SPIN-TRIPLET SUPERFLUIDITY OF NEUTRON MATTER WITH SKYRME FORCES IN STRONG MAGNETIC FIELD NEAR T_C

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A dense homogeneous superfluid pure neutron matter (SPNM) with the effective Skyrme forces (depending on the density n of the neutrons) and with spin-triplet p–wave pairing (similar to ^{3}He-A$_1$ and ^{3}He-A$_2$) in a strong uniform static magnetic field H is studied in the framework of a generalized non-relativistic Fermi-liquid theory. General formulas (valid for arbitrary parameterization of the Skyrme forces) are derived analytically for the phase transition temperatures $T_{c1,2}$ of the neutron matter from normal to superfluid states of ^{3}He-A$_1$ and ^{3}He-A$_2$ types, respectively. The functions $T_{c1,2}(H,n)$ are linear with respect to H (up to sufficiently high magnetic fields) and are non-monotone functions of density. Figures for $(T_{c1}(H,n)-T_{c2}(H,n))/H$ are plotted in the range $0.8n_0 \lesssim n \lesssim 3n_0$ (n_0=0.17 fm^{-3} is the saturation density of the symmetric nuclear matter) for selected RATP, SkO' and Gs parameterizations of the Skyrme forces which have different power dependences on density. Such phases of dense SPNM may exist in cores of magnetized neutron stars.

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1. INTRODUCTION

The superfluid phases of ^3He and superfluid pure neutron matter (SPNM) (existing inside liquid core of neutron stars at subnuclear $n \lesssim n_0$ (where n_0 =0.17 fm^{-3} is the saturation density of the symmetric nuclear matter) and supernuclear ($n > n_0$) densities of neutrons; see, e.g., [1] and references therein) are important examples of superfluid Fermi liquids (SFLs) with spin-triplet pairing. Here we have investigated superdense SPNM with p-wave pairing of $^3He - A_{1,2}$ type in a steady homogeneous magnetic field $\mathbf{H}$ and have used the generalized non-relativistic Fermi-liquid approach [2] for derivation nonlinear integral equations for the order parameter (OP) and effective magnetic field (EMF) $\mathbf{H}_{eff}$ inside SPNM [4,5] which are valid at arbitrary temperatures from the interval $0 \le T \le T_c$ (T_c is the normal–superfluid phase transition (PT) temperature). The effective Skyrme interaction between neutrons depending on the neutron density n (see review [3] and Ref. [4, 5]) have been used. Further we have found analytically the approximate solutions of the obtained integral equations in the vicinity of the PT temperature $T_{c0}(n)$ of the NM to superfluid state with triplet p-wave pairing (without magnetic field) and have obtained the general approximate formulas for the PT temperatures $T_{c1,2}(H,n)$ for arbitrary parameterization of the Skyrme interaction. These functions $T_{c1,2}(H,n)$ are linear with respect to the H up to sufficiently high magnetic fields (but $H << \varepsilon_F / |\mu_n|$, where $\varepsilon_F(n)$ is the Fermi energy of NM and $\mu_n < 0$ is the magnetic dipole moment of neutron). We have specified formulas for $T_{c1,2}(H,n)$ for the so-called RATP, SkO' and Gs parameterizations [6-8] of the Skyrme forces and the corresponding figures were plotted. These figures demonstrate the behavior of PT temperature splitting $(T_{c,1}(H,n) - T_{c,2}(H,n))/H$ as non-monotonic function of n at the variation of neutron density in the permissible range, $0.8n_0 \lesssim n \lesssim 3n_0$ (where the non-relativistic Fermi-liquid theory is valid).

Other authors studied phase transitions of NM to superfluid states with triplet pairing without (see, e.g., Ref. [9-14]) and with the effect of magnetic field [15] within other approaches and using different nucleon-nucleon effective interactions inside NM with several simplifying assumptions (e.g., neglecting the dependence of neutron effective mass on NM density).

2. EQUATIONS FOR THE OP AND EMF FOR SPNM WITH THE SKYRME FORCES AND TRIPLET PAIRING

As is known [1], the OP for the so-called non-unitary phase (NU) of $^3He - A_2$ type with p-wave pairing has the form

$$\Delta_\alpha^{A_2}(\mathbf{p}) = (\Delta_+ \hat{\mathbf{d}}_\alpha + i\Delta_- \hat{\mathbf{e}}_\alpha)\psi(\hat{\mathbf{p}}),$$
$$\psi(\hat{\mathbf{p}}) \equiv (\hat{m}_j + i\hat{n}_j)\hat{\mathbf{p}}_j, \quad \hat{\mathbf{p}} \equiv \mathbf{p}/p. \qquad (1)$$

Here $\Delta_\pm(T) \equiv (\Delta_\uparrow(T) \pm \Delta_\downarrow(T))/2$; $\hat{\mathbf{d}}$ and $\hat{\mathbf{e}}$ are mutually orthogonal real unit vectors in spin space, $\hat{\mathbf{d}} \cdot \hat{\mathbf{e}} = 0$, $\hat{\mathbf{d}}^2 = \hat{\mathbf{e}}^2 = 1$; $\hat{\mathbf{m}}$ and $\hat{\mathbf{n}}$ are mutually orthogonal real unit vectors in orbital space, $\hat{\mathbf{m}} \cdot \hat{\mathbf{n}} = 0$, $\hat{\mathbf{m}}^2 = \hat{\mathbf{n}}^2 = 1$. The value $\eta(\mathbf{p}) \equiv |\Delta(\mathbf{p}) \times \Delta^*(\mathbf{p})| \ne 0$ for NU phases of SFL or SPNM in particular. Note that the superfluid phase of $^3He - A_1$ type is realized at the condition with $\Delta_\downarrow = 0$, $\Delta_\uparrow \ne 0$.

We have chosen the effective Skyrme forces as the interaction between neutrons for SPNM with spin-triplet p-wave pairing in spatially uniform magnetic field $\mathbf{H}$. A set of coupled equations for the OP of the $^3He - A_2$ type and effective magnetic field (EMF) $\mathbf{H}_{eff}$ inside SPNM is simplified in the case of Skyrme interaction because the normal Fermi-liquid Landau's exchange amplitudes $F_l^a \neq 0$ only for $l = 0$ and $l = 1$ (in contrast to the superfluid ^3He, when it is necessary to take into account in general case also the amplitudes $F_l^a \neq 0$ with $l > 1$, see e.g. [16]). As a result, using general formulas for anomalous and normal distribution functions of quasiparticles [16, 17] (neutrons) for SPNM in magnetic field we have derived a set of integral equations for $\xi(p)$ and $\Delta_\uparrow^{A_2}$, $\Delta_\downarrow^{A_2}$. In this case for SPNM $\boldsymbol{\xi}(\mathbf{p}) = \xi(p)\mathbf{H}/H \equiv -\mu_n \mathbf{H}_{eff}(p)$ ($\mu_n \approx -0.60308 \cdot 10^{-17}$ MeV/G is the magnetic dipole moment of neutron [18]) and for $\xi(p)$ we have equation [4]:

$$\xi(p) = -\mu_n H + (r + sp^2)K_2(\xi) + sK_4(\xi). \tag{2}$$

Here $r = t_0' + (t_3'/6)n^\alpha$ and $s = (t_1' - t_2')/(4\hbar^2)$, $n \equiv yn_0$ is density of neutron matter; $t_0' = t_0 \cdot (1 - x_0)$, $t_1' = t_1 \cdot (1 - x_1)$, $t_2' = t_2 \cdot (1 + x_2)$, $t_3' = t_3 \cdot (1 - x_3)$ and $1/6 \le \alpha \le 1/3$ are parameters of the Skyrme interaction (cf. [3]). The functionals $K_\beta(\xi)$ (β=2, 4) in Eq. (2) have the form:

$$K_\beta(\xi) = \frac{1}{(2\pi)^2 \hbar^3} \int_{p_{\min}}^{p_{\max}} dq q^\beta \int_0^1 dx \kappa(q, x), \tag{3}$$

where

$$\kappa(q,x) = \frac{z(q) + \xi(q)}{E_+(q,x^2)} \tanh\left(\frac{E_+(q,x^2)}{2T}\right) - \frac{z(q) - \xi(q)}{E_-(q,x^2)} \tanh\left(\frac{E_-(q,x^2)}{2T}\right), \tag{4}$$

$$E_\pm^2 = q^2 \Delta_{\uparrow(\downarrow)}^2 (1 - x^2) + (z(q) \pm \xi(q))^2, \tag{5}$$

$z(q) = q^2/2m_n^* - \mu$ (m_n^* is the effective mass of neutron, μ is the chemical potential). We have taken into account that for SPNM with pairing of the $^3He - A_2$ type the OP can be written as $\Delta_{\uparrow(\downarrow)}^{A_2}(T,\xi,q) = q\Delta_{\uparrow(\downarrow)}(T,\xi)$, where functions $\Delta_{\uparrow(\downarrow)}(T,\xi)$ obey the following equations [4]:

$$\Delta_{\uparrow(\downarrow)}(T,\xi) = -\Delta_{\uparrow(\downarrow)}(T,\xi) \frac{c_3}{8\pi^2\hbar^3} \times \int_{p_{\min}}^{p_{\max}} dq q^4 \int_0^1 dx (1 - x^2) \tanh\left(\frac{E_\pm(q,x^2)/2T}{E_\pm(q,x^2)}\right) \tag{6}$$

($p_{\max} \gtrsim p_F$, $(p_{\max} - p_{\min})/p_F << 1$, p_F is the Fermi momentum). Here $c_3 \equiv t_2(1 + x_2)/\hbar^2 < 0$ is coupling constant leading to spin-triplet *p*-wave pairing of neutrons, which is expressed through the parameters t_2 and x_2 of the Skyrme interaction (cf. Ref. [3, 4]). Note that we consider here (in contrary to Ref. [4, 5]) a model of neutron Cooper pairing in a thin shell in the vicinity of the Fermi sphere.

This set of nonlinear integral Eqs. (2) and (6) for the EMF and OP give us the possibility to describe thermodynamics of superfluid non-unitary phases of $^3He - A_{1,2}$ type in dense SPNM with spin-triplet p-wave pairing in static uniform high magnetic field at arbitrary temperatures from the interval $0 \le T \le T_c(H)$. In general case these equations can't be solved analytically and it is necessary to use numerical methods for their solving. But we can solve Eqs. (2), (6) using analytical methods in the limiting case, when the temperature ($T \lesssim T_{c0}$) is near the PT temperature $T_{c0}(n)$ of dense NM to superfluid state (it is the theme of the section 3).

3. SOLUTIONS OF EQS. FOR THE OP AND EMF FOR DENSE SPNM NEAR T_C

The set of nonlinear integral Eqs. (2) and (6) [4] for the EMF and components of the OP was solved by analytical methods and as a result the approximate expressions were obtained for "reduced" (to dimensionless form) phase transition temperatures $t_{c1,2} \equiv T_{c1,2}/\varepsilon_F$ ($\varepsilon_F \equiv p_F^2/2m_n^*$ is the Fermi energy of neutrons) of NM to superfluid states of $^3He - A_{1,2}$ type with triplet *p*-wave pairing in high magnetic field (with spin projections of the Cooper pairs along and against the magnetic field direction):

$$t_{c1,2} \approx t_{c0}\left[1 \pm \frac{h}{I_0}(AI_A + BI_B)\right], \tag{7}$$

($t_{c0} \equiv T_{c0}/\varepsilon_F$). Functions $t_{c1,2}(a;h,y)$ depend on the cutoff parameter $a \equiv \varepsilon_{\max}/\varepsilon_F - 1$, which is the upper limit in the integrals I_0, I_A, I_B and in the integrals, which enter the structure of the functions *A* and *B* (their explicit form see below in Appendix A). Parameter a was introduced to avoid divergence of integrals and from the physical point of view it corresponds to the energy restriction of the quasiparticles (neutrons) by the maximal energy, i.e., $\varepsilon(p) = p^2/2m_n^* \le \varepsilon_{\max}$, which is somewhat larger than the Fermi energy ($\varepsilon_{\max} \gtrsim \varepsilon_F$), so that $a << 1$ for the effective Skyrme forces using here as the interaction between neutrons. For the validity of the Fermi-liquid theory the following inequalities should be true:

$$h \equiv \frac{|\mu_n| H}{\varepsilon_F(y)} < a << 1, \quad t_{c0} \equiv \frac{T_{c0}(a;y)}{\varepsilon_F(y)} < a << 1.$$

These inequalities mean small "smoothing" of the Fermi distribution step-function due to the influence of external magnetic field *H* and temperature $T \lesssim T_{c0}(a;y)$ on the neutron matter (where $y \equiv n/n_0$).

It was obtained the following equation for reduced temperature t_{c0} of PT for NM to the superfluid state with triplet p-wave pairing without magnetic field:

$$0 = 1 + c_3 \frac{n m_n^*}{4} I_0(a; y), \tag{8}$$

where the integral $I_0(a; y)$ has the form:

$$I_0(a;y) \equiv \int_{-a}^{a} dx \frac{\sqrt{(1+x)^3}}{x} \tanh\left(\frac{x}{2t_{c0}}\right) = \ell(a) + 2\ln\left(\frac{a}{2t_{c0}}\right). \tag{9}$$

It was obtained the following approximate expression for the function $\ell(a)$ at $2t_{c0} < a << 1$ (neglecting by small terms of the order a^5, a^6,...):

$$\ell(a) \approx b_0 + \frac{3a^2}{8} + \frac{3a^4}{256}, \tag{10}$$

$$b_0 = 2\left(1 - \frac{1}{9} + \frac{2}{75}\right) + 4\sum_{k=1}^{\infty}(-1)^{k+1} Ei(-2k) \approx 1.64932, \tag{11}$$

$$Ei(-x) = \int_{-\infty}^{-x} \frac{e^t}{t} dt.$$

From (8-11) we get the general formula for t_{c0}:

$$t_{c0} = \frac{a}{2}\exp\left(\frac{\ell(a)}{2} + \frac{2}{c_3 n_0}\frac{1}{y m_n^*}\right), \tag{12}$$

which is valid for all Skyrme parameterizations. Here $c_3 m_n^* n_0 / 2 < 0$ is the dimensionless value depending on the Skyrme parameters t_2 and x_2 (see after Eq. (6)); $m_n \approx 939.56563$ MeV/c^2 is the mass of free neutron [18]. Formulas (8), (12) contain the effective neutron mass m_n^*, which depends on the density of NM $n = y n_0$ according to the formula:

$$\frac{m}{m_n^*} = 1 + \frac{m y n_0}{4\hbar^2}\left[t_1(1 - x_1) + 3t_2(1 + x_2)\right]. \tag{13}$$

Here $m \approx (m_p + m_n)/2 \approx 938.91897$ MeV/c^2 is mean free nucleon mass [19]; parameters t_1, t_2, x_1, x_2 have specific values for each Skyrme parameterization.

Note that the Fermi energy of the pure NM with density $n = y n_0$ is defined by the formula:

$$\varepsilon_F(y) = (3\pi^2 y n_0)^{2/3}\frac{\hbar^2}{2m_n^*} \approx 60.8601 y^{2/3}\frac{m_n}{m_n^*} \text{ MeV}. \tag{14}$$

The integrals I_A and I_B in the general formulas (7) for the functions $t_{c1,2}(a; h, y)$ are defined as:

$$I_A(a;t_{c0}) \equiv \int_{-a}^{a} dx \sqrt{(1+x)^3}\frac{d}{dx}\left(\frac{\tanh\left(x/2t_{c0}\right)}{x}\right), \tag{15}$$

$$I_B(a;t_{c0}) \equiv \int_{-a}^{a} dx \sqrt{(1+x)^3}\, x \frac{d}{dx}\left(\frac{\tanh\left(x/2t_{c0}\right)}{x}\right) \tag{16}$$

(functions A and B in (7) are defined in Appendix A).

We have considered the so-called RATP, SkO' and Gs parameterizations of the Skyrme forces (see Ref. [6-8]) with small cutoff parameter $0.02 \le a \le 0.1$. This concretization has given us the possibility to plot the figures (using a mathematical program, e.g., "Maple10") for the functions (7) (accounting also (9)-(16)) which describe the linear in magnetic field splitting of the phase transition temperatures for NM with triplet p-wave pairing of the $^3He - A_{1,2}$ type. Here we represent Figs. 1-6 for the RATP, SkO' and Gs - variants of Skyrme interaction with power indexes $\alpha = 0.20$, $\alpha = 0.25$ and $\alpha = 0.30$, respectively, in their density dependence (see Appendix B).

4. CONCLUSION

Thus, the main new results obtained here (see also brief report [20]) for phase transitions of pure NM to the superfluid states with spin-triplet p-wave pairing of the $^3He - A_{1,2}$ type are the general approximate formulas (7) (with accounting of (9)-(16) and Appendix A for arbitrary parameterization of the Skyrme forces) for reduced PT temperatures $t_{c1,2}(a; h, y)$ which are functions linear of h in strong magnetic fields and nonlinear of the neutron density. In particular, using the RATP, SkO' and Gs parameterizations of the Skyrme interaction for pure NM enables to describe splitting of PT temperatures in strong magnetic field (but, e.g., for RATP–Skyrme forces we have that

$H << \varepsilon_{F,RATP}(y)/|\mu_n| \approx 1.0098 \cdot 10^{19} y^{2/3}(1+0.235y)$ G

see (13), (14)) on sufficiently wide interval of subnuclear and supernuclear densities of neutrons $0.8 \lesssim y \lesssim 3.0$ (see figures in Appendix B). Such ultra-strong magnetic fields (which may approach to $H_{\max} \lesssim 10^{18}$ G) are probably realized in the core region of "magnetars" (strongly magnetized neutron stars).

We represented Figs. 1-6 for the RATP, SkO' and Gs - variants of the Skyrme interaction. It follows from their analysis that with increasing of NM density in the interval $0.8 \lesssim y \lesssim 3.0$ the temperature splitting $\tau_{RATP}(a; y) \equiv [t_{c1}(a; h, y) - t_{c2}(a; h, y)]/h > 0$ (for a<<1) is non-monotone function of $y = n/n_0$ (in contrast to the case of superfluid phases $^3He - A_{1,2}$ where the temperature splitting grows monotonically with the density). These figures have common features and differences both qualitative and quantitative for different Skyrme forces.

The phenomenon of superfluidity in a NM at high densities $n > 3n_0$ (inside the fluid core of a neutron star) should be investigated in the framework of a relativistic

approach and with different interpretation of the hadron matter structure (including mesons, quarks, and other possible constituents). Here we have used the non-relativistic generalized Fermi-liquid approach [2, 4] because the following inequalities are valid for the Fermi energy (14):
$\varepsilon_{F,Skyrme}(y) << m_{Skyrme}c^2 \lesssim m_n c^2 \approx 939.56563$ MeV over the whole interval of NM density variation ($0.8 \lesssim y \lesssim 3.0$) studied here for RATP, SkO' and Gs variants of the Skyrme forces.

APPENDIX A

The functions $A(a;y,t_{c0})$, $B(a;y,t_{c0})$ (see Eq. (7)) have the form ($y = n/n_0$):

$$A(a;y,t_{c0}(a,y)) \equiv \frac{1}{D(a;y,t_{co})}\Big[1 + d_{12}y\frac{m_n^*}{m_n}(y)\big(i_1(a;t_{c0}) - i_3(a;t_{c0})\big)\Big], \quad \text{(A.1)}$$

$$B(a;y,t_{c0}(a,y)) \equiv \frac{i_1(a;t_{c0})}{D(a;y,t_{c0})} d_{12}y\frac{m_n^*}{m_n}(y) \times\left(1 + \frac{d_3 y^{\alpha} + d_0}{d_{12}y^{2/3}}\right), \quad \text{(A.2)}$$

$$D(a;y,t_{c0}(a,y)) \approx 1 - y^{1/3}\left(d_3 y^{\alpha} + d_0\right) \times\frac{m_n^*}{m_n}(y) i_1(a;t_{c0}) - 2d_{12}y\frac{m_n^*}{m_n}(y) i_3(a;t_{c0}) - d_{12}^2 y^2\left(\frac{m_n^*}{m_n}(y)\right)^2\left(i_1(a;t_{c0}) i_5(a;t_{c0}) - i_3^2(a;t_{c0})\right). \quad \text{(A.3)}$$

The coefficients d_{12}, d_3, d_0 take the following general form for all Skyrme parameterizations [3, 18]:

$$d_{12} = \frac{m_n c^2}{(\hbar c)^2}\frac{3n_0}{8}\cdot\left(t_1' - t_2'\right) \approx \left(t_1' - t_2'\right)\cdot 0.0015382753\left(\frac{1}{MeV\cdot fm^5}\right), \quad \text{(A.4)}$$

$$d_3 = \frac{m_n c^2}{(\hbar c)^2}\left(\frac{3n_0}{8\pi^4}\right)^{1/3} n_0^{\alpha}\cdot\frac{t_3'}{6} \approx t_3'\cdot 0.0020949843\cdot(0.17^{\alpha}/6)\left(\frac{1}{MeV\cdot fm^{3+3\alpha}}\right), \quad \text{(A.5)}$$

$$d_0 = \frac{m_n c^2}{(\hbar c)^2}\left(\frac{3n_0}{8\pi^4}\right)^{1/3}\cdot t_0' \approx t_0'\cdot 0.0020949843\left(\frac{1}{MeV\cdot fm^3}\right). \quad \text{(A.6)}$$

Here power index is $1/6 \le \alpha \le 1/3$ and the Skyrme parameters are $t_0' = t_0(1 - x_0)$, $t_1' = t_1(1 - x_1)$, $t_2' = t_2(1 + x_2)$, $t_3' = t_3(1 - x_3)$ (see after Eq. (2)). Integrals $i_j(a;t)$ (j=1,3,5) in (A.1-3) are defined as:

$$i_j(a;t) \equiv \int_{-a}^{a} dx\sqrt{(1+x)^j}\,\frac{d}{dx}\tanh\left(\frac{x}{2t}\right). \quad \text{(A.7)}$$

APPENDIX B

FIGURES FOR SPNM WITH RATP-SKYRME FORCES

$\tau_{RATP}(a;y)$

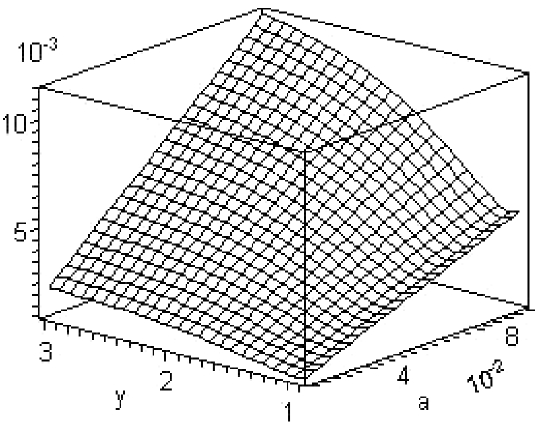

Fig. 1. *Splitting $\tau_{RATP}(a;y) \equiv \left(t_{c1}(a;h,y) - t_{c2}(a;h,y)\right)/h$ (in a magnetic field $h \equiv \frac{|\mu_n| H}{\varepsilon_F(y)} < a << 1$) of reduced phase transition (PT) temperatures of NM (with RATP parameterization of the Skyrme forces) to superfluid states of the ${}^3He - A_{1,2}$ type as a function of reduced density $y = n/n_0$ and small cutoff parameter a*

$\tau_{RATP}(0.1;y)$

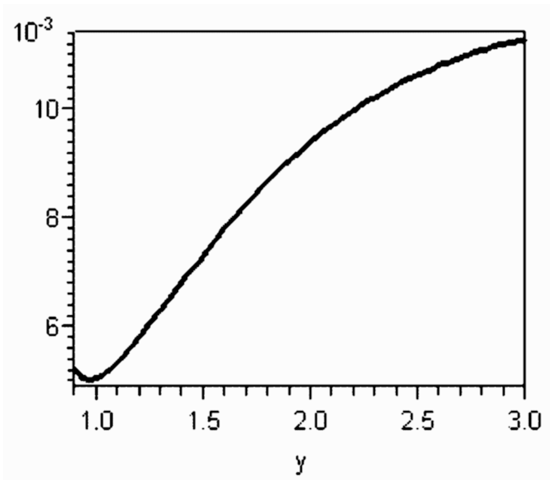

Fig. 2. *PT temperature splitting $\tau_{RATP}(0.1;y)$ for SPNM with RATP-Skyrme parameterization and p-wave pairing of the ${}^3He - A_{1,2}$ type in strong magnetic field as a function of reduced density y (cutoff $a = 0.1$)*

FIGURES FOR SPNM WITH SKO'-SKYRME FORCES

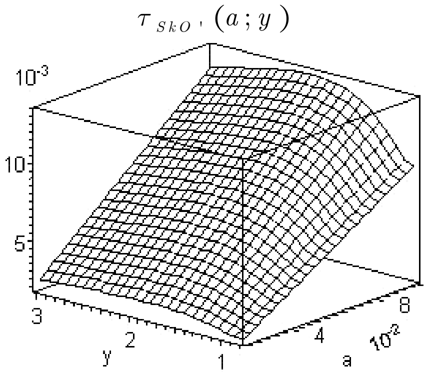

Fig. 3. *Splitting* $\tau_{SkO'}(a;y) \equiv \left(t_{c1}(a;h,y) - t_{c2}(a;h,y)\right)/h$ *(in a magnetic field* $h \equiv \frac{|\mu_n| H}{\varepsilon_F(y)} < a << 1$*) of reduced PT temperatures of NM (with SkO'-Skyrme parameterization) to superfluid states of the* $^3He - A_{1,2}$ *type as a function of reduced density* y *and small cutoff parameter a*

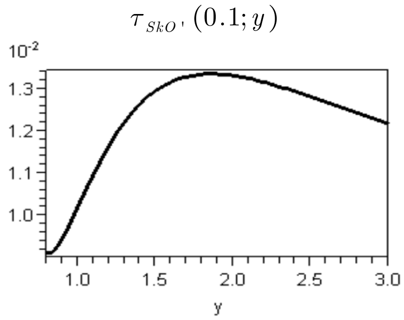

Fig. 4. *PT temperature splitting* $\tau_{SkO'}(0.1;y)$ *for SPNM with SkO'-Skyrme parameterization and p-wave pairing of the* $^3He - A_{1,2}$ *type in strong magnetic field as a function of reduced density* y *(cutoff* $a = 0.1$*)*

FIGURES FOR SPNM WITH GS-SKYRME FORCES

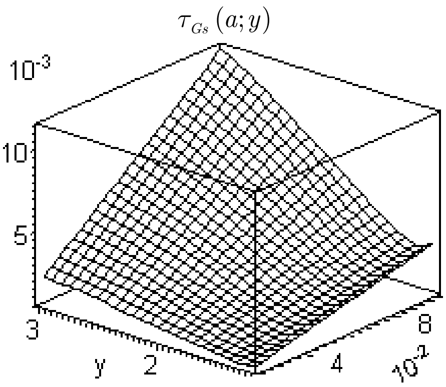

Fig. 5. *Splitting* $\tau_{Gs}(a;y) \equiv \left(t_{c1}(a;h,y) - t_{c2}(a;h,y)\right)/h$ *(in a magnetic field* $h \equiv \frac{|\mu_n| H}{\varepsilon_F(y)} < a << 1$*) of reduced PT temperatures of NM (with Gs-Skyrme parameterization) to superfluid states of the* $^3He - A_{1,2}$ *type as a function of reduced density* y *and small cutoff parameter a*

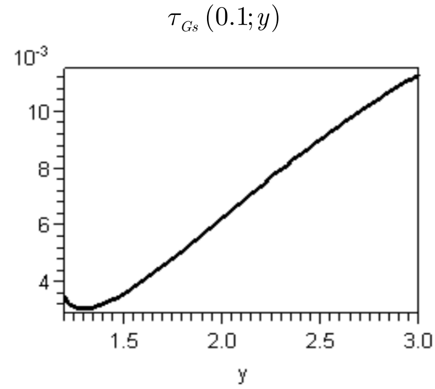

Fig. 6. *PT temperature splitting* $\tau_{Gs}(0.1;y)$ *for SPNM with Gs-Skyrme parameterization and p-wave pairing of the* $^3He - A_{1,2}$ *type in strong magnetic field as a function of reduced density* y *(cutoff* $a = 0.1$*)*

REFERENCES

1. D. Vollhardt and P. Wolfle. *The Superfluid Phases of Helium 3.* London: Taylor & Francis, 1990, 620 p.
2. A.I. Akhiezer, V.V. Krasil'nikov, S.V. Peletminskii, A.A. Yatsenko. Research on superfluidity and superconductivity on the basis of Fermi liquid concept //*Phys. Rep.* 1994, v. 245**,** N 1&2, p. 1-110.
3. M. Brack, C. Guet, H.-B. Hakansson. Selfconsistent semiclassical description of average nuclear properties – a link between microscopic and macroscopic models //*Phys. Rep.* 1985, v. 123, p. 275-364.
4. A.N. Tarasov. Equations for the order parameter and effective magnetic field for nonunitary phases of superfluid Fermi liquids with spin-triplet p-wave pairing //*Physica B***.** 2003, v. 329-333, Part 1, p. 100-101.
5. A.N. Tarasov. Phase transition temperatures of dense neutron matter with Skyrme interaction to superfluid states with spin-triplet pairing in high magnetic field //*Europhys. Lett.* 2004, v. 65 (5), p. 620-626.
6. M. Rayet, M. Arnould, F. Tondeur, G. Paulus. Nuclear forces and the properties of matter at high temperature and density //*Astron. Astrophys.* 1982, v. 116, p. 183-187.
7. P.-G. Reinhard, et al. *Shape coexistence and the effective nucleon-nucleon interaction.* nucl-th/990337, 1999.
8. J. Friedrich, P.-G. Reinhard. Skyrme-force parametrization: Least-squares fit to nuclear ground-state properties //*Phys. Rev. C***.** 1986, v. 33, p. 335-351.
9. D. Pines, M.A. Alpar. Superfluidity in neutron stars //*Nature* (London). 1985, v. 316, p. 27-32.
10. T. Takatsuka, R. Tamagaki. Superfluidity in neutron star matter and symmetric nuclear matter //*Prog. Theor. Phys. Suppl.* 1993, N 112, p. 27-65.
11. M. Hoffberg, A.E. Glassgold, R.W. Richardson, M. Ruderman. Anisotropic superfluidity in neutron star matter //*Phys. Rev. Lett.* 1970, v. 24, p. 775-777.

12. L. Amundsen, E. Østgaard. Superfluidity of neutron matter (II). Triplet pairing //*Nucl Phys. A.* 1985, v. 442, p. 163-188.
13. A.I. Akhiezer, A.A. Isayev, S.V. Peletminskii, A.P. Rekalo, A.A. Yatsenko. Theory of superfluidity of nuclear matter based on the Fermi-liquid approach //*Zh. Eksp. Teor. Fiz*. 1997, v. 112, p. 3-24 [in Russian].
14. D.G. Yakovlev, K.P. Levenfish, Yu.A. Shibanov. Cooling of neutron stars and superfluidity in their cores //*Uspekhi Fiz. Nauk.* 1999, v. 169, p. 825-868 [in Russian].
15. P. Muzikar, J.A. Sauls, J.W. Serene. $^3P_2$ pairing in neutron-star matter: Magnetic field effects and vortices //*Phys. Rev. D***.** 1980, v. 21, p. 1494-1502.
16. A.N. Tarasov. On the theory of superfluid Fermi liquid with spin-triplet pairing in a magnetic field //*Fiz. Nizk. Temp*. 1998, v. 24, p. 429-437 (in Russian). [*Low Temp. Phys*. 1998, v. 24, p. 324-330]; Some questions in the theory of a superfluid Fermi liquid with triplet pairing in a magnetic field //*Fiz. Nizk. Temp*. 2000, v. 26, p. 1059-1066 (in Russian). [*Low Temp. Phys*. 2000, v. 26, p. 785-790].
17. A.N. Tarasov. Self-consistency equations for nonunitary phases of superfluid Fermi liquid with spin-triplet pairing in a magnetic field //*Problems of Atomic Science and Technology.* 2001, № 6 (2), p. 356-359.
18. Review of Particle Properties //*Phys. Rev. D*. 1994, v. 50, Part 1, p. 1233, 1673, 1680.
19. E. Chabanat, P. Bonche, P. Haensel, J. Meyer, R. Schaeffer. A Skyrme parametrization from subnuclear to neutron star densities //*Nucl.Phys. A*. 1997, v. 627, p. 710-746.
20. A.N. Tarasov. Superfluidity of dense neutron matter with spin-triplet *p*-wave pairing in strong magnetic field //*AIP Conf. Proceed*. 2006, v. 850, p. 109-110.

ТРИПЛЕТНАЯ ПО СПИНУ СВЕРХТЕКУЧЕСТЬ НЕЙТРОННОЙ МАТЕРИИ С СИЛАМИ СКИРМА В СИЛЬНОМ МАГНИТНОМ ПОЛЕ ВБЛИЗИ T_C

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В рамках обобщенной нерелятивистской ферми-жидкостной теории изучается плотная однородная сверхтекучая чисто нейтронная материя (СНМ) с эффективными силами Скирма (зависящими от плотности *n* нейтронов) и с триплетным по спину *p*-спариванием (подобным ^{3}He-A$_1$ и ^{3}He-A$_2$) в сильном постоянном однородном магнитном поле *H.* Аналитически выведены общие формулы (справедливые для произвольной параметризации сил Скирма) для температур фазового перехода $T_{c1,2}$ нейтронной материи из нормального в сверхтекучие состояния типа ^{3}He-A$_1$ и ^{3}He-A$_2$, соответственно. Функции $T_{c1,2}(H,n)$ являются линейными по *H* (включая достаточно сильные магнитные поля) и немонотонными функциями плотности. Построены графики функции $(T_{c1}(H,n)-T_{c2}(H,n))/H$ в интервале изменения плотности $0.8n_0 \lesssim n \lesssim 3n_0$ (n_0=0.17 фм$^{-3}$ — плотность насыщения симметричной ядерной материи) для выбранных RATP, SkO' и Gs параметризаций сил Скирма, которые имеют разную степенную зависимость от плотности. Такие фазы плотной СНМ могут существовать в сердцевинах намагниченных нейтронных звезд.

СПІН-ТРИПЛЕТНА НАДПЛИННІСТЬ НЕЙТРОННОЇ МАТЕРІЇ З СИЛАМИ СКІРМА У СИЛЬНОМУ МАГНІТНОМУ ПОЛІ ПОБЛИЗУ T_C

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У рамках узагальненої нерелятивістської фермі-рідинної теорії вивчається густа однорідна надплинна суто нейтронна матерія (ННМ) з ефективними силами Скірма (що залежать від густини *n* нейтронів) та зі спін-триплетним *p*-спарюванням (подібним до ^{3}He-A$_1$ та ^{3}He-A$_2$) у сильному постійному однорідному магнітному полі *H.* Аналітично виведені загальні формули (які справедливі для довільної параметризації сил Скірма) для температур фазового переходу $T_{c1,2}$ нейтронної матерії з нормального в надплинні стани типу ^{3}He-A$_1$ та ^{3}He-A$_2$, відповідно. Функції $T_{c1,2}(H,n)$ є лінійними по *H* (включаючи достатньо сильні магнітні поля) та немонотонними функціями густини. Побудовані графіки функції $(T_{c1}(H,n)-T_{c2}(H,n))/H$ на інтервалі зміни густини $0.8n_0 \lesssim n \lesssim 3n_0$ (n_0=0.17 фм$^{-3}$ — густина насичення симетричної ядерної матерії) для відібраних RATP, SkO' та Gs параметризацій сил Скірма, які мають різний показник степеневої залежності від густини. Можливо, що такі фази густої ННМ існують у серцевинах намагнічених нейтронних зірок.