutrons with spin up and spin down are determined by the spin polarization parameter $\Pi$, which, after the self-consistent determination, is a function of the thermodynamic parameters $\rho, T, H$. Hence, the condition (14) determines the region in the domain of admissible values of the thermodynamic parameters, where the entropy of a spin polarized state demonstrates the expected behavior.

Fig. 4 shows the left-hand side $D$ of constraint (14) for the branches $\Pi_1$–$\Pi_3$ of spin polarization as a function of density at $H = 10^{18}$ G and temperature $T = 5$ MeV, at which the condition $\varepsilon_{F\sigma}/T \gg 1$ holds true. For the branch $\Pi_1$, the difference $D$ is negative up to the density $\rho_1 \approx 0.41 \rho_0$ (see the insert in Fig. 4), where it changes sign and remains positive for all larger densities. Besides, for the branches $\Pi_2$ and $\Pi_3$, the difference $D$ is positive for all densities at which the corresponding solutions of the self-consistent equations exist. These features explain the above mentioned unusual behavior of the entropy for various branches of spin polarization in neutron matter with the Skyrme interaction under the presence of a strong magnetic field. Note that such an unexpected behavior of the entropy was also found.
for the states with spontaneous spin polarization (in the absence of the magnetic field) in neutron matter with the Skyrme interaction (Ríos, Polls & Vidaña 2005) and antiferromagnetically spin ordered states in symmetric nuclear matter with the Gogny D1S interaction (Isayev & Yang 2004b, Isayev 2005, Isayev 2007).

IV. CONCLUSIONS

We have studied the impact of finite temperatures on the spin structure in the magnetar interior, approximating the neutron star matter by pure neutron matter and taking the Skyrme effective interaction as a potential of NN interaction (SLy7 parametrization). According to the scalar virial theorem, strong magnetic fields up to $10^{18}$ G can be relevant for the interior regions of magnetars. It has been shown that, together with the thermodynamically stable branch of solutions for the spin polarization parameter corresponding to the case when the majority of neutron spins are oriented opposite to the direction of the magnetic field (negative spin polarization), the self-consistent equations, beginning from some threshold density, have also two other branches of solutions corresponding to positive spin polarization. The influence of finite temperatures on spin polarization remains moderate in the Skyrme model, at least, up to temperatures relevant for protoneutron stars. In particular, a thermodynamic analysis, based on the calculation of the free energy for different branches of spin polarization, shows that the scenario with the metastable state characterized by positive spin polarization, considered at zero temperature (Isayev & Yang 2009), is preserved at finite temperatures as well. This is one of the important conclusions of the given research. The possible existence of a metastable state with positive spin polarization will affect the neutrino opacities of a neutron star matter in a strong magnetic field, and, hence, will influence the cooling history of a neutron star (Reddy et al. 1999).

We have also shown that above certain density the entropy for various branches of spin polarization in neutron matter with the Skyrme interaction in a strong magnetic field demonstrates the unusual behavior being larger than that of the nonpolarized state. To clarify this point, we have provided the corresponding low-temperature analysis. It has been shown that this unexpected behavior should be addressed to the dependence of the entropy of a spin polarized state on the effective masses of spin-up and spin-down neutrons and to a certain inequality constraint on them which is violated in the respective density range.

It is worthy to note that in the given research a neutron star matter was approximated by pure neutron matter. This should be considered as a first step towards a more realistic description of neutron stars taking into account a finite fraction of protons with the charge neutrality and beta equilibrium conditions. In particular, some admixture of protons can affect the onset densities of enhanced polarization in a neutron star matter with the Skyrme interaction (Isayev & Yang 2004a). Nevertheless, at such strong magnetic fields, one can expect that the proton fraction is relatively small and even can completely disappear in the dense interior of a magnetar (Mao et al. 2003).

ACKNOWLEDGEMENTS

J.Y. was supported by grant 2010-0011378 from Basic Science Research Program through NRF of Korea funded by MEST and by grant R32-2009-000-10130-0 from WCU project of MEST and NRF through Ewha Womans University.

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