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A_1–A_2 splitting in pure ^{3}He in nematic aerogel

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Here, we present the results of vibrating wire experiments in pure ^{3}He (without ^{4}He coverage) in nematic aerogel. We investigated the dependence of splitting of the superfluid transition temperature of ^{3}He in aerogel on magnetic field. In addition to our previous work, we used a wider range of magnetic fields (up to 31 kOe) and managed to detect both the "upper" and "lower" superfluid transition temperatures. The solid paramagnetic ^{3}He layer on the aerogel strands activates the magnetic scattering channel. According to theory, it should result in linear splitting at high (≥ 20 kOe) fields, while at lower fields the splitting is expected to be nonlinear. We were able to observe this nonlinearity, but we have a discrepancy with theoretical predictions regarding the range of fields where nonlinearity occurs. Possible reasons for this are discussed.

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Introduction. A vibrating wire (VW) resonator, immersed in liquid ^{3}He with an aerogel sample attached to it, is a powerful technique to study superfluidity of ^{3}He in aerogel. Previously, by means of nuclear magnetic resonance (NMR) the polar phase of ^{3}He [1] was discovered in so-called nematic aerogel, consisting of strands with almost parallel orientation. Later on, using VW with a sample of nematic aerogel we have observed the β phase in high magnetic fields [2]. For stabilization of these new phases it was essential to preplate the aerogel strands with few atomic layers of ^{4}He [1–3] to fully remove solid paramagnetic ^{3}He from the aerogel surface and ensure a specular scattering for ^{3}He quasiparticles. In this Letter, we present results of VW experiments with pure ^{3}He in nematic aerogel in magnetic fields up to 31 kOe. In this case, in low magnetic fields instead of the transition to the polar phase, the transition to the A phase with substantial suppression of a superfluid transition temperature in aerogel T_{ca} takes place [3], because now the aerogel strands are covered with $\sim$2 atomic layers of paramagnetic solid ^{3}He leading to a diffusive type of scattering with the magnetic scattering channel. In higher fields, we detect "upper" (T_{ca1}) and "lower" (T_{ca2}) superfluid transition temperatures with the A_1 phase in between. The observed A_1–A_2 splitting contradicts theoretical predictions.

Methods. We used a sample of nematic aerogel with a size along strands ≈ 2.6 mm and transverse sizes $\sim 2 \times 3$ mm. The sample consists of nearly parallel mullite strands with diameters of ≤ 14 nm and has a porosity of 95.2 %. 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 is excited by the Lorentz force on an alternating current, passing through the wire in magnetic field. Motions of the wire generate a Faraday voltage measured with a lock-in amplifier by sweeping the frequency. The strands of the aerogel were oriented along the direction of oscillations. The experiments were carried out at a pressure of 15.4 bar and in magnetic fields 1.1 and 19.4–31 kOe. In-phase and quadrature signals are joint fitted to Lorentz curves to extract resonance frequency and width of the signal.

From the previous VW experiments [4] it was found that $T_{ca1}|_{H=0} \equiv T_{ca} \approx 0.95\, T_c$, where the superfluid transition temperature in bulk ^{3}He $T_c = 2.083$ mK, and below T_{ca1} the second oscillating mode in aerogel [5] is excited which is coupled near T_{ca1} to the main flapping resonance of the aerogel wire itself [6]. Here, by scanning in a wider frequency range, we measure and analyze together both resonance modes.

Results. Firstly, we measure the temperature dependencies of the resonance width and frequency of the main mode of the aerogel VW in different fields (e.g., the width at $H = 27$ kOe is shown in the insert of

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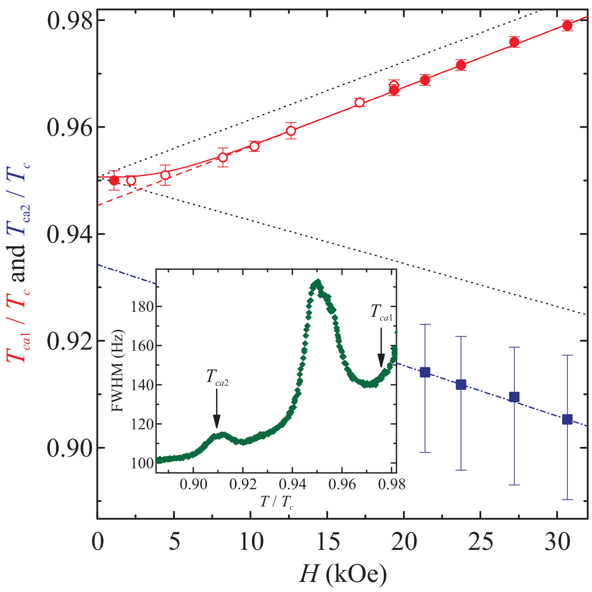

Fig. 1. (Color online) The A_1–A_2 splitting of a superfluid transition temperature of pure ^{3}He in nematic aerogel in magnetic field. The circles correspond to T_{ca1} (open circles are from [4]), the squares correspond to T_{ca2}. The solid line is the best fit with Eq. (1), the dashed line is a linear extrapolation of the high-field T_{ca1} data to a zero field, and the dash-dotted line is a linear fit of the T_{ca2} data. Dotted lines correspond to the A_1–A_2 splitting in bulk ^{3}He scaled to a superfluid transition temperature of $0.95T_c$ [7]. The error bars on the T_{ca2} data indicate a characteristic peak size. Insert: Temperature dependence of the resonance width of the main mode of the aerogel VW at $H = 27$ kOe. Arrows indicate T_{ca1} and T_{ca2}

Fig. 1). The peak-like behavior on the temperature dependence of the width is due to an interaction between the main and second resonance modes: on warming in superfluid ^{3}He in aerogel, the frequency of the second mode decreases and, at some point, it reaches the frequency of the first mode resulting in a sharp increase in the resonance width of the first mode [6]. T_{ca1} is determined from the resonance width versus frequency graph (which is an implicit function of temperature) as described in [4].

Secondly, we have managed to detect an additional feature on the temperature dependencies of the resonance width and frequency of the main mode at lower temperatures. We associate the local maximum on the temperature dependence of the width with T_{ca2} (see the insert of Fig. 1). This feature is not seen at $H \leq 19.4$ kOe, so we were unfortunate in our previous experiments [4].

The results for the A_1–A_2 splitting in pure ^{3}He in nematic aerogel are shown in Fig. 1: T_{ca2} has a linear dependence in applicable magnetic fields, while T_{ca1} has a nonlinearity in a low field region. In a paramagnetic model of the spin exchange [8, 9], the splitting is expected to be modified by the effect of magnetic scattering of ^{3}He quasiparticles by polarizable ^{3}He spins coating the aerogel strands, so that the splitting becomes non-linear at lower fields and linear at fields ≥ 20 kOe as the saturation of magnetization of solid ^{3}He takes place:

$$T_{ca1,2} = T_{ca} \pm \left(\eta_{1,2} - C_{1,2}\frac{\tanh \alpha H}{\alpha H}\right) H, \qquad (1)$$

where $\eta_{1,2} \sim 1\,\mu$K/kOe are the splitting parameters in the absence of spin exchange [7], $\alpha = \gamma\hbar/(2kT_{ca})$, γ is the gyromagnetic ratio, k is the Boltzmann constant, $C_{1,2} \sim 1\,\mu$K/kOe are the spin-exchange parameters [9]. The solid line in Fig. 1 is the best fit using Eq. (1) with η_1, C_1, and α as fit parameters. And according to this fit $\alpha \approx 0.215\,\text{kOe}^{-1}$, which is almost 6 times higher than the theoretical value $\alpha = \gamma\hbar/(2kT_{ca}) \approx 0.037\,\text{kOe}^{-1}$ meaning that the observed region of nonlinearity is 6 times smaller than expected. This big discrepancy of our results with the theory suggests that the paramagnetic model of spin exchange [8, 9] is not applicable.

Probably, the observed effect is due to fluctuations of an amplitude of the order parameter caused by a magnetic scattering [10]. While in high magnetic fields the splitting is linear and these fluctuations should obviously be suppressed, in low magnetic fields (much smaller than its spin saturation value) fluctuations can have more influence on the splitting rather than a spin-exchange scattering channel, which is known to be proportional to the average spin [8, 9]. The gap of $\approx 0.01T_c$ on the splitting at zero field, presumably due to a systematic error in determination of T_{ca1} and T_{ca2}.

Conclusions. In the paper by means of aerogel VW resonator in pure ^{3}He (without ^{4}He coverage) we have measured the field dependence of T_{ca1} in nematic aerogel in expanded magnetic fields and have established that a region of nonlinearity of this dependence is about 6 times smaller than expected from theory. Besides, we have managed to detect T_{ca2} in nematic aerogel at higher magnetic fields. Linear sections of the A_1–A_2 splitting of pure ^{3}He in nematic aerogel are found to have basically the same slopes as expected in bulk ^{3}He. Further experimental and theoretical work is needed for interpretation of the results.

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Conflict of interest. The authors of this work declare that they have no conflicts of interest.

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