New topological phases of superfluid ^{3}He stabilized by nanostructured confinement

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1. *Introduction.*

2. *Identification of the polar phase and polar distorted A phase by NMR*

3. *Polar phase in squeezed nematic aerogel*

4. *Observation of the β phase*

Bulk superfluid ^{3}He

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

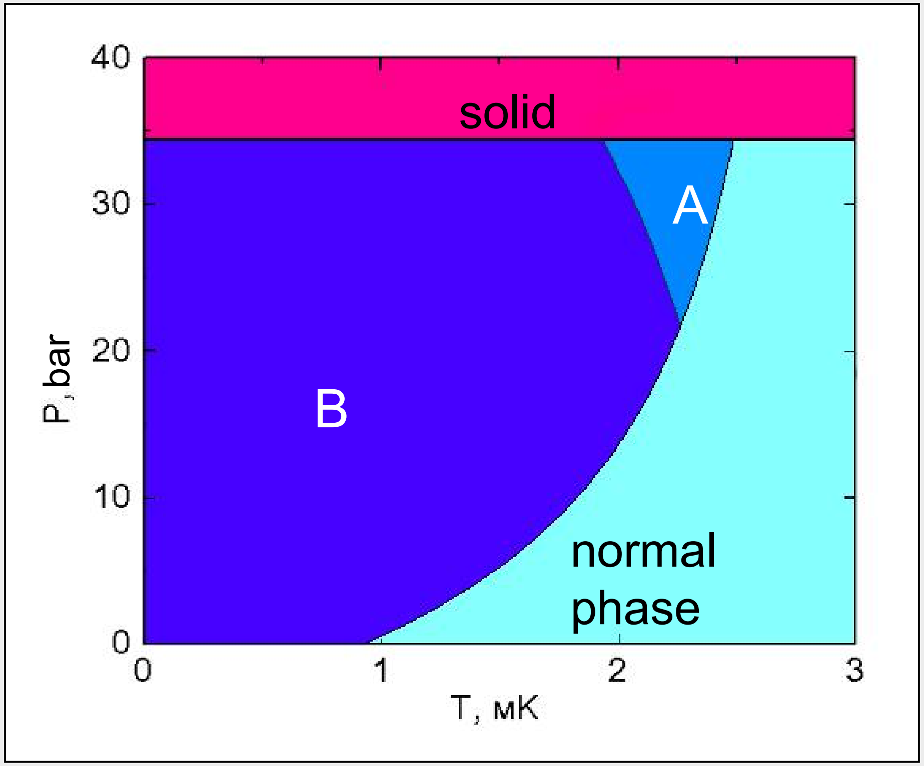
$$F_c = -\alpha\,\mathrm{Sp}\,(AA^+) + \beta_1\,|\,\mathrm{Sp}\,(A\tilde{A})\,|^2 + \beta_2\,[\mathrm{Sp}\,(AA^+)]^2 + \beta_3\,\mathrm{Sp}\,[(A^+A)\,(A^+A)^*] + \beta_4\mathrm{Sp}\,[(AA^+)^2] + \beta_5\mathrm{Sp}\,[(AA^+)\,(AA^+)^*]$$

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 phases with the lowest energy are realized (A and B phases).

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

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

*In the **A phase** projection of spin of Cooper pairs on a specific direction is +1 or -1, i.e. here only ↑↑ and ↓↓ spin states are present.*



The degeneracy over spin projections is lifted by magnetic field -- the additional term in free energy ($\propto H_\mu H_\nu A_{\mu j} A^*_{\nu j}$) appears and A_1 phase with only ↑↑ pairs becomes favorable in a narrow (~0.02 T_c in field of 10 kOe) region near T_c. So we have the splitting of T_c into 2 transitions: at $T_{A1}=T_c+\eta_1 H$ and at $T_{A2}=T_c-\eta_2 H$.

Landau free energy for bulk superfluid ^{3}He in aerogel:

$$
\begin{aligned}
F_c = & -\alpha\,\mathrm{Sp}\,(AA^+) + \beta_1\,|\,\mathrm{Sp}\,(A\widetilde{A})\,|^2 + \beta_2\,[\mathrm{Sp}\,(AA^+)]^2 + \\
& + \beta_3\,\mathrm{Sp}\,[(A^+A)\,(A^+A)^*] + \beta_4\mathrm{Sp}\,[(AA^+)^2] + \beta_5\mathrm{Sp}\,[(AA^+)\,(AA^+)^*] \\
& + k_{jl} A_{\mu j} A^*_{\mu l}
\end{aligned}
$$

In the bulk superfluid ^{3}He, where Cooper pairs are formed into a state with L= 1, T_c is degenerate with respect to 3 projections of orbital angular momentum.

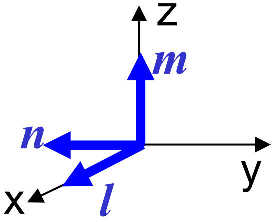
Degeneracy of T_c over the orbital projections is lifted by a global orbital anisotropy. Such anisotropy can be induced by a large stretching anisotropy of aerogel where the substate with $L_z = 0$ should be favorable in comparison with substates with $L_z=+1$ or -1.

K.Aoyama,R.Ikeda, Phys.Rev. B (2006) – *polar phase may be realized in anisotropic aerogel in case of an effective mean free path of ³He quasiparticles is longer along some specific direction.*
This prediction is supported by further theoretical works: J.A.Sauls (2013), I.A.Fomin (2014), R.Ikeda (2015)

Pure ABM:

$$A_{\mu\nu} = \Delta_0 d_\mu (m_\nu + i n_\nu)$$

Gap vanishes at 2 points
on Fermi sphere

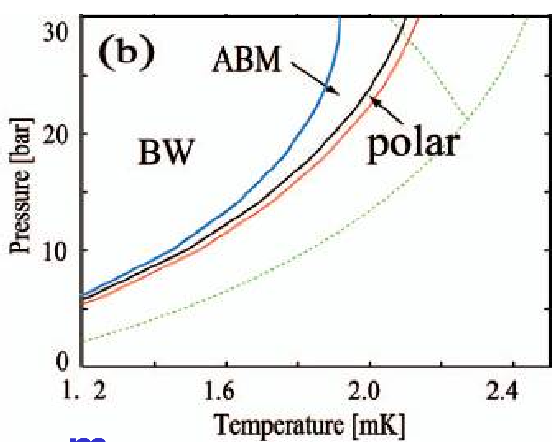


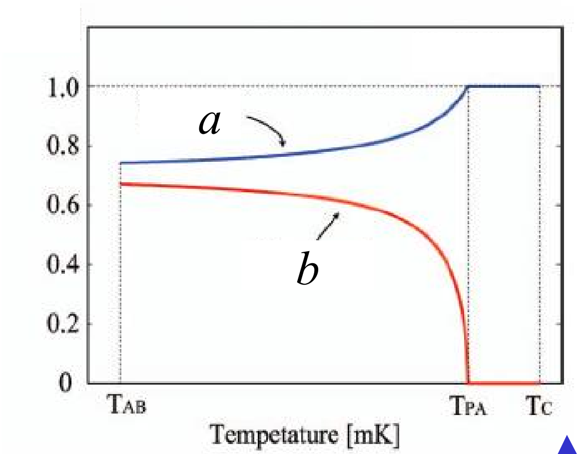
$$\boldsymbol{l} = \boldsymbol{m} \times \boldsymbol{n}$$

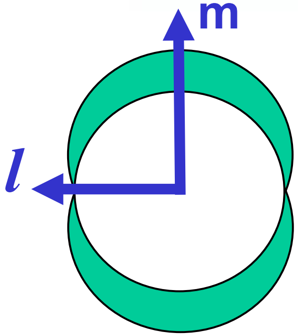
Polar:

$$A_{\mu\nu} = \Delta_0 e^{i\varphi} d_\mu m_\nu$$

Gap is zero on the circle
on Fermi sphere



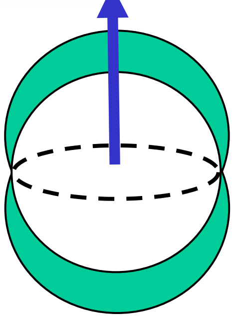




$a = b$

$$A_{\mu\nu} = \Delta e^{i\varphi} d_\mu (a m_\nu + i b n_\nu)$$

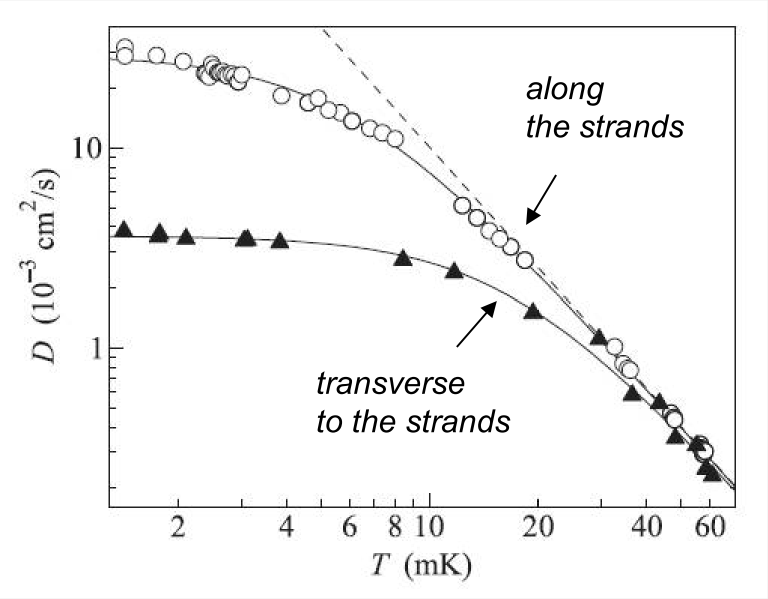
$$(a^2 + b^2 = 1)$$



$b = 0$

Nematic aerogels:

Obninsk aerogel *(Leypunskiy Institute, Obninsk).*
Material: AlOOH (produced for the first time in 2002).
Overall densities (mg/cm^3): 8-50
Corresponding porosities: 99.7 - 97.9%
Mean diameter of the strands: ~8 nm
Nafen *(ANF Technology Ltd, Tallinn)*
Material: Al_2O_3.
Overall densities (mg/cm^3): 72, 90, 243 and 910
Corresponding porosities: 98.2 – 77.2%
Mean diameter of the strands: ~9 nm
Mullite *(Metallurg Eng., Tallinn)*
Material: Al_2O_3+SiO_2.
Overall density (mg/cm3): 150
Corresponding porosity: 95.2 %
Mean diameter of the strands: <14 nm



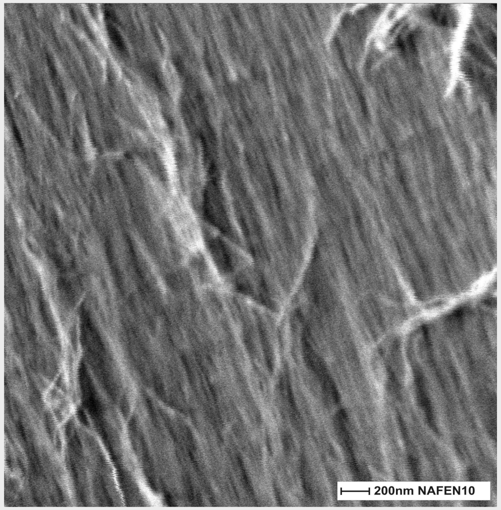
Spin diffusion of ^{3}He in nafen-243 at P=2.9 bar.

nafen-243: $D_{\parallel}/D_{\perp} \approx 8.1$

nafen-90: $D_{\parallel}/D_{\perp} \approx 3.3$

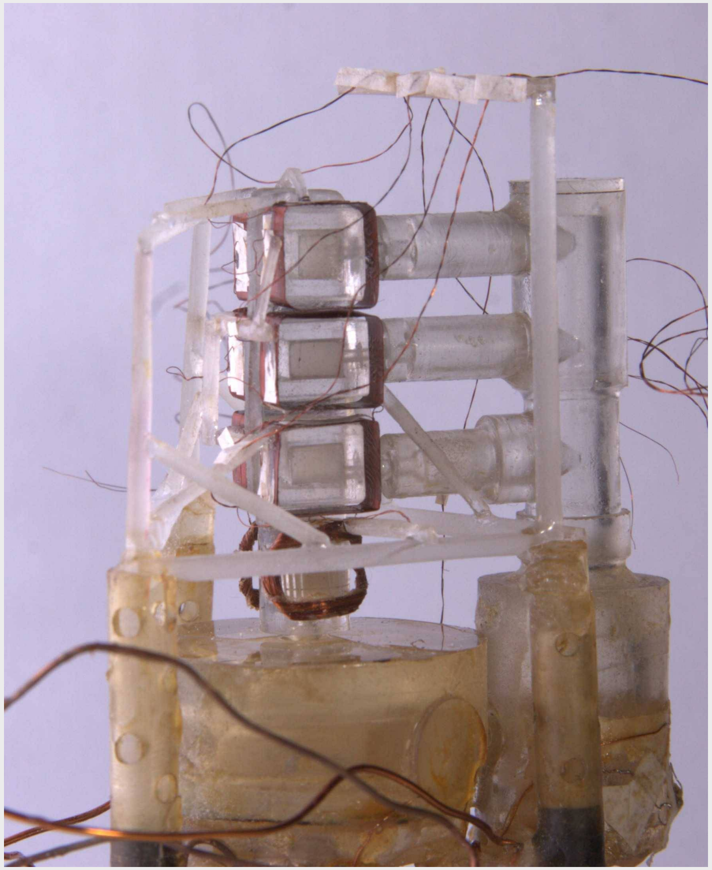
Mullite-150: $D_{\parallel}/D_{\perp} \approx 3.8$

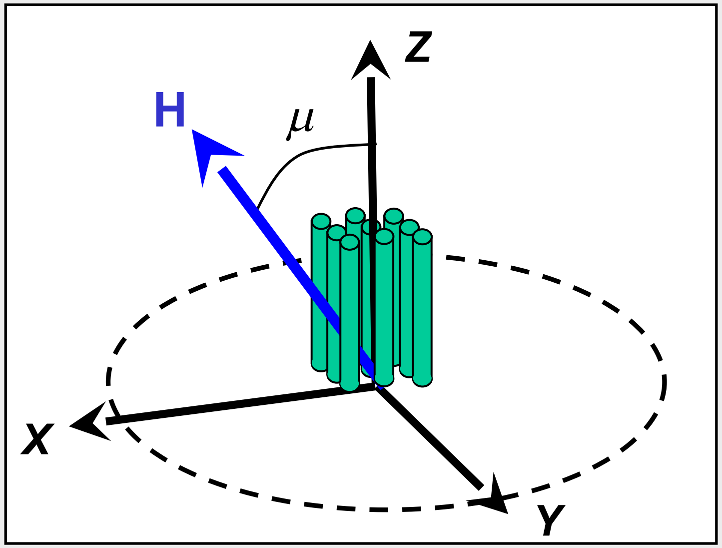
Obninsk-30: $D_{\parallel}/D_{\perp} \approx 1.9$



SEM picture of nafen-90

One of the experimental cells

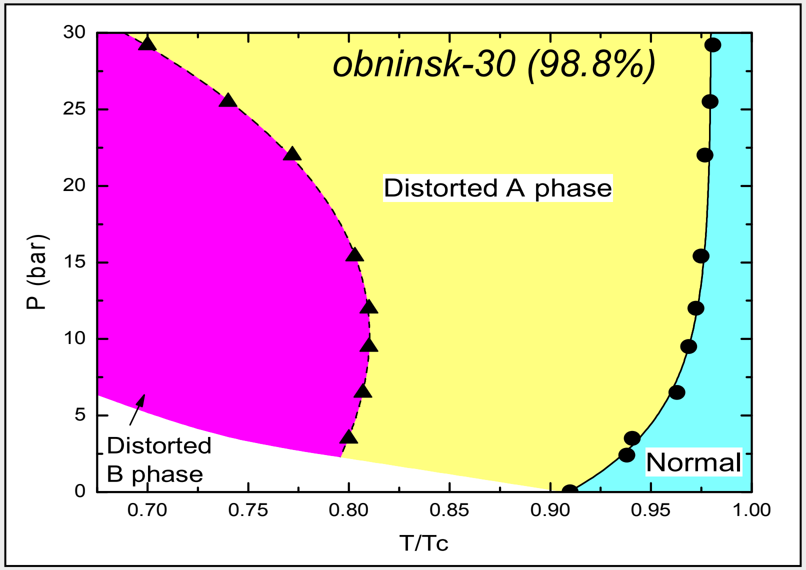


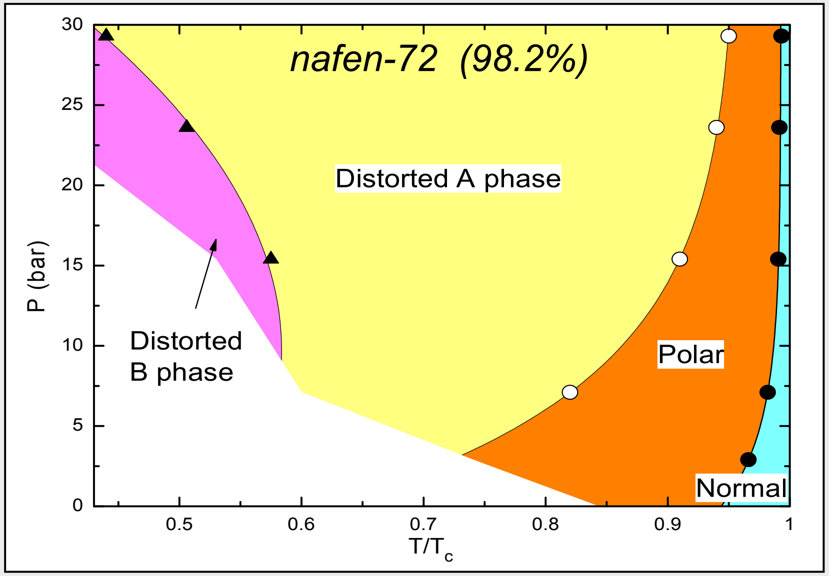


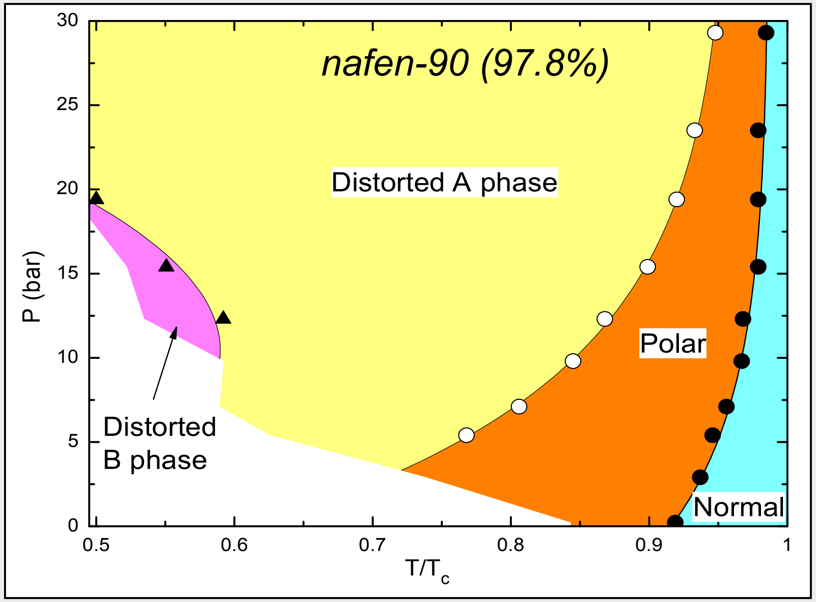
P= 0 – 29.3 bar
H= 104 – 425 Oe (0.338 – 1.39 MHz)

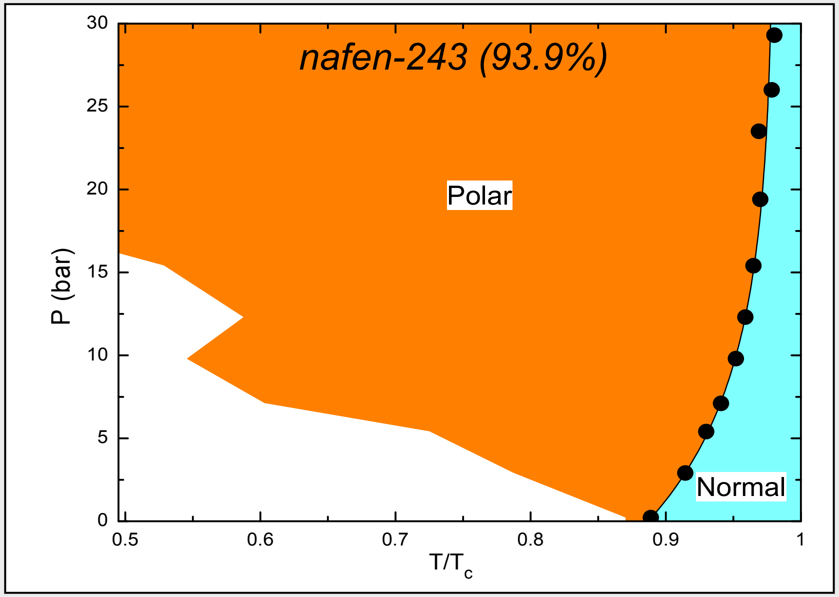
In most of experiments samples of aerogel were preplated with ~2.5 atomic layers of ^{4}He!

Phase diagrams (the strands are covered by ~2.5 atomic layers of ^{4}He)









Askhadullin et al.,*JETP Lett.* (2012, 2014).
Dmitriev et al., *JETP* (2014, 2020).
Dmitriev et al., *PRL* (2015).

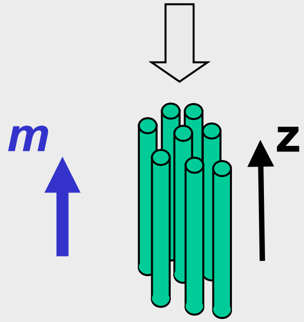
entification of polar and polar distorted A phases by NMR

G.E.Volovik, JLTP (2008): local inhomogeneties of aerogel may destroy
long-range order of A phase ⇨ Larkin-Imry-Ma (LIM) state of $\boldsymbol{l}$ and $\boldsymbol{n}$.
LIM length (~1 μm) << dipole length (~10 μm)
Experimental confirmation: Dmitriev at al. JETP Lett. (2010)

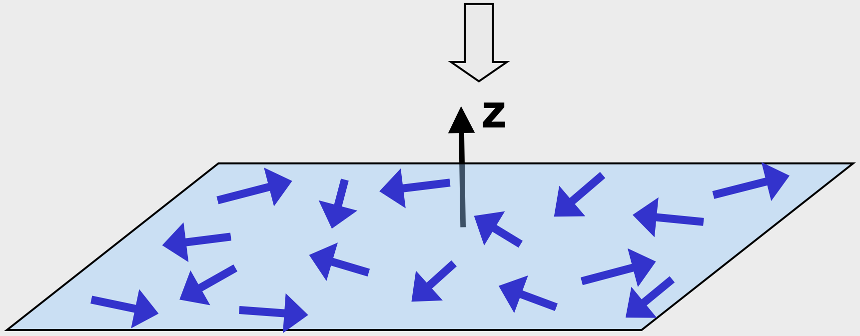
Polar distorted A phase (or pure A phase) in nematic aerogel also should be in 2D LIM state:

$$A_{\mu j} = \Delta_0 e^{i\varphi} d_\mu (a m_j + i b n_j); \qquad \boldsymbol{l} = \boldsymbol{m} \times \boldsymbol{n}$$

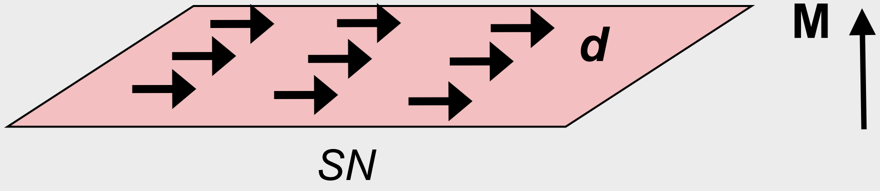
Aerogel strands



$\boldsymbol{n}$ **or** $\boldsymbol{l}$ in real space

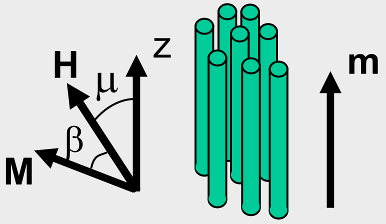


Spin vector **d** is oriented normal to magnetization and its uniform distribution has the lowest energy (spin nematic, SN, state).



$$U_D \propto a^2 (\boldsymbol{dm})^2 + b^2 (\boldsymbol{dn})^2$$

NMR frequency shift in A, distorted A and polar phases:



pulse NMR:

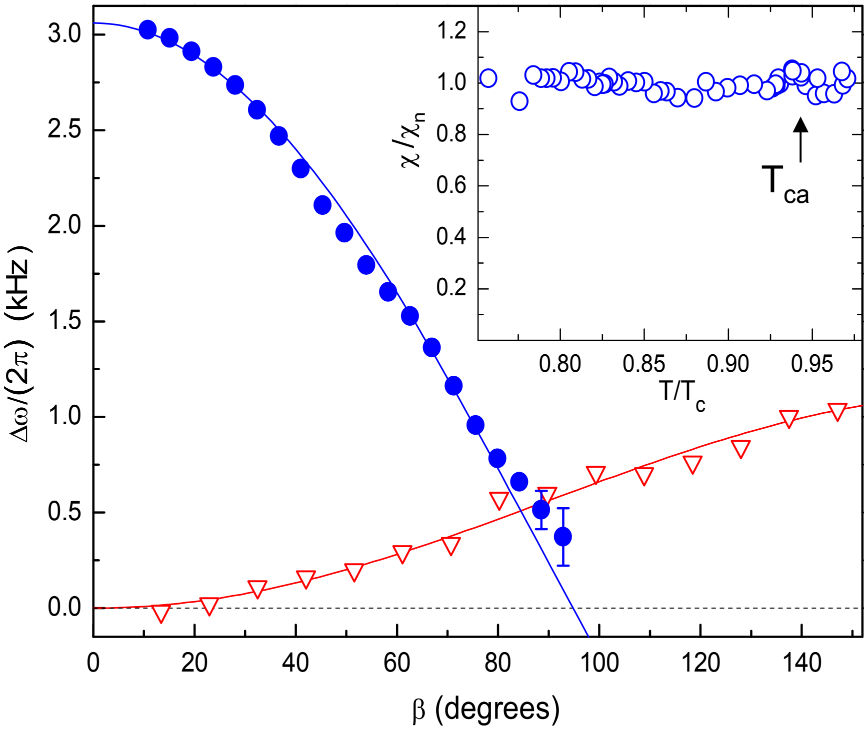
$$\mu = 0: \quad \Delta\omega = \frac{\Omega_L^2}{2\omega}\cos\beta$$

$$\mu = 90^\circ: \quad \Delta\omega = \frac{\Omega_L^2}{2\omega}\,\frac{1-\cos\beta}{4}$$

CW NMR:

$$\mu = 0: \quad \Delta\omega = \frac{\Omega_L^2}{2\omega}$$

$$\mu = 90^\circ: \quad \Delta\omega = 0$$

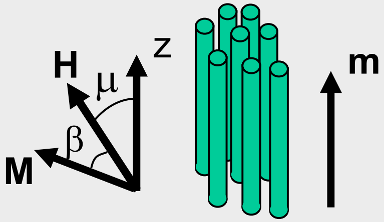


Pulse NMR and spin susceptibility (³He in nafen-243)

Circles: $\mu = 0$, *P=19.4 bar,*
$\omega/2\pi$=*880 kHz, T =0.78 Tc.*
Triangles: μ=90°, *P=7.1 bar,*
$\omega/2\pi$=*359 kHz, T=0.83 Tc.*
Insert: P=7.1 bar, μ=*0.*

Solid lines are theoretical curves with $\Omega_L^2/2\omega$ *measured in CW NMR at* μ=*0.*

NMR frequency shift in A, distorted A and polar phases:



pulse NMR:

$\mu = 0:$ $\Delta\omega = \frac{\Omega_L^2}{2\omega}\cos\beta$

$\mu = 90^\circ:$ $\Delta\omega = \frac{\Omega_L^2}{2\omega}\frac{1-\cos\beta}{4}$

CW NMR:

$\mu = 0:$ $\Delta\omega = \frac{\Omega_L^2}{2\omega}$

$\mu = 90^\circ:$ $\Delta\omega = 0$

In the weak coupling limit Ω_L *for polar distorted A and pure polar phases can be calculated in terms of the Leggett frequency of the pure A phase:*

$$A_{\mu j} = \Delta_0 e^{i\varphi}\hat{d}_\mu(a\hat{m}_j + ib\hat{n}_j)$$

Distorted A (2D LIM): $\Omega_L^2 = \frac{4-6b^2}{3-4a^2b^2}\Omega_A^2$

$$A_{\mu j} = \Delta_0 e^{i\varphi}\hat{d}_\mu\hat{m}_j$$

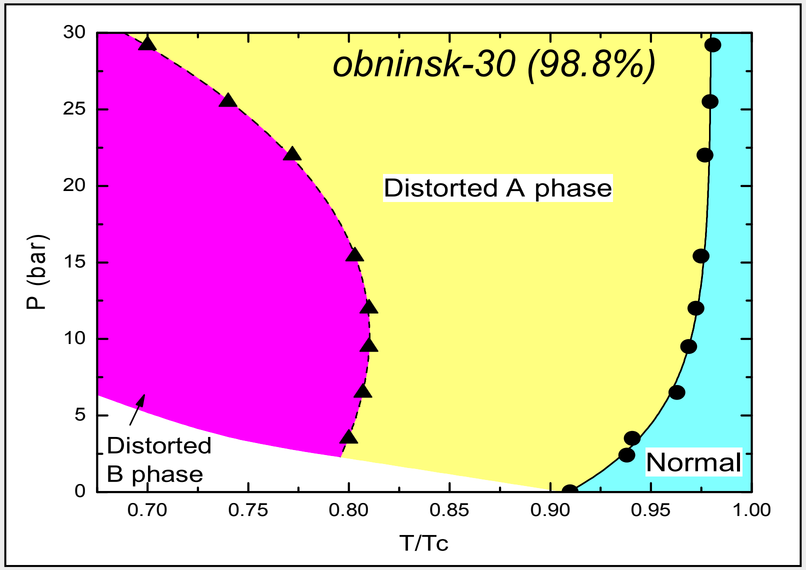
Polar: $\Omega_L^2 = \frac{4}{3}\Omega_A^2$

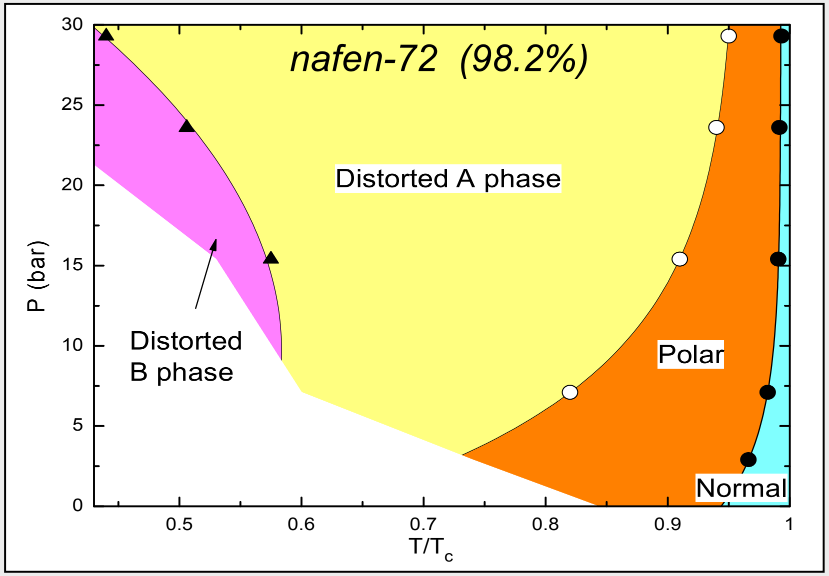
For the pure polar phase CW NMR shift for μ*=0:* $2\omega\Delta\omega = \frac{4}{3}\Omega_A^2$

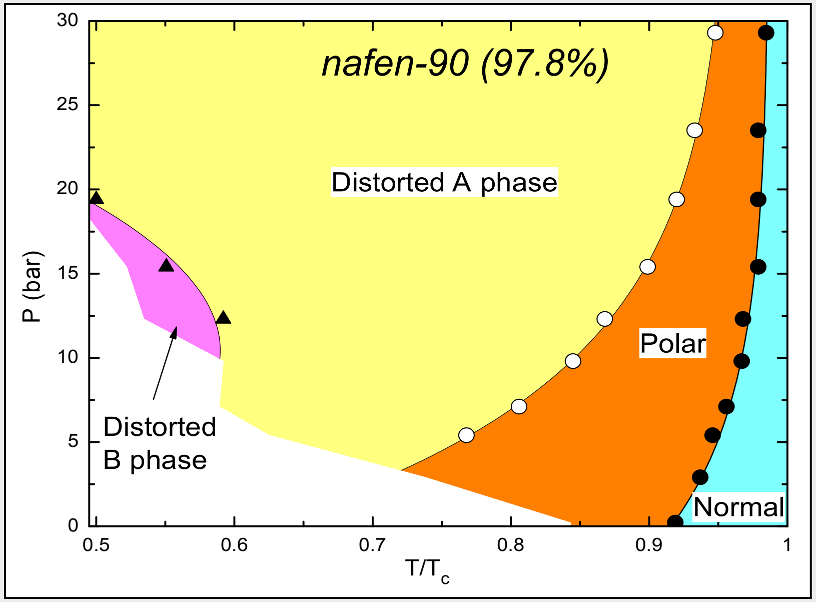
For the pure A phase CW NMR shift for μ*=0:* $2\omega\Delta\omega = \frac{1}{2}\Omega_A^2$

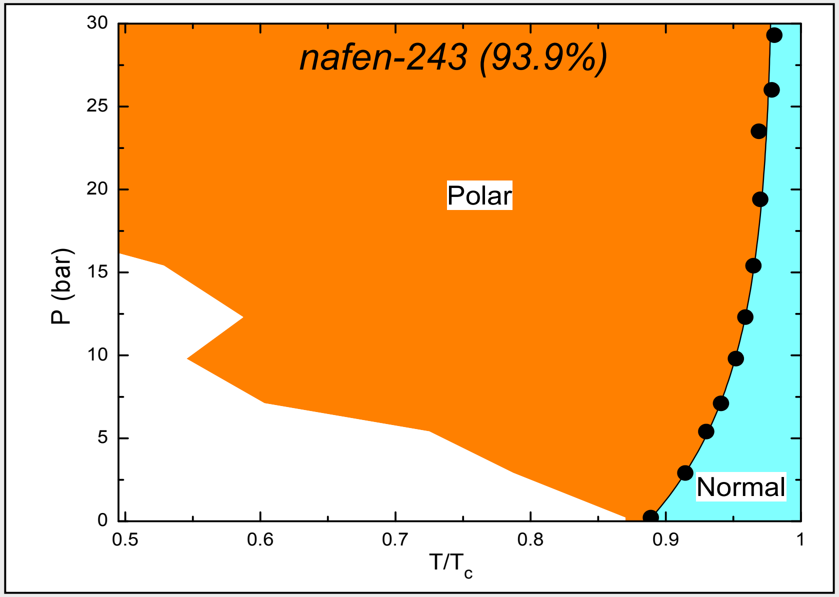
If suppression of T_c *is small then we can use the bulk value of* Ω_A^2 *for comparison.*

Phase diagrams (the strands are covered by ~2.5 atomic layers of ^{4}He)





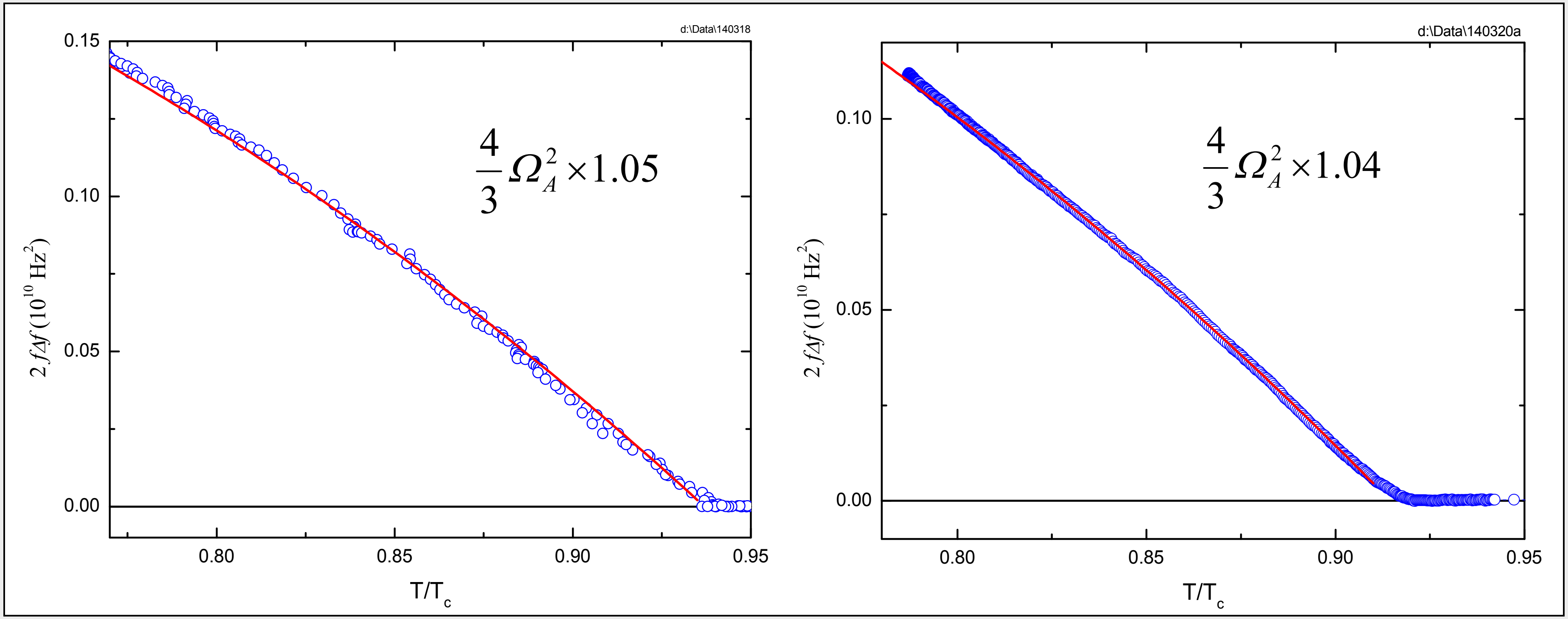




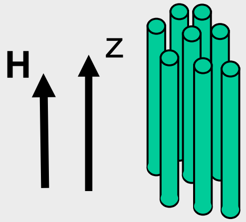
Askhadullin et al.,*JETP Lett.* (2012, 2014).
Dmitriev et al., *JETP* (2014, 2020).
Dmitriev et al., *PRL* (2015).

CW NMR frequency shifts in ^{3}He in nafen samples for H oriented along the strands

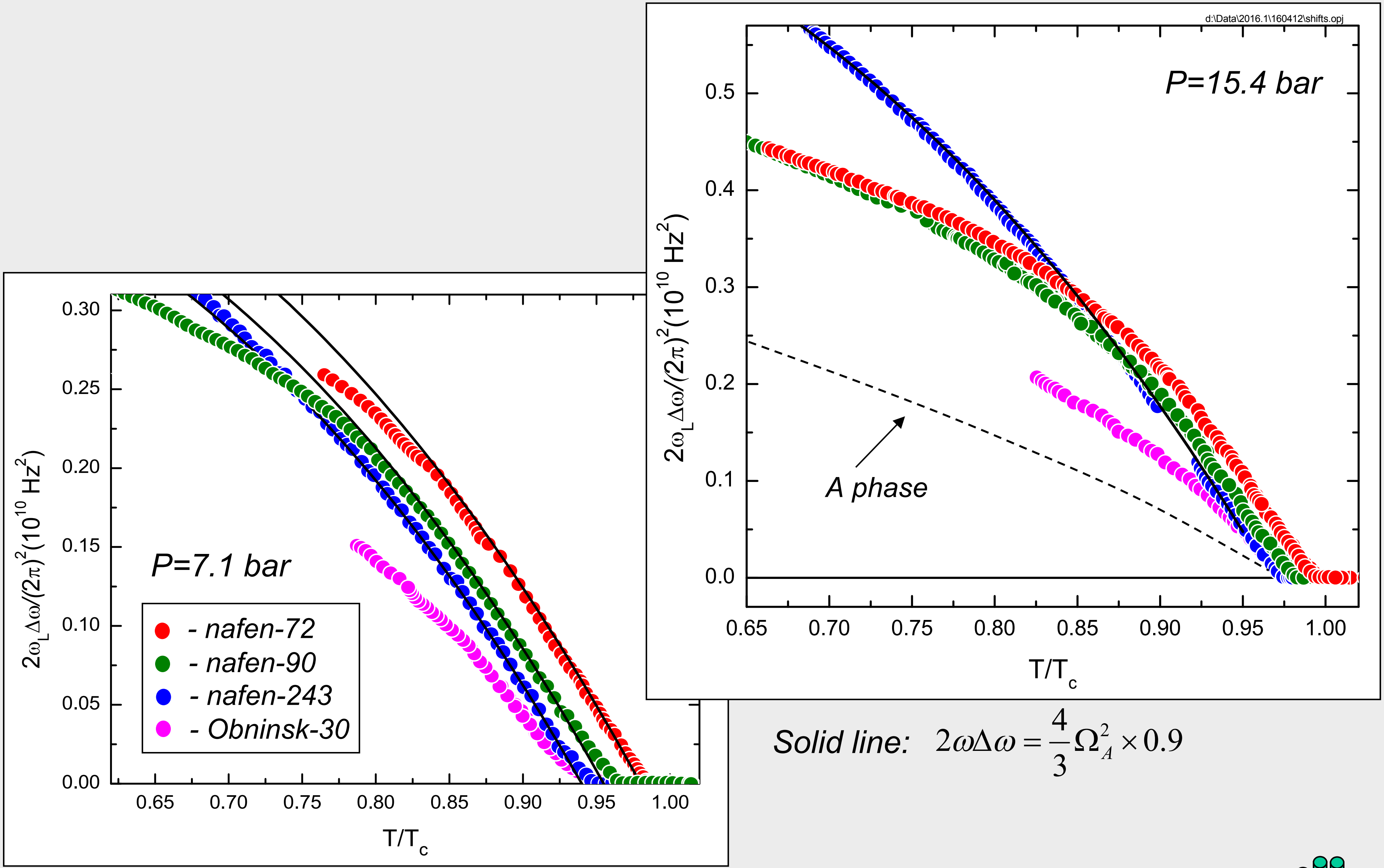
nafen-90 *nafen-243*



P=2.9 bar

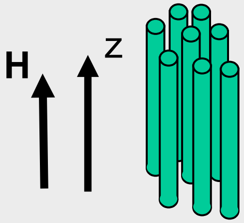


CW NMR frequency shifts in ^{3}He in different samples for H oriented along the strands

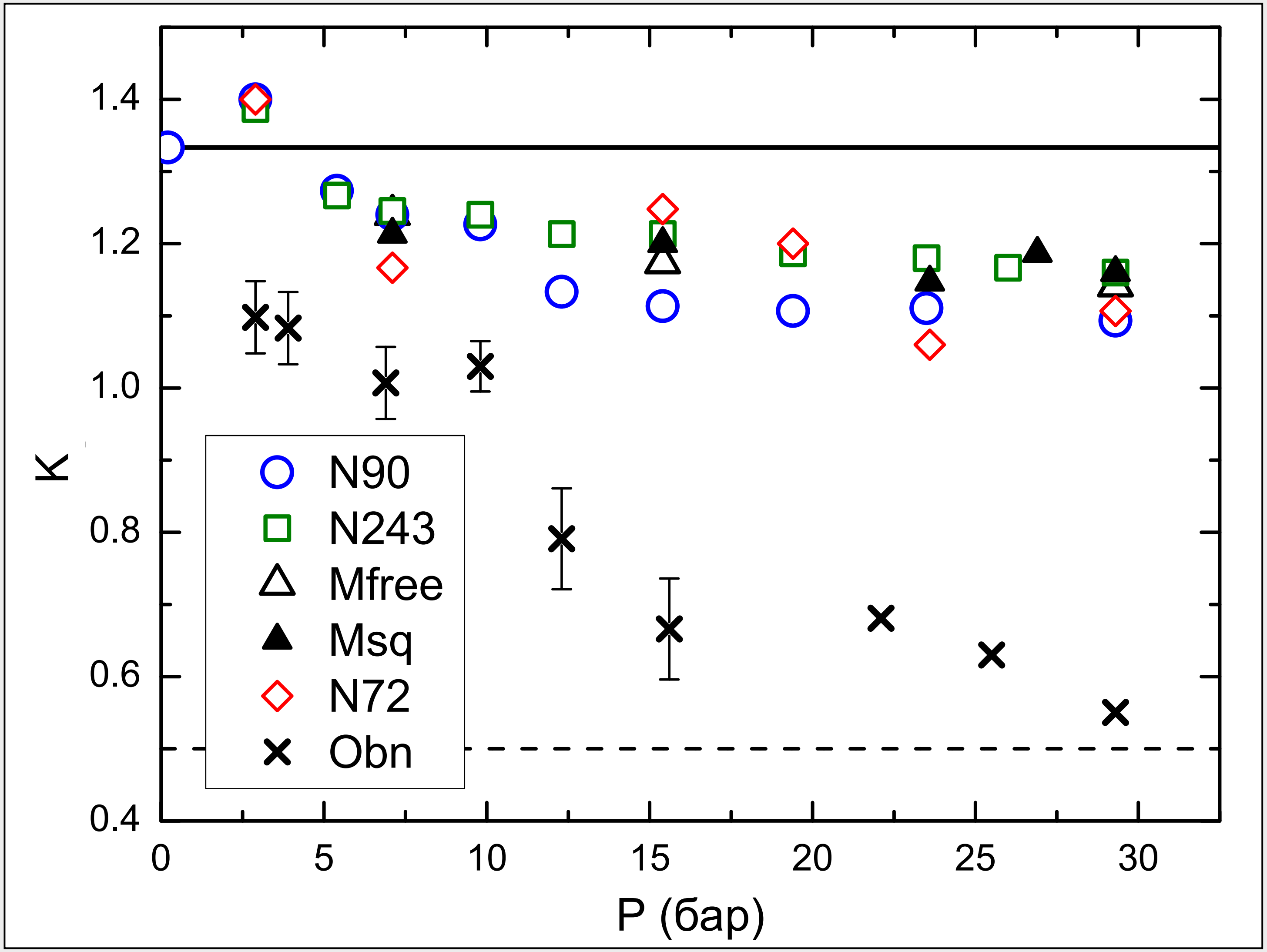


Solid line: $2\omega\Delta\omega = \frac{4}{3}\Omega_A^2 \times 0.9$

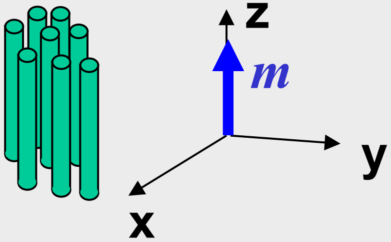
Solid lines correspond to $2\omega\Delta\omega = \frac{4}{3}\Omega_A^2 \times 0.93$

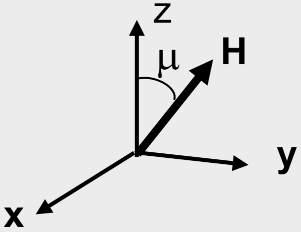


Dependence of $K = 2\omega\Delta\omega / \Omega_A^2$ in different samples on pressure

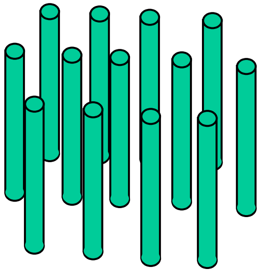


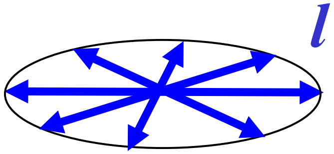
$$A_{\mu\nu} = d_{\mu}(a m_{\nu} + i b n_{\nu})$$





$$\mathbf{l} = \mathbf{m} \times \mathbf{n}$$

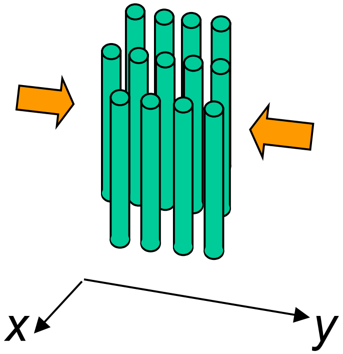


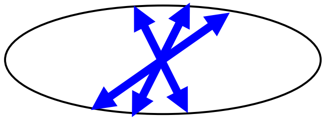


$$\langle l_x^2 \rangle = \langle l_y^2 \rangle = \frac{1}{2}$$

$$\mu = 0 \quad \Rightarrow \quad \Delta\omega = \frac{\Omega_A^2}{2\omega}\left(\frac{4-6b^2}{3-4a^2b^2}\right)$$

$$\mu = 90^\circ \quad \Rightarrow \quad \Delta\omega = 0$$





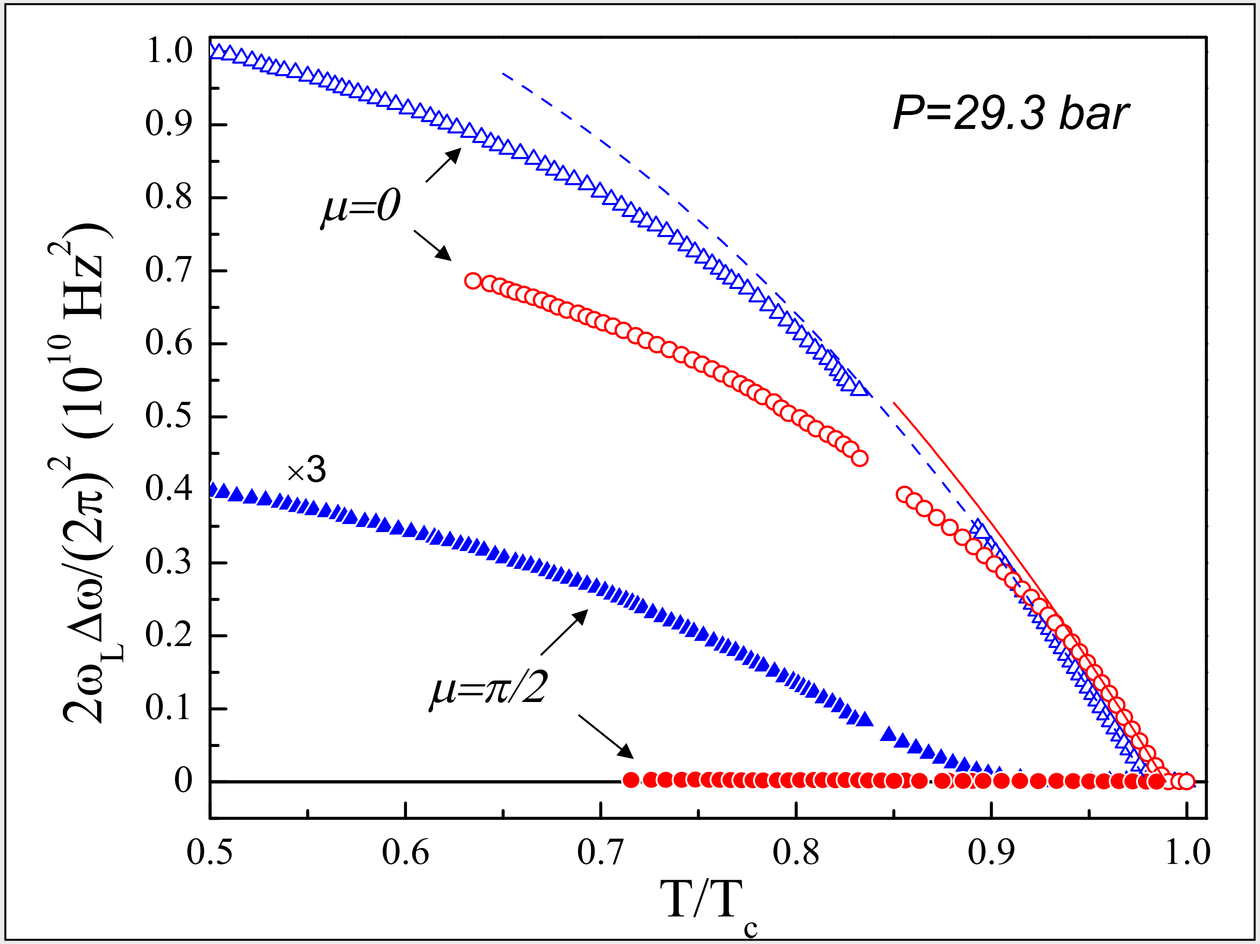
$$\langle l_x^2 \rangle > \langle l_y^2 \rangle,$$

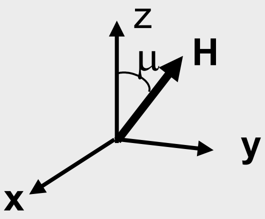
$$0 < \langle l_y^2 \rangle < \frac{1}{2}$$

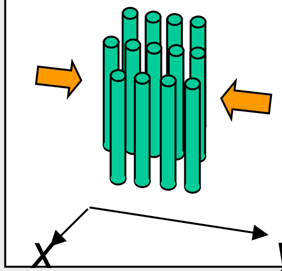
$$\mu = 0 \;\Rightarrow\; \Delta\omega = \frac{\Omega_A^2}{2\omega}\left(\frac{4-6b^2+2b^2\left(1-2\langle l_y^2\rangle\right)}{3-4a^2b^2}\right)$$

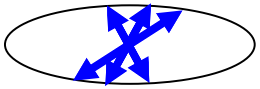
$$\mu = 90^\circ \;\Rightarrow\; \Delta\omega = \frac{\Omega_A^2}{2\omega}\left(\frac{4}{3-4a^2b^2}\right)b^2\left(1-2\langle l_y^2\rangle\right)$$

NMR frequency shift in original (red) and squeezed (blue) mullite nematic aerogel









$$\langle l_x^2\rangle > \langle l_y^2\rangle,$$

$$0 < \langle l_y^2\rangle < \frac{1}{2}$$

$$\mu = 0 \;\Rightarrow\; \Delta\omega = \frac{\Omega_A^2}{2\omega}\left(\frac{4-6b^2+2b^2\left(1-2\langle l_y^2\rangle\right)}{3-4a^2b^2}\right)$$

$$\mu = 90^\circ \;\Rightarrow\; \Delta\omega = \frac{\Omega_A^2}{2\omega}\left(\frac{4}{3-4a^2b^2}\right)b^2\left(1-2\langle l_y^2\rangle\right)$$

Thus, identification of the observed distorted A and pure polar phases in ^{3}He in namatic aerogel is based on the following points:

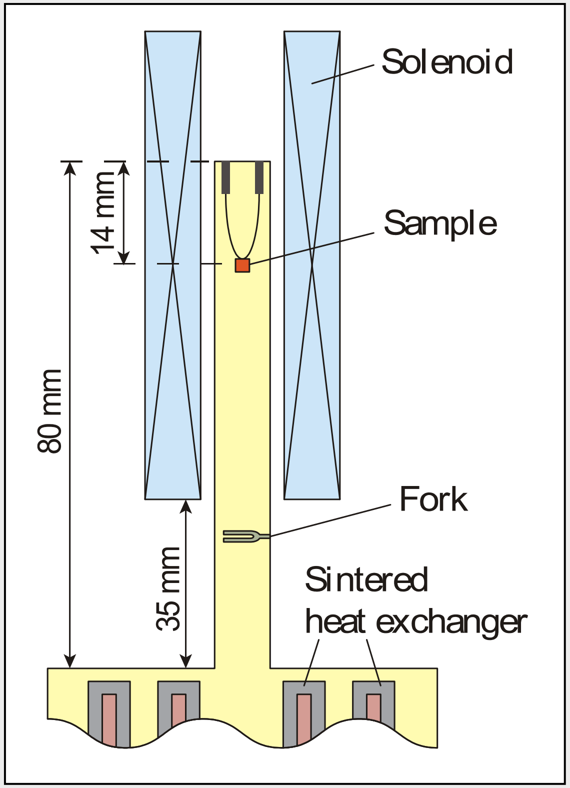
1. Susceptibility and pulse NMR measurements show that the observed high temperature phases can be A, distorted A or polar.

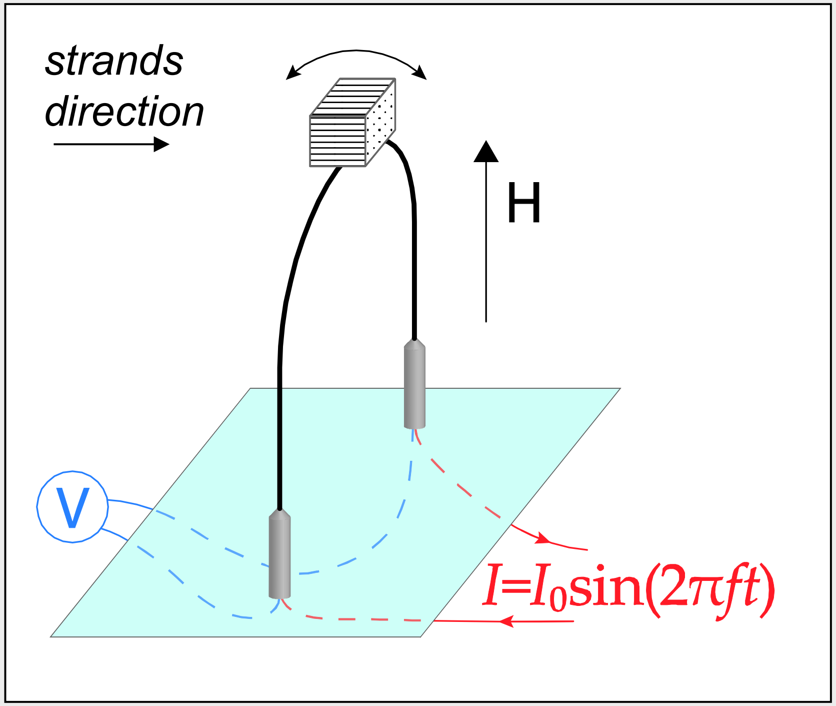
2. Measurements of the absolute value of the NMR frequency shift in nafen and mullite samples with different densities show that near T_{ca} we always get the polar phase. In low density samples at lower temperatures the 2nd order transition into the polar distorted A phase occurs.

3. For $\mu=\pi/2$ the nonzero NMR frequency shift appears in the polar distorted A phase in squeezed sample .

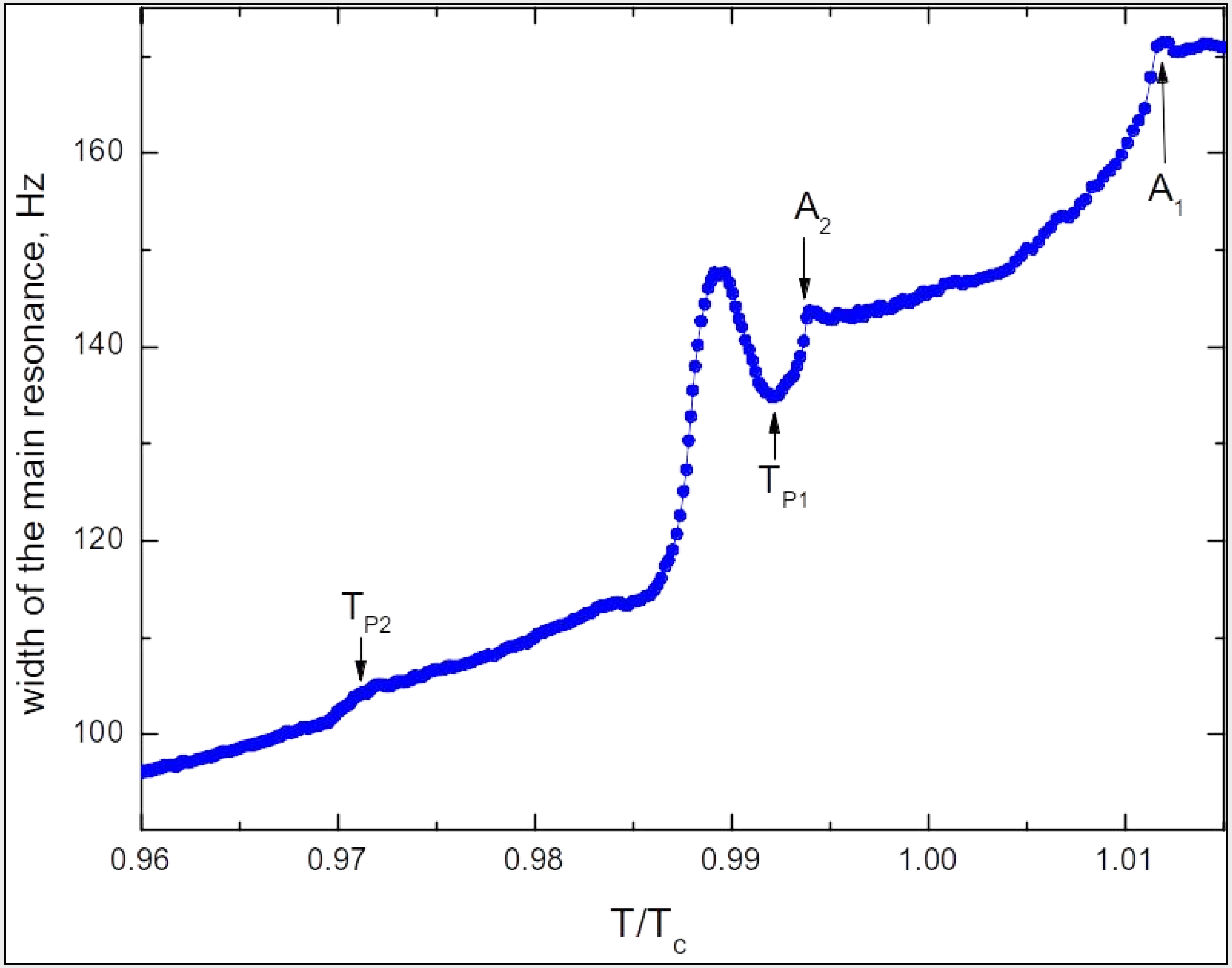
In the polar phase also there are only ↑↑ and ↓↓ pairs. In strong magnetic field we can expect that the degeneracy over spin projections will be lifted and in a narrow region near the superfluid transition so called ***phase*** *(with only ↑↑pairs) will be favorable instead of the polar phase.*

The order parameter of the β phase is $A_{\mu\nu} = \Delta_0(\hat{d}_\mu + i\hat{e}_\mu)\hat{m}_\nu$



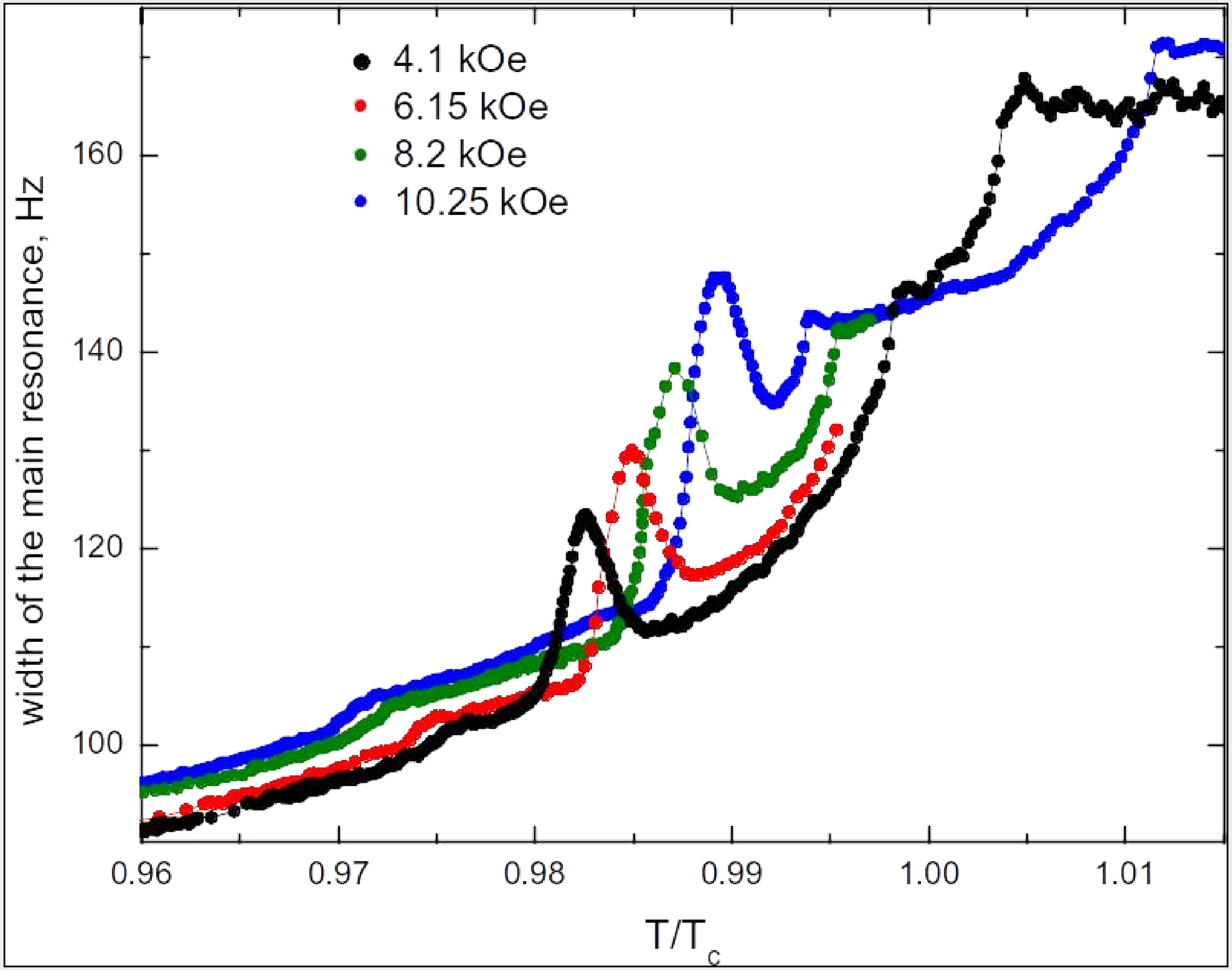


Width of the main resonance of VW. H=10.25 kOe, P=15.4 bar

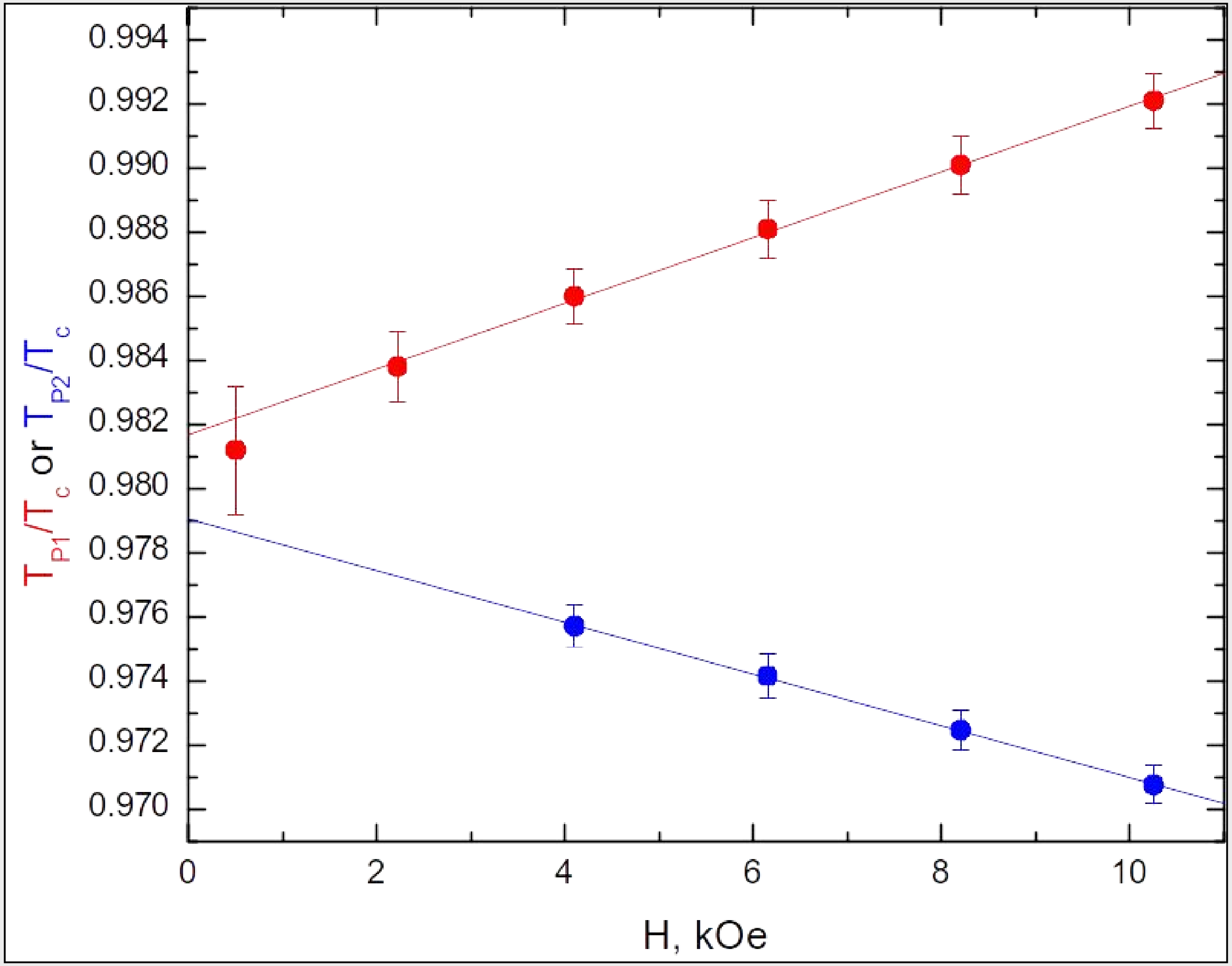


Our interpretation:
Arrows mark transitions (on cooling): to A_1 and then to A_2 phases (in bulk ^{3}He);
then to β phase (T_{P1}) in aerogel, and to distorted β phase (T_{P2}), which then continuously is transformed to polar phase.

Width of the main resonance of VW in different H. P=15.4 bar



T_{P1} and T_{P2} vs H. P=15.4 bar



$$\left(T_{P1}-T_{ca}\right)/\left(T_{ca}-T_{P2}\right)=1.27$$

Theory predicts that this ratio equals $-\beta_{15}/\beta_{12345}$ *. In bulk* ^{3}*He this value at 15.4 bar is 1.36.*

Conclusions:

1. *Using vibrating wire we observe the superfluid transition into the polar phase in ^{3}He confined by nematic aerogel.*
2. *In high magnetic field we observe splitting of the superfluid transition temperature due to appearance of the superfluid β phase.*