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Oscillating nematic aerogel in superfluid ^{3}He

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Introduction. Superfluidity of ^{3}He in aerogel can be investigated using a vibrating wire (VW) resonator immersed in liquid ^{3}He with an aerogel sample attached to it. In this case an appearance of the superfluid fraction of ^{3}He in aerogel influences resonant properties of the VW. Such experiments have been done previously only with silica aerogel [1, 2] where superfluid phases have the same order parameters as A and B phases of bulk ^{3}He. In particular, these experiments have allowed to estimate the temperature dependence of the superfluid fraction in superfluid phases of ^{3}He in aerogel. In this Letter, we present results of VW experiments with ^{3}He in the so-called nematic aerogel consisting of strands with almost parallel orientation. The superfluid transition of ^{3}He in nematic aerogel occurs into a new phase (polar phase) that does not exist either in bulk ^{3}He or in ^{3}He in silica aerogel [3]. In nematic aerogel this phase has a superfluid gap with line of zeroes in the plane perpendicular to the direction of the strands [4].

Methods. We used a sample of nematic aerogel with a size along strands ≈ 2.6 mm and transverse sizes $\sim 3 \times 3$ mm. The sample consists of nearly parallel mullite strands with diameters of ≤ 14 nm and has a porosity of 95.2 %. Similar sample (which was cut from the same original piece and was placed in a separate cell of the same experimental chamber) has been used in nuclear magnetic resonance (NMR) experiments in ^{3}He [5] confirming that the superfluid transition of ^{3}He occurs into the polar phase. The present sample was glued using a small amount of epoxy resin to a 240 μm NbTi wire, bent into the shape of an arch. The mechanical flapping resonance of the wire was excited by the Lorentz force of an alternating current, passing through the wire in magnetic field. Motions of the wire generate a Faraday voltage measured with a lock-in amplifier. The strands of the aerogel were oriented along the direction of oscillations. The experiments were carried out at pressures 7.1, 15.4, and 29.3 bar and in magnetic fields 305–1650 Oe. In-phase and quadrature signals were jointly fitted to Lorentz curves in order extract a resonance frequency f_a and a resonance width of the signal Δf_a. To stabilize the polar phase, the samples were preplated with $\gtrsim 2.5$ atomic layers of ^{4}He [6].

Results. In Figure 1 we show temperature dependencies of the resonance frequency and width measured

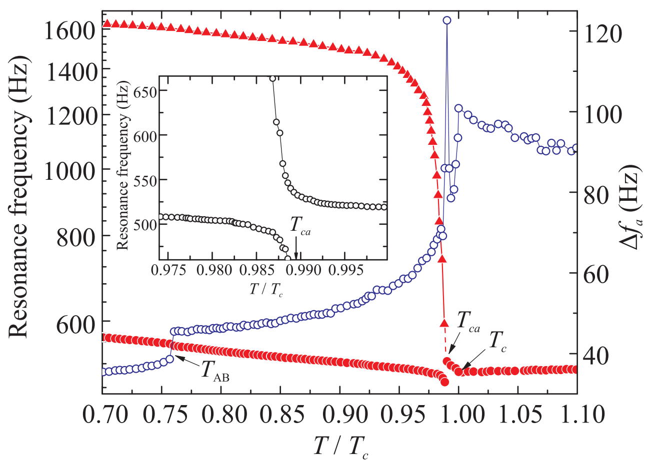

Fig. 1. (Color online) Temperature dependencies of the resonance width of the main resonance (open circles) and of the frequencies of the main (filled circles) and the second (filled triangles) resonances. Arrows mark T_{ca}, T_c, and AB transition in bulk ^{3}He at $T = T_{\rm AB}$. Inset: Two branches of the wire resonance versus temperature near T_{ca}. $P = 29.3$ bar, $T_{ca} \approx 0.989\, T_c$, $H = 1650$ Oe

at 29.3 bar. On cooling in normal ^{3}He, the resonance width is increasing and f_a is decreasing due to the Fermi-liquid behavior of the viscosity of bulk ^{3}He. Then a rapid decrease of the width (a rise of the frequency) is observed indicating a superfluid transition in bulk ^{3}He at $T = T_c$. On further cooling, the second resonance appears (filled triangles in Fig. 1) accompanied by the spike in the width of the main resonance. This additional resonance mode appears just below the superfluid transition temperature of ^{3}He in the sample

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used in NMR experiments [5]. Therefore, we conclude that this resonance is due to the superfluid transition of ^{3}He into the polar phase in the oscillating sample at $T_{ca} \approx 0.989\,T_c$. Although we have not been able to observe a clear resonance peak at frequencies lower than 470 Hz, we assume that on cooling from T_{ca} the frequency of the second mode rapidly grows from 0 and slightly lower T_{ca} becomes close to the frequency of the main resonance resulting in an interaction (repulsion) between these modes. The repulsion is clearly seen in the inset to Fig. 1 where we show the evolution of resonance frequencies during slow passage through T_{ca}. For clarity, below T_{ca} we continue to call as the main resonance the mode with a smaller frequency. On cooling, the resonance frequency of another (the second) mode (f_{a2}) is increasing up to 1600 Hz at $T = 0.75\,T_c$. Similar behavior of the resonance frequencies was observed at lower pressures.

We suppose that the second mode is an analog of a so-called slow sound mode observed in silica aerogel in superfluid helium [7, 8]. The point is that in aerogel the normal fluid component is clamped to the matrix, since the viscous penetration depth is much larger than an average distance between strands ($\approx$60 nm in our sample). However, the skeleton of aerogel is elastic and the normal component can move together with the strands. Therefore, the superfluid component and the combined normal fluid and aerogel matrix can move in opposite directions, resulting in a second-sound-like mode [7] whose resonant frequency grows from 0 on cooling below T_{ca}. In superfluid ^{3}He in silica aerogel such mode was observed in the low-frequency sound measurements [8]. We are dealing with a highly anisotropic aerogel which is soft in the direction normal to the strands but is rigid in the direction along the strands. Therefore, in our case the slow mode should correspond to periodic deformations of the sample in the direction normal to the strands. We note that we detect motions of the wire, but we can excite and detect the slow mode in aerogel, even if its resonance frequency is far from the original VW mechanical resonance. It means that even well below T_{ca} this second resonance is strong enough to affect the wire oscillations.

Frequencies of both modes should essentially depend on the superfluid fraction of ^{3}He in the aerogel. Therefore, our measurements can be used to estimate this fraction. However, for this purpose the interaction between the main and the second modes should be taken into account. Unfortunately, the theoretical model of the slow mode in ^{3}He in aerogel described in [7, 8] is not applicable to our strongly anisotropic sample and further development of the theory is necessary for treatment of our results.

Conclusions. Using VW techniques we have observed a superfluid transition of ^{3}He in nematic aerogel accompanied by the appearance of the second (slow sound) mode inside the aerogel. Resonance frequencies and widths of the main and slow sound modes are measured in a wide range of temperatures. We think that a theoretical model of the slow mode in nematic aerogel might allow to estimate a superfluid density fraction inside our sample.

Our results are promising for experiments on searching for the beta phase in nematic aerogel [9, 10], a new superfluid phase of ^{3}He that must exist in a narrow temperature region (proportional to the value of magnetic field) right below T_{ca}, and on cooling from the beta phase a transition to the distorted beta phase should be observed as a kink on a superfluid fraction versus temperature plot [10]. The latter can be seen in the resonant frequencies in VW experiments. In present experiments the maximal magnetic field which we were able to apply is 1650 Oe. In this field the range of existence of the beta phase is expected to be about $0.005\,T_c$ [10]. Unfortunately, this range of temperatures is nearly the same as the range, wherein the interaction of the observed resonance modes is strong and the frequency of the slow sound resonance is rapidly changing. This, together with errors in determination of resonance frequencies, has prevented us from detecting any clear kink on temperature dependencies of f_a and f_{a2}.

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