Influence of Exchange Scattering on Superfluid $^3\text{He}$ states in Nematic Aerogel

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Superfluid state in bulk liquid $^3\text{He}$ is realized in form of A or B phases. Uniaxially anisotropic aerogel (nafen) stabilizes transition from the normal to the polar superfluid state that on further cooling transfers by the second order phase transition to the axipolar orbital glass state (Phys. Rev. Lett. 115, 165304 (2015)). This is the case in nafen aerogel preplated by several atomic layers of $^3\text{He}$. When the pure liquid $^3\text{He}$ fills the same nafen aerogel a solid-like layer of $^3\text{He}$ atoms coats the aerogel structure. The polar state is not formed anymore and phase transition occurs directly to the axipolar phase (Phys. Rev. Lett. 120, 075301 (2018)). The calculation taking into account the exchange scattering shows that it can decrease the degree of anisotropy that was in its absence. The derived anisotropy of spin diffusion coefficient in globally anisotropic aerogel is determined by the same parameter which controls the polar state emergence that allows to check the effect of anisotropy suppression by the exchange scattering.

I. INTRODUCTION.

The superfluid state of liquid $^3\text{He}$ is formed by means the Cooper pairing with spin and orbital angular momentum equal to 1. In isotropic space the phase transition in superfluid state depending on pressure occurs either in A or in B superfluid phase [1]. Investigation of superfluid phases in high porosity aerogel allows to study an influence of impurities on superfluidity with nontrivial pairing [2, 3]. It has been found that similar to bulk $^3\text{He}$ two superfluid A-like and B-like phases exist in $^3\text{He}$ in aerogel [4] but both the superfluid fraction and the temperature at which the superfluid is manifested are suppressed from their bulk values [2]. The interesting possibility is opened in globally anisotropic aerogel lifting the degeneracy between the different superfluid phases with p-pairing. There was shown [6] that in case of uniaxial easy-axis anisotropy a new superfluid phase of $^3\text{He}$, the polar phase, may be stabilized below the transition temperature. It was also predicted [2, 6] that on further cooling a second order transition into a polar-distorted A phase should occur. Indeed, quite recently, the first observation of the polar phase has been reported [7]. This phase appears in $^3\text{He}$ confined in new type of "nematically ordered" aerogel called "nafen" with a nearly parallel arrangement of strands which play the role of ordered impurities. There was shown that in nafen the transition to the superfluid state always occurs to the polar phase and the region of its existence increases with density of strands.

To avoid a paramagnetic signal from surface solid $^3\text{He}$, the nafen samples in the measurements [7] were preplated by $\sim 2.5 \ \ ^4\text{He}$ monolayers. Then the new experiment series has been performed in the same samples filled by pure $^3\text{He}$ [8]. This case the temperature of superfluid transition is suppressed more strongly and this effect increases with strands density such that in the most dense nafen the superfluid state does not emerge at all. The superfluid transition occurs directly to the polar-distorted A-phase without formation of intermediate region of polar-state. The small addition of $^4\text{He}$ in the surface $^4\text{He}$ layer, corresponding to 0.1 monolayer, also completely kills superfluidity at 29.3 Bar in the most dense nafen, and in the less dense aerogel noticeably suppresses the critical temperature. This case also, the transition occurs directly to the distorted A-state. Similar situation has been registered also even in preplated by $^4\text{He}$ other type of nematically ordered aerogel called "Obninsk aerogel" [7] where the superfluid transition occurs directly to the distorted A-phase.

The different pairing states of superfluid $^3\text{He}$ in a random medium with global uniaxial anisotropy can be compared making use the second order in the order parameter GL free energy density. It consists of isotropic part common for all the superfluid phases with p-pairing and the anisotropic part

$$F^{(2)} = F_i^{(2)} + F_a^{(2)} = \alpha_0 \left( \frac{T}{T_c} - 1 \right) A_{\alpha i} A_{\alpha i}^* + \eta_{ij} A_{\alpha i} A_{\alpha j}^*, \tag{1}$$

where $T_c = T_c(P)$ is the the transition temperature in superfluid state suppressed in respect of transition temperature in the bulk liquid $T_{c0}(P)$. The medium uniaxial anisotropy with anisotropy axis parallel to $\hat{z}$ direction coincident in our case with the average direction of aerogel strands is given by the traceless tensor

$$\eta_{ij} = \eta \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}. \tag{2}$$
In absence of global anisotropy \((\eta = 0)\) all p-wave phases have the same critical temperature. The degeneracy between them is lifted only due to the forth order terms in the order parameter GL free energy density. At positive \(\eta > 0\) the polar state with the order parameter of the form

\[
A_{\alpha i} = aV_{\alpha}z_i,
\]

(3)

where \(V_\alpha\) is the real unit vector, has the lowest energy of anisotropy

\[
F_\alpha = -2\eta|a|^2.
\]

(4)

Hence, it has the highest critical temperature \(T_{c1}\) of transition from the normal state. At some lower temperature \(T_{c2}\) it passes to the more energetically profitable distorted A-state with the order parameter

\[
A_{\alpha i} = V_\alpha (a\hat{z}_i + ib(\hat{x}_i \cos \alpha + \hat{y}_i \sin \alpha))
\]

with the Cooper pair angular momentum \(\hat{l} = \hat{x} \sin \alpha + \hat{y} \cos \alpha\), locally ordered in the basal plane on the scale \(L\) which exceeds the coherence length \(\xi_0\) but is smaller than the dipole length \(\xi_d\) such that the space average \(\langle \sin^2 \alpha \rangle = \langle \cos^2 \alpha \rangle = 1/2\). The pure polar state exists in the temperature interval roughly determined by the energy of anisotropy difference between of the polar and the distorted A-states \[6\]

\[
T_{c1} - T_{c2} \approx \frac{\eta}{\alpha_0} T_c
\]

(5)

Hence, at small \(\eta\) parameter the temperature interval of the polar state existence is small and hardly observable.

In the paper, I derive the anisotropy tensor Eq.(2) in globally anisotropic aerogel taking into account both the potential and the exchange scattering of quasiparticles of liquid \(^3\)He on \(^3\)He atoms localized at the strands surface. It is shown that the exchange scattering can decrease the degree of anisotropy that was in its absence. The following derivation of spin diffusion current shows that anisotropy of spin diffusion coefficient in globally anisotropic aerogel is expressed through the same parameter which determined the polar state emergence. So, the anisotropy decrease of spin diffusion in nafen filled by pure \(^3\)He can serve as the direct indication of suppression of anisotropy by the exchange scattering. Being mainly interested in the role of anisotropy of exchange scattering I neglect throughout this paper by the possible temperature dependence of the amplitude of exchange scattering due to the Kondo effect. The latter can increase the magnitude of the pair breaking by the magnetic scattering and also give rise to the temperature dependence of the spin diffusion coefficient.

**II. SUPERFLUID \(^3\)HE IN UNIAXIALLY ANISOTROPIC AEROGEL WITH MAGNETIC SCATTERING.**

The quasiparticle interaction with the nafen strands is modelled by the interaction with the randomly distributed impurities including the anisotropic potential and the anisotropic exchange part

\[
H_{int} = \sum_i \int d^3r \psi_\alpha^\dagger (r) [u(r - r_i)\delta_{\alpha\beta} + J(r - r_i)\sigma_{\alpha\beta}S] \psi_\beta(r),
\]

(6)

where \(S\) is the spin of the impurity and \(\sigma\) is the \(^3\)He quasiparticles spin matrices.

The exchange scattering in an isotropic aerogel has been considered by Sauls and Sharma \[8\] and by Baranidze and Kharadze \[10\]. They have shown that if the scattering amplitude on impurities includes an exchange part then the critical temperatures splitting of transitions \(A_1\) and \(A_2\) under an external field \(H\) decreases in comparison with the impurity free case

\[
T_{A1} - T_{A2} = (\gamma_0 - \gamma_{imp})H.
\]

The effect arises due to an interference of scalar and exchange scattering such that

\[
\gamma_{imp} \propto uJ
\]

is proportional to the product of the corresponding amplitudes. In our case the field is small and this effect is negligible but one needs to consider a suppression of \(T_c\) by the anisotropic scattering.
To find critical temperature of superfluid transition in globally anisotropic aerogel one must calculate the second order terms in the Landau free energy functional

$$F^{(2)} = \frac{1}{3} \left\{ \frac{1}{V} \delta_{ij} \delta_{\mu \nu} - T \sum_{\omega} \int \frac{d^3 p}{(2\pi)^3} \hat{p}_i \Gamma^{\mu \nu}_{ij}(\mathbf{p}, \omega) G(\mathbf{p}, \omega) G(-\mathbf{p}, -\omega) \right\} A^*_{\mu i} A_{\nu j},$$  

(7)

where $V$ is constant of $p$-wave triplet pairing, $A_{\mu i}$ is the superfluid state order parameter, $\mu = (x, y, z)$ and $i = (x, y, z)$ are the spin and orbital indices. Here, $\hat{p}_i$ are projections of momentum unit vector $\frac{\mathbf{p}}{|\mathbf{p}|}$ on $i = (x, y, z)$ coordinate axis, $\omega = \pi T (2n + 1)$ is the fermion Matsubara frequency, everywhere I put $\hbar = 1$.

$$G(\mathbf{p}, \omega) = \frac{1}{i \omega - \xi_{\mathbf{p}} - \Sigma_{\mathbf{p}}(\omega)}$$  

(8)

is the normal state quasiparticle Green function and $\Gamma^{\mu \nu}_{ij}(\mathbf{p}, \omega)$ is the vertex part. The self-energy part is given by equation

$$\Sigma_{\mathbf{p}}(\omega) = \int \frac{d^3 p'}{(2\pi)^3} \frac{U^2_{\mathbf{p} - \mathbf{p}'}(\omega)}{i \omega - \xi_{\mathbf{p}'}}.$$  

(9)

Here, according to Abrikosov and Gor’kov [11] the ”impurity line” $U^2_{\mathbf{p} - \mathbf{p}'}$ arises after averaging over impurity positions and also over the orientation of the spins of all impurity atoms $\langle S_i S_k \rangle = \frac{1}{3} S(S + 1) \delta_{ik}$, where in our particular case $S = 1/2$. Then taking into account $\sigma^i_{\alpha \gamma} \sigma^i_{\gamma \alpha} = \frac{3}{4}$ we obtain

$$U^2_{\mathbf{p}} = n_i (u^2_{\mathbf{p}} + \langle S_i \sigma^i_{\alpha \gamma} S_k \sigma^k_{\gamma \alpha} \rangle)^2_{\mathbf{p}} = n_i (u^2_{\mathbf{p}} + \frac{1}{4} S(S + 1) J^2_{\mathbf{p}}) = \frac{1}{2\pi N_0 \tau} \left( 1 - \delta \left[ \frac{p_z^2}{2} - \frac{1}{2} (p_x^2 + p_y^2) \right] \right),$$  

(10)

where $n_i$ is impurity concentration, $N_0$ is the density of states per one spin projection, $\tau$ is the isotropic part of mean free time and $\delta$ is the degree of anisotropy. Thus, self energy is

$$\Sigma_{\mathbf{p}}(\omega) = -\frac{i}{2\tau} \left( 1 - \delta \left[ \frac{p_z^2}{2} - \frac{1}{2} (p_x^2 + p_y^2) \right] \right) \text{sign} \omega.$$  

(11)

Unlike Ref.5 the anisotropic part of $U^2_{\mathbf{p}}$ is chosen such that $\int \frac{d^3 p}{(2\pi)^3} U^2_{\mathbf{p}} = \frac{1}{2\pi N_0 \tau}$ and taken with the opposite to Ref.5 sign. Along with the isotropic part the ”impurity line” includes global aerogel uniaxial anisotropy consisting from two independent parts: the potential part and the exchange one

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \frac{1}{\tau_{ex}}, \quad \frac{\delta}{\tau} = \frac{\delta_0}{\tau_0} + \frac{\delta_{ex}}{\tau_{ex}}.$$  

(12)

Each of them is characterized by its own degree of anisotropy: $\delta_0$ and $\delta_{ex}$.

The vertex part must be determined from the integral equation

$$\Gamma^{\mu \nu}_{ij}(\mathbf{p}, \omega) = \hat{p}_j \delta_{\mu \nu} + n \int \frac{d^3 p'}{(2\pi)^3} \left[ u^2_{\mathbf{p} - \mathbf{p}'} + \frac{1}{3} S(S + 1)(g^i)^{\mu}_{\alpha \beta} \sigma^i_{\alpha \gamma} \sigma^i_{\beta \gamma} g^{\nu}_{\lambda \rho} J^2_{\mathbf{p} - \mathbf{p}'} \right] \Gamma^{\mu \nu}_{ij}(\mathbf{p}', \omega) G(\mathbf{p}', \omega) G(-\mathbf{p}', -\omega).$$  

(13)

This is known [11] that for the case of singlet superconductivity the exchange part of scattering in this equation is given by

$$\frac{1}{3} S(S + 1) g^{\alpha \beta}_{\alpha \beta} \sigma^i_{\alpha \gamma} \sigma^i_{\beta \gamma} g^{\nu}_{\lambda \rho} J^2_{\mathbf{q}} = -\frac{1}{4} S(S + 1) J^2_{\mathbf{q}},$$  

(14)

where the matrix $\hat{g} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$, and the superscript ”t” implies transposition. As result, there are two different ”scattering time” originating from the self-energy and the vertex [11]. The corresponding combination for the triplet pairing is

$$\frac{1}{3} S(S + 1)(g^i)^{\mu}_{\alpha \beta} \sigma^i_{\alpha \gamma} \sigma^i_{\beta \gamma} g^{\nu}_{\lambda \rho} J^2_{\mathbf{q}} = \frac{1}{4} S(S + 1) J^2_{\mathbf{q}} \delta_{\mu \nu}.$$  

(15)
where \( g_{\lambda \rho} = (-\sigma_\lambda \rho, i \delta_{\lambda \rho}, \sigma_\lambda \rho) \), such that the "scattering time" originating from the self-energy and the vertex are equal to each other. Thus, the Eq. 13 is

\[
\Gamma_j^{\nu \rho}(p, \omega) = \hat{p}_j \delta_{\mu \nu} + \int \frac{d^3p'}{(2\pi)^3} \overleftrightarrow{\partial_p^2} \Gamma_j^{\nu \rho}(p', \omega) G(p', \omega) G(-p', -\omega)
\]

and its solution has the form

\[
\Gamma_j^{\nu \rho}(\omega, p) = \left\{ \hat{p}_j + \Gamma_{\nu} \left[ \hat{p}_z \hat{x}_j - \frac{1}{2} (\hat{p}_x \hat{x}_j + \hat{p}_y \hat{y}_j) \right] \right\} \delta_{\mu \nu},
\]

where for the \( \delta \ll 1 \)

\[
\Gamma_{\nu} = \frac{\delta}{3\tau} \left[ \omega + \frac{1}{2\tau} \text{sign} \omega \right] + \mathcal{O}(\delta^2).
\]

Substitution of these expressions to eq. 16 yields

\[
F_2 = \alpha A_{\mu i}^* A_{\mu i} - 2\eta \left[ A_{\mu z}^* A_{\mu z} - \frac{1}{2} (A_{\mu x}^* A_{\mu x} + A_{\mu y}^* A_{\mu y}) \right],
\]

where

\[
\alpha = \frac{N_0}{3} \left[ \ln \frac{T}{T_c 0} + \psi \left( \frac{1}{2} + \frac{1}{4\pi T \tau} \right) - \psi \left( \frac{1}{2} \right) - \frac{1}{3 \cdot 4\pi T \tau} \psi^{(1)} \left( \frac{1}{2} + \frac{1}{4\pi T \tau} \right) \right],
\]

\[
\eta = \frac{8N_0}{45} \frac{\delta}{4\pi T \tau} \psi^{(1)} \left( \frac{1}{2} + \frac{1}{4\pi T \tau} \right),
\]

Here, \( \psi(z) \), \( \psi^{(1)}(z) \) are the digamma function and its first derivative.

At \( \delta > 0 \) critical temperature of phase transition to the superfluid state is maximal for polar phase Eq. 18 and determined by the equation

\[
\alpha - 2\eta = 0.
\]

In the limit of weak scattering \( 4\pi T \tau_c >> 1 \) the transition to the polar state occurs at

\[
T_{c1} = T_{c0} - \frac{\pi}{8\tau} + \frac{11\pi}{60\tau} \delta.
\]

According to Eq. 12 the degree of global anisotropy \( \delta \) is determined by two independent terms originating from the potential and exchange scattering. The latter can in principle suppress the anisotropy. This also must reveal itself in the decrease of the spin diffusion anisotropy. In the next section I derive the spin diffusion current in normal liquid \(^3\)He flowing through the media filled by the randomly distributed impurities with globally anisotropic potential and exchange potential of scattering. The anisotropy of spin diffusion coefficient is expressed through the same parameter of anisotropy \( \delta \).

### III. SPIN CURRENT

The spin current in neutral Fermi liquid is calculated \[12, 13\] as response to the gradient of angle of rotation of the spin space \( \omega_i = \nabla_i \theta \),

\[
\hat{j}_i = -\frac{\delta H}{\delta \omega_i},
\]

where

\[
H = \frac{1}{2m} \int d^3r (\overleftrightarrow{D_i^\alpha \psi}) ^\dagger \overleftrightarrow{D_i^\alpha} \psi + H_{\text{int}},
\]
\[ D_i^{\alpha\beta} = -i\delta_{\alpha\beta} \nabla_i + \frac{1}{2} \sigma_{\alpha\beta} \omega_i, \]  
(26)

and \( H_{\text{int}} \) includes the Fermi liquid interaction and the interaction with impurities Eq. (3).

At low temperatures the collisions between the Fermi liquid quasiparticles induce negligibly small correction to the spin diffusion due to the scattering on aerogel strands. On the other hand, as it was already mentioned, we are mainly interested in the spin current anisotropy in the anisotropic media and will ignore the temperature dependence of exchange amplitude of scattering due to the Kondo effect. This case is one can work with field theory technique for \( T=0 \). The response on the gauge field \( \omega_i \) is calculated in complete analogy with response to the usual vector potential \( A_j \) in calculation of electric current in an isotropic metal with randomly distributed impurities performed in [14]. The spin current at finite wave vector \( k \) and external frequency \( \omega \) is

\[
\mathbf{j}_i(k, \omega) = \frac{i}{4m} Tr \int_{-\infty}^{+\infty} \frac{dz}{2\pi} \int \frac{d^3p}{(2\pi)^3} p_i \sigma_{\alpha\beta}(\sigma_{\beta\alpha} \omega_j) \Pi_j - \frac{1}{4} \delta \omega_i, 
\]  
(27)

where \( n \) is the number of atoms in the unit volume, function \( \Pi_j \) is determined by equation

\[
\Pi_j(p, p - k) = G(p, \varepsilon)G(p - k, \varepsilon - \omega) \left[ p_j + \int \frac{d^3p'}{(2\pi)^3} U^2(p - p') \Pi_j(p', p' - k) \right], 
\]  
(28)

\[ p = (p, \varepsilon), \quad k = (k, \omega), \]

\[
G(p, \varepsilon) = \frac{1}{\varepsilon - \xi_p - \Sigma_p(\varepsilon)}, 
\]  
(29)

\( U^2(p) \) is determined by Eq. (14), \( \Sigma_p(\varepsilon) \) is given by Eq. (11). The vertex correction does not introduce changes in the spin structure of Eq. (27) due to the identity \( \sigma_{\alpha\lambda}^{\dagger} \sigma_{\mu\alpha}^{\dagger} \sigma_{\mu\beta} \sigma_{\beta\lambda} = \sigma_{\alpha\beta} \sigma_{\beta\alpha}^{\dagger} \).

At \( k = 0, \omega = 0 \) the first term in current expression (27) cancels out the second "diamagnetic" term. We are interested to calculate the current at \( k = 0, \omega \neq 0 \). This case,

\[
\mathbf{j}_i = \frac{i}{4m} Tr \int_0^{\omega} d\varepsilon \int \frac{d^3p}{(2\pi)^3} p_i \sigma_{\alpha\beta}(\sigma_{\beta\alpha} \omega_j) \Pi_j(k = 0) 
\]  
(30)

and the solution of Eq. (28) in the linear approximation in respect to \( \delta \) and at \( \omega \tau \ll 1 \) is

\[
\Pi_j(k = 0) = G(p, \varepsilon)G(p, \varepsilon - \omega) \left\{ p_j + \frac{2}{3} \delta \left( \hat{p}_z \hat{z}_j - \frac{1}{2} (\hat{p}_x \hat{x}_j + \hat{p}_y \hat{y}_j) \right) \right\}. 
\]  
(31)

Substituting it in Eq. (30) we obtain

\[
\mathbf{j}_i = \frac{1}{6} \left\{ \delta_{ij} + \frac{16}{15} \delta \left[ \hat{z}_i \hat{z}_j - \frac{1}{2} (\hat{x}_i \hat{x}_j + \hat{y}_i \hat{y}_j) \right] \right\} i \omega \tau N_0 v_F^2 \mathbf{\omega}. 
\]  
(32)

Here \( v_F \) is the Fermi velocity. Making use the Larmor theorem

\[
\gamma \mathbf{H} = \frac{\partial \mathbf{\theta}}{\partial t} = -i \omega \mathbf{\theta} \]  
(33)

where \( \gamma = 2\mu \) is the gyromagnetic ratio, \( \mu \) is the magnetic moment of \(^3\)He atoms, one can rewrite the expression for current as

\[
\mathbf{j}_i = -\frac{1}{3} \left\{ \delta_{ij} + \frac{16}{15} \delta \left[ \hat{z}_i \hat{z}_j - \frac{1}{2} (\hat{x}_i \hat{x}_j + \hat{y}_i \hat{y}_j) \right] \right\} \tau N_0 v_F^2 \mathbf{\mu} \nabla_j \mathbf{H}. 
\]  
(34)

To rewrite the spin current as the magnetic diffusion current one should multiply both sides of this equation by \( 2\mu \) to obtain

\[
\mathbf{j}_i^M = -\frac{1}{3} \left\{ \delta_{ij} + \frac{16}{15} \delta \left[ \hat{z}_i \hat{z}_j - \frac{1}{2} (\hat{x}_i \hat{x}_j + \hat{y}_i \hat{y}_j) \right] \right\} \tau v_F^2 \mathbf{\omega} \nabla_j \mathbf{M}, 
\]  
(35)

where the Fermi-liquid magnetization is \( \mathbf{M} = 2\mu^2 N_0 \mathbf{H} \). Thus, the spin diffusion currents along with and perpendicular to the direction of nafen strands are

\[
j_x^M = -\frac{1}{3} \left( 1 + \frac{16}{15} \delta \right) \tau v_F^2 \nabla_x \mathbf{M}, \quad j_y^M = -\frac{1}{3} \left( 1 - \frac{8}{15} \delta \right) \tau v_F^2 \nabla_y \mathbf{M} 
\]  
(36)

correspondingly. One can demonstrate that the similar calculation taking into account the Fermi liquid renormalization adds in this formulas the pre-factor \( (1 + F_\delta^2)(1 + F_\delta^3/3) \).
IV. CONCLUSION

The degree of global anisotropy is determined by two independent terms Eq. (12) originating from the potential and exchange scattering. Thus, the exchange scattering changes the width of temperature interval of polar state existence in the globally anisotropic aerogel. The alteration of the spin diffusion coefficient due to the exchange scattering is proportional to the same parameter $\delta$. This allows to check experimentally the effectiveness of suppression of anisotropy by the exchange scattering.

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