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Spin diffusion in liquid ^{3}He confined in planar aerogel

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Introduction. Measurements of spin diffusion in liquid ^{3}He in high porosity materials (e.g., in aerogels) allow to get information about their structure. Aerogels consist of nanoscale strands. At very low temperatures (~ 1 mK) the density of ^{3}He quasiparticles becomes so small that the aerogel limits their mean free path and the diffusion. Spin echo technique was used to investigate spin diffusion of ^{3}He in isotropic silica aerogels [1, 2] and in nematic aerogels [3, 4] whose strands are nearly parallel to one another [5]. In the latter case an anisotropic spin diffusion was observed. Strong anisotropy of nematic aerogel also leads to existence of a new superfluid phase of ^{3}He – the polar phase [6].

Here we present results of theoretical and experimental studies of spin diffusion in another type of anisotropic aerogel-like material, which we call the planar aerogel. Like nematic aerogel, it is an axially symmetric macroscopically uniform system which has a high porosity p and consists of approximately cylindrical strands of nearly the same diameter d. Directions of the strands, however, are uniformly distributed in a plane perpendicular to the symmetry axis z.

Theory. We extend the theory of low temperature spin diffusion in normal ^{3}He in anisotropic aerogel [4] to the case of planar aerogel. We neglect the influence of collisions between ^{3}He quasiparticles in comparison with that of aerogel-quasiparticle scattering. We assume this scattering to be elastic, preserving energy and spin (as expected for ^{4}He coated strands [7]) and take all strands to be perpendicular to z. Axially symmetric diffusion tensor has two distinct principal values, $D^{xx} = D^{yy}$ and D^{zz}. Two limits are considered: specular and diffuse scattering (denoted by the subscripts "S" and "D").

The kinetic equation for spin diffusion in Fermi-liquid has the form [4]:

$$(\boldsymbol{\psi} \cdot \hat{\mathbf{p}}) = \int (\chi(\hat{\mathbf{p}}) - \chi(\hat{\mathbf{p}}'))\, \mathrm{d}\sigma(\hat{\mathbf{p}}, \hat{\mathbf{p}}'),$$

where the hat denotes the unit vector, $\mathrm{d}\sigma(\hat{\mathbf{p}}, \hat{\mathbf{p}}')$ is the differential $\mathbf{p} \to \mathbf{p}'$ scattering cross section, and $\boldsymbol{\psi} = 2\pi^2\hbar^3\,(1+F_0^a)\,\nabla M/(p_F m^*)$. To solve this equation, the distribution function $\chi(\hat{\mathbf{p}})$ is expanded in terms of spherical harmonics $Y_{lm}(\hat{\mathbf{p}})$

$$\chi(\hat{\mathbf{p}}) = \psi\frac{\pi d}{1-p}\sqrt{\frac{4\pi}{3}}\sum_{l,m} C^{lm} Y_{lm}(\hat{\mathbf{p}}).$$

Coefficients of the expansion are evaluated numerically (see the full version) giving in the specular limit

$$D_{\mathrm{S}}^{xx} = 0.445(1+F_0^a)\frac{v_F d}{1-p},\ D_{\mathrm{S}}^{zz} = 0.226(1+F_0^a)\frac{v_F d}{1-p}$$

and in the diffuse reflection limit

$$D_{\mathrm{D}}^{xx} = 0.468(1+F_0^a)\frac{v_F d}{1-p},\ D_{\mathrm{D}}^{zz} = 0.187(1+F_0^a)\frac{v_F d}{1-p}.$$

Details of experiment. The sample of planar aerogel was produced from mullite nematic aerogel consisting of strands with $d \approx 10$ nm. The aerogel was first divided into individual fibers (by stirring in alcohol), which were consequently dried to form a network mostly oriented in one plane (inset of Fig. 1) with $p \approx 0.88$. The sample as a stack of three 4×4 mm plates with thickness of ≈ 1 mm each was placed in a separate cell of our experimental chamber (similar to that described in [8]). Before filling the chamber with ^{3}He, the sample was coated by ≈ 2.5 atomic layers of ^{4}He.

Experiments were carried out using spin echo technique at the pressure of 2.9 bar in the magnetic field of 140 Oe (the Larmor frequency is 453 kHz) along z-axis. Two systems of gradient coils were used to apply the field gradient in x and z directions. Necessary temperatures were obtained by a nuclear demagnetization cryostat and measured by a quartz tuning fork.

We obtained spin echo decay curves by measuring the echo amplitude after $\pi/2 - \tau - \pi$ pulses, where τ is the delay between pulses. The measurements were done at temperatures 1.5–80 mK for two directions of the gradient and at several values of the gradients (265–786 mOe/cm).

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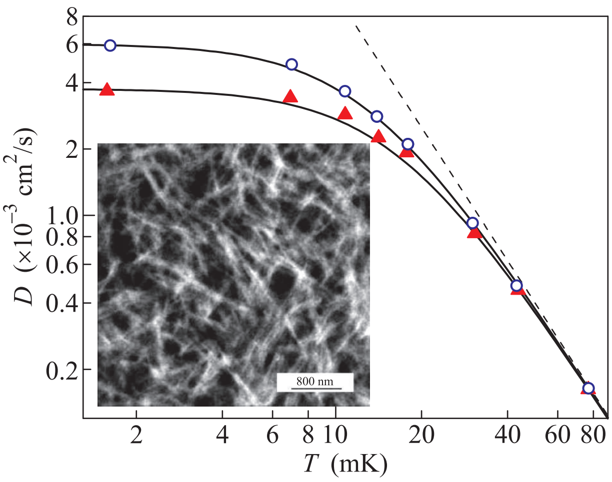

Fig. 1. (Color online) Temperature dependence of the spin diffusion coefficients in planar aerogel: $D^{xx}(T)$ (circles) and $D^{zz}(T)$ (triangles). Inset: scanning electron microscope image of the surface of planar aerogel

Experimental results. The echo amplitude is [9]:

$$I = I_0 \exp(-2\tau/T_2 - A\tau^3), \tag{1}$$

where T_2 is a spin-spin relaxation time and A for an anisotropic media has a form of

$$A = \frac{2}{3}\gamma^2 D^{lm} G^l G^m. \tag{2}$$

Here γ is a gyromagnetic ratio of ^{3}He, $\mathbf{G}$ is a gradient vector of the magnetic field.

The value of spin diffusion coefficient is determined by fitting the data by Eq. (1). The observed dependence of I/I_0 on $G^2\tau^3$ does not depend on $\mathbf{G}$ at all temperatures, so the term with T_2 in Eq. (1) can be neglected.

Temperature dependencies of diffusion coefficients shown in Fig. 1 were measured for two orientations of the gradient: parallel (D^{xx}) and perpendicular (D^{zz}) to the aerogel plane. The data were fitted by the equation:

$$D^{-1}(T) = D^{-1}_{\mathrm{bulk}}(T) + D^{-1}, \tag{3}$$

where the contributions of collisions between quasiparticles $D_{\mathrm{bulk}} \propto T^{-2}$ (the diffusion coefficient in bulk ^{3}He) and that of quasiparticle-aerogel scattering $D \equiv D(0)$ are separated. Solid lines in Fig. 1 are the best fits to Eq. (3), the dashed line is the diffusion in bulk ^{3}He (the extrapolation to 2.9 bar of data in [10]). Thus, we get principal values of the spin diffusion tensor in planar aerogel in zero temperature limit: $D^{xx} = 0.0059\,\mathrm{cm}^2/\mathrm{s}$, $D^{zz} = 0.0036\,\mathrm{cm}^2/\mathrm{s}$ with accuracy of $\pm 10\,\%$.

Discussion. We define zero-temperature mean free paths λ_z and λ_x of ^{3}He quasiparticles by the equation: $D = v_F \lambda (1 + F_0^a)/3$. For $v_F = 5397\,\mathrm{cm/s}$ and $F_0^a = -0.717$ [11] we get $\lambda_z = 71\,\mathrm{nm}$ and $\lambda_x = 116\,\mathrm{nm}$.

From the theory for our sample ($d \approx 10\,\mathrm{nm}$ and $p \approx 0.88$) we expect to have the following spin diffusion coefficients $D_{\mathrm{S}}^{xx} = 0.00583\,\mathrm{cm}^2/\mathrm{s}$, $D_{\mathrm{S}}^{zz} = 0.00296\,\mathrm{cm}^2/\mathrm{s}$ and $D_{\mathrm{D}}^{xx} = 0.00613\,\mathrm{cm}^2/\mathrm{s}$, $D_{\mathrm{D}}^{zz} = 0.00245\,\mathrm{cm}^2/\mathrm{s}$. The experimental results are more consistent with the specular scattering model. We note that inaccuracies in d and p do not influence the ratio D^{xx}/D^{zz}, and the discrepancy between the experimentally observed $D^{xx}/D^{zz} = 1.64$ and $D_{\mathrm{S}}^{xx}/D_{\mathrm{S}}^{zz} = 1.97$ is probably due to incomplete alignment of aerogel strands in one plane. For diffuse scattering the theory predicts $D_{\mathrm{D}}^{xx}/D_{\mathrm{D}}^{zz} = 2.50$.

The observed strong anisotropy of ^{3}He spin diffusion is of a particular interest for nuclear magnetic resonance experiments with superfluid ^{3}He in planar aerogel where the A phase with the orbital vector oriented perpendicular to the plane is expected to emerge [12] as well as the effect of a magnetic scattering can be manifested, which was presumably the case for superfluid ^{3}He in nematic aerogel [13].

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