Measurements of spin diffusion in liquid $^3$He in “ordered” aerogel

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Abstract.

We report measurements of spin diffusion in normal phase of liquid $^3$He confined to “ordered” aerogel. This aerogel consists of Al$_2$O$_3$·H$_2$O strands which are nearly parallel to each other at macroscopic distances. At low temperatures strong anisotropy of such aerogel may be detected as anisotropy of $^3$He spin diffusion. Experiments were done at pressure of 2.4 bar using spin echo techniques for two orientations of magnetic field gradient (parallel and normal to the strands). Values of spin diffusion for these two directions of the gradient were found to be different at temperatures below $\sim$20 mK. In zero temperature limit the ratio of obtained principal values of the spin diffusion tensor is about 2.

1. Introduction

It is known that anisotropy of aerogel significantly influences properties of superfluid phases of $^3$He in aerogel. Such influence was experimentally studied using nearly isotropic SiO$_2$ aerogels with some degree of squeezing or stretching [1, 2]. Squeezing anisotropy can be obtained by compressing the sample along some axis. It is much more complicated to get homogeneously stretched sample by mechanical stress, so such samples are usually obtained as a result of a growing process. Stretching in this case is relatively small. However, studies of $^3$He in aerogel with high degree of stretching can be done using new aerogel, which we call “ordered” aerogel [3]. Distinctive feature of this aerogel is nearly parallel arrangement of Al$_2$O$_3$·H$_2$O strands at macroscopic distances (3-5 mm). Thickness of the strands (5 - 50 nm) is somewhat larger than that in “standard” aerogels (see Fig. 1) but is still comparable with $^3$He superfluid correlation length. Properties of liquid $^3$He in “ordered” aerogel should therefore correspond to those in an infinitely stretched silica aerogel. This is a good candidate system for a polar pairing state predicted theoretically for large stretching [4]. Anisotropy of this aerogel can also influence the properties of normal $^3$He, e.g. spin diffusion coefficient. Well below Fermi temperature in bulk liquid $^3$He the mean free path of quasiparticles and the spin diffusion coefficient are both proportional to $T^{-2}$, where $T$ is the temperature. Aerogel strands limit these values at low enough $T$. For example, in zero temperature limit the mean free paths for 95% and 98% open silica aerogels were found to be equal to 58 nm and 130 nm respectively [5, 6]. Spin diffusion in “ordered” aerogel is expected to be anisotropic. Observation of this anisotropy was the aim of experiments described below.
2. Details of experiments
The “ordered” aerogel grows by 3-5 mm thick layers, so that each subsequent layer has larger porosity (from 96.7% to 99.5% [3]) and layers with different porosity have the same thickness of strands but differ by number of strands per unit volume.

We have used two aerogel samples with different porosities which we estimate to be \( \sim 97\% \) and \( \sim 99\% \) because they have been cut from the layers with maximal and minimal densities (although the porosity of the samples were not measured). Samples had a form of cylinder with diameter \( \sim 4 \) mm and with heights 2.6 mm (more dense) and 3.2 mm (less dense sample). Axes of the cylinders were oriented along aerogel strands and along the direction of external steady magnetic field. The samples were placed freely in cylindrical cells made from Stycast-1266 epoxy resin, so that 70\% of the cell volumes were filled by aerogel. To avoid paramagnetic signal from solid \(^3\)He, the samples were preplated by \( \sim 2.5 \) monolayers of \(^4\)He. The cells were surrounded by transverse NMR coils. Two systems of gradient coils were used to compensate magnetic field inhomogeneity and to apply the controlled magnetic field gradient in longitudinal and transverse directions. Experiments were carried out in magnetic field of 346 Oe (NMR frequency is 1.12 MHz) at 2.4 bar. The necessary temperatures were obtained by nuclear demagnetization cryostat and were measured by a quartz tuning fork. We assume that the fork resonance width in normal \(^3\)He is proportional to \( T^{-1} \) [7] and that at high temperature the spin diffusion coefficient is not affected by aerogel (for the resonance line width of 64.6 Hz the measured value of spin diffusion coefficient was \( 5.46 \cdot 10^{-4} \) cm\(^2\)/s which corresponds to the diffusion coefficient in bulk \(^3\)He at \( T=42.8 \) mK [9]).

Spin echo decay curves were obtained by standard two-pulse method: we measured amplitude of the echo after \( \pi/2 - \tau - \pi \) pulses, where \( \tau \) is the delay between pulses. The measurements were carried out for two directions of magnetic field gradient (parallel and perpendicular to the direction of aerogel strands) and at several values of the gradients (0.3 ÷ 1.5 Oe/cm). Most experiments were done using denser sample of aerogel and (unless stated otherwise) below we present data for this sample. Results for less dense sample were qualitatively the same.

3. Results
Expression for the spin echo amplitude

\[
I = I_0 \exp(-2\tau/T_2 - A\tau^3)
\]

\( (1) \)
can be found from Bloch-Torrey equations [8]. With an obvious generalization for an anisotropic media, the coefficient \( A \) here is given by

\[
A = \frac{2}{3}\gamma^2 D^{lm}G^lG^m,
\]

\( (2) \)
where $\gamma$ is the gyromagnetic ratio, $G^l$ is the magnetic field gradient, and $D^{lm}$ is the spin diffusion tensor. In an axially symmetric system this tensor has two principal values $D^\parallel$ and $D^\perp$ where the superscript characterizes the orientation with respect to the symmetry axis.

In order to estimate $T_2$ we have made measurements in homogeneous magnetic field and discovered that the term with $T_2$ in Eq.(1) can be neglected for the purpose of our experiment. For example, at $T \sim 5$ mK the measured $T_2$ was $\sim 50$ ms while characteristic echo decay time for $G=0.68$ Oe/cm was $\sim 6$ ms. This assumption is also justified by the fact that the curves obtained for different $G$ coincide in Fig. 2, where the typical echo decay curves are shown.

The large-$\tau$ slope of the curve (solid line) in Fig. 2 gives the value of spin diffusion coefficient of $^3$He in aerogel ($D_a$). The small-$\tau$ deviation from the solid line is due to the presence of bulk $^3$He in the system. At low temperatures the diffusion in bulk $^3$He [9] is faster than that in aerogel, so in the first approximation the data should be fitted by a sum of two signals with different diffusion coefficients. The values of $D_a$ obtained by these two types of fit are the same.

The measured temperature dependence of $D_a$ for two orientations of $G$ is shown in Fig. 3. In order to obtain a value of $D_a$ in zero temperature limit these dependencies were fitted by the equation

$$D_a^{-1}(T) = D_b^{-1}(T) + D_a^{-1}(0),$$

(3)

where $D_b \propto T^{-2}$ is the diffusion coefficient in bulk $^3$He. At low temperatures $D_a(T)$ is significantly smaller than $D_b(T)$, the same result was earlier obtained in silica aerogels. Remarkably the values of $D_a$ in “ordered” aerogel for two orientations of $G$ are different. In the limit $T \rightarrow 0$ the principal values of the diffusion tensor diverge by almost a factor of two: $D_\parallel(0) \approx 0.044$ cm$^2$/s and $D_\perp(0) \approx 0.023$ cm$^2$/s.

4. Discussion
Spin diffusion in $^3$He is determined by quasiparticle collisions, most of them in the zero temperature limit are between quasiparticles and aerogel matrix. If the aerogel were isotropic,
the diffusion coefficient would be

$$D_a(0) = \frac{1}{3} v_F (1 + F_a^0) \lambda,$$

where $v_F$ is the Fermi velocity, $F_a^0$ is the Landau Fermi-liquid parameter and $\lambda$ is quasiparticle mean free path which is on the order of magnitude of the distance between aerogel strands. To account for experimental values of $D_a^\parallel(0)$ and $D_a^\perp(0)$, the mean free path would have to be $\lambda^\parallel \approx 850 \text{ nm}$ and $\lambda^\perp \approx 450 \text{ nm}$ (1600 nm and 1100 nm respectively for the less dense aerogel).

This confirms that diffusion in “ordered” aerogel cannot be characterized by an effective mean free path alone. The diffusion tensor should depend on the microscopic aerogel structure and on the quasiparticle-strand collision nature. Kinetic equation in a simple model of diffuse scattering on parallel infinite cylindrical strands gives $D_a^\parallel/D_a^\perp = (\pi^2 + 16)/8 \approx 3.23$. This is larger than experimentally obtained ratio. The discrepancy could probably be attributed to the irregularities (see Fig. 1) of the strands shape.

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