

# Transverse and longitudinal nuclear magnetic resonance in superfluid $^3\text{He}$ in anisotropic aerogel

V. V. Dmitriev<sup>1</sup>), D. A. Krasnikhin, N. Mulders\*, V. V. Zavjalov, D. E. Zmeev

*P. L. Kapitza Institute for Physical Problems RAS, 119334 Moscow, Russia*

*\*Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716, USA*

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It was found that properties of nuclear magnetic resonance of both superfluid phases of  $^3\text{He}$  in anisotropic aerogel can be described in terms of the bulk superfluid order parameters with the orbital order parameter vector fixed by anisotropy of the aerogel sample. It was also shown that by a proper squeezing it is possible to get the sample with isotropic NMR properties.

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**Introduction.** The system “liquid  $^3\text{He}$  + high porosity silica aerogel” allows to investigate the influence of disorder on  $p$ -wave superfluidity. The disorder is introduced by the aerogel strands. The diameter of the strands ( $\sim 30$  Å) is much less than the correlation length of the bulk superfluid  $^3\text{He}$  and a characteristic distance between them is large enough, so the superfluidity of  $^3\text{He}$  is not fully suppressed [1, 2]. In a weak magnetic field there exist two superfluid phases of  $^3\text{He}$  in aerogel called  $A$ -like and  $B$ -like [3]. The  $A$ -like phase appears on cooling from the normal phase at pressures above  $\approx 20$  bar and exists in rather large temperature range in a metastable (supercooled) state.

It is established [3, 4] that the  $B$ -like phase is analogous to the  $B$  phase of “usual” bulk  $^3\text{He}$ , i.e. it is described by the same Balian-Werthamer (BW) order parameter as the bulk  $B$  phase. It is also known [3] that the  $A$ -like phase belongs to the family of Equal Spin Pairing (ESP) phases, but the exact structure of its order parameter is still unclear. G.E. Volovik suggested that the  $A$ -like phase in aerogel is described by the Larkin-Imry-Ma (LIM) model with spatially random orientation of Anderson-Brinkman-Morel (ABM) order parameter [5, 6]. In the bulk  $A$  phase the order parameter is also described by the ABM model, but it is spatially homogeneous. I.A. Fomin has proposed the so called “robust” ESP phase – the phase in which the orientation of the order parameter is not influenced by the presence of aerogel – as a possible candidate for the  $A$ -like phase [7, 8].

In previous experiments in aerogel with porosity of about 98% [3, 9–11] (and with aerogels of 97.5% and 99.3% porosity [12–14]) it was found that properties of

nuclear magnetic resonance (NMR) of the  $A$ -like phase are different from the properties of the  $A$  phase of bulk  $^3\text{He}$ . The observed NMR properties also do not correspond well to both LIM and “robust” phase models [11]. Recent experiments with 98% aerogel [15] have clarified the problem: it was found that in squeezed by 1–2% aerogel sample the  $A$ -like phase behaves as the  $A$  phase of the bulk  $^3\text{He}$  with vector  $\hat{\mathbf{l}}$  fixed along the axis of deformation (i.e. along the axis of anisotropy). This observation agrees with recent theoretical studies, where it was shown that even for small anisotropy ( $\sim 1\%$ ) spatially homogeneous  $A$  phase order parameter is more favorable than LIM or “robust” state [16, 17]. Consequently, if the sample is inside a glass tube as probably was in [3, 14] (or there is no large enough gap between the sample and epoxy walls of the cell or spacers fixing the sample as it was in [9–11]) then a difference in thermal contraction coefficients of aerogel and the walls could result in uncontrolled deformation and complicate interpretation of the results.

Here we present and compare the results of our recent NMR studies of the  $A$ -like and the  $B$ -like phases in 3 aerogel samples. As it is shown below two of them were anisotropic, while the third one had isotropic NMR properties.

**Experimental details.** Experiments were done at pressures of 26.0 bar and 28.6 bar in the magnetic fields range of 40–467 Oe (corresponding to NMR frequencies from 132 to 1517 kHz). We used 98.2% porosity aerogel in which silica strands occupy only about 1.8% of the whole volume. Three experimental cells (similar to that described in [4, 10]) with three different aerogel samples were used. The samples had a cylindrical form (sample 1: diameter=4mm, height=3.5mm; samples 2 and 3: diameter=5mm, height=1.5mm) with the axis ori-

<sup>1</sup>) e-mail: dmitriev@kapitza.ras.ru

ented along  $\mathbf{z}$ . Samples 1 and 2 were laying freely inside the epoxy cells, so that there were large enough gaps ( $\approx 0.15$  mm) between the sample and the side and top walls. Correspondingly we believe that no additional deformation could appear during cooldown from room temperature due to thermal shrinkage of the cell, which is expected to be about 1%. Sample 3 was fixed in the cell by 4 paper spacers (0.15 mm thick, width=0.5 mm and the length along  $\mathbf{z}$ -axis is 1.5 mm). The spacers were glued to the side walls and the aerogel sample was presumably squeezed by them in the  $\mathbf{x}$ - $\mathbf{y}$  plane after cooldown from room temperature.

The cells were surrounded by transverse NMR coils with their axes oriented along the  $\mathbf{x}$  direction. Standard NMR setup was used, i.e. radiofrequency (RF) excitation was applied to the NMR circuit; the voltage across the coil was amplified by a preamplifier and then detected by lock-in amplifier (in case of continuous wave, CW, NMR) or by digital oscilloscope (in case of pulsed NMR). Cell with sample 1 also had a superconducting longitudinal NMR coil for the longitudinal resonance experiments. The corresponding NMR circuit was cold and had the fixed frequency (9095 Hz) with the quality factor of 1860. External steady magnetic field  $\mathbf{H}$  could be rotated in the  $\mathbf{z}$ - $\mathbf{y}$  plane: most of the experiments were done for  $\mathbf{H}\parallel\mathbf{z}$  (longitudinal field) and for  $\mathbf{H}\perp\mathbf{z}$  (transverse field).

The temperature was obtained by copper nuclear demagnetization refrigerator and was measured with a vibrating wire viscometer and a quartz tuning fork situated in a large volume connected to the experimental cell by a short ( $\approx 5$  mm) and narrow (diameter of 1 mm) channel. In order to avoid signal from paramagnetic solid  $^3\text{He}$  on the surface of aerogel strands, all our aerogel samples were preplated with  $\sim 2.5$  atomic layers of  $^4\text{He}$ . Consequently no Curie-Weiss behavior of spin susceptibility was observed in our experiments.

**CW NMR experiments in samples 1 and 2.** For  $\mathbf{H}\parallel\mathbf{z}$  it was found that in samples 1 and 2 CW NMR line in the  $A$ -like phase had large negative frequency shift from the Larmor value. The value of the shift was of the same order as in [15]. We also observed that the negative shift converts to positive as the direction of the external magnetic field is changed to  $\mathbf{H}\perp\mathbf{z}$ . It is known that in the ABM phase the frequency shift from the Larmor value ( $\Delta\omega$ ) depends on the angle  $\xi$  between  $\mathbf{H}$  and the orbital vector  $\hat{\mathbf{l}}$ :

$$\Delta\omega = -\frac{\Omega_A^2}{2\omega} \cos(2\xi), \quad (1)$$

where  $\omega$  is the NMR frequency and  $\Omega_A$  is the Leggett frequency. Accordingly our observations can be explained

if we suggest that the  $A$ -like phase in samples 1 and 2 corresponds to the ABM model and both these samples are intrinsically anisotropic with the main axis of anisotropy directed along  $\mathbf{z}$ . It was also found that the anisotropy of sample 1 was not homogeneous: for  $\mathbf{H}\perp\mathbf{z}$  at low enough temperature CW NMR line was rather broad and had 3 distinct maxima (line  $c$  in Fig.1). The

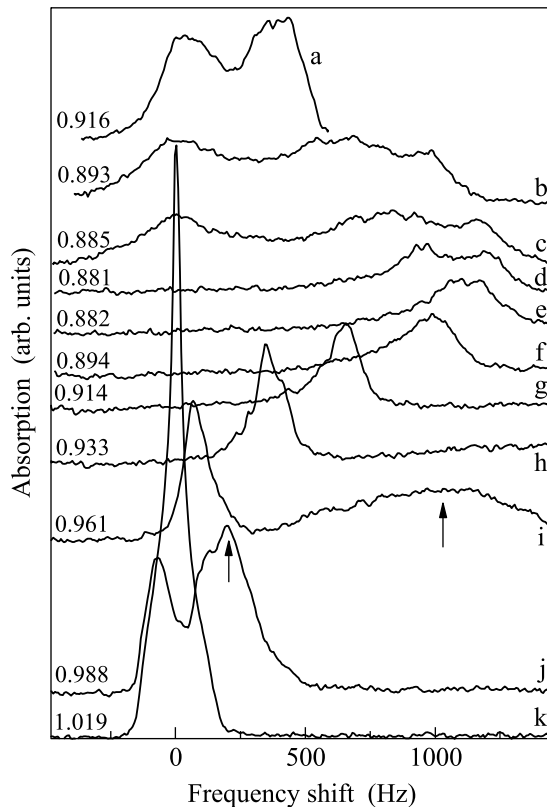


Fig.1. CW NMR lines in sample 1 in transverse field ( $\mathbf{H}\perp\mathbf{z}$ ) obtained by cooling from the normal phase down to onset of the  $A$ -like  $\rightarrow$   $B$ -like transition and subsequent warming (for clarity the lines are shifted in  $y$ -direction). Temperatures in units  $T/T_{ca}$  are shown near each NMR line, where  $T_{ca}$  is the superfluid transition temperature of  $^3\text{He}$  in aerogel.  $P = 26.0$  bar,  $H = 58.3$  Oe,  $T_{ca} = 0.80 T_c$ , where  $T_c$  is the superfluid transition temperature of bulk  $^3\text{He}$

observed maxima can be attributed to 3 parts of the sample where  $\xi$  is approximately equal to  $90^\circ$  (i.e.  $\hat{\mathbf{l}}\parallel\mathbf{z}$ ),  $70^\circ$  and  $45^\circ$  correspondingly ( $\Delta\omega$  is maximal at  $\xi=90^\circ$  and equals zero at  $\xi=45^\circ$ ). The temperature width of the transition from the  $A$ -like to  $B$ -like phase in sample 1 was rather wide ( $\sim 0.02 T_{ca}$ ) and it was found that at first the transition occurred for the less shifted part of the  $A$ -like phase NMR line (see lines  $c, d, e$  in Fig.1). This allowed us to cool the sample down to the  $A$ -like  $\rightarrow$   $B$ -like transition region and then warm up so that the  $A$ -

like phase survived only in part of the sample (lines  $e$ - $j$  in Fig.1) and the other part was in the  $B$ -phase (the  $B$ -like phase signal has much larger frequency shift and in Fig.1 it can be seen only near  $T_{ca}$  as shown by arrows near lines  $i$  and  $j$ ). The obtained in such a way NMR lines in the  $A$ -like phase were rather narrow and we used them for the quantitative measurements assuming that they correspond to the part of sample 1 where  $\hat{\mathbf{I}} \parallel \mathbf{z}$  and  $\xi=90^\circ$  (or  $\xi=0^\circ$  in the case of longitudinal orientation of  $\mathbf{H}$ ). In particular, when we rotated  $\mathbf{H}$  at a fixed temperature from transverse to longitudinal orientation ( $\mathbf{H} \parallel \mathbf{z}$ ) the shift of the  $A$ -like phase line changed the sign, but the absolute value of the shift remained the same as it is expected from (1). The obtained dependencies of the frequency shift in the  $A$ -like phase on temperature may be recalculated to  $\Omega_A^2$  (open symbols in Fig.2).

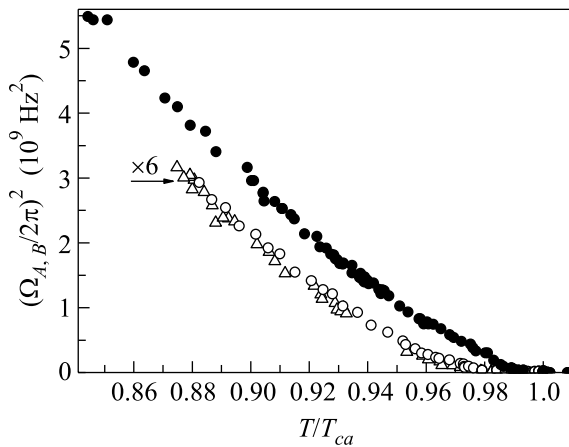


Fig.2. Leggett frequencies  $\Omega_B$  and  $\Omega_A$  in sample 1 calculated from transverse NMR frequency shift assuming  $\hat{\mathbf{I}} \parallel \mathbf{z}$ .  $\bullet$  – the  $B$ -like phase;  $\Delta, \circ$  – the  $A$ -like phase, calculated from positive and negative frequency shift data correspondingly. Note that data for  $\Omega_A^2$  are multiplied by a factor of 6.  $T_{ca} = 0.80 T_c$ ,  $P = 26.0$  bar

In sample 1 we also carried out longitudinal NMR experiments. In these experiments we were sweeping the temperature while recording the signal from the longitudinal NMR coil. To simplify the interpretation we describe below the results where the  $A$ -like phase was left only in the region of the sample where  $\hat{\mathbf{I}} \parallel \mathbf{z}$ . For the ABM order parameter the frequency of longitudinal NMR  $\Omega_{\parallel}$  should depend on  $\xi$ :

$$\Omega_{\parallel} = \Omega_A \sin(\xi). \quad (2)$$

The axis of our longitudinal coil was oriented along  $\mathbf{z}$  (or along  $\hat{\mathbf{I}}$ ) so we were not able to see longitudinal NMR signal for  $\mathbf{H} \perp \mathbf{z}$ . Therefore we used angles  $\xi=0^\circ$  and  $60^\circ$  between  $\mathbf{H}$  and  $\hat{\mathbf{I}}$  (or  $\mathbf{z}$ ). In accordance with (2) no

longitudinal NMR signal in the  $A$ -like phase was found for  $\xi=0^\circ$  while for  $\xi=60^\circ$  the longitudinal NMR signal was clearly seen. The obtained relationship between the transverse resonant frequency and the longitudinal resonant frequency recalculated to the case  $\mathbf{H} \perp \hat{\mathbf{I}}$  was found to well correspond to the ABM phase:

$$\Delta\omega = (0.52 \pm 0.04) \frac{\Omega_{\parallel}^2}{\omega}. \quad (3)$$

The vector  $\hat{\mathbf{I}}$  in the  $B$ -like phase is also oriented by the anisotropy [15, 18]. For  $\mathbf{H} \parallel \mathbf{z}$  the  $B$ -like phase line had only positive frequency shift with a sharp peak near the Larmor value (which corresponds to  $\hat{\mathbf{I}} \parallel \mathbf{H}$  for the BW order parameter) and there was no problem to distinguish it from the  $A$ -like phase signal. For  $\mathbf{H} \perp \mathbf{z}$  the signal from the  $B$ -like phase had large positive frequency shift and interfered with the  $A$ -like phase signal only close to the superfluid transition temperature in aerogel  $T_{ca}$  (see lines  $i$  and  $j$  in Fig.1). Sometimes after the  $A$ -like  $\rightarrow$   $B$ -like transition the high frequency end of the  $B$ -like phase NMR line had a narrow sharp peak. Following [19, 20] we attributed this peak to the textural defect in which vector  $\mathbf{n}$  of the BW order parameter is perpendicular to  $\mathbf{H}$ . The corresponding frequency shift can be recalculated to the Leggett frequency of the  $B$ -like phase (black circles in Fig.2). Note that the frequency shifts in the  $A$ -like and  $B$ -like phases depend on temperature in a different way: on warming the frequency shift in the  $A$ -like phase drops to zero at the temperature about  $0.02 T_{ca}$  lower than in the  $B$ -like phase. This result shows that at least near  $T_{ca}$  the  $A$ -like phase does not exactly correspond to the spatially homogeneous ABM phase.

#### Pulsed NMR experiments in the $A$ -like phase.

The results of pulsed NMR experiments is another argument that allows us to conclude that the  $A$ -like phase in anisotropic aerogel has the same order parameter as in the bulk  $A$  phase. The pulsed NMR experiments were performed in  $^3\text{He}$  in sample 2. CW NMR properties in this sample were the same as in sample 1 the only difference being that the NMR line had only one broad peak, which implies that anisotropy in sample 2 was more homogeneous. Unfortunately we were not able to perform pulsed NMR in longitudinal field due to the bulk  $B$  phase in the gaps between the aerogel sample and the cell walls. This signal was close to the Larmor value and in the observed total free induction decay signal (FIDS) interfered with the signal from the  $A$ -like phase. In transverse field the signal from the  $B$  phase was shifted far enough from the  $A$ -like phase signal, so that we were able to apply long enough ( $\sim 0.2$  ms) and intense RF pulses to tip magnetization only in the  $A$ -like phase. Note that in this orientation of  $\mathbf{H}$  the situation is

similar to the case of bulk  $^3\text{He-A}$ , where  $\hat{\mathbf{l}}$  is fixed perpendicular to  $\mathbf{H}$  by spin-orbital interaction. The results of pulsed NMR experiments in the  $A$ -like phase in transverse field are shown in Fig.3. The obtained dependence

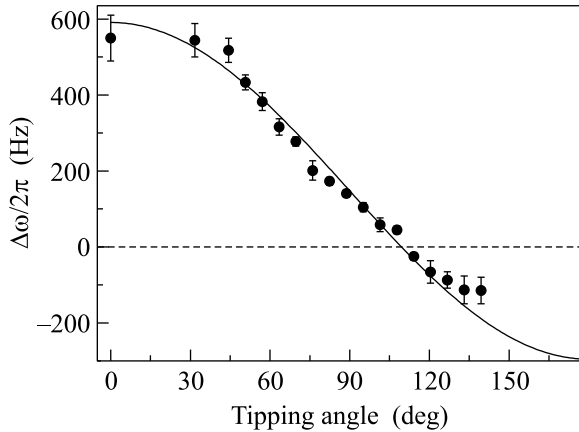


Fig.3. Initial frequency shift of FIDS versus tipping angle  $\beta$  in the  $A$ -like phase in sample 2. The point at  $\beta = 0^\circ$  is from CW NMR measurements. Solid line is the best fit of expression (4) to the data with  $A/2\pi = 590$  Hz.  $H = 97.3$  Oe,  $P = 28.6$  bar,  $T = 0.933 T_{ca}$ ,  $T_{ca} = 0.82 T_c$

of the FIDS frequency shift  $\Delta\omega$  on the magnetization tipping angle  $\beta$  can be described as

$$\Delta\omega = A \left( \frac{1 + 3 \cos \beta}{4} \right) = \frac{\Omega_A^2}{8\omega} (1 + 3 \cos \beta). \quad (4)$$

This dependence is characteristic of the ABM order parameter [21] and was observed earlier in the bulk  $A$  phase [22].

**NMR experiments in sample 3.** Samples 2 and 3 were cut from the same aerogel rod with a high-speed diamond wheel saw. However NMR properties of sample 3 in the  $A$ -like phase were quite different from the properties of sample 2. We found that in sample 3 mean frequency shift of the NMR absorption line (the first moment of the line) was positive and did not depend on the angle  $\psi$  between  $\mathbf{z}$  and  $\mathbf{H}$  (see Fig.4). The value of the shift (recalculated to the same conditions) was 5-6 times smaller than the absolute value of the shift in the  $A$ -like phase in sample 2 for transverse and longitudinal orientations. It is possible that after cooling from room temperature sample 3 was compressed in the  $x$ - $y$  plane by the side wall spacers. Computer simulations of 1% squeezing by our spacers show that in  $\sim 60\%$  of the sample the increase of the density in transverse plane should be in the range of 0.4-1%. This compression may compensate possible intrinsic longitudinal anisotropy and two situations may realize. The first: the anisotropy axis is deflected from  $\mathbf{z}$  by some angle which is different

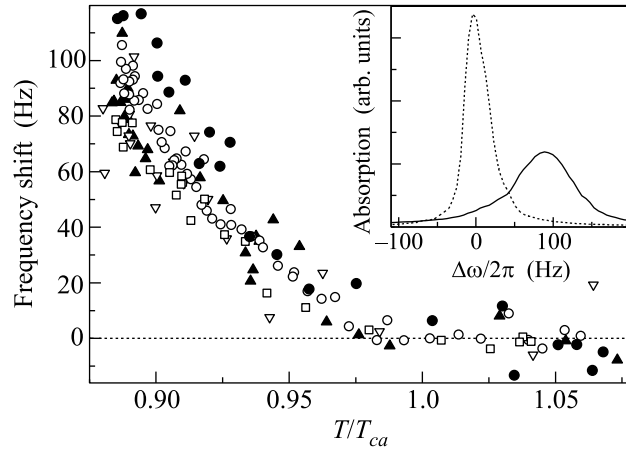


Fig.4. The frequency shift (the first moment of the CW NMR absorption line) in the  $A$ -like phase versus temperature in sample 3 for different angles  $\psi$  between  $\mathbf{H}$  and  $\mathbf{z}$ .  $\circ - \psi = 0^\circ$ ,  $\square - \psi = 15^\circ$ ,  $\bullet - \psi = 31^\circ$ ,  $\nabla - \psi = 51^\circ$ ,  $\blacktriangle - \psi = 60^\circ$ .  $H = 142$  Oe,  $P = 26.0$  bar. Insert: CW NMR absorption lines for  $\psi = 0^\circ$ . Dashed line -  $T = 1.09 T_{ca}$ , solid line -  $T = 0.89 T_{ca}$

in different parts of the sample due to the inhomogeneity of compression. Correspondingly  $\xi$  and  $\Delta\omega$  should essentially vary over the sample. The second: in the main part of the sample the compression decreases the intrinsic longitudinal anisotropy below some critical value, so that some state with isotropic NMR properties (e.g. LIM or "robust") becomes more favorable. The first situation probably was realized in [12] where the observed NMR line in the  $A$ -like phase was very broad and where the mean frequency shift depended on orientation of  $\mathbf{H}$ . In our case the second situation is more probable because CW NMR line in the  $A$ -like phase had positive frequency shift for any  $\psi$  and was rather narrow (see the insert in Fig.4).

We also have done pulsed NMR experiments in sample 3 for  $\psi = 0^\circ$ . It was found that the frequency shift of the FIDS from the Larmor value is approximately proportional to  $(1 + \cos \beta)$  (Fig.5). We should note that the same dependence of the FIDS frequency on the tipping angle as in Fig.5 was observed in [14] in 97.5% aerogel where in CW NMR experiments the frequency shift in the  $A$ -like phase was also positive and small [13, 14] and of the same order as in sample 3. Small and positive frequency shift in the  $A$ -like phase in CW NMR was observed also in another aerogel sample [11]. The problem of identification of the order parameter of the  $A$ -like phase in these cases remains unsolved.

**Conclusions.** We have confirmed that the behavior of the  $A$ -like and  $B$ -like states of superfluid  $^3\text{He}$  in anisotropic aerogel can be described in terms of the cor-

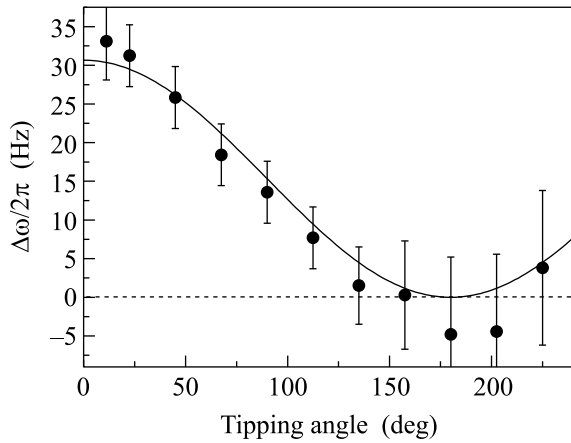


Fig.5. Initial frequency shift of FIDS versus tipping angle  $\beta$  in the  $A$ -like phase in sample 3. Solid line is the best fit of the data by  $A(1 + \cos \beta)$  with  $A = 15.4$  Hz.  $H = 528$  Oe,  $P = 26.0$  bar,  $T = 0.89 T_{ca}$

responding bulk order parameters (ABM and BW) assuming that the orbital order parameter vector  $\hat{\mathbf{I}}$  in both phases is fixed along the anisotropy axis. The same statement was reported in [15]. Here is the summary of our observations indicating such a behavior.

1. The dependence of the FIDS on the magnetization tipping angle in the  $A$ -like phase is the same as in the  $A$  phase of bulk superfluid.
2. The relationship between the frequencies of longitudinal and transverse resonances in the  $A$ -like phase is the same as in the bulk  $A$  phase. At low enough temperatures the ratio of the Leggett frequencies in the  $A$ -like and  $B$ -like phases is close to that in bulk superfluid.
3. The frequency shift in the  $A$ -like phase changes from negative to positive as the magnetic field  $\mathbf{H}$  is rotated from longitudinal to transverse orientation with respect to the anisotropy axis. The absolute value of the shift is the same in these two orientations. No longitudinal resonance is observed in the longitudinal orientation.
4. The CW NMR signal in the  $B$ -like phase has a large peak near the Larmor frequency in longitudinal orientation of  $\mathbf{H}$  and is significantly shifted in the transverse orientation of  $\mathbf{H}$ .

Nevertheless the observed behavior of the  $A$ -like phase in anisotropic aerogel at temperatures close to  $T_{ca}$  is not completely described by the model of spatially homogeneous ABM order parameter: it remains unclear why on warming the frequency shift in the  $A$ -

like phase drops to zero at essentially lower temperature than in the  $B$ -like phase. We also have observed that the  $A$ -like  $\rightarrow B$ -like transition temperature depends on the NMR frequency shift. The same observation was reported in [15], but in our experiments the transition at first occurred in parts of the sample where the absolute values of the frequency shift are smaller, that is opposite to the results of [15].

We should note that in the described experiments the  $A$ -like phase was obtained by cooling from the normal phase without any additional external perturbations. However it was found that if during cooldown through  $T_{ca}$  we apply a set of RF tipping pulses (even as small as  $12^\circ$ ) then NMR properties of the obtained  $A$ -like phase change: the shift of the CW NMR line essentially decreases and the frequency shift of FIDS in pulsed NMR becomes proportional to  $\cos \beta$  [23].

The results obtained in sample 3 show that the anisotropy may be compensated by squeezing the aerogel in proper direction. The NMR properties of the obtained state can not be described by the model of homogeneous ABM phase or by smooth variation of orientation of  $\hat{\mathbf{I}}$  of the ABM phase over macroscopic distance. At the same time our results do not exclude the states with isotropic NMR properties: the Larkin-Imry-Ma state of the ABM phase, in which the orientational long-range order is destroyed at distances smaller than the dipole length; and the “robust” state. At the moment we cannot distinguish between the two states.

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