23. Pivovarov Yu L, Shirokov A A *Yad. Fiz.* **44** 882 (1986) [*Sov. J. Nucl. Phys.* **44** 569 (1986)]
24. Dubin A Yu *Yad. Fiz.* **52** 1243 (1990) [*Sov. J. Nucl. Phys.* **52** 790 (1990)]
25. Fusina R, Kimball J C *Nucl. Instrum. Meth. B* **27** 368 (1987)
26. Pivovarov Yu L *Nucl. Instrum. Meth. B* **145** 96 (1998)
27. Miller P D et al. *Nucl. Instrum. Meth. B* **13** 56 (1986)
28. Okorokov V V, Proshin S V, Preprint No. 13 (Moscow: Institute for the Theoretical and Experimental Physics, 1980)
29. Okorokov V V et al., Preprint No. 49 (Moscow: Institute for the Theoretical and Experimental Physics, 1990)
30. Auth C, Winter H *Phys. Rev. A* **62** 012903 (2000)
31. Ito T et al. *Nucl. Instrum. Meth. B* **164** 68 (2000)
32. Winter H et al. *Nucl. Instrum. Meth. B* **157** 32 (1999)
33. Azuma T et al. *Phys. Rev. Lett.* **83** 528 (1999)
34. Komaki K et al. *Nucl. Instrum. Meth. B* **146** 19 (1998)
35. Crawford O H *Nucl. Instrum. Methods* **170** 21 (1980)
36. Azuma T et al. *Nucl. Instrum. Meth. B* **135** 61 (1998)
37. Hatke N et al. *Nucl. Instrum. Meth. B* **135** 307 (1998)
38. Kimura K et al. *Nucl. Instrum. Meth. B* **135** 419 (1998)
39. Hecht T, Winter H *Phys. Lett. A* **243** 306 (1998)
40. Salin A, Arnau A, Echenique P M *Phys. Rev. A* **57** 2772 (1998)
41. Kimura K, Mannami M *Phys. Rev. A* **57** 1121 (1998)
42. Auth C et al. *Phys. Rev. Lett.* **79** 4477 (1997)
43. Hatke N et al. *Phys. Rev. Lett.* **79** 3395 (1997)
44. Pivovarov Yu L et al. *Nucl. Instrum. Meth. B* **119** 283 (1996)
45. Forster J S et al. *Nucl. Instrum. Meth. B* **107** 27 (1996)
46. Stepanov A V *Zh. Eksp. Teor. Fiz.* **109** 1489 (1996) [*JETP* **82** 801 (1996)]
47. de Abajo F J G, Echenique P M *Nucl. Instrum. Meth. B* **115** 299 (1996)
48. Kimura K et al. *Phys. Rev. Lett.* **76** 3850 (1996)
49. Geissel H et al. *Izv. Ross. Akad. Nauk, Ser. Fiz.* **59** (11) 185 (1995)
50. Stepanov A V *Yad. Fiz.* **58** 2166 (1995) [*Phys. Atom. Nucl.* **58** 2052 (1995)]
51. Takabayashi Y "High precision spectroscopy of helium-like heavy ions with resonant coherent excitation", Doctor Thesis (Tokyo: Tokyo Metropoliten Univ., 2001)
52. Okorokov V V, in *X Intern. Conf. on Atomic Collisions in Solids, 1981, Lyon, France* (unpublished)

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Superfluid phases of ^{3}He in aerogel

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1. Introduction

The superfluidity of pure ^{3}He, in which there is Cooper pairing into a state with total spin 1, has been thoroughly studied, and in many cases it has been found that there is quantitative agreement between theory and experiment [1]. The study of the effect of impurities on superfluid ^{3}He is undoubtedly of great interest for the theory of systems with nontrivial Cooper pairing. The only substance that can be dissolved in liquid ^{3}He at low temperatures is ^{4}He. However, the solubility of ^{4}He in ^{3}He falls off exponentially with temperature, and at $T \sim 1$ mK, i.e., at temperatures at which ^{3}He is a superfluid, is practically zero. Recently there has emerged another possibility for introducing impurities into superfluid ^{3}He connected with the technology of producing low-density aerogel. Aerogel is a 'loose tangle' of SiO_2 strands about 30 Å in diameter, with the characteristic distance between the strands being 500 – 1000 Å (we are speaking about what is known as 98% aerogel with a density of 38 mg cm^{-3}, in which 98% of the volume is free and with which most experiments in this field are conducted). The coherence length of superfluid ^{3}He amounts to several hundred angstroms, i.e., much longer than the strand diameter, in view of which the strands act as impurities.

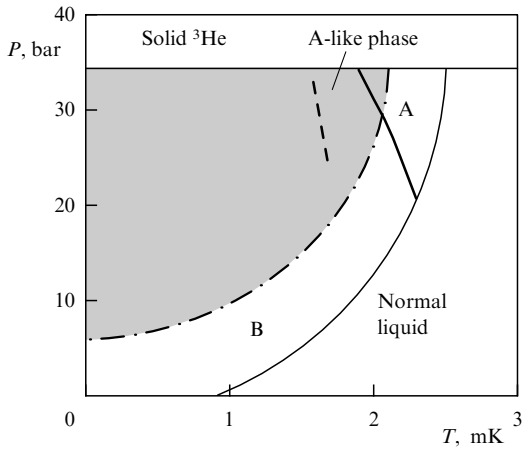

Figure 1. Phase diagram of pure ^{3}He and ^{3}He in 98% aerogel in a weak magnetic field. The hatched section corresponds to the superfluidity region of ^{3}He in aerogel, and the dashed line denotes the line of transitions from the supercooled A-like phase into the B-like phase when the sample is cooled.

Intensive studies of ^{3}He in aerogel began after Porto and Parpia [2] and Sprague et al. [3] discovered that low-density aerogel does not suppress superfluidity completely; rather, it somewhat lowers the superfluid transition temperature (by 20 – 30% at pressures of 20 – 30 bar). As a result, the phase diagram of superfluid ^{3}He in aerogel was established (e.g., see Refs [3 – 7]), which turned out to be similar to the phase diagram of bulk ^{3}He (Fig. 1). It occurred that, depending on the conditions, two superfluid phases were realized, and these were called (by analogy with bulk ^{3}He) the A-like phase and the B-like phase. Note, however, that there is a qualitative difference between the phase diagrams of 'ordinary' bulk ^{3}He and of ^{3}He in aerogel. In a weak magnetic field, the transition into the A-like phase becomes noticeable only on cooling starting from the normal phase, and the A-like phase is metastable (the dashed line in Fig. 1 shows the approximate position of the transition line from the supercooled A-like phase into the B-like phase). It is impossible to observe a clear transition into the A-like phase on warming from the B-like phase, which is, apparently, an indication that such a transition takes place very close to the temperature of the superfluid transition of ^{3}He in aerogel (T_{ca}). In bulk ^{3}He, the A phase can also be in a supercooled metastable phase, but, in contrast to ^{3}He in aerogel, its supercooling region is comparable to its region of existence in an equilibrium state (Fig. 1 shows the A – B equilibrium transition line).

Experiments involving aerogel can be carried out either with pure ^{3}He or in the presence of a small amount of ^{4}He. In the first case, the nuclear magnetic resonance (NMR) signal is strongly influenced by the solid paramagnetic ^{3}He that covers the surface of the strands with two monolayers (because of the van der Waals interaction) and has a high magnetic susceptibility at ultralow temperatures. As a result, near the superfluid transition point the amplitude of the NMR signal from the solid monolayers severalfold exceeds the amplitude of the signal from liquid helium, whose susceptibility is temperature-independent, which complicates the interpretation of the

NMR experiments. Addition of ^{4}He leads to a situation in which solid ^{3}He is replaced by nonmagnetic ^{4}He, so that the NMR signal is determined solely by liquid ^{3}He. It has been established that the presence of ^{4}He has no effect on the phase diagram, i.e., one can expect the internal properties of the superfluid phases of ^{3}He in aerogel not to change either, although the presence of ^{4}He may affect the spatial distribution (texture) of the order parameter or, for instance, the dynamics of the transition between superfluid phases [8].

Magnetic susceptibility measurements done with aerogel to which ^{4}He was added [4, 9] have shown that the magnetic susceptibility of the B-like phase drops with a decrease in temperature, while in the A-like phase it is temperature-independent. Such behavior of the susceptibility is a characteristic feature of many phases which possible (at least in principle) for Cooper pairing with spin 1, which makes it impossible to draw conclusions about the structure of the order parameter. The researchers, however, made a natural assumption that the B-like phase is an analog of the B phase of bulk ^{3}He in which the magnetic susceptibility behaves similarly and that the A-like phase is an analog of the A phase of bulk ^{3}He in which the susceptibility is temperature-independent.

The goal of our experiments described below was to obtain new data on superfluid ^{3}He in aerogel that would enable us to unambiguously identify the superfluid phases. Some of our results have been described in Refs [10, 11]. Here we limit ourselves to describing those experiments where the surface of the aerogel strands was covered by a sufficient amount of ^{4}He (we estimated this amount to be 2 to 4 monolayers). The experiments were carried out by the methods of pulsed and continuous wave NMR in magnetic fields ranging from 284 to 1082 Oe (the corresponding NMR frequencies varied from 922 kHz to 3.51 MHz) with a pressure of 25.5 bar in the experimental cell. The necessary temperature was attained by using nuclear demagnetization. Stycast-1266 epoxy resin was used as the material for the experimental chamber, which had two cells of the same cylindrical shape (the internal dimensions were 5.3 mm in diameter and 5.6 mm in height) connected to the heat exchanger of the demagnetization stage by long (1 cm) and narrow (1 mm in diameter) channels (a schematic of the chamber can be found in Ref. [10]). The first cell (cell No. 1) was almost completely filled with a sample of 98% aerogel (gaps between aerogel and the cell walls of about 0.15 mm were left), while in the second cell (cell No. 2) the aerogel sample was shaped like a tablet 5 mm in diameter and approximately 2.4 mm high and was placed roughly in the middle of the cell (the distance between the upper surface of the tablet and the inner surface of the cell's cap was roughly 1.8 mm). The external magnetic field was directed parallel to the axes of the cells.

2. Experiments with the B-like phase

In identifying the B phase in bulk ^{3}He, whose order-parameter structure was proposed by Balian and Werthamer [12], the pulsed NMR method proved to be highly effective. The order parameter of the Balian–Werthamer phase is the matrix $\mathbf{R}(\mathbf{n}, \theta)$ which describes the rotation of the spin space in relation to the orbital space about the unit vector $\mathbf{n}$ through a certain angle θ. The energy related to the dipole–dipole interaction of the spins in a Cooper pair is proportional to $(1 + 4\cos\theta)^2$ and reaches its minimum when $\theta = \theta_0 = \arccos(-1/4) \approx 104°$. For magnetization deflection angles $\beta < \theta_0$, there is combined precession of the magnetization vector $\mathbf{M}$ and the unit vector $\mathbf{n}$; here, if we ignore the energy related to the interactions between the order parameter and the cell walls, vector $\mathbf{n}$ precesses (as well as vector $\mathbf{M}$) about the external magnetic field $\mathbf{H}$, while the instantaneous orientation of $\mathbf{n}$ is determined by the condition for minimum dipole energy. In this case the dipole torque acting on the spin is zero and the precession frequency is equal to the Larmor frequency ω_L. If $\beta > \theta_0$, there can be no such orientation of $\mathbf{n}$ at which the dipole torque is zero, with the result that there emerges a positive shift of the frequency from the Larmor value [13]:

$$\omega = \omega_L - \frac{4\Omega_B^2}{15\omega_L}\,(1 + 4\cos\beta)\,,$$

where Ω_B is the Leggett frequency, which characterizes the magnitude of the dipole interaction. The dependence of the NMR frequency on the magnetization deflection angle with a singularity at $\beta \approx 104°$ is characteristic only of the Balian–Werthamer phase. Hence, to verify that the B-like phase has an order parameter whose structure is that of the order parameter of the Balian–Werthamer phase (i.e., corresponds to the B-phase of bulk ^{3}He), we measured the dependence of the free-precession frequency on β in the B-like phase. To this end, we applied a short pulse at the NMR frequency to the sample (cell No. 1), which deflected the magnetization by a certain angle. The signal of free precession (induction) was recorded into the memory of a computer, and the time dependences of the signal's frequency and amplitude were determined. The phase transitions in ^{3}He in aerogel were quite evident from the changes in the frequency and duration of the induction signal when small ($\beta < 20°$) tipping pulses were applied. When the temperature was lowered below the superfluid transition point of ^{3}He in aerogel ($T_{ca} \approx 0.76T_c$, where $T_c = 2.37$ mK is the transition temperature in bulk ^{3}He), two consecutive transitions were observed. First, a transition to the A-like phase occurred, where for small values of β the frequency shift from the Larmor value was negative, and then (at a temperature of approximately $\sim 0.85T_{ca}$) a B-like phase emerged, in which the frequency shift is positive for all values of β. When warming starts from the B-like phase, there is only one transition at $T = T_{ca}$, with the signal's frequency shift changing in proportion to $(1 - T/T_{ca})$.

Figure 2 shows the time dependences of the amplitude and frequency of the induction signal obtained in the B-like phase for different tipping pulses at a fixed temperature. The curves representing the time dependence of frequency were extrapolated to $t = 0$ (direct frequency measurements at $t = 0$ are impossible due to the finite dead time of the receiving circuit), and the function $\omega = \omega(\beta)$ was determined (Fig. 3). The singularity in Fig. 3 at $\beta \approx 104°$ is an unambiguous indication that the B-like phase is an analog of the B-phase of bulk ^{3}He. The very fact that for $\beta < \theta_0$ the frequency shift is finite can be explained as follows. In unperturbed bulk ^{3}He-B, the cell walls have a marked effect on the orientation of $\mathbf{n}$. In equilibrium near a wall oriented parallel to $\mathbf{H}$, vector $\mathbf{n}$ is deflected from $\mathbf{H}$ by an angle of about 63°. In the case of linear continuous wave NMR, when the angle β is small, the precession of $\mathbf{n}$ is not about $\mathbf{H}$ but about the equilibrium position of $\mathbf{n}$, which leads to a finite dipole moment and hence to a shift in frequency. As a result, the absorption line has a characteristic asymmetric shape: a peak at the Larmor frequency and a long 'tail' extending to the high-frequency

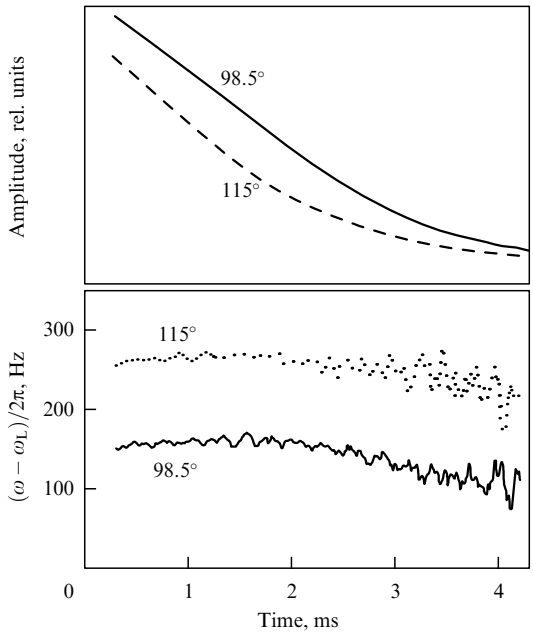

Figure 2. Time dependence of the amplitude and frequency of the induction signal for initial magnetization deflection angles of 98.5° and 115° in ^{3}He in aerogel (cell No. 1). $H = 1.01$ kOe and $T \approx 0.83T_{ca}$.

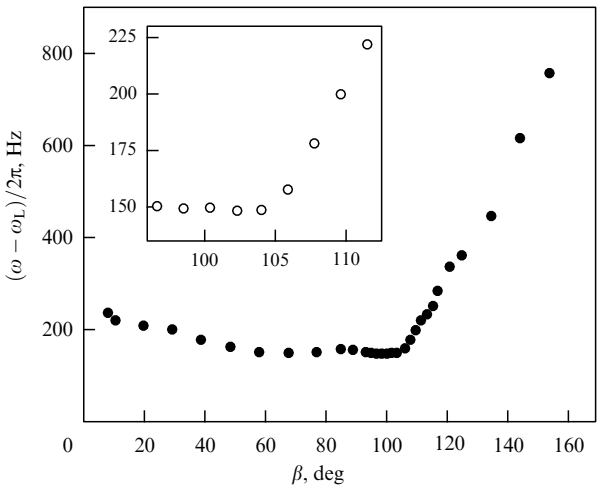

Figure 3. Initial frequency of the induction signal from ^{3}He in aerogel (cell No. 1) as a function of the deflection angle. The inset shows in greater detail the region of deflection angles close to 104°. $H = 1.01$ kOe and $T \approx 0.83T_{ca}$.

region that is determined by the texture of **n**. Usually, under pulsed NMR (i.e., at large values of β) there occurs a texture transition, and both **n** and **M** precess in the entire volume in the same way as in the absence of walls [14]. The critical angle at which this transition occurs is determined, in particular, by the geometry of the cell, and if the cell is small, this angle may be very large. Spatial inhomogeneities of aerogel greatly affect the equilibrium texture of **n** (i.e., act as additional walls), which follows from the signals of linear continuous wave NMR, where the high-frequency tail of the NMR line has an appreciably higher intensity than it does in bulk ^{3}He under the same conditions. Thus, the texture of the order parameter of ^{3}He in aerogel is more rigid than in bulk ^{3}He confined to a cell of the same size, and even at large values of β the above-mentioned texture transition apparently does not take place (or takes place only within a fraction of the sample).

An important property of the B phase of bulk ^{3}He is the possibility of flow of spin supercurrents. This leads, together with the characteristic dependence of the NMR frequency on β, to the possibility of formation of a homogeneously precessing domain (HPD) [15]. In the entire HPD volume the magnetization is deflected by an angle somewhat larger than θ_0 and precesses in phase even in a nonuniform external magnetic field. The constancy of the precession frequency in the entire volume is achieved because the spatial distribution of β ensures at each point the necessary frequency shift, which compensates for the nonuniformity of the magnetic field. The spin supercurrents guarantee the stability of HPDs: any violation of the uniformity of precession leads to the appearance of currents that restore the uniformity. An HPD can be formed and sustained by using continuous wave NMR [16]. Suppose that a radio-frequency (rf) field of frequency ω_{rf} is applied to a ^{3}He-B sample placed in a closed cell and that the dc external magnetic field has a homogeneous gradient directed along the z axis. Let ω_{rf} be smaller than the minimum value of the Larmor frequency over the sample. Let us now reduce the homogeneous component $\mathbf{H}_0$ of the magnetic field. At a certain moment in time the resonance condition $\omega_{rf} = \omega_L$ will be met at the boundary of the sample, $z = 0$, and if the amplitude of the rf field is sufficiently large (~ 0.01 Oe in our experiments), the magnetization deflection angle in this region may reach or even exceed 104°. As a result, an HPD is formed in this region, and its size increases, so that the coordinate of the domain wall separating the HPD and the region where magnetization is in a state close to equilibrium is specified by the condition that $\omega_{rf} = \omega_L(z_w)$. A further decrease in $\mathbf{H}_0$ may lead to a situation in which the HPD fills the entire cell. As the HPD becomes longer, the rate of longitudinal magnetic relaxation in the bulk of the HPD grows (in particular, an increase in the magnitude of the local shifts of the frequencies from the Larmor values leads to a speedup of relaxation according to the Leggett – Takagi mechanism [17]) and, finally, the HPD is destroyed. If at a certain HPD length the rf field is switched off, the size of the HPD decreases at a rate determined by magnetic relaxation. Here the coherent nature of the precession is retained, and one may observe a long-lived induction signal (LLIS), i.e., a signal whose duration is much longer than the dephasing time, which is specified by the gradient of the external field. The instantaneous LLIS frequency is equal to the Larmor value at the position of the domain wall, and as relaxation develops it decreases to $\omega_L(z = 0)$.

We were able to observe the formation of an HPD in the B phase of ^{3}He in aerogel in both cells mentioned above. Figure 4 shows the NMR signals from cell No. 2 as $\mathbf{H}_0$ decreases for different amplitudes of the rf field (we use on the horizontal axis a conventional coordinate defined by the ratio $z = (\gamma H - \omega_{RF})/\gamma \nabla H$, which is equal to the coordinate of the domain wall for the case where the HPD does not fill the entire cell). At an amplitude of the rf field of ~ 0.006 Oe, no HPD is formed (the dashed curve is the signal whose strength is multiplied by 4), although there is a small surge near the value $z = 0$, which indicates an attempt of such formation. At an rf field amplitude of ~ 0.01 Oe (solid curve) the shape and amplitude of the NMR line change dramatically. This is due to the formation of an HPD, which, as H_0 changes, is first formed in bulk ^{3}He, then becomes longer, enters aerogel, and finally fills up the entire cell. The bends in the NMR line at

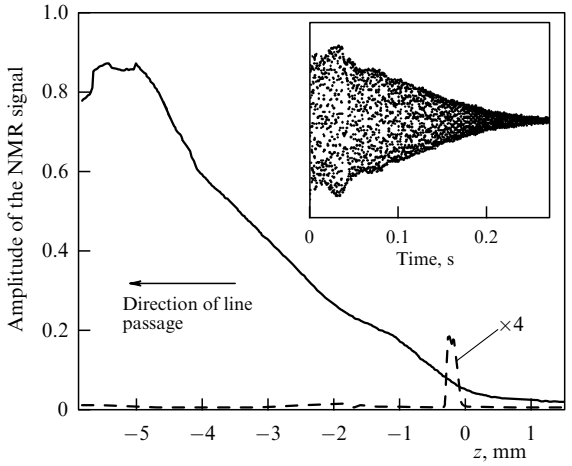

Figure 4. Amplitude of continuous NMR signals from cell No. 2 for different amplitudes of the rf field (h). The solid curve corresponds to $h \sim 0.01$ Oe and the dashed curve to $h \sim 0.006$ Oe (for the sake of clarity, the data represented by the dashed curve have been multiplied by 4). The inset shows an LLIS right after the rf field is switched off, with an approximately 4.9-mm long HPD grown at $h \sim 0.01$ Oe. $\nabla H = 0.94$ Oe cm^{-1}, $H = 284$ Oe, and $T \approx 0.66 T_{ca}$.

$z \approx 1.8$ mm and $z \approx 4.2$ mm are, obviously, related to the passage of the domain wall through the aerogel–bulk boundaries. The inset in Fig. 4 shows an LLIS (as it was recorded by the digital oscilloscope) obtained after an HPD with a length of approximately 4.9 mm was 'grown' in the cell and the rf field was switched off. The characteristics of this signal correspond to the expected ones: the frequency gradually decreases to $\omega_L(z = 0)$, and the duration is on the order of 200 ms, which is much longer than the dephasing time, which is determined by the gradient of the external field (~ 0.7 ms in our case).

3. Experiments with the A-like phase

The magnetic susceptibility of the A phase of bulk ^{3}He is temperature-independent, i.e., the phase has no pairs with a zero projection of spin on the direction of the magnetic field. It is assumed that the order parameter of the A phase corresponds to the one proposed by Anderson, Brinkman, and Morel (e.g., see Ref. [1]). Here, the dipole energy is proportional to $-(\mathbf{l} \cdot \mathbf{d})^2$, where $\mathbf{l}$ and $\mathbf{d}$ are vectors common for a macroscopic volume of ^{3}He that describe the orientations of the orbital and spin angular momenta of the pair. In equilibrium and in the absence of walls, $\mathbf{d} \perp \mathbf{M}$ and $\mathbf{d} \parallel \mathbf{l}$ (the latter follows from the condition for minimum dipole energy). Under NMR conditions, the motion of magnetization (and hence the motion of $\mathbf{d}$) lead to a finite dipole moment even at small values of β [18]:

$$\omega = \omega_L + \frac{\Omega_A^2}{8\omega_L}(1 + 3\cos\beta)\,,$$

where Ω_A is the Leggett frequency for the A phase. At small values of β, the frequency shift is positive, and at $\beta = \arccos(-1/3) \approx 109°$, its sign changes. The susceptibility measurements done by Barker et al. [4] have shown that in the A-like phase of ^{3}He in aerogel there is equal-spin pairing, i.e., there are no pairs with a zero projection of spin on the direction of the magnetic field as in the case of bulk ^{3}He-A. However, the dependence of the NMR frequency on the magnetization deflection angle is quite different. When the values of β are small, there is a negative frequency shift [4], with the magnitude of this shift beginning to decrease as β grows, and at angles greater than $\sim 90°$ the shift becomes positive [11]. A negative frequency shift for small β may, in principle, be observed in the A phase [19] under conditions of a special restricted geometry. In equilibrium, the walls of the cell align $\mathbf{l}$ perpendicularly to the surface within a narrow layer whose thickness is on the order of the dipole length $l_d \sim 10^{-3}$ cm. Accordingly, within a narrow gap oriented perpendicularly to $\mathbf{H}$, we have $\mathbf{d} \perp \mathbf{l}$ and the dipole energy is maximum. An analysis of the equations of motion suggests in this case that the frequency shift is negative. If we assume that the presence of aerogel has a marked effect on the texture of $\mathbf{l}$ but that on the average the anisotropy of aerogel is small (indications of this can be found in the results of NMR experiments in which the field $\mathbf{H}$ can be rotated [20]), then after averaging over all possible directions of $\mathbf{l}$ the dipole moment acting on the spin proves to be zero, i.e., the NMR frequency in the A phase of ^{3}He in aerogel should not be shifted from its Larmor value. We also note that the negative frequency shift at small β has been observed for different samples of 98% aerogel (while a positive frequency shift has never been observed). For instance, our aerogel samples were grown at the University of Delaware (Newark, Del., USA), which sets them apart from the samples used by Barker et al. [4, 20].

Thus, the NMR properties of the A-like phase do not provide a final answer to the problem of identifying this phase. Recently, Fomin in his theoretical paper [21] showed that, at least very close to the superfluid transition temperature, the axiplanar phase in the presence of aerogel is more favorable than the A phase. The magnetic susceptibility measurements do not contradict this possibility.

4. Conclusion

Our experiments leave no doubt that the B-like superfluid phase of ^{3}He in aerogel corresponds to the Balian–Werthamer phase (i.e., the B phase of bulk ^{3}He). We also found that the spin supercurrents in ^{3}He-B in aerogel play an important role in spin dynamics, just as they do in bulk ^{3}He-B. As for the A-like phase, the existing experimental data do not make it possible to identify such a phase. A possible alternative to the A phase is the axiplanar phase.

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References

1. Vollhardt D, Wölfle P *The Superfluid Phases of ^{3}He* (London: Taylor & Francis, 1990)
2. Porto J V, Parpia J M *Phys. Rev. Lett.* **74** 4667 (1995)
3. Sprague D T et al. *Phys. Rev. Lett.* **75** 661 (1995)
4. Barker B I et al. *Phys. Rev. Lett.* **85** 2148 (2000)
5. Gervais G et al. *Phys. Rev. B* **66** 054528 (2002)
6. Porto J V, Parpia J M *Phys. Rev. B* **59** 14583 (1999)
7. Alles H et al. *Physica B* **255** 1 (1998)
8. Dmitriev V V et al. "Experiments on A-like to B-phase transitions of ^{3}He confined to aerogel" *Physica B* **329–333** 320 (2003)
9. Sprague D T et al. *Phys. Rev. Lett.* **77** 4568 (1996)
10. Dmitriev V V et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **76** 371 (2002) [*JETP Lett.* **76** 312 (2002)]

11. Dmitriev V V et al. "Pulsed NMR experiments in superfluid ^{3}He confined in aerogel" *Physica B* **329 – 333** 296 (2003)
12. Balian R, Werthamer N R *Phys. Rev.* **131** 1553 (1963)
13. Brinkman W F, Smith H *Phys. Lett. A* **53** 43 (1975); Osheroff D D, Corruccini L R, in *Proc. of the 14th Intern. Conf. on Low Temperature Physics LT-14* Vol. 1 (Ed. M Krusius, M Vuorio) (Amsterdam: North-Holland, 1975) p. 100
14. Borovik-Romanov A S et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **37** 600 (1983) [*JETP Lett.* **37** 716 (1983)]; Golo V L, Leman A A, Fomin I A *Pis'ma Zh. Eksp. Teor. Fiz.* **38** 123 (1983) [*JETP Lett.* **38** 146 (1983)]
15. Borovik-Romanov A S et al. *Zh. Eksp. Teor. Fiz.* **88** 2025 (1985) [*Sov. Phys. JETP* **61** 1199 (1985)]; Fomin I A *Zh. Eksp. Teor. Fiz.* **88** 2039 (1985) [*Sov. Phys. JETP* **61** 1207 (1985)]
16. Borovik-Romanov A S et al. *Zh. Eksp. Teor. Fiz.* **96** 956 (1989) [*Sov. Phys. JETP* **69** 542 (1989)]
17. Leggett A J, Takagi S *Ann. Phys.* (New York) **106** 79 (1977)
18. Brinkman W F, Smith H *Phys. Lett. A* **51** 449 (1975); Osheroff D D, Corruccini L R *Phys. Lett. A* **51** 447 (1975)
19. Ahonen A I, Krusius M, Paalanen M A *J. Low Temp. Phys.* **25** 421 (1976)
20. Barker B I et al. *J. Low Temp. Phys.* **113** 635 (1998)
21. Fomin I A *Pis'ma Zh. Eksp. Teor. Fiz.* **77** 285 (2003) [*JETP Lett.* **77** 240 (2003)]