New superfluid phases of ^{3}He

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Bulk superfluid ^3He

Cooper pairing into the state with L=1 and S=1.

Order parameter: 3x3 matrix $A_{\mu\nu}$

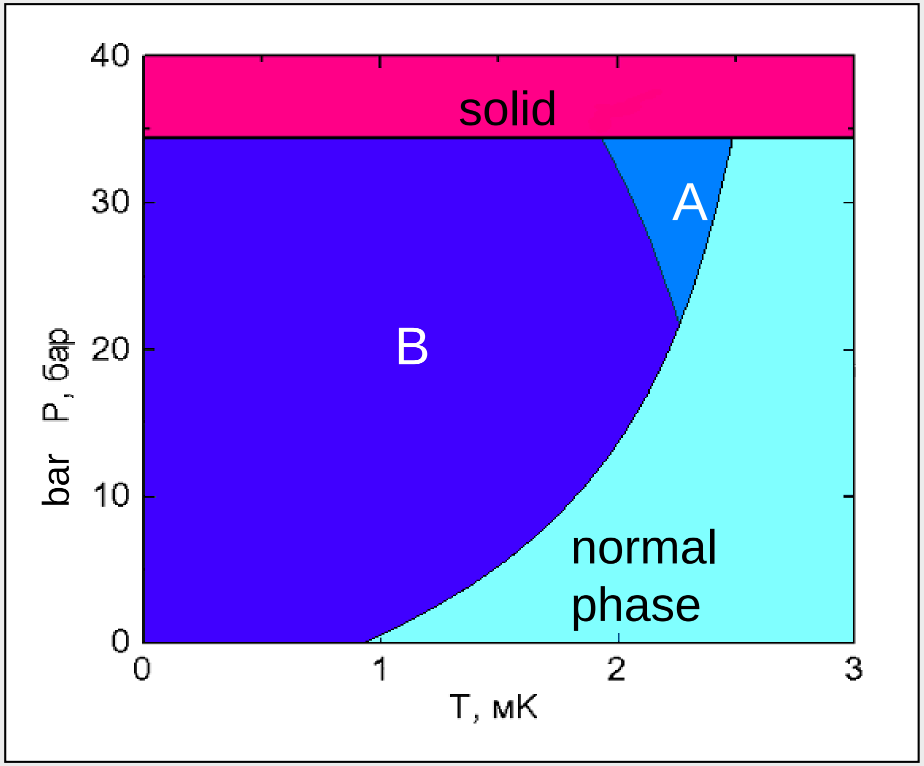
$$F_c = -\alpha\, Sp\,(AA^+) + \beta_1\, |\,Sp\,(A\tilde{A})\,|^2 + \beta_2\,[Sp\,(AA^+)]^2 + $$
$$+ \beta_3\, Sp\,[(A^+A)\,(A^+A)^*] + \beta_4 Sp\,[(AA^+)^2] + \beta_5 Sp\,[(AA^+)\,(AA^+)^*].$$

In bulk superfluid ^3He 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: $$A_{\mu\nu} = \Delta e^{i\varphi} \mathbf{R}(\mathbf{n}, \theta)$$

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



The degeneracy over spin projections is lifted by magnetic field -- the additional term $\propto H_\mu H_\nu A_{\mu j} A^*_{\nu j}$ in F_c appears and A_1 phase becomes favorable in a narrow (~0.02 T_c in field of 10 kOe) region near T_c. In the A_1 phase there are only ↑↑ pairs.

A_1 phase: $$A_{\mu\nu} = \Delta_0 (\hat{d}_\mu + i\hat{e}_\mu)(\hat{m}_\nu + i\hat{n}_\nu)$$

The degeneracy over orbital projections may be lifted in [3]He in globally anisotropic aerogel. The additional term in the Ginzburg-Landau free energy is $\eta_{jl} A_{\mu j} A^*_{\mu l}$. *In [3]He in nematic aerogel it makes favorable the* ***polar phase*** *(* $A_{\mu\nu} = \Delta_0 e^{i\varphi} \hat{d}_\mu \hat{m}_\nu$ *) and polar distorted A (PdA) phase.*

These phases were observed in NMR experiments with different samples of nematic aerogel (e.g., see a short review JETP ***131****, 2 (2020)).*

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 ***β phase*** *(with only ↑↑ pairs) will be favorable instead of the polar phase.*

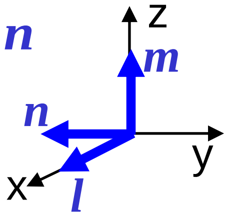
The order parameter of the β phase is $A_{\mu\nu} = \Delta_0 (\hat{d}_\mu + i\hat{e}_\mu)\hat{m}_\nu$

More theory about β phase: E.Surovtsev JETP ***128****, 477 (2019);* ***129****, 1055 (2019).*

*K.Aoyama, R.Ikeda, Phys.Rev. B **73**, 060504 (2006): in aerogel with a specific anisotropy new superfluid phases of 3He can exist*

A phase: $\boldsymbol{l} = \boldsymbol{m} \times \boldsymbol{n}$

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



Gap vanishes at 2 points on Fermi sphere

Polar distorted A (PdA) phase:

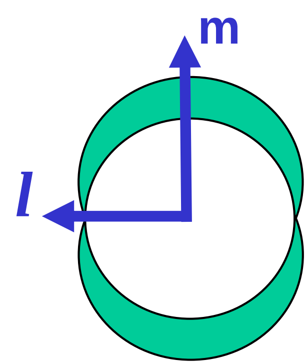
$$A_{\mu\nu} = \Delta_0 e^{i\varphi} d_\mu (a m_\nu + i b n_\nu)$$

$$(a^2 + b^2 = 1; \;\; a > b)$$

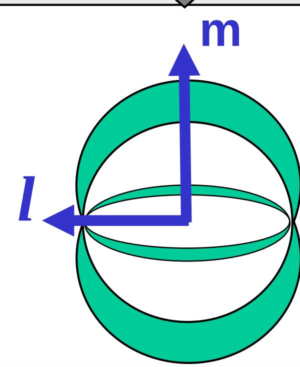
Polar:

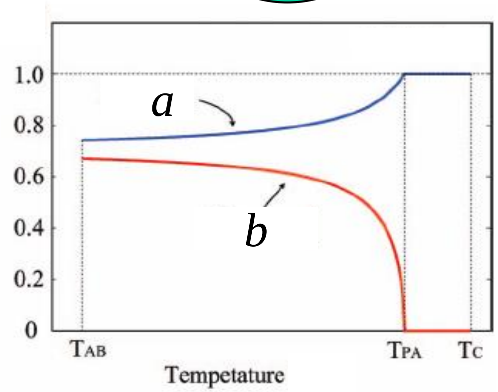
$$A_{\mu\nu} = \Delta_0 e^{i\varphi} d_\mu m_\nu$$

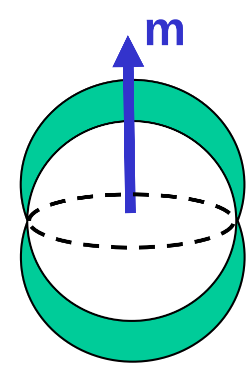
Gap is zero on the circle on Fermi sphere



$$\frac{\boldsymbol{b}^2}{\boldsymbol{a}^2} = 1$$



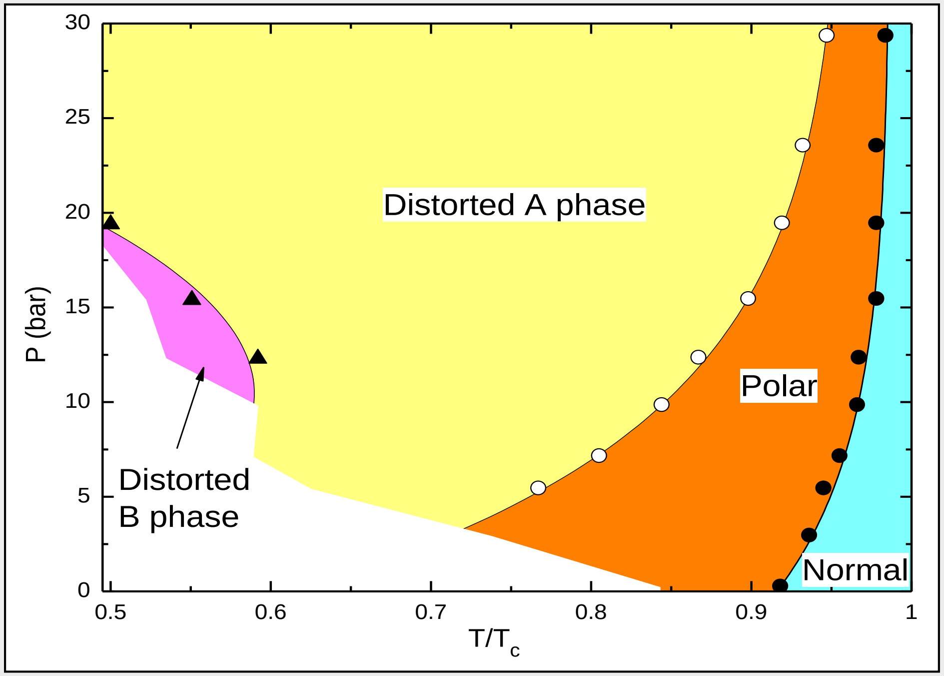




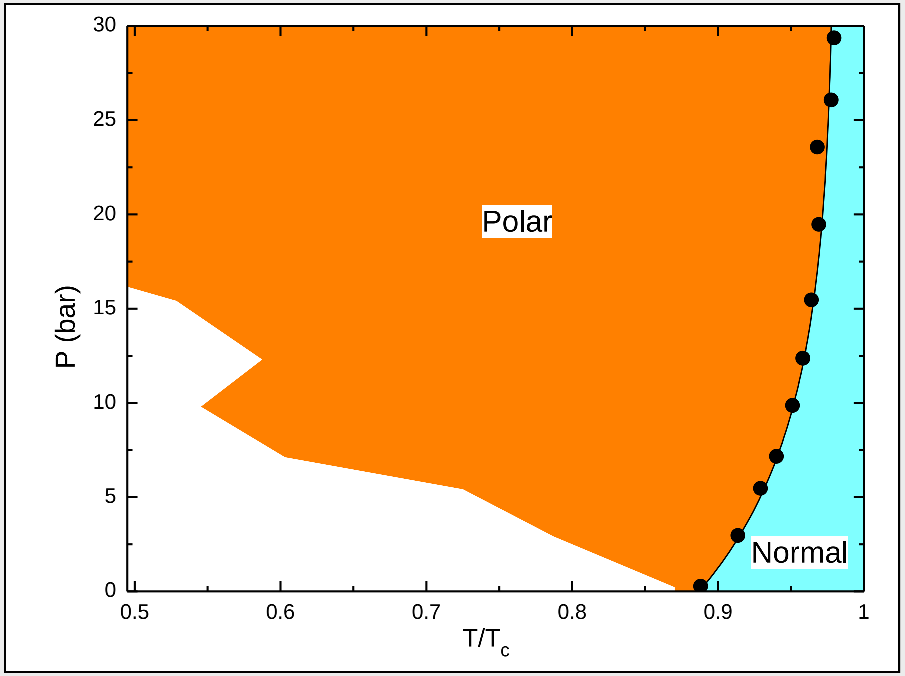
$$\frac{\boldsymbol{b}^2}{\boldsymbol{a}^2} = 0$$

Phase diagrams of ^{3}He in nafen (the strands are covered by ^{4}He)

nafen-90 (porosity 97.8%)



nafen-243 (porosity 93.9%)



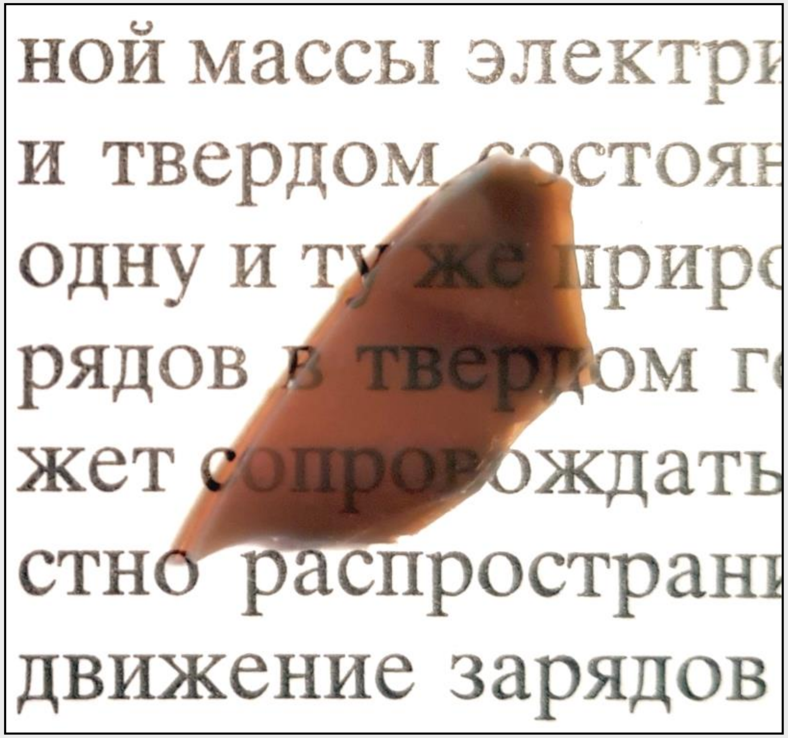
Note: temperature is normalized to T_c (superfluid transition temperature in bulk ^{3}He).

Further experiments performed in Aalto university showed an existence of half-quantum vortices as well as proved the existence of the Dirac nodal line in energy gap of the polar phase (PRL 2016, arxiv: 1908.01645)

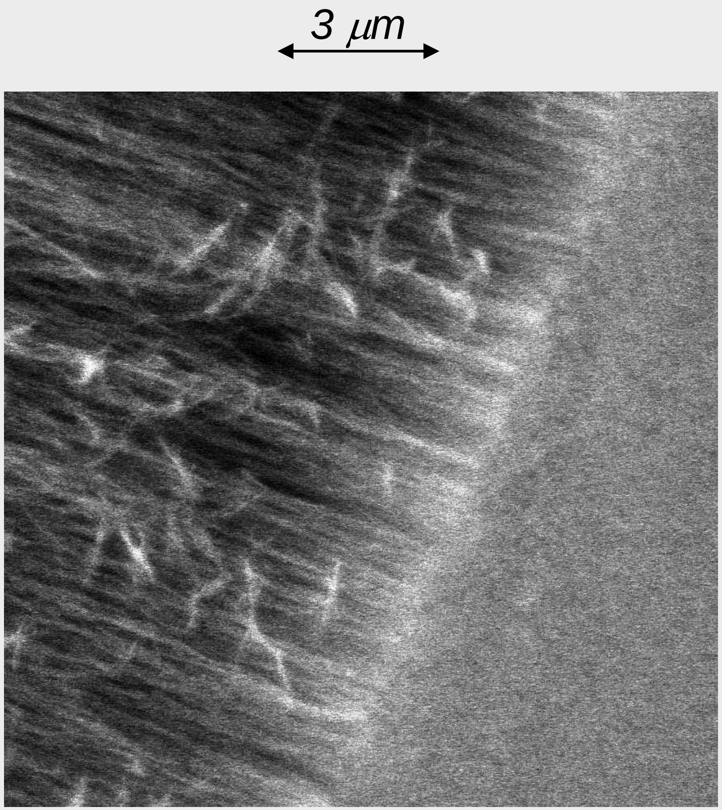
In experiments described below we used mullite nematic aerogel

Strands diameter < 14 nm *($\rho \approx 3.1$ g/cm^3).*

***Porosity**: ~96%*



Original sample with thickness of 2.6 mm. Strands are normal to the plane.



SEM photo of the edge of the sample

One of the samples was used in NMR experiments in low fields.
Two samples were used in experiments with vibrating wires (in low and high fields). In all experiments strands of the samples were preplated by a few atomic layers of 4He to avoid solid paramagnetic 3He on the surfaces.

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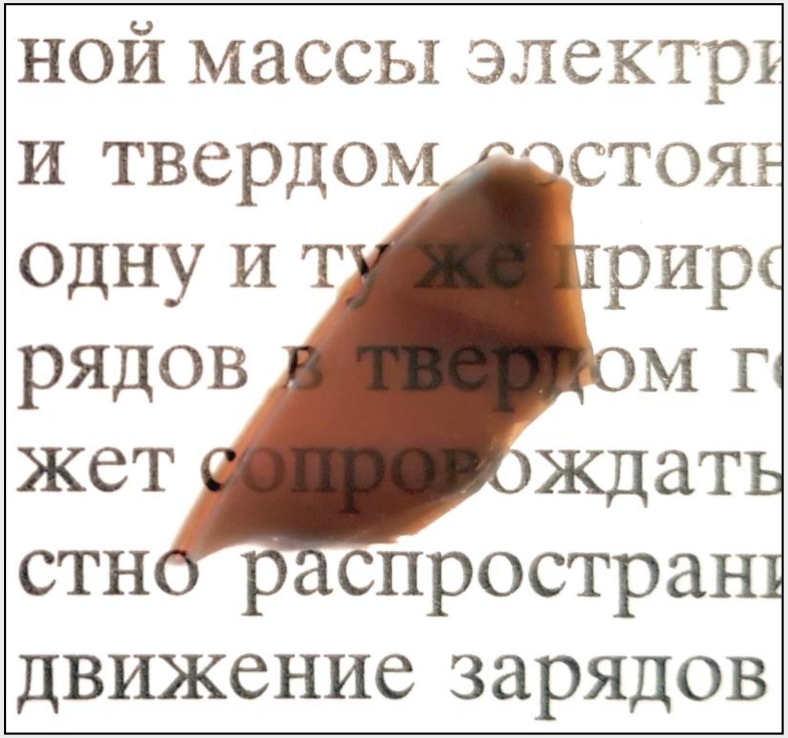

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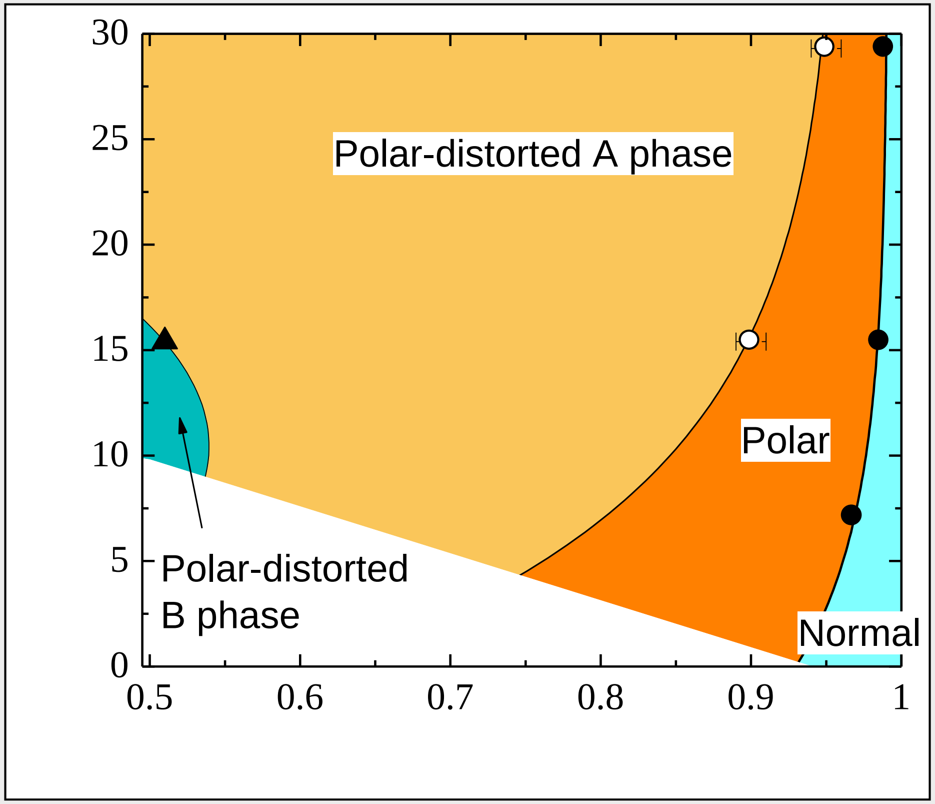

T_c is the superfluid transition temperature of bulk ^{3}He

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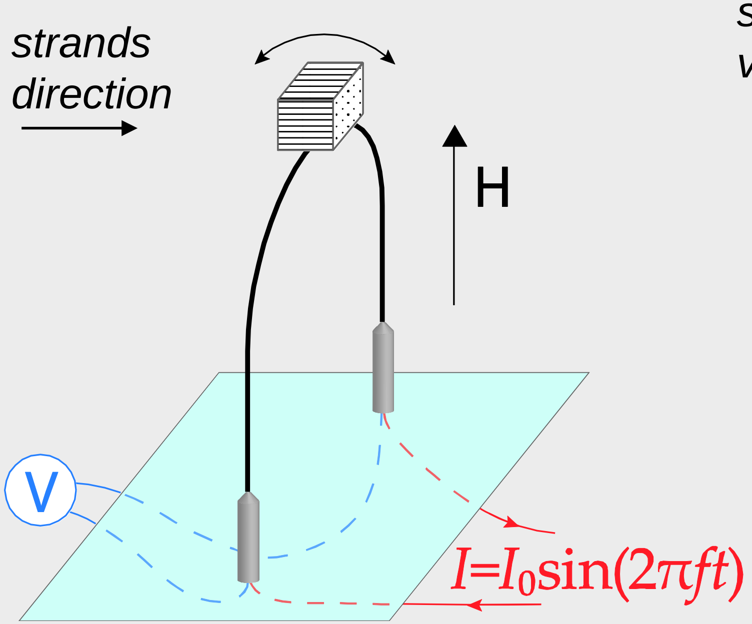
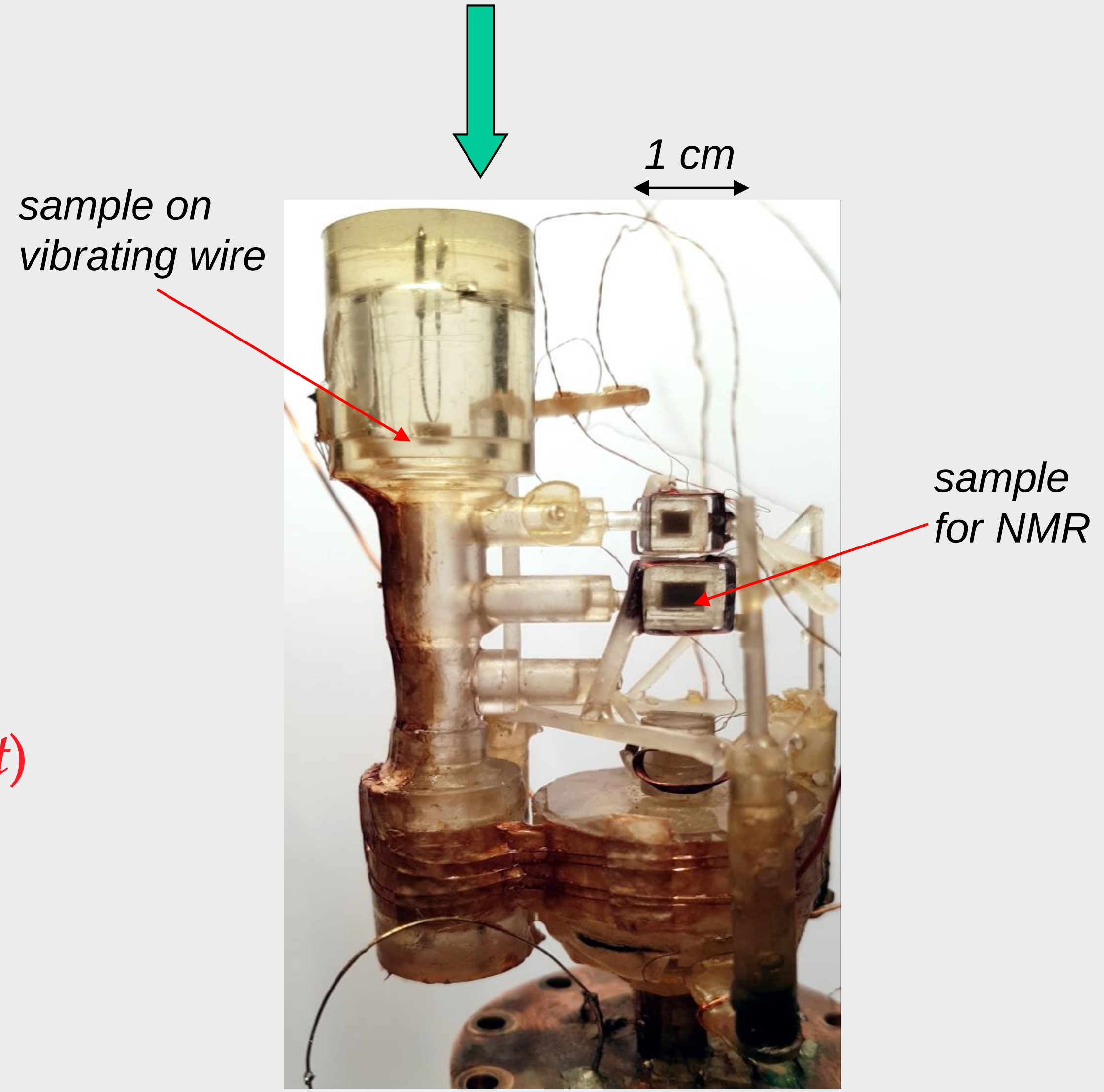
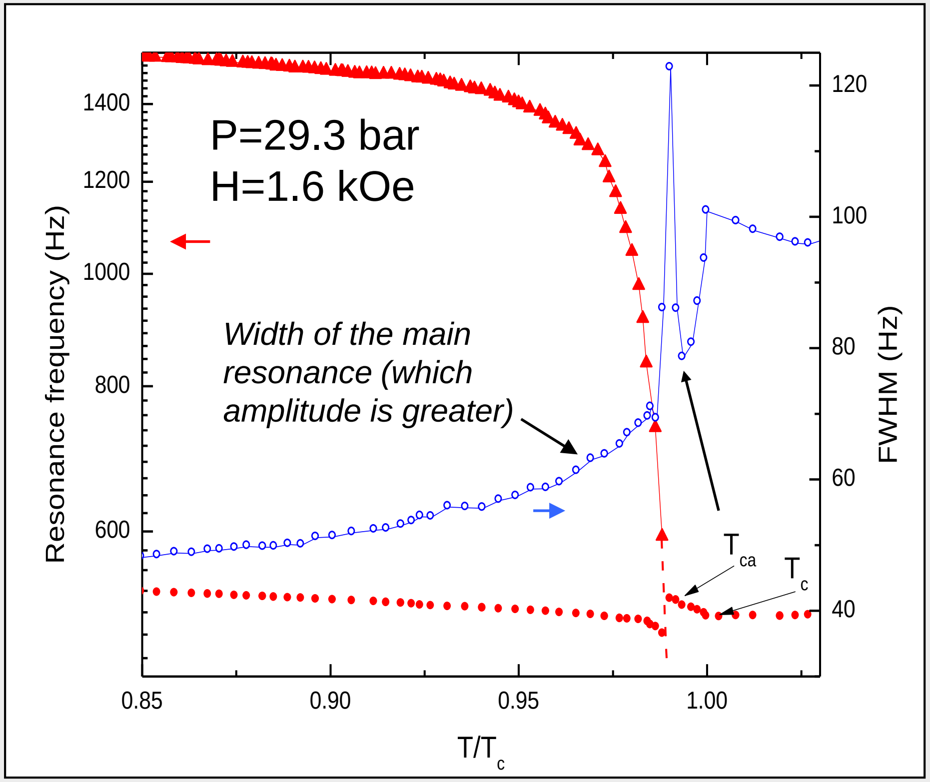
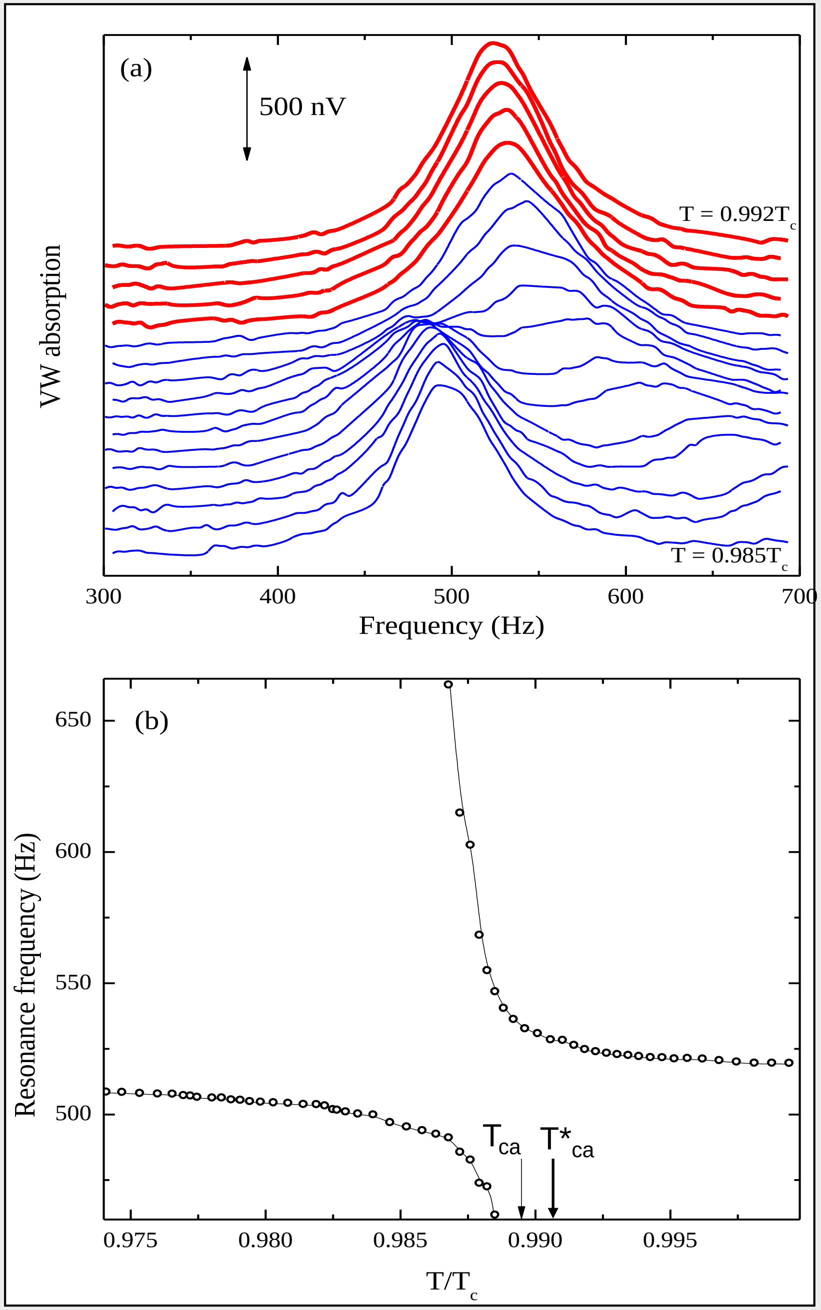
Two samples were used in experiments with vibrating wires (in low and high fields). In all experiments strands of the samples were preplated by a few atomic layers of 4He to avoid solid paramagnetic 3He on the surfaces.

In order to detect β phase we used a vibrating wire (VW) with nematic aerogel sample attached to it. At first experiments were done in moderate magnetic fields (up to 1.6 kOe) using this cell.



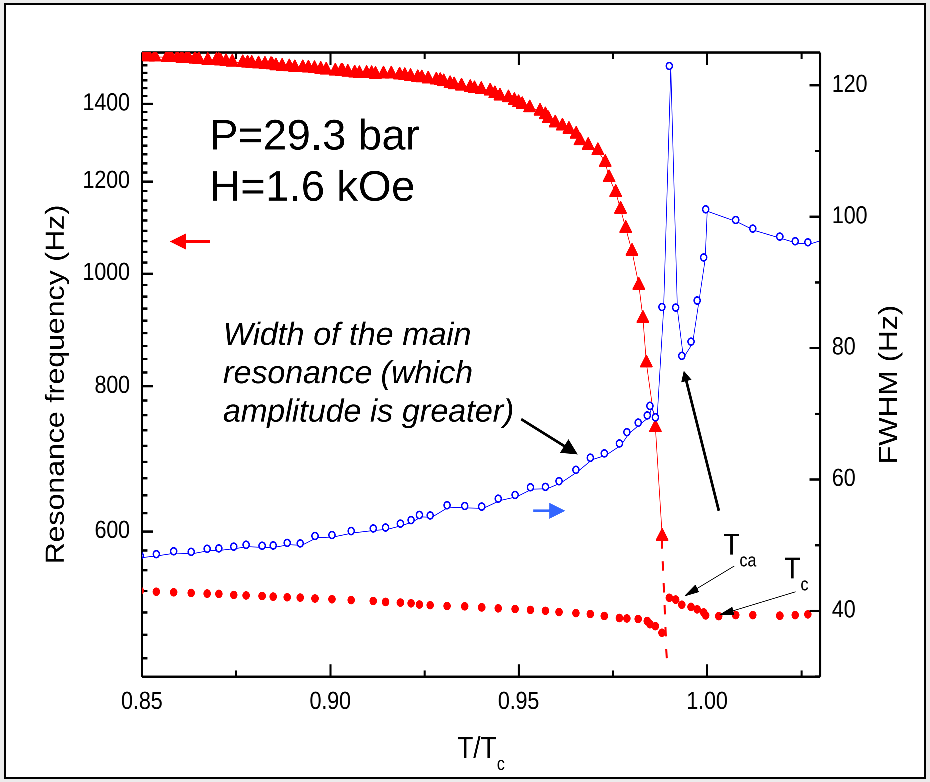


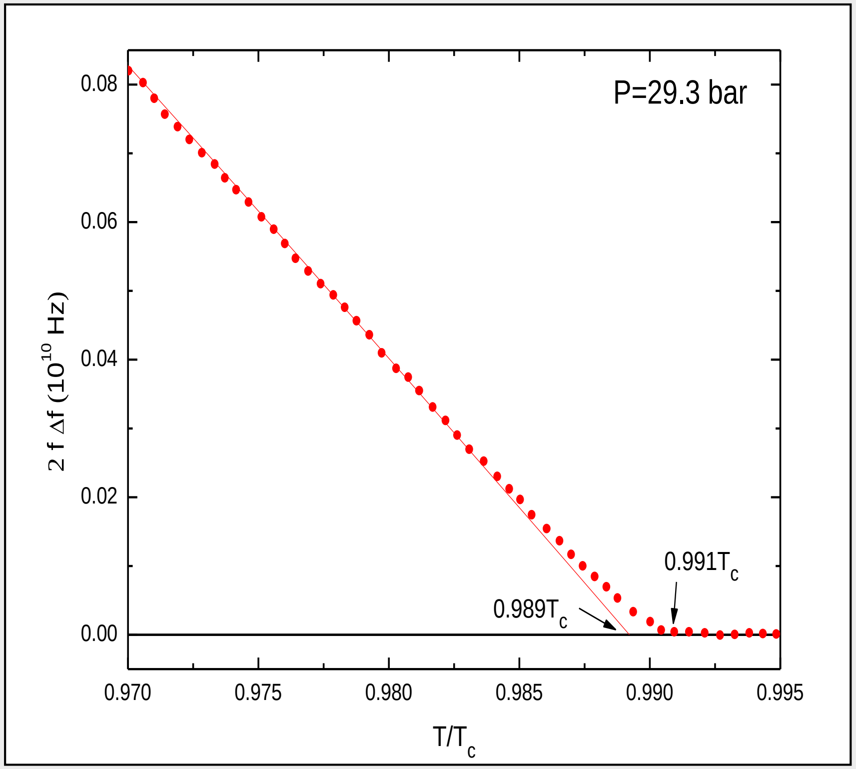




It was found that below T_{ca} an additional resonance mode appears. This mode presumably is due to that the superfluid component inside aerogel and the combined normal fluid and aerogel matrix can move in opposite directions, resulting in a second-sound-like mode which frequency grows from 0 on cooling from T_{ca} (JETP Lett. ***112****, 780 (2020)). This mode is similar to "slow sound" mode in ^{3}He in silica aerogel (PRL* ***82,*** *3492 (1999)).*

On cooling the width of the main VW resonance starts to increase at $T \approx T_{ca}$. A systematic error ~ $0.002T_c$ in determination of T_{ca} is possible due to final width of the superfluid transition of ^{3}He in aerogel.





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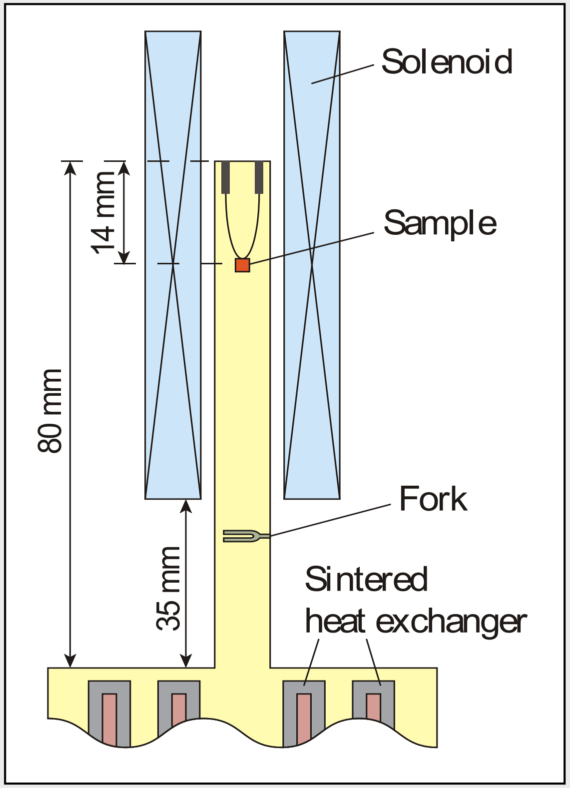
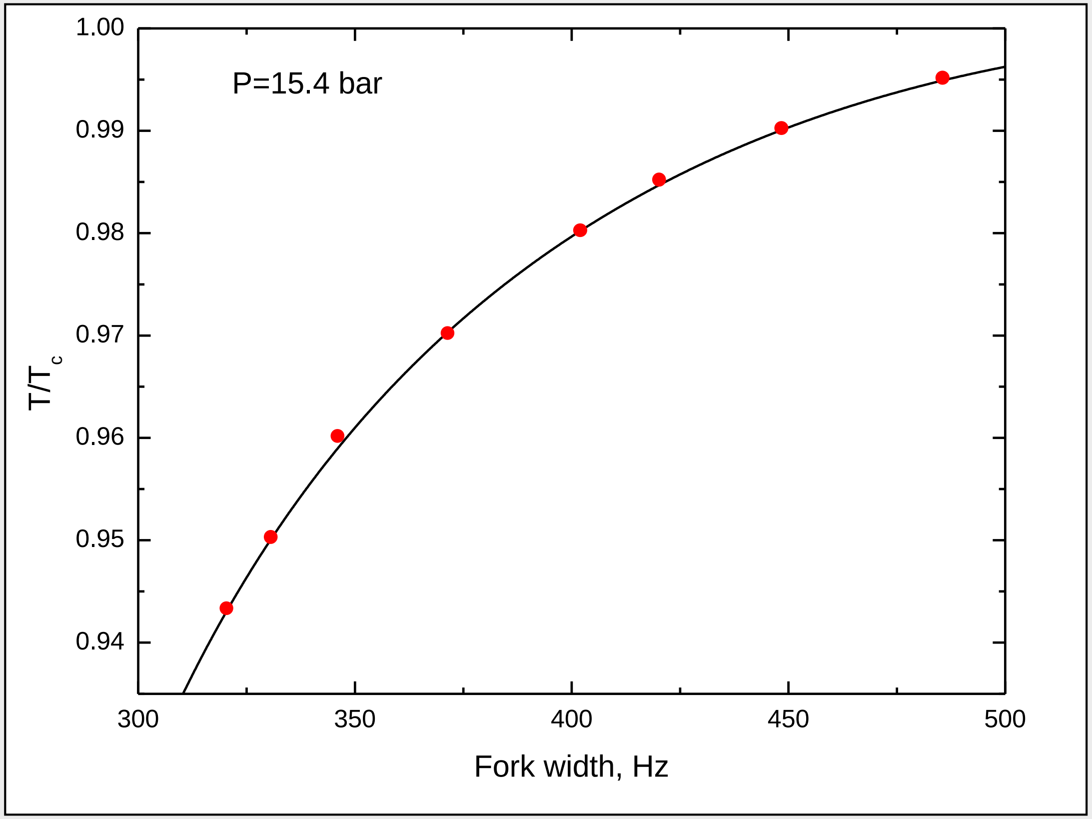
NMR frequency shift in ^{3}He in mullite sample. Solid line is the best fit by the dependence expected to the polar phase

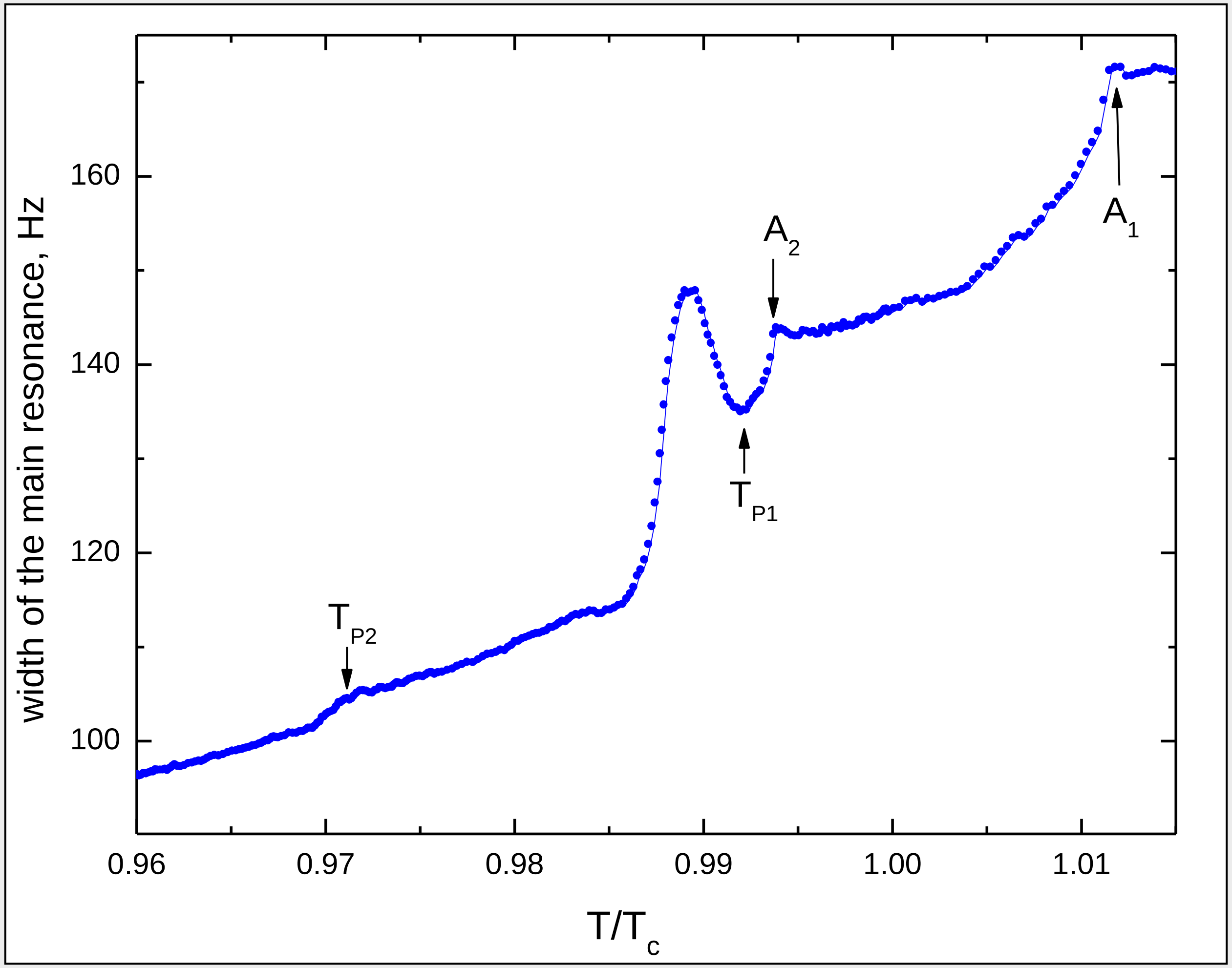
Experiments in high magnetic fields



For calibration of the fork we used the additional large solenoid (not shown) which field was homogeneous at distance ~100 mm. We measured the fork resonance width in the B phase just before B-A transition in different magnetic fields.
We use data for dependence of T_{BA} on H given by "3He calculator" of Northwestern LT Group which are based on I.Hahn PhD thesis (1993).

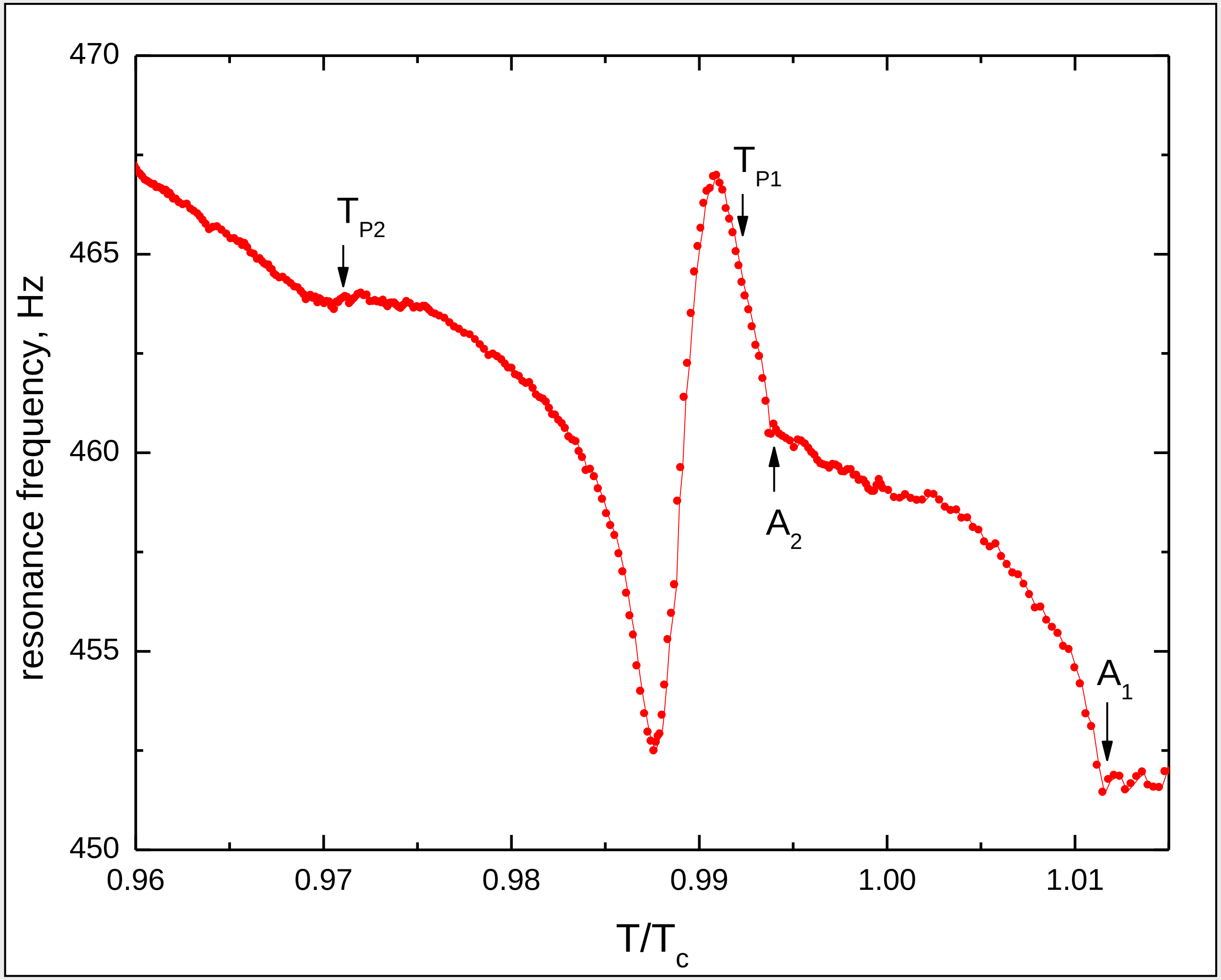


Width of the main resonance of VW. H=10.25 kOe, P=15.4 bar



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 continuously transformed to polar phase.

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



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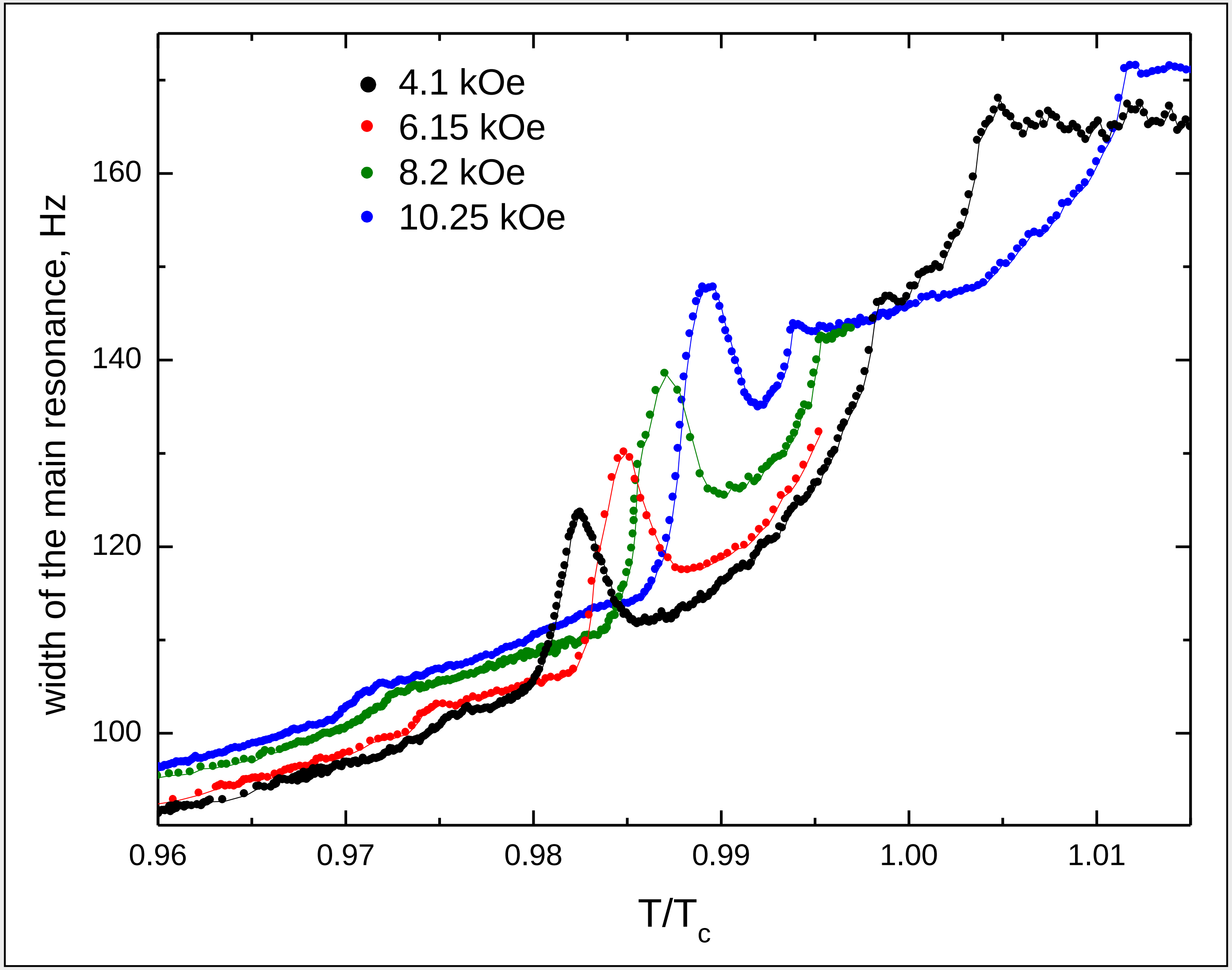
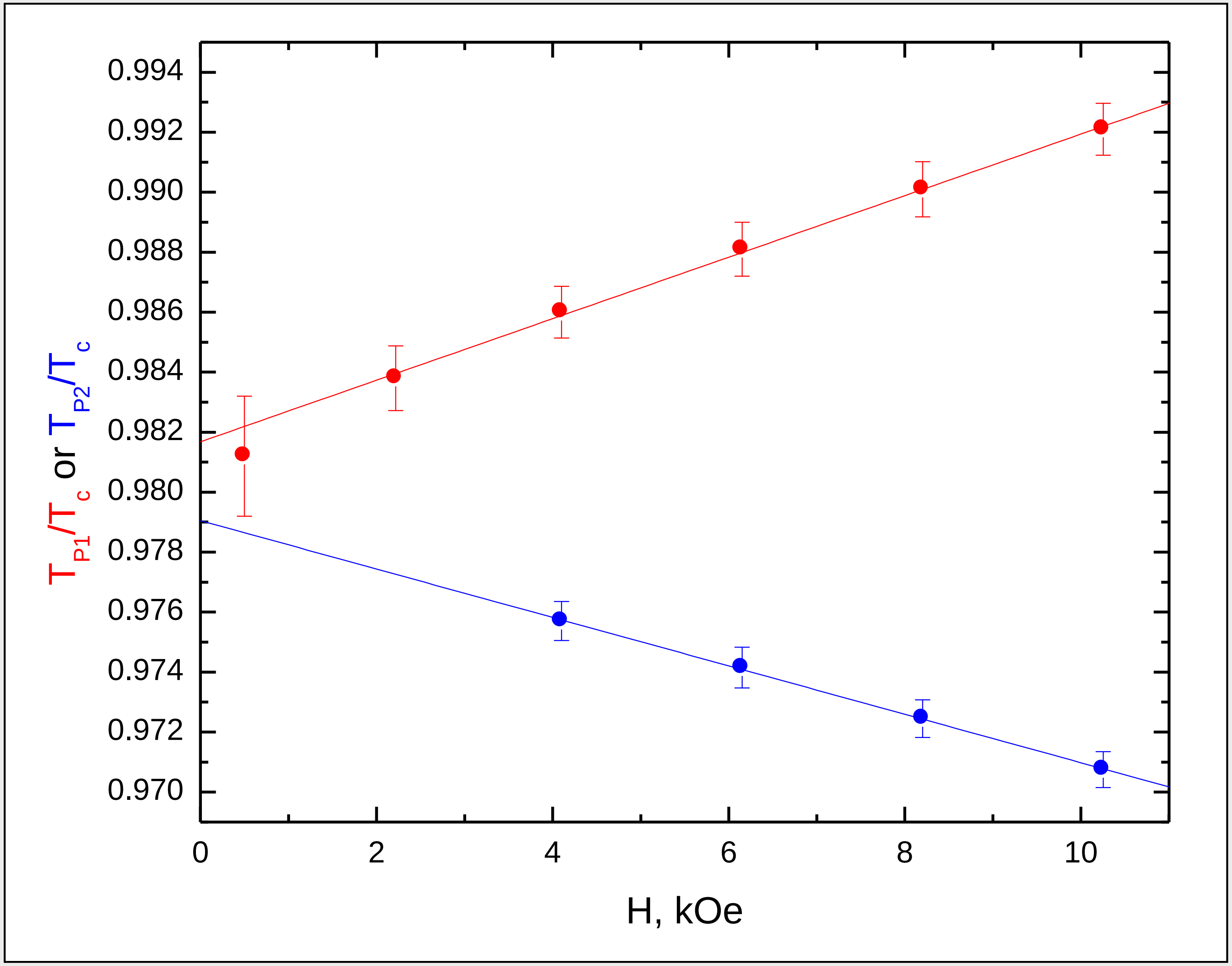
Width of the main resonance of VW in different H. P=15.4 bar



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 ^3He 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.*