Superfluid ^{3}He in anisotropic aerogels

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Superfluid ^{3}He in aerogel.

Bulk superfluid ^{3}He is absolutely pure and it is an ideal object for tests of theoretical models of superfluidity and superconductivity with unconventional Cooper pairing.

Important question: how impurities influence on the superfluid states. It is possible to investigate if we use ^{3}He confined in aerogel.

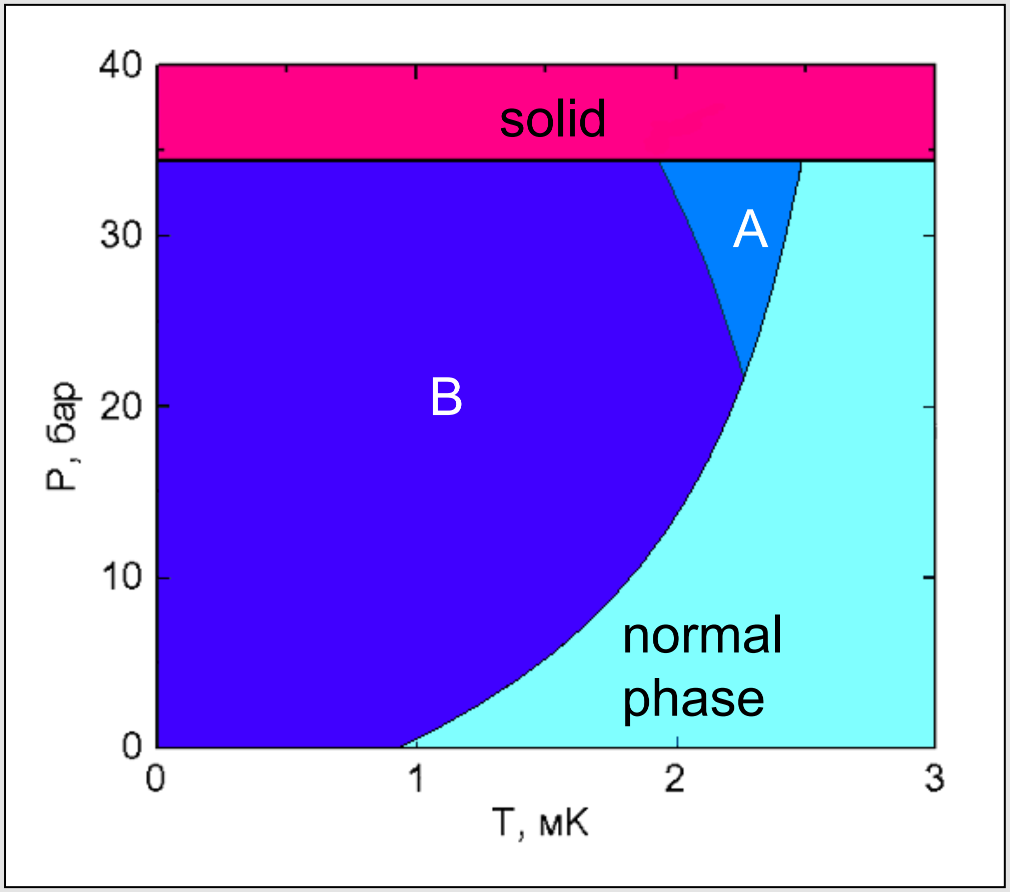
It is also important that aerogel can be globally anisotropic – it allows to investigate the influence of anisotropic impurities on superfluidity.

Bulk superfluid ^{3}He

Cooper pairing into the state with L=1 and S=1.
Order parameter: 3x3 matrix $A_{\mu\nu}$

$$F_c = -\alpha\,\mathrm{Sp}\,(AA^+) + \beta_1\,|\,\mathrm{Sp}\,(A\tilde{A})\,|^2 + \beta_2\,[\mathrm{Sp}\,(AA^+)]^2 + \beta_3\,\mathrm{Sp}\,[(A^+A)(A^+A)^*] + \beta_4\mathrm{Sp}\,[(AA^+)^2] + \beta_5\mathrm{Sp}\,[(AA^+)(AA^+)^*]$$

In bulk superfluid ^{3}He in isotropic space, T_c and the free energy are degenerate with respect to 3 projections of orbital angular momentum and to 3 projections of spin. In principal, many superfluid phases are possible, but only 2 phases with the lowest free energy are realized (A phase with ABM order parameter and B phase with BW order parameter).



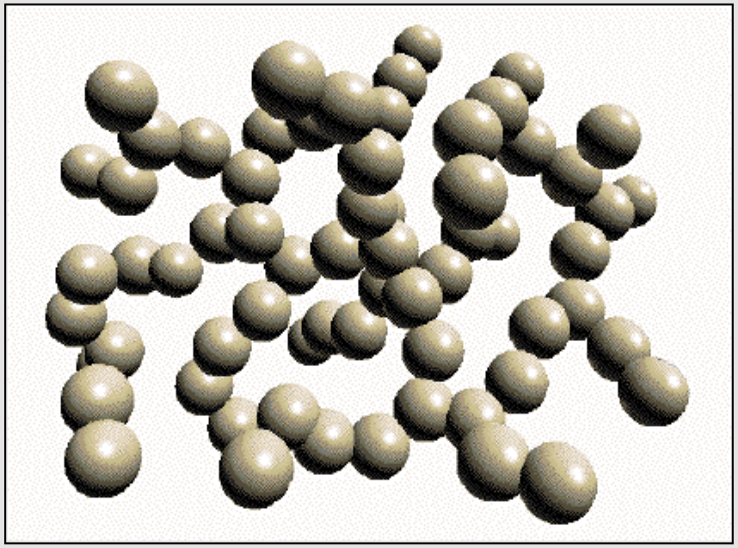
A phase (ABM): $A_{\mu\nu} = \Delta_0 e^{i\varphi}\hat{d}_\mu(\hat{m}_\nu + i\hat{n}_\nu)$

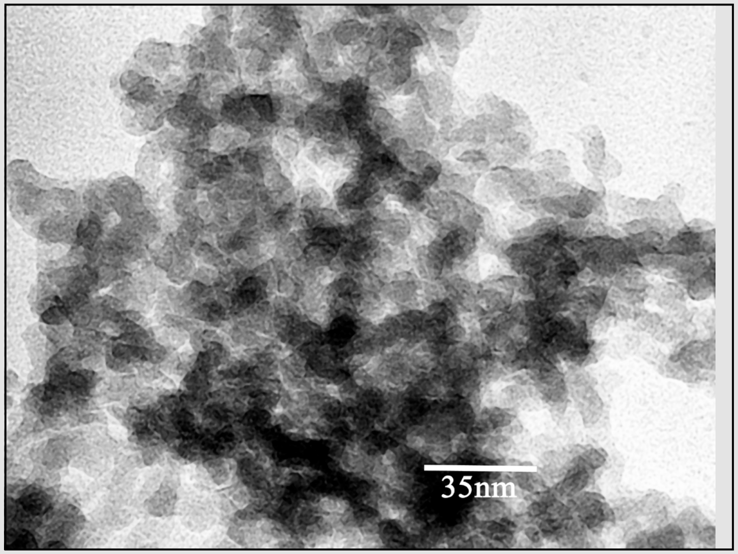
B phase (BW): $A_{\mu\nu} = \Delta e^{i\varphi}\boldsymbol{R}(\boldsymbol{n},\theta)$

The degeneracy over spin projections is lifted by magnetic field → the additional term in the free energy ($\propto H_\mu H_\nu A_{\mu j} A^*_{\nu j}$) appears and A_1 phase is stabilized in a narrow region near T_c.

Superfluid ^{3}He in silica aerogel.

In most of the experiments 98% open silica aerogels used (with porosities 97.5-99.5%) . They consists of SiO_2 strands with a diameter ~3 nm, which is less than the superfluid coherence length (20-80 nm). The distance between strands ~100 nm.



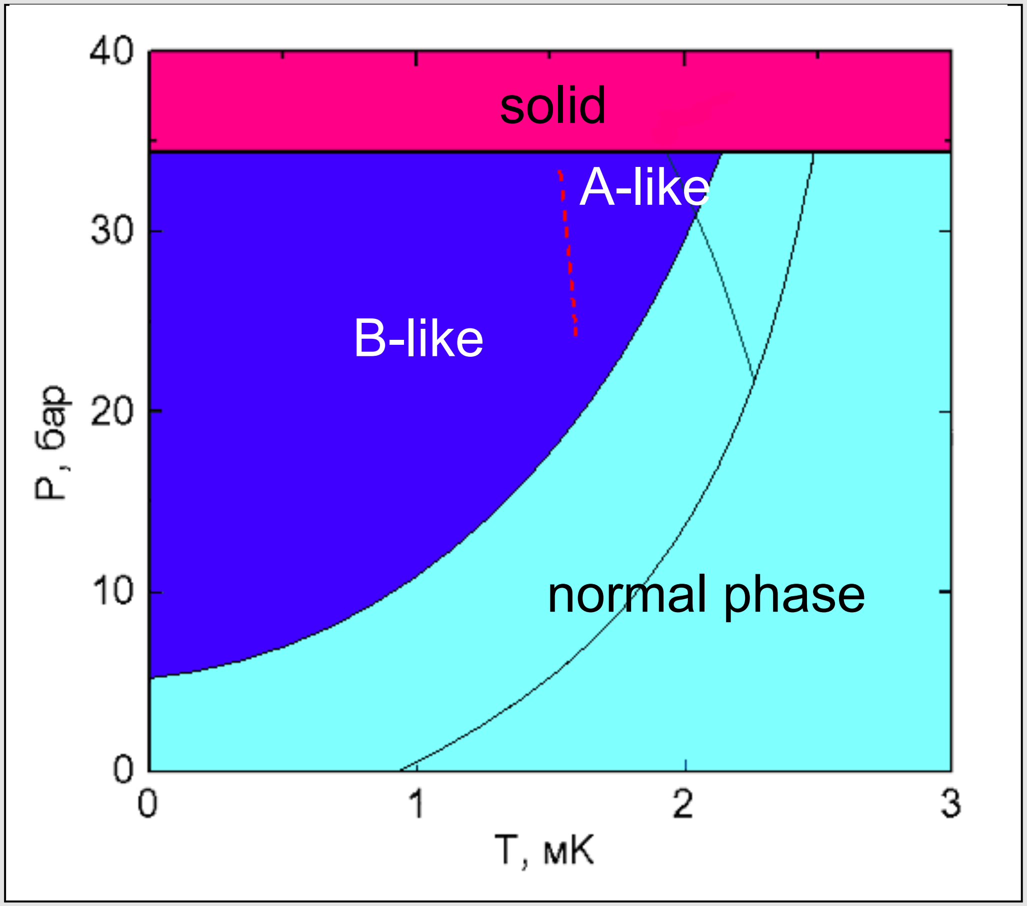


www.mtsc.unt.edu

^{3}He in silica aerogel

Discovery:
J.V.Porto and J.M.Parpia, PRL. (1995);

D.T.Sprague, T.M.Haard, J.B.Kucia, M.R.Rand, Y.Lee, P.J.Hamot, W.P.Halperin, PRL (1995)



A-like and B-like phases have the same order parameters as A and B phases.

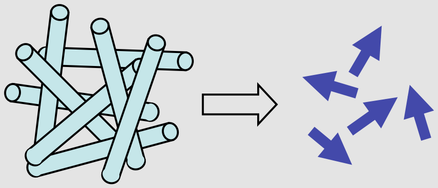
A-like phase = ABM phase: $A_{\mu\nu} = d_\mu(m_\nu + i n_\nu); \quad \boldsymbol{l} = \mathbf{m} \times \mathbf{n}$

B-like phase = BW phase: $A_{\mu\nu} = \mathbf{R}(\mathbf{n}, \theta)$

G.E.Volovik, JLTP (2008): local inhomogeneties of aerogel can destroy long-range order of ABM phase.

⇨ *Larkin-Imry-Ma (LIM) state of* $\boldsymbol{l}$.

LIM length (~1 mkm) << dipole length



Larkin-Imry-Ma (LIM) state in the ABM phase of ^{3}He in aerogel with uniaxial anisotropy:

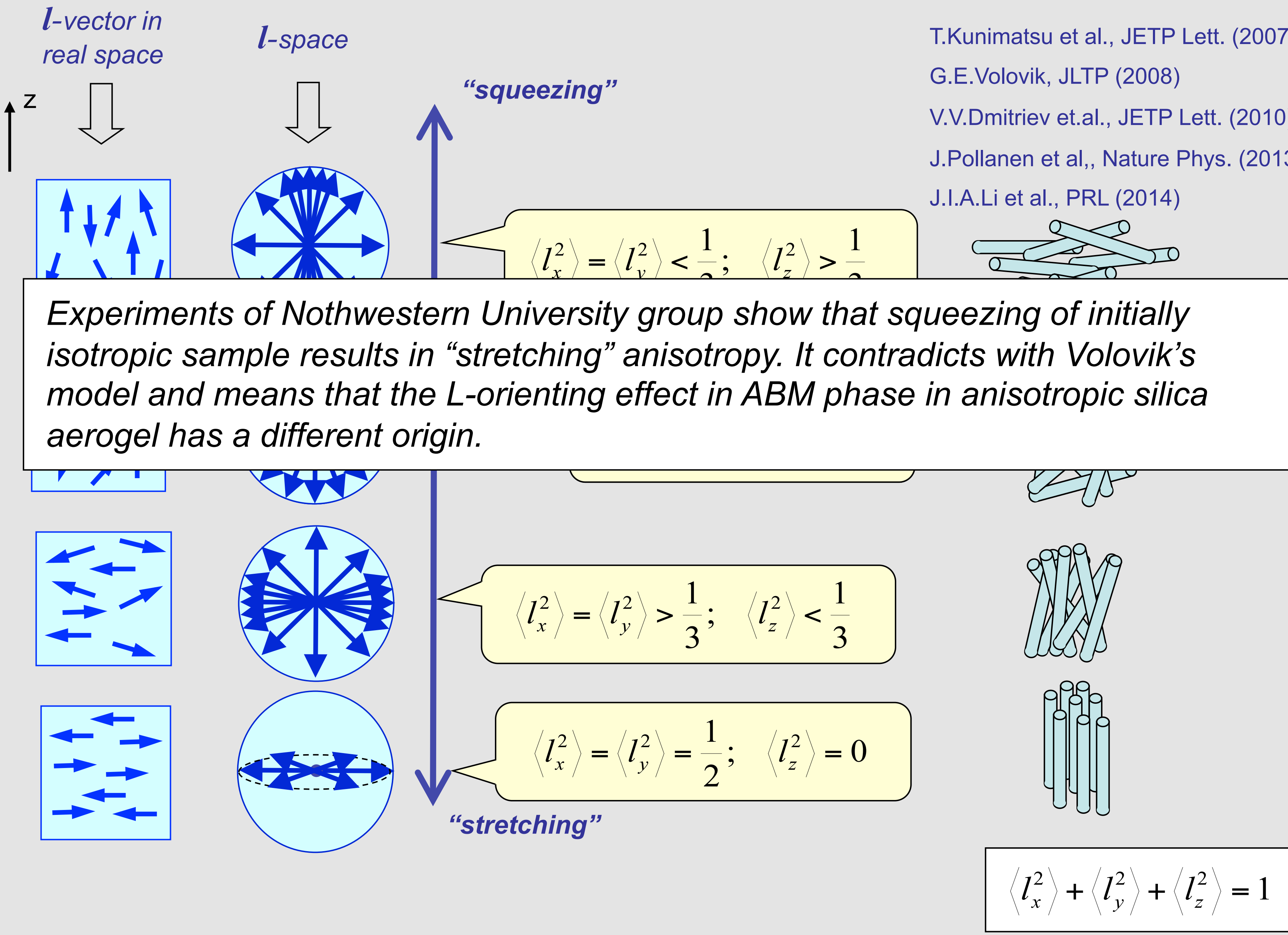
T.Kunimatsu et al., JETP Lett. (2007)

G.E.Volovik, JLTP (2008)

V.V.Dmitriev et.al., JETP Lett. (2010)

J.Pollanen et al,, Nature Phys. (2013)

J.I.A.Li et al., PRL (2014)



Experiments of Nothwestern University group show that squeezing of initially isotropic sample results in "stretching" anisotropy. It contradicts with Volovik's model and means that the L-orienting effect in ABM phase in anisotropic silica aerogel has a different origin.

Thus, experiments with globally anisotropic silica aerogels show that spatial structure of the order parameter and phase diagram may be essentially changed by the anisotropy.

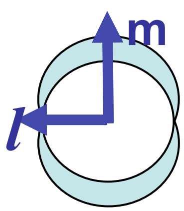
Globally anisotropic aerogel also may result in appearance of new superfluid phases which do not exist in bulk ^3He. This is due to that the degeneracy over orbital projections may be lifted in globally anisotropic aerogel.

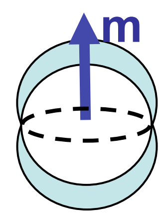
The additional term in the Ginzburg-Landau free energy is $\eta_{jl} A_{\mu j} A^*_{\mu l}$

Theory predicts that in case of strong "stretching" anisotropy we may get polar distorted ABM phase or pure polar phase.

K.Aoyama,R.Ikeda, Phys.Rev. B (2006)

ABM	polar distorted ABM	polar
$A_{\mu\nu} = \Delta_0 d_\mu (m_\nu + i n_\nu)$	$A_{\mu\nu} = \Delta e^{i\varphi} d_\mu (a m_\nu + i b n_\nu)$ $(a^2 + b^2 = 1)$	$A_{\mu\nu} = \Delta_0 e^{i\varphi} d_\mu m_\nu$





Another possibility is a distorted axi-planar phase

$$A_{\mu\nu} = \Delta_0 d_\mu m_\nu + i \Delta_1 d_\mu n_\nu + \Delta_2 e_\mu l_\nu$$

I.A.Fomin, E.V.Surovtsev, JETP Lett. (2013)

“Nematically ordered” (N-) aerogels:

2 types: “Obinisk” aerogel (AlOOH strands) and nafen (Al_2O_3 strands).

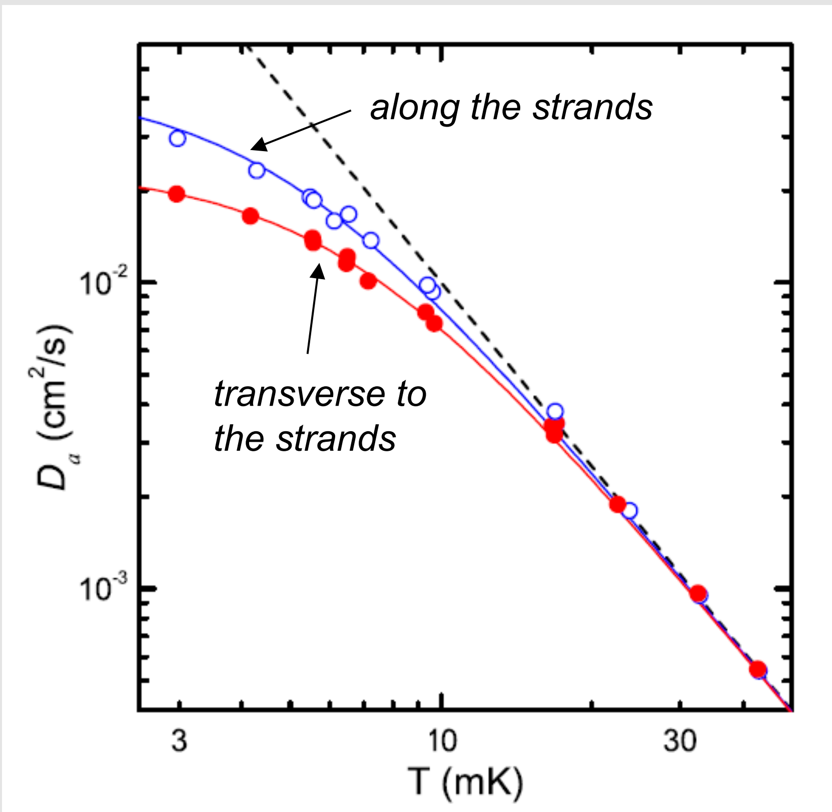
Properties:

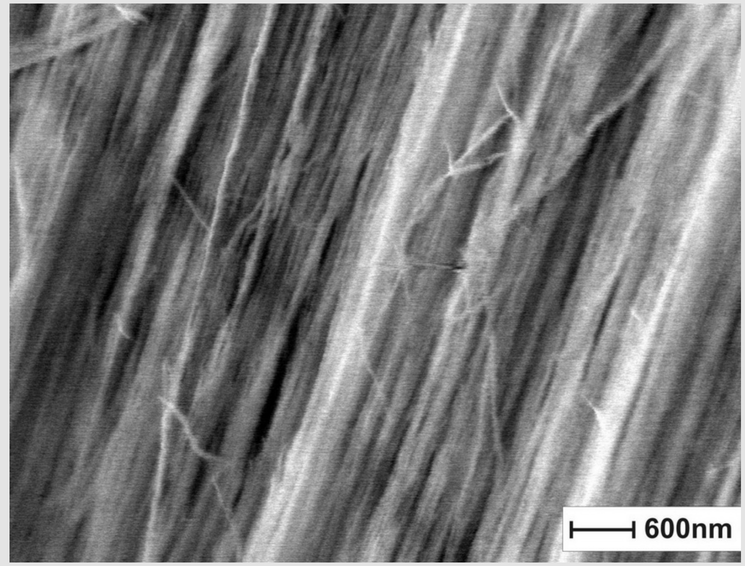
sample	density (mg/cm^3)	porosity (%)	diam.of strands (nm)	$D_{\|} / D_{\perp}$	$\lambda_{\|}$ (nm)	$\lambda_{\perp\|}$ (nm)
Obninsk	30	98.7	9	1.9	850	450
nafen	90	97.8	8	3.3	960	290
nafen	243	93.9	9	8.1	570	70

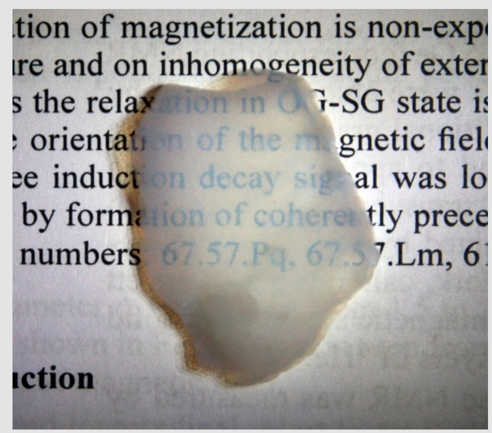
AlOOH aerogel produced in Leypunskiy Institute of Power Engeneering (Obninsk, Moscow region)

R.Sh.Askhadullin et al., J. of Phys.: Conf. Ser., **98**, 072012 (2008)

Effective density: 8-50 mg/cm^3
Diameter of strands: 6-9 nm
Distance between strands: ~100 nm

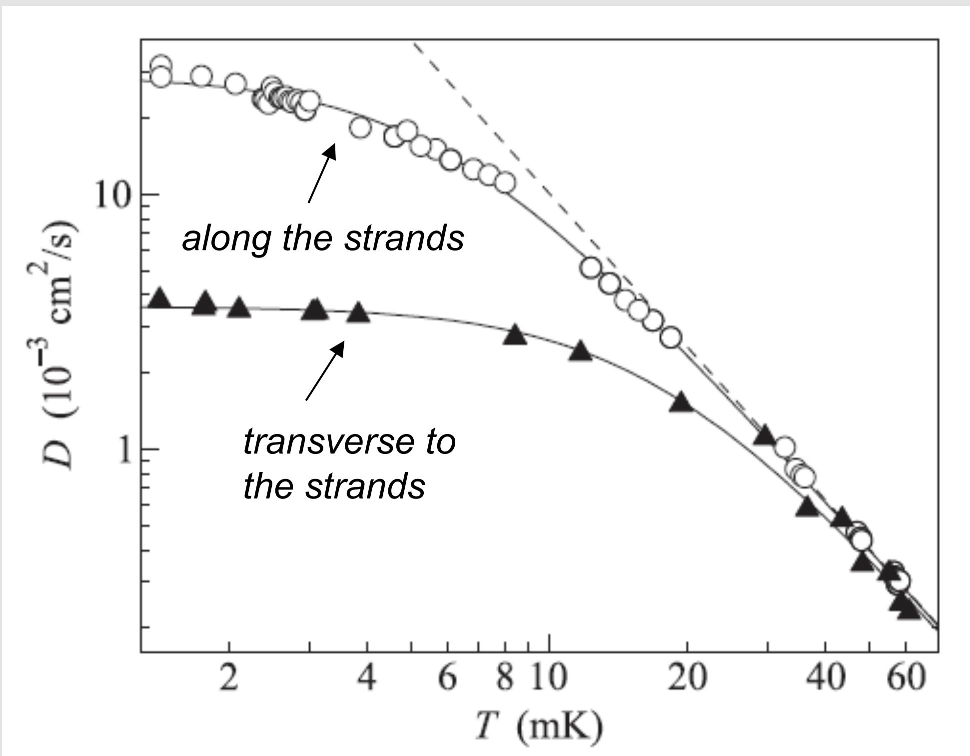




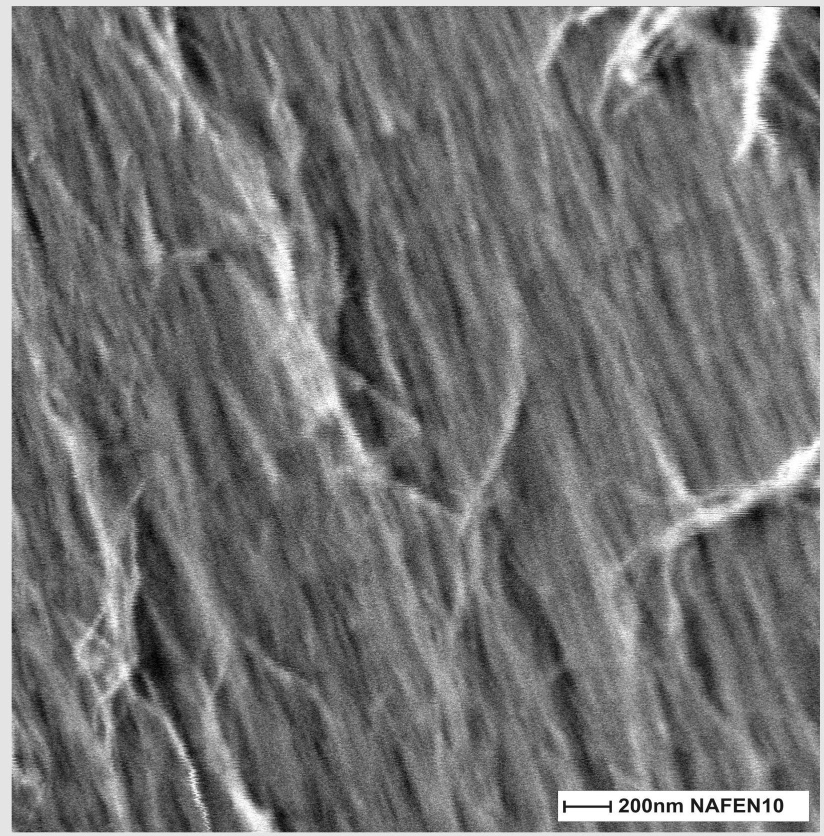


Al_2O_3 aerogel ("Nafen") produced by ANF Technology Ltd (Tallinn, Estonia)

Effective density: 90 mg/cm³ (97.8% open) or 243 mg/cm³ (94% open)
Diameter of strands: ~8 nm
Distance between strands: ~40-70 nm
For 90 mg/cm³ sample mean free paths along and transverse to strands are 960 and 290 nm, for 243 mg/cm³ sample mean free paths along and transverse to strands are 570 and 70 nm.



Spin diffusion of ³He in nafen-243 at P=2.9 bar

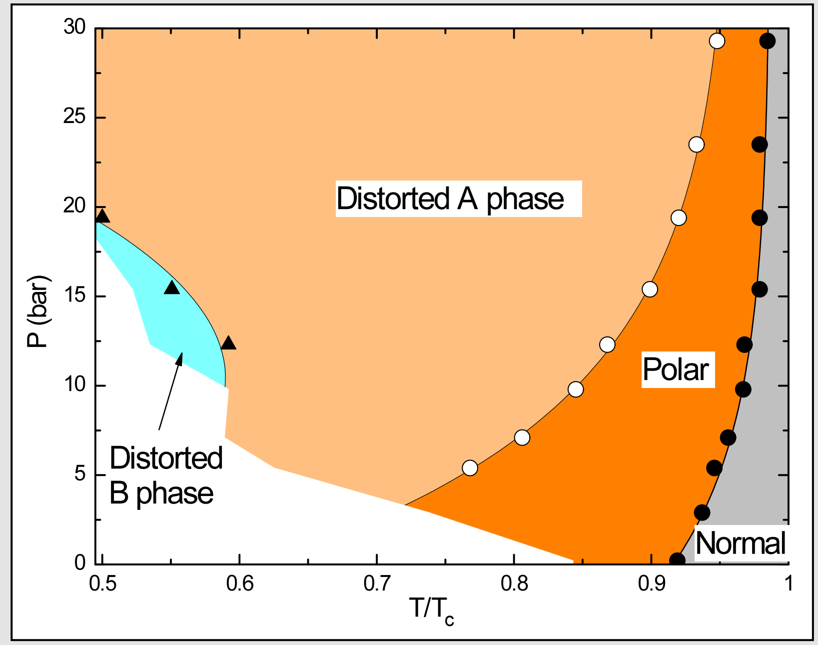


SEM picture for 90 mg/cm³ sample

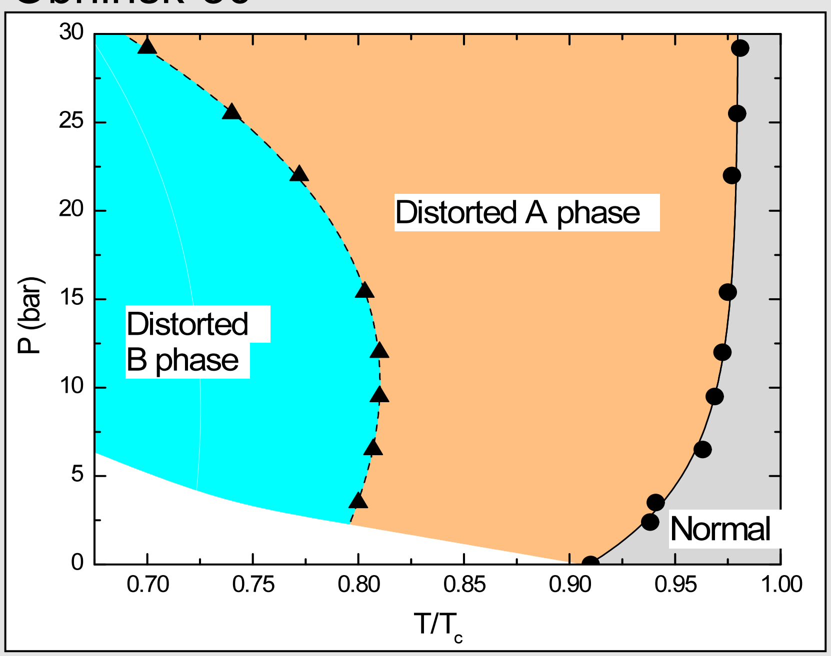
Phase diagrams of ^{3}He in N-aerogel:

1. *More dense – more "polar"*
2. *Suppression of T_c is very small in comparison with silica aerogel.*

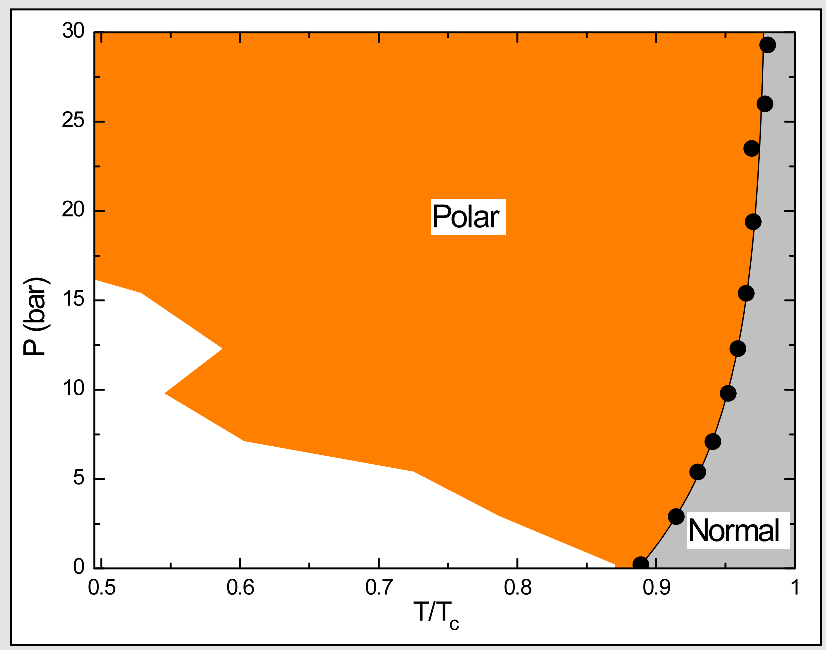
nafen-90



Obninsk-30



nafen-243



Open questions:

a) What is the origin of the L-orientation effect in the ABM phase of ^{3}He in silica aerogel?

b) Can we obtain distorted A and B phases in nafen-243 at low enough temperature? Can we obtain the transition from pure polar phase into the distorted B phase?

c) ^{3}He in N-aerogels with higher densities where diameter of strands will be of the same order (or smaller) as the distance between strands. Does polar phase exist in Obninsk samples?

d) Rotating ^{3}He in N-aerogel (half-quantum vortices, what we will get after B-A transition etc.)

e) Axi-planar phase in ^{3}He in N-aerogel.

f) What about other superfluids (superconductors) with unconventional pairing?

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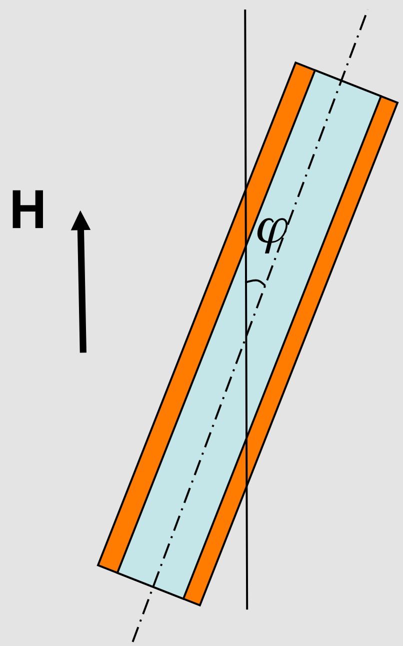
In absence of ^{4}He solid ^{3}He on the surface of aerogel strands should result in NMR frequency shift in normal ^{3}He.

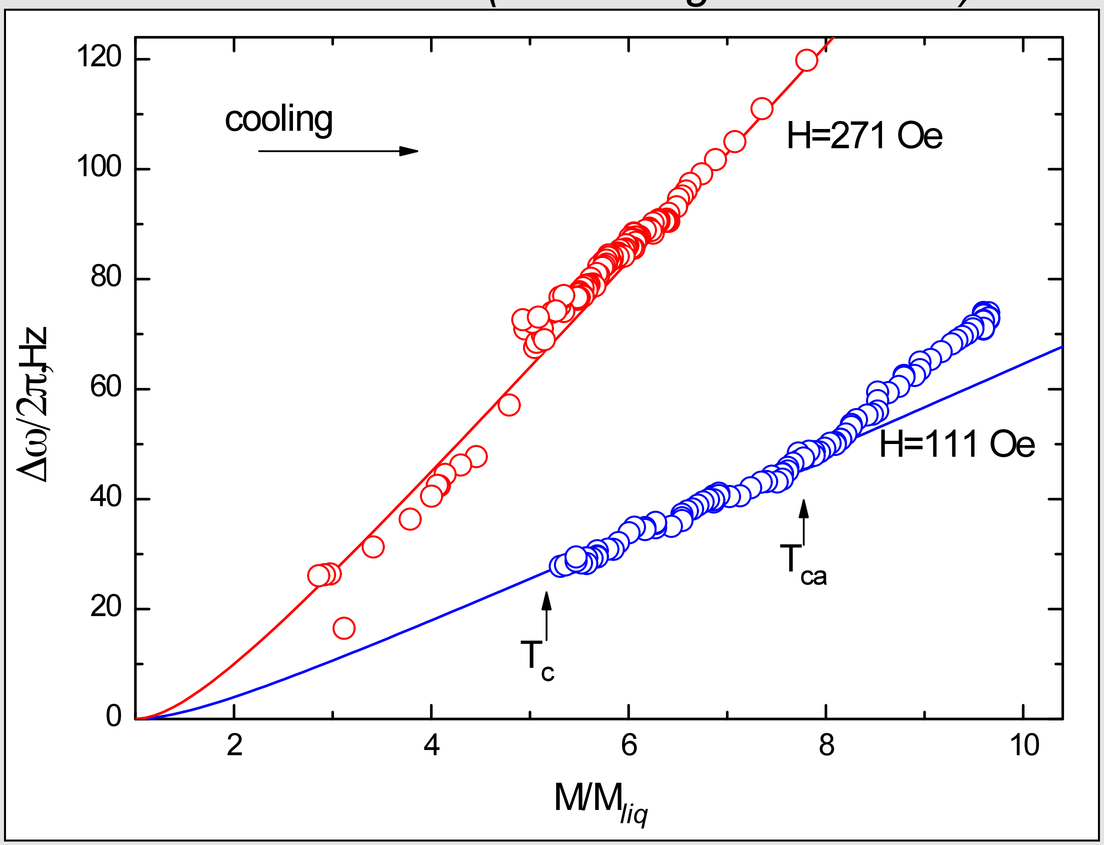


The mean frequenct shift in solid ^{3}He at a separate strand:

$$\Delta\omega \approx \pi\gamma\chi H(2 - 3\sin^2\varphi)$$

For isotropic distribution the mean shift is zero, but if strands have the preferable orientation along H then a nonzero positive shift should be visible in high magnetic fields.

Pure ^{3}He in nafen-243 (H is along the strands)



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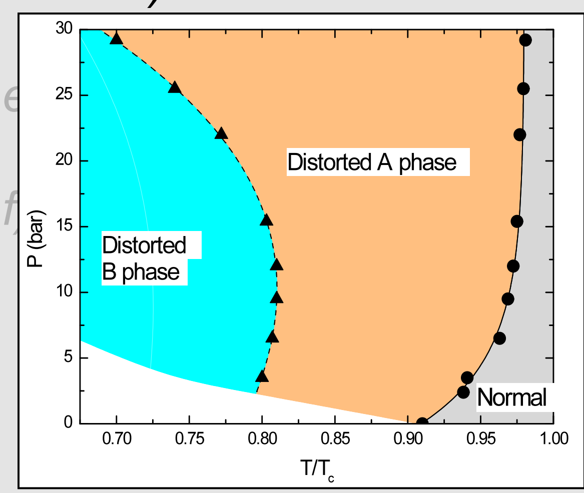

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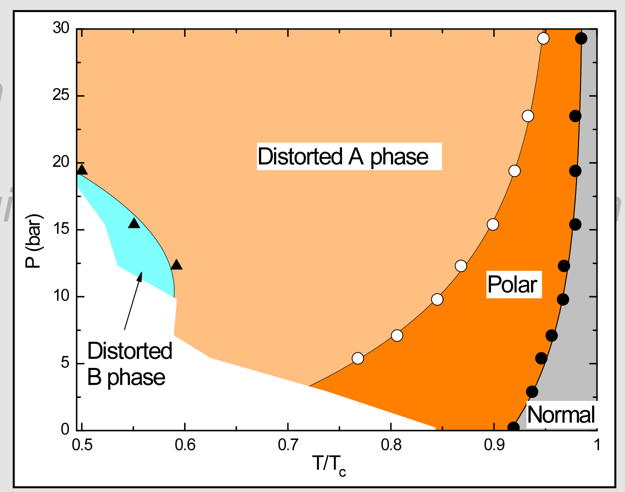
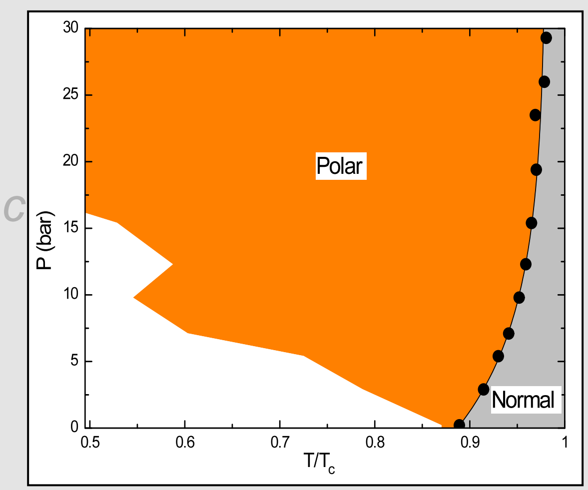


nafen-90



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f) *V*

I.A. Fomin, E.V. Surovtsev, JETP Lett. (2013) – *axi-planar phase of ^{3}He may be realized in stretched aerogel*

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The end