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Some comments on superfluid ^{3}He placed in globally deformed aerogel

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New experimental results focused on the behavior of the superfluid A-like phase placed in globally deformed aerogel environment are considered. We compare experimental data collected by using optically attested axially stretched silica aerogel, on the one hand, and "nematically ordered" aerogel consisting of nearly parallel $Al_2O_3 \cdot H_2O$ polymer strands, on the other. In the case of axially stretched silica aerogel the point of view was adopted according to which the orbital anisotropy axis $\hat{\mathrm{l}}$ is long-ranged. The experiments were carried out by pulsed NMR techniques in keeping the direction of an externally applied magnetic field normal to aerogel stretching axis. We have generalized the dipole-locked configuration for arbitrary angle of inclination of the magnetic field with respect to aerogel stretching axis. The experimental data collected in using "nematically ordered" aerogel can't be reconciled with above-mentioned results.

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An efficient way of exploring the impact of quenched disorder on the phase diagram of unconventional Cooper condensate can be realized in placing spin-triplet P-wave superfluid ^{3}He in the medium of high porosity aerogel. In 1995 first such experiments were undertaken [1, 2] and since then a large amount of the data has been accumulated in using silica aerogel with an intricate spatial structure of SiO_2 polymer strands.

Among first results an expected suppression of the critical temperature of transition to superfluid state was confirmed. More intriguing problem was the establishment of possible modification of the phase diagram of the pure superfluid ^{3}He. The interpretation of experimental data was supported by theoretical efforts [3–7] in which the role of quasi-particle scattering from aerogel structure in modifying the superfluid ^{3}He phase diagram is considered.

Motivated by the lack of the reliable way of controlling the quality of aerogel samples in a number of experiments, the new class of silica aerogel has been fabricated in using optical methods of the quality control. In this way a series of new experimental data were accumulated. According to theoretical arguments [8] the orbital axis of ^{3}He-A should be oriented in the direction of globally deformed aerogel density anisotropy. In particular, in the case of axially stretched aerogel $\hat{\mathrm{l}}$ is expected to be lying in the easy plane normal to aerogel stretching axis. This orbital configuration was investigated experimentally [9] in using optically certificated samples. In Ref. [9] the point of view is adopted that the orbital vector $\hat{\mathrm{l}}$ is long-ranged. The experiments were carried out by the pulsed NMR techniques in keeping the direction of externally applied magnetic field normal to aerogel stretching axis.

In what follows we consider the case of a general orientation of the magnetic field $\mathbf{H} = H\hat{\mathbf{z}}$ with respect to aerogel stretching axis $\hat{\boldsymbol{\zeta}}(\hat{\mathbf{z}} \cdot \hat{\boldsymbol{\zeta}} = \cos\theta)$. Since the fingerprint of the order parameter structure of the superfluid state is the character of the dipole shift $\delta\omega$ of the NMR frequency from the Larmor value $\omega_{\mathrm{L}} = gH$ one has to start from the dipole-dipole (spin-orbit) potential

$$U_D = -\frac{1}{2}\chi_\perp(\Omega_A/g)^2(\hat{d} \cdot \hat{\mathbf{l}})^2, \tag{1}$$

appropriate to the doubly anisotropic Cooper condensate with unit vectors $\hat{\mathbf{d}}$ and $\hat{\mathbf{l}}$ marking the anisotropy axis in spin and orbital spaces, correspondingly. In the axially stretched aerogel

$$\hat{\mathbf{l}} = \hat{\boldsymbol{\xi}}\cos\varphi + \hat{\boldsymbol{\eta}}\sin\varphi, \quad \hat{\boldsymbol{\xi}} \times \hat{\boldsymbol{\eta}} = \hat{\boldsymbol{\zeta}}, \tag{2}$$

and for the spin-orbital function $f = (\hat{\mathbf{d}} \cdot \hat{\mathbf{l}})^2$ it is found that

$$f = (d_x l_x + d_y l_y + d_z l_z)^2, \tag{3}$$

where

$$\begin{cases} l_x = (\hat{\mathbf{x}} \cdot \hat{\boldsymbol{\xi}}\cos\varphi + (\hat{\mathbf{x}} \cdot \hat{\boldsymbol{\eta}})\sin\varphi, \\ l_y = (\hat{\mathbf{y}} \cdot \hat{\boldsymbol{\xi}}\cos\varphi + (\hat{\mathbf{y}} \cdot \hat{\boldsymbol{\eta}})\sin\varphi, \\ l_z = (\hat{\mathbf{x}} \cdot \hat{\boldsymbol{\xi}}\cos\varphi + (\hat{\mathbf{z}} \cdot \hat{\boldsymbol{\eta}})\sin\varphi. \end{cases} \tag{4}$$

In keeping the orientation of $\mathbf{H}$ in the (ζ, ξ) plane it can be shown that

$$f = d_x^2\cos^2\varphi\cos^2\theta + d_y^2\sin^2\varphi + d_z^2\cos^2\varphi\sin^2\theta +$$

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$$+d_x d_y \sin 2\varphi \cos\theta + d_x d_z \cos^2\varphi \sin 2\theta + d_y d_z \sin 2\varphi \sin\theta. \tag{5}$$

It is to be remembered that according to Ref. [9] the azimuthal angle φ in (ξ, η) plane is considered as a long-ranged parameter. Before considering the spin-dynamical regime (pulsed NMR) one has to construct an initial (equilibrium) spin-orbital configuration. In the presence of a strong magnetic field $\hat{\mathbf{d}}_0 = \hat{\mathbf{x}}\cos\psi + \hat{\mathbf{y}}\sin\psi$ and

$$f_0 = (\sin\varphi\sin\psi + \cos\varphi\cos\psi\cos\theta)^2. \tag{6}$$

In choosing $\psi = \varphi = \pi/2$ the Leggett (dipole locked) spin-orbital configuration is attained with $f_0 = 1$ which realizes an absolute minimum of $U_D^{(0)}$ irrespective of the magnetic field inclination angle θ with respect to aerogel stretching axis $\hat{\boldsymbol{\zeta}}$.

Now, spin-dynamical regime can be constructed in the standard way as

$$f(t) = [\hat{\mathbf{d}}(t)\cdot\hat{\mathbf{l}}]^2, \quad d_i(t) = R_{ij}(\alpha,\beta,\gamma) d_{0j}, \tag{7}$$

where the triad (α, β, γ) of Euler angles appears with β being the tip angle from the equilibrium orientation of the magnetization. In using Eq. (5) and adopting the initial configuration ($\varphi = \pi/2$, $\hat{\mathbf{d}}_0 = \hat{\mathbf{y}}$) it is found that

$$f(t) = d_y^2(t) = R_{yy}^2(\alpha,\beta,\gamma) =$$
$$= \frac{1}{4}\left[1 + \cos^2\beta + \frac{1}{2}(1+\cos\beta)^2\cos 2(\alpha+\gamma)\right] +$$
$$+ \frac{1}{4}\sin^2\beta(\cos 2\alpha + \cos 2\gamma) + \frac{1}{8}(1-\cos\beta)^2\cos 2(\alpha-\gamma). \tag{8}$$

From Eq. (8) the time-averaged (Van der Pol) approximation is extracted as

$$\bar{f} = \frac{1}{4}\left[1 + \cos^2\beta + \frac{1}{2}(1+\cos\beta)^2\cos 2\phi\right], \tag{9}$$

where the "slow" phase $\phi = \alpha + \gamma$ which can be excluded in favour of minimization of the dipole-dipole potential $\bar{U}_D$. This is achieved in choosing the stationary value of $\phi = \phi_{\rm st} = 0$, so that

$$\bar{U}_D\big|_{\phi_{\rm st}} = -\frac{1}{2}\chi_\perp(\Omega_A/g)^2\cdot\frac{1}{4}\left(\frac{3}{2} + \cos\beta + \frac{3}{2}\cos^2\beta\right). \tag{10}$$

Consequently the dipole shift $\delta\omega$ of the NMR frequency from the Larmor value is found as the function of the tip angle β from the equilibrium orientation of the magnetization:

$$\delta\omega(\beta) = (\Omega_A^2/2\omega_{\rm L})\left(\frac{1}{4} + \frac{3}{4}\cos\beta\right), \tag{11}$$

reproducing the well known Brinkman–Smith formula [10] appropriate to bulk ^{3}He-A. According to the present consideration this answer is θ-independent because it develops in the background of the Leggett equilibrium configuration with $\psi = \varphi = \pi/2$. It would be desirable to verify this conclusion experimentally in using the same type of samples as in Ref. [9].

In addressing the axially compressed aerogel it is expected [8] that in this case the orbital axis $\hat{\mathbf{l}}$ will be captured along the deformation axis $\hat{\boldsymbol{\zeta}}$. In Ref. [11] it was argued that due to the used preparation procedure the orbital configuration with $\hat{\mathbf{l}} \parallel \hat{\boldsymbol{\zeta}}$ was realized. It was found that CW NMR displays a large negative frequency shift from the Larmor value (see also Ref. [12]). The pulsed NMR description of $\hat{\mathbf{l}} \parallel \hat{\boldsymbol{\zeta}}$ case in the presence of a tilted magnetic field can be constructed (see Refs. [13, 14]). In the axially compressed case the dipole frequency shift

$$\delta\omega(\beta,\theta) = (\Omega_A^2/2\omega_{\rm L})[-\cos\beta + (1/4)(1+7\cos\beta)\sin^2\theta]. \tag{12}$$

At $\theta = 0$ (which is used in Ref. [11]) the negative shift is reproduced. On the other hand, at $\vartheta = \pi/2$ the Brinkman–Smith answer is found because in this particular magnetic field orientation the initial (equilibrium) value $f_0 = \cos^2\psi\sin^2\theta$, so that at $\vartheta = \pi/2$ and $\hat{\mathbf{d}}_0 = \hat{\mathbf{x}}$ the Leggett configuration with $f_0 = 1$ is realized. It is to be mentioned that in using a torsion oscillator techniques [15] it was not confirmed the alignment of $\hat{\mathbf{l}}$ along aerogel compression axis.

Returning back to the problem of an axially stretched aerogel it is to be mentioned that recently a new type of aerogel samples comprising $Al_2O_3 \cdot H_2O$ polymer strands aligned along a common axis was used [16]. The orientation of an externally applied magnetic field could be inclined with respect to the "nematically ordered" (almost 100% stretched) aerogel axis in order to explore the θ-dependence of the dipole shift of the frequency from the Larmor value in pulsed NMR. According to Ref. [16] the dipole frequency shift is well described as

$$\delta\omega(\beta,\theta) = (\Omega^2/2\omega_{\rm L})[\cos\beta + (1/4)(1-5\cos\beta)\sin^2\theta] \tag{13}$$

and at $\Omega^2 = \Omega_A^2/2$ reproduces the answer found for the $U(1)$ LIM model [13] (see, also Ref. [14]). Alternatively it is possible that the dipole frequency shift given by the formula (13) signals the appearance of the polar phase [17] with $\Omega^2 = 4\Omega_A^2/3$. In any case the results given in Ref. [9] can't be reconciled with the dipole frequency shift described by Eq. (13).

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