Pis'ma v ZhETF, vol. 108, iss. 11, pp. 772 – 773

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

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Submitted 29 October 2018

DOI: 10.1134/S0370274X18230066

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 ($\sim 1\,\mathrm{mK}$) 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 $d\approx 10\,\mathrm{nm}$. 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 $4\times 4\,\mathrm{mm}$ plates with thickness of $\approx 1\,\mathrm{mm}$ 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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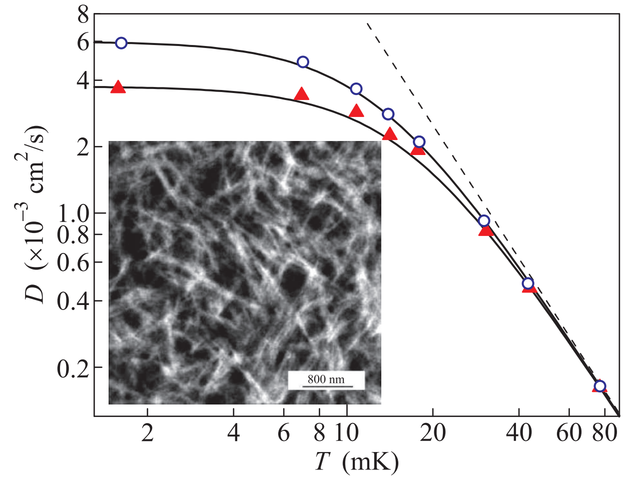

Fig. 1. (Color online) Temperature dependence of the spin diffusion coefficients in planar aerogel: $D^{xx}(T)$ (circles) and $D^{zz}(T)$ (triangles). Inset: scanning electron microscope image of the surface of planar aerogel

Experimental results. The echo amplitude is [9]:

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

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

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

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:

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

where the contributions of collisions between quasiparticles $D_{\text{bulk}} \propto T^{-2}$ (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: $D^{xx} = 0.0059\,\text{cm}^2/\text{s}$, $D^{zz} = 0.0036\,\text{cm}^2/\text{s}$ 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 $v_F = 5397\,\text{cm/s}$ and $F_0^a = -0.717$ [11] we get $\lambda_z = 71\,\text{nm}$ and $\lambda_x = 116\,\text{nm}$.

From the theory for our sample ($d \approx 10\,\text{nm}$ and $p \approx 0.88$) we expect to have the following spin diffusion coefficients $D_{\text{S}}^{xx} = 0.00583\,\text{cm}^2/\text{s}$, $D_{\text{S}}^{zz} = 0.00296\,\text{cm}^2/\text{s}$ and $D_{\text{D}}^{xx} = 0.00613\,\text{cm}^2/\text{s}$, $D_{\text{D}}^{zz} = 0.00245\,\text{cm}^2/\text{s}$. 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 $D_{\text{S}}^{xx}/D_{\text{S}}^{zz} = 1.97$ is probably due to incomplete alignment of aerogel strands in one plane. For diffuse scattering the theory predicts $D_{\text{D}}^{xx}/D_{\text{D}}^{zz} = 2.50$.

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].

Theoretical studies were supported in part by the Program of the Presidium of Russian Academy of Sciences "Actual problems of low temperature physics". The experiments were supported by grant of the Russian Science Foundation (project # 18-12-00384).

Full text of the paper is published in JETP Letters journal. DOI: 10.1134/S0021364018230017

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