# SELF-CONSISTENCY EQUATIONS FOR NONUNITARY PHASES OF SUPERFLUID FERMI LIQUID WITH SPIN-TRIPLET PAIRING IN A MAGNETIC FIELD

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The generalized Fermi-liquid approach is used (with taking into account of the spin-exchange Fermi-liquid interaction) for description of different nonunitary phases of neutral paramagnetic superfluid Fermi liquid (SFL) with spin-triplet pairing of the $^3He$ type (and also for the dense superfluid pure neutron matter (SNM) existing inside core of neutron stars) in a strong magnetic field. In particular, the systems of connected nonlinear integral equations for the order parameter and effective magnetic field are obtained on the basis of energy functional (with Landau exchange amplitudes $F_0^a \neq 0$ and $F_2^a \neq 0$) which is quadratic in distribution functions of quasiparticles for nonunitary phases of $^3He - A_2$ type for SFL (or SNM) in a strong static and uniform magnetic field at any temperatures $0 \leq T \leq T_c$ ($T_c$ is the normal - superfluid transition temperature).

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## GENERAL DESCRIPTION OF THE METHOD

This research is devoted to theoretical analysis of superfluid Fermi liquids (SFL) with spin-triplet pairing in a magnetic field. We consider a SFL consisting of electrically neutral fermions possessing a magnetic moment. Such SFL include, for example, the superfluid phases of $^3He$ and the extreme limit of isospin-asymmetric nuclear matter, namely superfluid pure neutron matter (SNM) (existing inside core of neutron stars). These phases were studied by many authors on the basis of different methods (see, for example, the reviews [1,2] and monographs [3-5]).

The Fermi-liquid approach generalized to superfluid systems [6-8] was used in [9,10] to derive a system of coupled equations for the order parameter (OP), effective magnetic field (EMF) and energy of quasiparticles of a superfluid Fermi liquid in the general case of spin-triplet pairing (spin of a pair is $s = 1$, orbital angular momentum $l$ of a pair is an arbitrary odd number) in static uniform magnetic field, taking into account the Landau spin-exchange normal Fermi-liquid (NFL) interaction at temperatures $0 \leq T \leq T_c$.

In this research general equations from [9,10] are used for deriving the equations for the OP and EMF which are valid for nonunitary superfluid phases of $^3He - A_2$ type (and SNM) with taking into account only the p-wave pairing interaction ($s = 1$, $l = 1$) and with $F_0^a \neq 0$, $F_2^a \neq 0$ in the spin-exchange NFL interaction. We restrict ourselves to the case of thermodynamic equilibrium.

To describe the equilibrium states of superfluid phases of $^3He$ type in sufficiently strong static uniform magnetic field $\mathbf{H}$ we introduce the energy functional (EF) $E(f, g, g^+; H)$ for this SFL, which is invariant to phase transformations and rotations both in coordinate and spin spaces separately. The EF can be written in the form (for details see [8,9,10])

$$E(f, g, g^+; H) = E_0(f; H) + E_1(f) + E_2(g, g^+). \quad (1)$$

Here $f_{12} \equiv Sp\rho\, a_2^+ a_1$ and $g_{12} \equiv Sp\rho\, a_2 a_1$, $g_{12}^+ \equiv Sp\rho\, a_2^+ a_1^+$ are the normal and abnormal distribution functions (DF) for quasiparticles ($\rho$ is the statistical operator, $a_1^+$ and $a_1$ are the creation and annihilation operators for Fermi quasiparticles in the state $1 \equiv \mathbf{p}_1, s_1$, where $\mathbf{p}_1$ is the momentum and $s_1$ is the spin component along the quantization axis).

Expression (1) contains the energy of noninteracting fermions ($^3He$ atoms or neutrons in the case of SNM) $E_0(f; H)$ in a magnetic field, the energy functional $E_1(f)$ possessing the above mentioned symmetry properties, which describes NFL interactions:

$$E_1(f) = \frac{1}{2V} \sum_{\mathbf{p}_1 \mathbf{p}_2} [f_0(\mathbf{p}_1) F_1(\mathbf{p}_1, \mathbf{p}_2) f_0(\mathbf{p}_2) +$$

$$+ f_\alpha(\mathbf{p}_1)(\mathbf{p}_1) F_2(\mathbf{p}_1, \mathbf{p}_2) f_\alpha(\mathbf{p}_2)], \quad (2)$$

where we take into account the fact that in spatially homogeneous case under investigation

$$f_{12} = [f_0(\mathbf{p}_1)\delta_{s_1 s_2} + f_\alpha(\mathbf{p}_1)(\sigma_\alpha)_{s_1 s_2}]\delta_{\mathbf{p}_1, \mathbf{p}_2} \quad (3)$$


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($V$ is the volume occupied by the SFL, $\sigma_\alpha$ are the Pauli matrices, $\alpha = 1,2,3$). NFL functions $F_1(\mathbf{p}_1,\mathbf{p}_2)$ and $F_2(\mathbf{p}_1,\mathbf{p}_2)$ of interaction between quasiparticles (introduced by Landau) depend on the angle $\theta$ between $\mathbf{p}_1$ and $\mathbf{p}_2$ lying on the Fermi surface, and hence can be expanded into a series in Legendre polynomials:

$$F_{1,2}(\theta) = \sum_{l=0}^{\infty}(2l+1)F_{1,2}^{(l)}P_l(\cos\theta). \qquad (4)$$

Here, in accordance with [9,10], we have denoted by $F_{1,2}^{(l)}$ the NFL Landau's amplitudes, but in the literature such amplitudes are usually symbolized by $F_l^{s,a}$ (see, e.g., [4,5,11]).

Finally, the last term in (1), which satisfies the properties of invariance listed above, can be chosen, for example, in a form quadratic in $g$, i.e.

$$E_2(g,g^+) = \frac{1}{V}\sum_{\mathbf{p}_1\mathbf{p}_2} g_\alpha^*(\mathbf{p}_1)L_t(\mathbf{p}_1,\mathbf{p}_2)g_\alpha(\mathbf{p}_2), \qquad (5)$$

where

$$g_\alpha(\mathbf{p}) = \frac{1}{2i}Sp_s g(\mathbf{p})\sigma_2\sigma_\alpha = -g_\alpha(-\mathbf{p}).$$

Expression (5) contains abnormal Fermi-liquid function of interaction $L_t(\mathbf{p}_1,\mathbf{p}_2)$ between quasiparticles leading to triplet pairing. In the following we shall take into account only p-wave pairing between $^3He$ atoms (or neutrons), i.e.

$$L_t(\mathbf{p}_1,\mathbf{p}_2) = -3(\hat{\mathbf{p}}_1\cdot\hat{\mathbf{p}}_2)L^{(1)}, \qquad (L^{(1)}>0). \qquad (6)$$

The OP for superfluid phases of $^3He$ type has the form in the spatially homogeneous case (see [9,10])

$$\Delta_{12} = 2\frac{\partial E_2(g,g^+)}{\partial g_{21}^+} = i\Delta_\alpha(\mathbf{p}_1)(\sigma_\alpha\sigma_2)_{s_1s_2}\delta_{\mathbf{p}_1,-\mathbf{p}_2},$$
$$\Delta_\alpha(-\mathbf{p}) = -\Delta_\alpha(\mathbf{p}). \qquad (7)$$

The energy matrix for quasiparticles is defined as

$$\varepsilon_{12}(f;H) = \frac{\partial E(f,g,g^+;H)}{\partial f_{21}} =$$
$$= \left[\varepsilon(\mathbf{p}_1;f)\delta_{s_1s_2} + \xi_\beta(\mathbf{p}_1;f)(\sigma_\beta)_{s_1s_2}\right]\delta_{\mathbf{p}_1,\mathbf{p}_2}, \qquad (8)$$

where the function $\xi(\mathbf{p})$ is associated with the effective magnetic field $\mathbf{H}_{eff}(\mathbf{p})$ inside SFL (or SNM) through formula [9,10]:

$$\xi_\beta(\mathbf{p}) \equiv -\mu_n(H_{eff}(\mathbf{p}))_\beta \qquad (9)$$

($\mu_n$ is the magnetic dipole moment of nuclei of $^3He$ atom (or neutron)).

From (5)-(7) it follows the equation for the OP:

$$\Delta_\alpha(\mathbf{p}) = -\frac{3L^{(1)}}{V}\sum_{\mathbf{p}'}(\mathbf{p}\cdot\mathbf{p}')g_\alpha(\mathbf{p}'), \qquad (10)$$

and from (2),(3) and (8),(9) we find the equation for $\xi_\alpha(\mathbf{p})$:

$$\xi_\alpha(\mathbf{p}) = -\mu_n H_\alpha + \frac{1}{2V}\sum_{\mathbf{p}'}F_2(\mathbf{p},\mathbf{p}')f_\alpha(\mathbf{p}'). \qquad (11)$$

The general explicit expressions for abnormal and normal DF $g_\alpha(\mathbf{p})$ and $f_\alpha(\mathbf{p})$ for quasiparticles of the so-called nonunitary phases of SFL (or SNM) with spin-triplet pairing in a strong magnetic field $\mathbf{H}$ and at $0 \le T \le T_c$ have the following form [10]:

$$g_\alpha(\mathbf{p}) =$$
$$= \left(\frac{i}{2}\left[\vec{\beta},\vec{\Delta}\right]_\alpha + \xi_\alpha\left(\vec{\xi}\cdot\vec{\Delta}\right)\right)\frac{2[\Phi_-(\mathbf{p},\mathbf{v}_n) - \Phi_+(\mathbf{p},\mathbf{v}_n)]}{E_+^2(\mathbf{p}) - E_-^2(\mathbf{p})} -$$
$$-\frac{\Delta_\alpha}{2}[\Phi_+(\mathbf{p},\mathbf{v}_n) + \Phi_-(\mathbf{p},\mathbf{v}_n)], \qquad (12)$$

$$f_\alpha(\mathbf{p}) = \left(z\frac{\beta_\alpha}{2} + \mathrm{Re}\Delta_\alpha\left(\vec{\xi}\cdot\vec{\Delta}^*\right)\right)\frac{2[\Phi_-(\mathbf{p},\mathbf{v}_n) - \Phi_+(\mathbf{p},\mathbf{v}_n)]}{E_+^2(\mathbf{p}) - E_-^2(\mathbf{p})} -$$
$$-\frac{\xi_\alpha}{2}[\Phi_+(\mathrm{p},\mathrm{v}_n) + \Phi_-(\mathrm{p},\mathrm{v}_n)] +$$
$$\beta_\alpha\frac{[\Psi_+(\mathbf{p},\mathbf{v}_n) - \Psi_-(\mathbf{p},\mathbf{v}_n)]}{E_+^2(\mathbf{p}) - E_-^2(\mathbf{p})}. \qquad (13)$$

Here the functions $E_\pm(\mathbf{p})$, which are the energies of the quasiparticles in the SFL (or SNM) (with spin projections parallel and antiparallel to the magnetic field), have the following general form

$$E_\pm^2(\mathbf{p}) \equiv \alpha(\mathbf{p}) \pm \sqrt{\beta^2(\mathbf{p}) + \gamma^2(\mathbf{p})}, \qquad (14)$$

where

$$\alpha(\mathbf{p}) \equiv |\Delta(\mathbf{p})|^2 + z^2(\mathbf{p}) + \xi^2(\mathbf{p}),$$

$$\beta_\alpha(\mathbf{p}) \equiv \eta(\mathbf{p})l_\alpha(\mathbf{p}) + 2z(\mathbf{p})\xi_\alpha(\mathbf{p}), \quad \gamma(\mathbf{p}) \equiv 2\left|\xi(\mathbf{p})\cdot\Delta(\mathbf{p})\right|,$$

$$z(\mathbf{p}) \equiv \varepsilon(p) - \mu, \quad \mathbf{l}(\mathbf{p}) \equiv \frac{i}{\eta(\mathbf{p})}\left[\vec{\Delta}(\mathbf{p})\times\vec{\Delta}^*(\mathbf{p})\right],$$

and $\varepsilon(p)$ is the kinetic energy of a quasiparticle, $\mu$ is the chemical potential. The value $\eta(\mathbf{p}) \equiv |\Delta(\mathbf{p})\times\Delta^*(\mathbf{p})|$ is nonzero for the nonunitary phases of SFL with triplet pairing. The functions $\Phi_\pm$ and $\Psi_\pm$ in (12), (13) are given by the formulas:

$$\Phi_\pm(\mathbf{p},\mathbf{v}_n) \equiv$$
$$\equiv \frac{1}{4E_\pm(\mathbf{p})}\left[th\left(\frac{E_\pm(\mathbf{p}) + \mathbf{p}\cdot\mathbf{v}_n}{2T}\right) + th\left(\frac{E_\pm(\mathbf{p}) - \mathbf{p}\cdot\mathbf{v}_n}{2T}\right)\right],$$

$$\Psi_{\pm}(\mathbf{p},\mathbf{v}_n) \equiv$$
$$\equiv \frac{1}{4}\left[ th\left(\frac{E_{\pm}(\mathbf{p}) + \mathbf{p}\cdot\mathbf{v}_n}{2T}\right) - th\left(\frac{E_{\pm}(\mathbf{p}) - \mathbf{p}\cdot\mathbf{v}_n}{2T}\right)\right]. \quad (15)$$

Here $\mathbf{v}_n$ is the normal component velocity of the SFL (we assume that the superfluid component is at rest, $\mathbf{v}_s = 0$).

We stress that in the derivation of formulas (12) and (13) we have not specified the structure of the energy functional $E(f, g, g^+; H)$ but have only assumed that it has certain invariance properties mentioned above. The universal formulas (12) and (13) for the anomalous $g_\alpha(\mathbf{p})$ and normal $f_\alpha(\mathbf{p})$ distribution functions of the quasiparticles are valid in the general case for arbitrary nonunitary ($\eta \neq 0$) phases of a SFL (or SNM) (with $v_n \neq 0$ but $v_s = 0$) with triplet pairing (with $s = 1$ and $l$ an arbitrary odd integer) in a sufficiently strong static uniform magnetic field with allowance for the Landau Fermi-liquid exchange interaction.

## EQUATIONS FOR THE ORDER PARAMETER AND EFFECTIVE MAGNETIC FIELD

Knowing the explicit form of the quasiparticle DFs for a specific choice of structure of the energy functional (e.g., see (1), (2) and (5)) we can obtain a system of coupled equations (from (10), (11)) for the order parameter $\Delta_\alpha(\mathbf{p})$ (7) and effective magnetic field $\mathbf{H}_{eff}(\mathbf{p})$ (9) for the different phases of the SFL (or SNM).

Let us consider the nonunitary superfluid phase of $^3He-A_2$ type in the case of triplet $p$-wave pairing. The order parameter for such phase has the form:

$$\Delta_\alpha^{(A_2)}(\mathbf{p}) = \left(\Delta_+ \hat{d}_\alpha + i\Delta_- \hat{e}_\alpha\right)\psi(\hat{\mathbf{p}}),$$

$$\psi(\hat{\mathbf{p}}) \equiv (\hat{m}_j + i\hat{n}_j)\hat{p}_j, \qquad \hat{\mathbf{p}} \equiv \mathbf{p}/p. \quad (16)$$

Here $\hat{\mathbf{d}}$ 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 structure of functions $\Delta_\pm(T) \equiv \left(\Delta_{\uparrow\uparrow}(T) \pm \Delta_{\downarrow\downarrow}(T)\right)/2$ corresponds to the case of Cooper pairing in the states with spin projections, which are equal to 1 and –1 on the quantization axis **H**. In the nonunitary phase of the $^3He-A_1$ type $\Delta_{\downarrow\downarrow} = 0$ and in the limit of zero magnetic field the unitary phase $(\eta = 0)$ of the $^3He-A$ type with $\Delta_{\uparrow\uparrow} = \Delta_{\downarrow\downarrow} \equiv \Delta_0$ is realized.

Thus, in the case of the energy functional of SFL (or SNM) quadratic in the DFs of quasiparticles we have obtained the following system of equations for the functions $\Delta_+(T,\xi)$ and $\Delta_-(T,\xi)$ (from Eqs. (10), (12) and (16)):

$$\Delta_+\psi(\hat{\mathbf{p}}) = \frac{3L^{(1)}}{(2\pi)^3}\int d^3p_1(\hat{\mathbf{p}}\cdot\hat{\mathbf{p}}_1)\psi(\hat{\mathbf{p}}_1)\left\{\Delta_+ \frac{1}{2}(\Phi_+ + \Phi_-) + \right.$$
$$\left. + \left[\Delta_-\left(\frac{1}{2}(\eta + 2z\xi_l) + i\xi_d\xi_e\right) + \Delta_+\xi_d^2\right]\frac{2(\Phi_+ - \Phi_-)}{E_+^2 - E_-^2}\right\},$$
(17.a)

$$\Delta_-\psi(\hat{\mathbf{p}}) = \frac{3L^{(1)}}{(2\pi)^3}\int d^3p_1(\hat{\mathbf{p}}\cdot\hat{\mathbf{p}}_1)\psi(\hat{\mathbf{p}}_1)\left\{\Delta_- \frac{1}{2}(\Phi_+ + \Phi_-) + \right.$$
$$\left. + \left[\Delta_+\left(\frac{1}{2}(\eta + 2z\xi_l) - i\xi_d\xi_e\right) + \Delta_-\xi_e^2\right]\frac{2(\Phi_+ - \Phi_-)}{E_+^2 - E_-^2}\right\}.$$
(17.b)

Here all functions, which are inside the braces $\{\ldots\}$, depend on the vector $\mathbf{p}_1$ and we have introduced by definition the functions $\xi_d(\mathbf{p}) \equiv (\xi(\mathbf{p})\cdot\hat{\mathbf{d}})$, $\xi_e(\mathbf{p}) \equiv (\xi(\mathbf{p})\cdot\hat{\mathbf{e}})$ and $\xi_l(\mathbf{p}) \equiv (\xi(\mathbf{p})\cdot\mathbf{l})$.

In deriving the equations for the effective magnetic field $\mathbf{H}_{eff}(\mathbf{p})$ inside the SFL (or SNM) it has been taken into account the expansion (4) of the normal function of Fermi-liquid exchange interaction $F_2(\mathbf{p},\mathbf{p}_1)$ into a series in Legendre polinomials, in which we kept only the $F_2^{(0)}$ and $F_2^{(2)}$ Landau exchange amplitudes, i.e.

$$F_2(\mathbf{p},\mathbf{p}_1) \approx F_2^{(0)} + 5P_2(\hat{\mathbf{p}},\hat{\mathbf{p}}_1)F_2^{(2)},$$

(we have set $F_2^{(l)} = 0$ for $l = 4,6,\ldots$). In the case when $F_2^{(2)} \neq 0$ the function $\xi(\mathbf{p})$ depends on the $\mathbf{p}$ and, generally speaking, is not collinear to external magnetic field $\mathbf{H}$.

Utilizing the explicit expressions (13) for $f_\alpha(\mathbf{p})$ [10] we have obtained the following system of nonlinear integral equations for the scalar functions $\xi_d(\mathbf{p})$, $\xi_e(\mathbf{p})$ and $\xi_l(\mathbf{p})$ (in the case when both the normal and superfluid components of the SFL (or SNM) are at rest, i.e. with velocities $\mathbf{v}_n = 0$, $\mathbf{v}_s = 0$):

$$\xi_d(\mathbf{p}) = -F_2^{(0)}\Omega_d^{(0)} - F_2^{(2)}\Omega_d^{(2)}P_2(\hat{\mathbf{p}}\cdot\hat{\mathbf{H}}),$$
$$\xi_e(\mathbf{p}) = -F_2^{(0)}\Omega_e^{(0)} - F_2^{(2)}\Omega_e^{(2)}P_2(\hat{\mathbf{p}}\cdot\hat{\mathbf{H}}), \quad (18)$$
$$\xi_l(\mathbf{p}) = -\mu_n H - F_2^{(0)}\Omega_l^{(0)} - F_2^{(2)}\Omega_l^{(2)}P_2(\hat{\mathbf{p}}\cdot\hat{\mathbf{H}}).$$

Here $\mathbf{H} \parallel \mathbf{l}$ and unknown functions $\Omega_a^{(0)}$ and $\Omega_a^{(2)}$ ($a \equiv \{d,e,l\}$) are defined by the formulas:

$$\Omega_a^{(0)} \equiv \frac{1}{2(2\pi)^2}\int_{-1}^{1} d(\cos\theta_1)\kappa_a(\cos\theta_1),$$
$$\Omega_a^{(2)} \equiv \frac{5}{4(2\pi)^2}\int_{-1}^{1} d(\cos\theta_1)(3\cos^2\theta_1 - 1)\kappa_a(\cos\theta_1). \quad (19)$$

We have introduced in the formulas (19) the following functions $\kappa_a(\hat{\mathbf{p}}_1)$:

$$\kappa_d \equiv \int_0^{p_{\max}} dp_1 p_1^2 \xi_d(\mathbf{p}_1)\left[\left(z^2(p_1) + \right.\right.$$
$$\left. + \Delta_+^2 \sin^2\theta_1\right)\frac{\Phi_+(\mathbf{p}_1) - \Phi_-(\mathbf{p}_1)}{\frac{1}{2}\left(E_+^2(\mathbf{p}_1) - E_-^2(\mathbf{p}_1)\right)} +$$

$$+\frac{1}{2}\left(\Phi_+(\mathbf{p}_1)+\Phi_-(\mathbf{p}_1)\right)\Bigg], \quad (20.a)$$

$$\kappa_e \equiv \int_0^{p_{max}} dp_1 p_1^2 \xi_e(\mathbf{p}_1)\Big[\Big(z^2(p_1)+$$

$$+\Delta_-^2 \sin^2\theta_1\Big)\frac{\Phi_+(\mathbf{p}_1)-\Phi_-(\mathbf{p}_1)}{\frac{1}{2}\left(E_+^2(\mathbf{p}_1)-E_-^2(\mathbf{p}_1)\right)}+$$

$$+\frac{1}{2}\left(\Phi_+(\mathbf{p}_1)+\Phi_-(\mathbf{p}_1)\right)\Bigg], \quad (20.b)$$

$$\kappa_I \equiv \int_0^{p_{max}} dp_1 p_1^2 \left[\xi_I(\mathbf{p}_1)\left(z^2(p_1)\frac{\Phi_+(\mathbf{p}_1)-\Phi_-(\mathbf{p}_1)}{\frac{1}{2}\left(E_+^2(\mathbf{p}_1)-E_-^2(\mathbf{p}_1)\right)}+\right.\right.$$

$$\left.+\frac{1}{2}\left(\Phi_+(\mathbf{p}_1)+\Phi_-(\mathbf{p}_1)\right)\right)+$$

$$\left.+z(p_1)\Delta_+\Delta_-\sin^2\theta_1\frac{\Phi_+(\mathbf{p}_1)-\Phi_-(\mathbf{p}_1)}{\frac{1}{2}\left(E_+^2(\mathbf{p}_1)-E_-^2(\mathbf{p}_1)\right)}\right]. \quad (20.c)$$

## CONCLUSION

Thus, for the description of the equilibrium properties of the SFL (or SNM) in the case of spin-triplet pairing in the state with $\Delta_\alpha(\mathbf{p})$ of the form (16) in a high static and uniform magnetic field it is necessary to solve the systems of connected nonlinear integral equations (17.a), (17.b) and (18) (with taking into account definitions (19) and (20.a-c)). In the general case at arbitrary temperatures from the interval $0 \le T \le T_c$ these equations cannot be solved analytically (but they can be solved, for example, by the using of the numerical methods). These results generalize the work [12] (where Fermi-liquid corrections were neglected) and our previous work [13] (where only $F_2^{(0)}$ NFL exchange Landau amplitude was taken into account).

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