3.3 Sound Propagation in ^{3}He: Zero Sound

normal (first) sound: quasi particles reach local equilibrium by collisions $\omega\tau \ll 1$

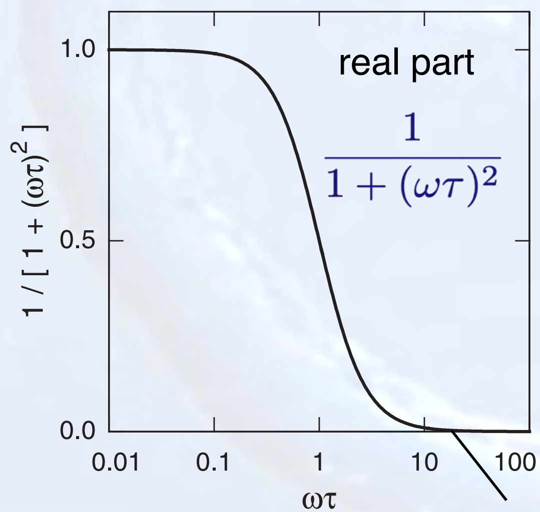
frequency of sound wave

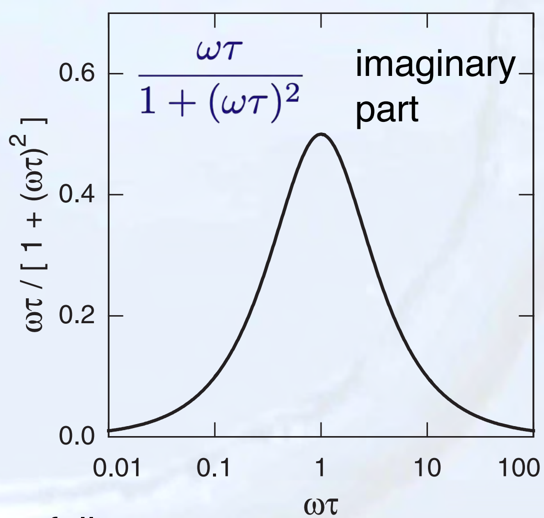
zero sound: collision-less propagation of sound $\omega\tau \gg 1$

^{3}He: particle density fluctuations in one region lead to density fluctuations in neighboring regions

→ propagation of sound-like modes → zero sound

Debye relaxation process (transition from hydrodynamic regime to collision-less regime)





systems cannot follow

3.3 Sound Propagation in ^{3}He: Zero Sound

- high T: $\omega\tau \ll 1$ ⟶ hydrodynamic regime: first sound
- low T: $\omega\tau \gg 1$ ⟶ collision-less regime: zero sound, longitudinal
  transversal
  collision-less spin waves

compare with classical gas

mean free path > wavelength ⟶ no sound propagation

but ^{3}He

- strongly interacting particles
- force on quasiparticle does not stem from direct neighbors, but from all atoms
- density fluctuations can propagate without collisions
- transversal modes are also possible

General theoretical description of zero sound is rather complicated ⟶ here only results

⟹ collective modes with $\omega\tau \gg 1$ ⟶ zero sound

⟹ 2 different sound modes (similar to first sound) and collision-less spin waves

3.3 Sound Propagation in ^{3}He: Zero Sound

longitudinal sound:

$$v_1 = \frac{v_F}{3}\sqrt{\frac{(1+F_0)}{(1+\frac{1}{3}F_1)}} \qquad \omega\tau \ll 1$$

$$v_0 = v_1\left[1+\frac{2}{5}\left(\frac{1+\frac{1}{5}F_2}{1+F_0}\right)\right] \qquad \omega\tau \gg 1$$

difference of zero and first sound: $\frac{v_0 - v_1}{v_1} = \frac{2}{5}\frac{(1+\frac{1}{5}F_2)}{(1+F_0)}$

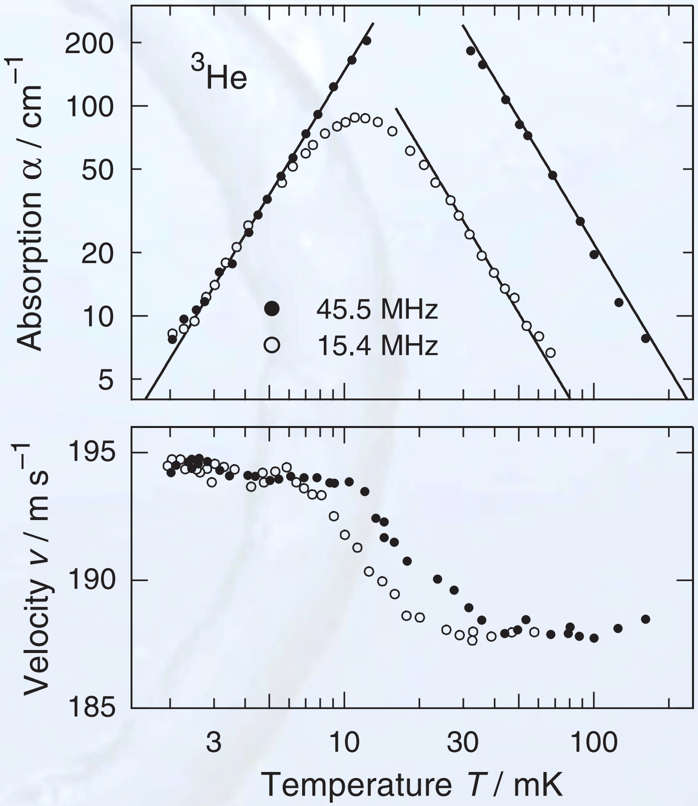
$\longrightarrow$ $(v_0 - v_1) \approx 6\,\mathrm{m\,s^{-1}}$

intermediate temperatures: $\frac{v}{v_1} = 1 + \frac{v_0 - v_1}{v_1}\frac{\omega^2\tau_s^2}{1+\omega^2\tau_s^2}$

sound attenuation: $\frac{\alpha v}{\omega} = -2\,\frac{v_0 - v_1}{v_1}\frac{\omega\tau_s}{1+\omega^2\tau_s^2}$

limiting cases: $\alpha_1 = A_1\omega^2\tau \propto \omega^2 T^{-2}$

$\alpha_0 = A_0\tau^{-1} \propto T^2$



→ excellent agreement with Landau theory

3.3 Sound Propagation in ^{3}He: Zero Sound

transversal sound:

ordinary liquids ⟶ no transversal sound mode

^{3}He

- $\omega\tau \ll 1$ hydrodynamical regime ⟶ diffuse shear mode
- $\omega\tau \gg 1$ real solution for $F_1 > 6$

impossible at normal pressure: $F_1 = 5.2$

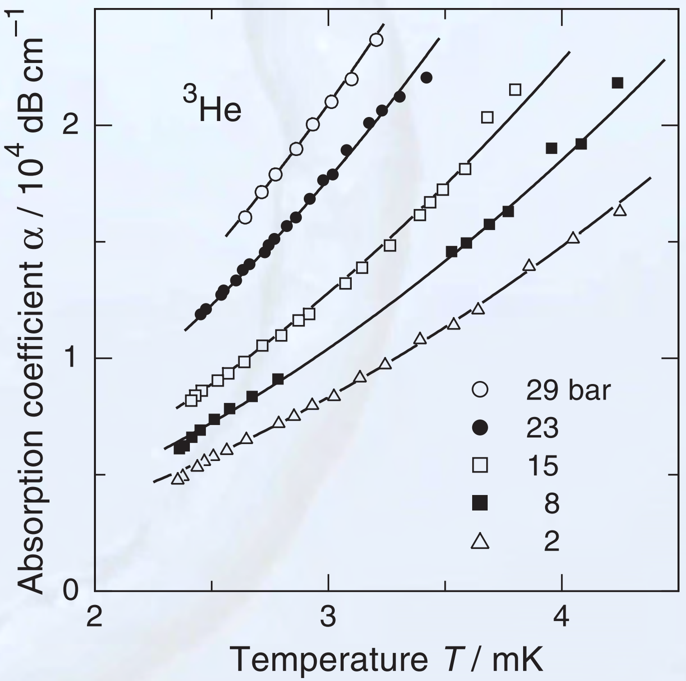
but F_1 depends on pressure

$F_1 = 5.2 \ldots 15$ — melting pressure

attenuation: $\alpha_0 \propto T^2$

experimental results

- narrow T range, very high damping
- sound transducers spaced by 25 μm
- damping depends on pressure



3.3 Sound Propagation in ^{3}He: Zero Sound

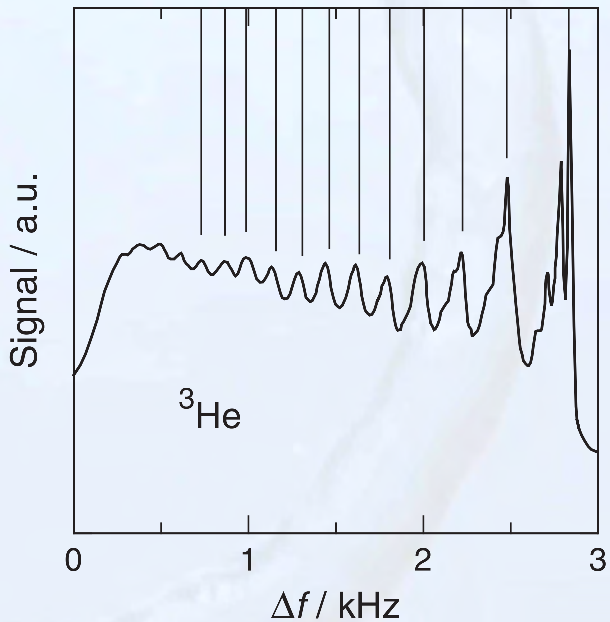
collision-less spin waves: (predicted by Silin 1957)

spin transport $D_\mathrm{s} = \frac{1}{3}\,\tau_\mathrm{D}\,v_\mathrm{F}^2\left(1 + \frac{1}{4G_0}\right)$

spin transport
- $\omega\tau \ll 1$ ⟶ normal spin diffusion
- $\omega\tau \gg 1$ ⟶ collision-less spin waves

experimental results

- standing spin waves
- linear magnetic field gradient $44\,\mathrm{mT\,m^{-1}}$
- rectangular absorption “line”
- maxima of spin wave resonance on top



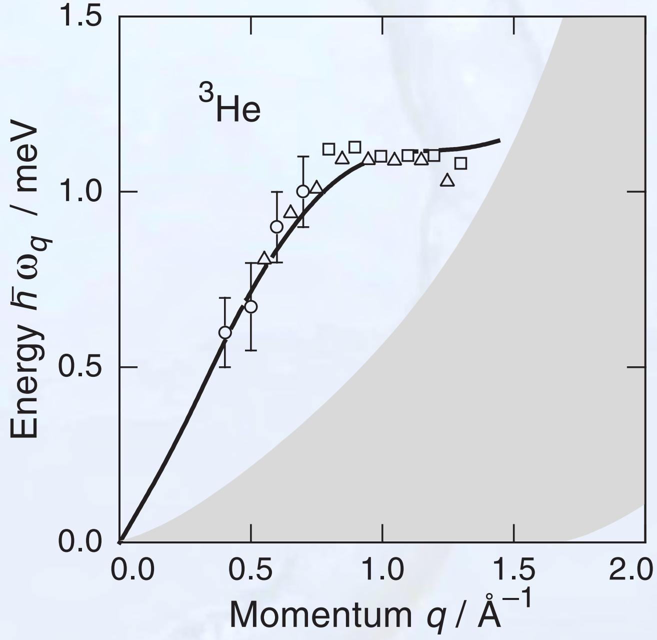
3.3 Sound Propagation in ^{3}He: Zero Sound

Dispersion of zero sound modes:

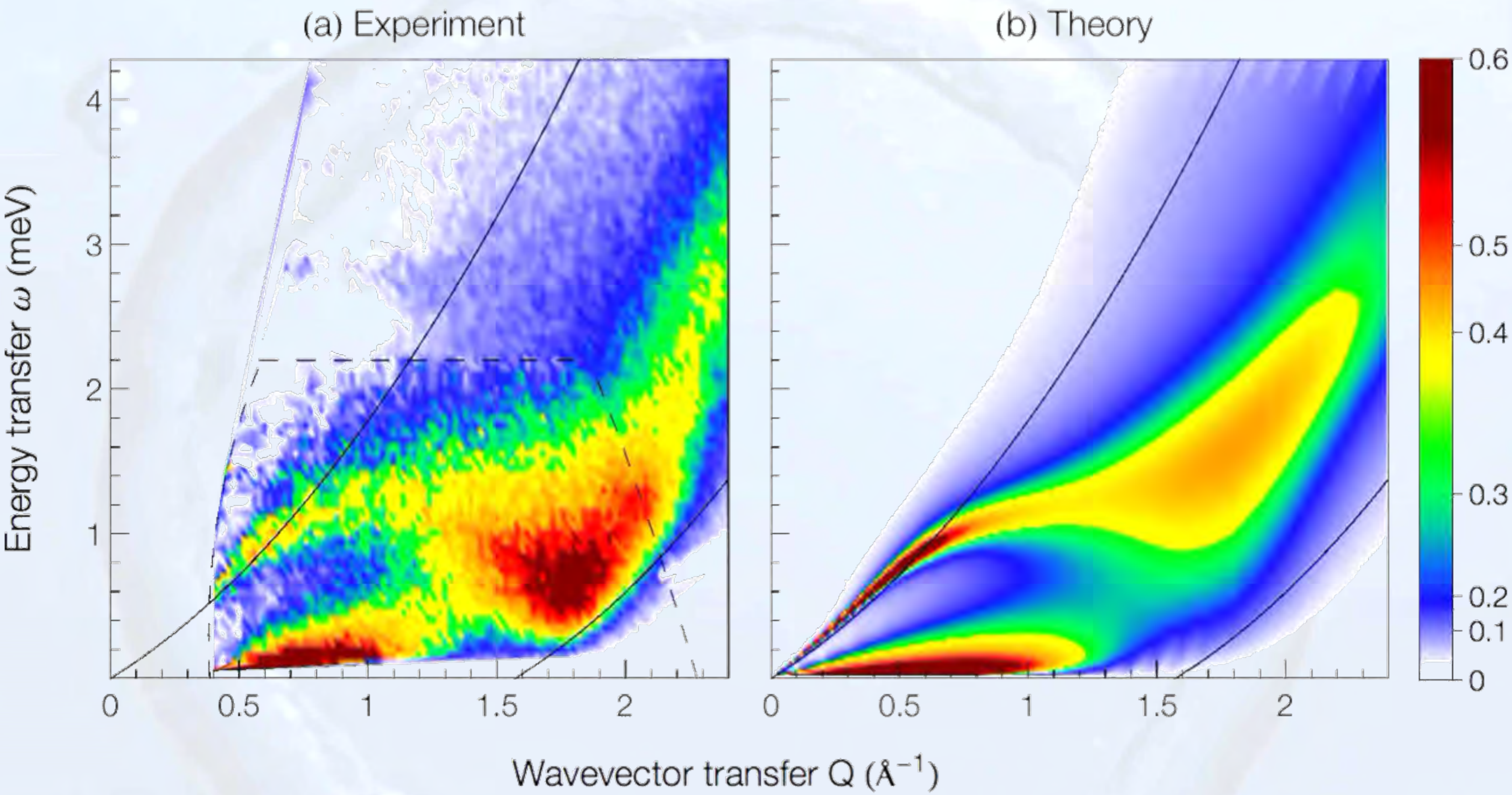
experimental determination very difficult

capture cross section very high

ultralow temperatures $T < 20$ mK

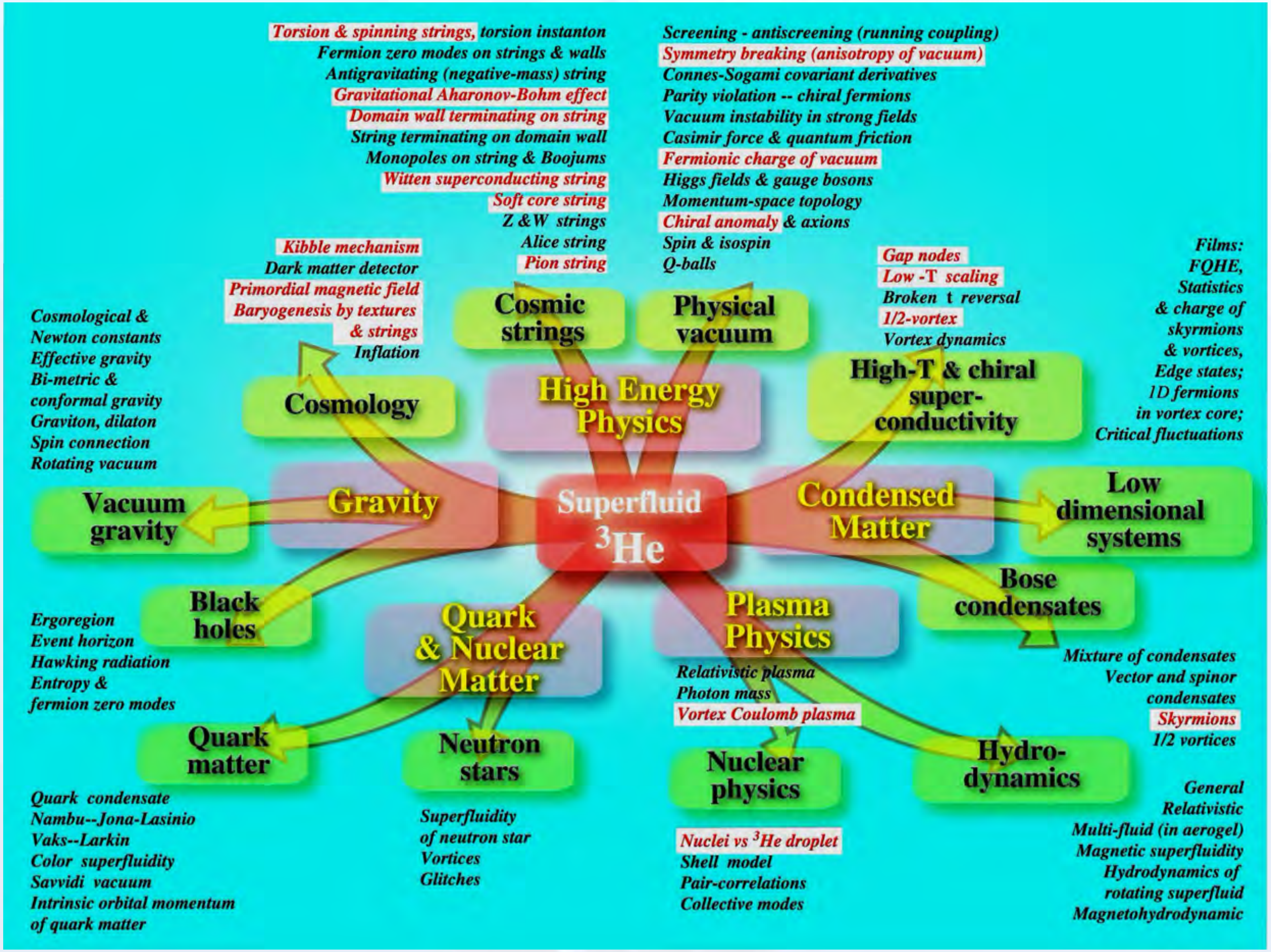


3.3 Sound Propagation in ^{3}He: Zero Sound



4. Superfluid ^{3}He

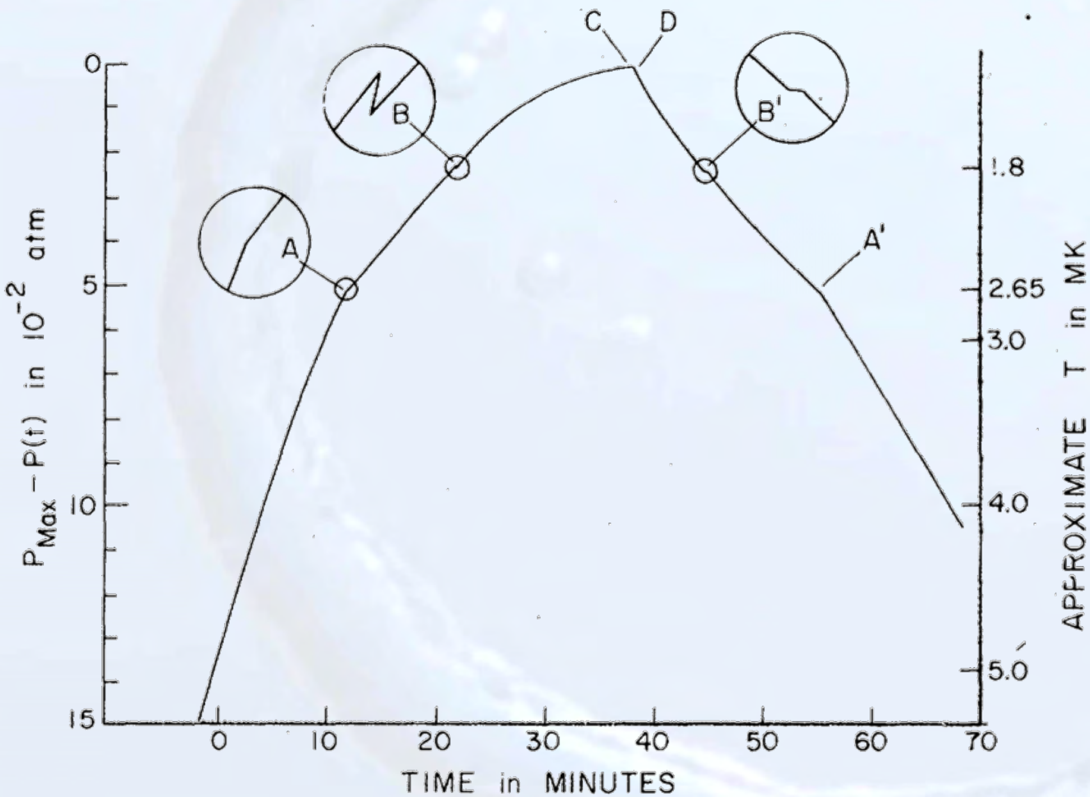
A model for all physics in our universe?

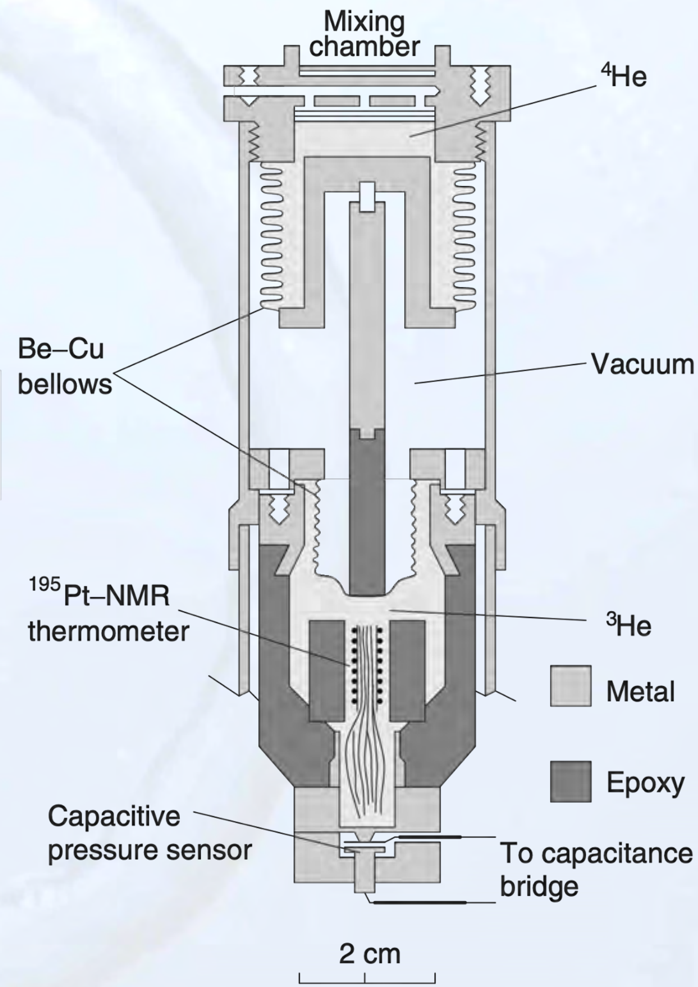


Discovery of superfluid ^{3}He

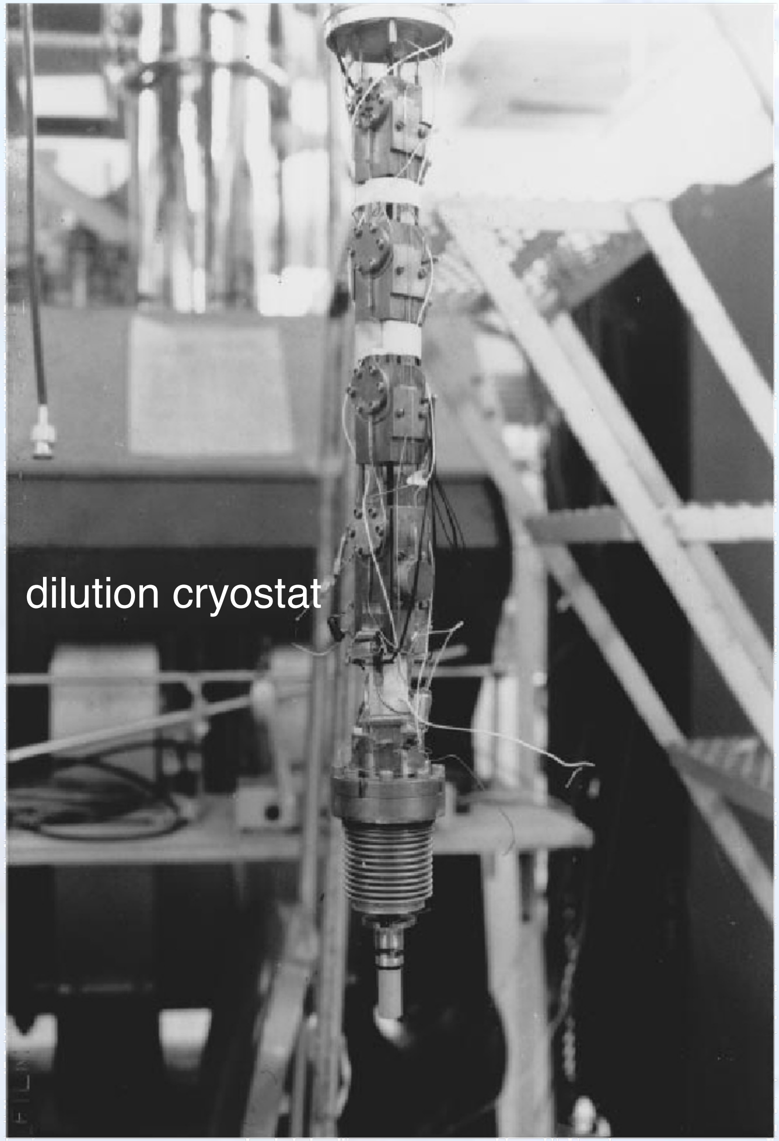
Douglas Osheroff, Bob Richardson, Dave Lee

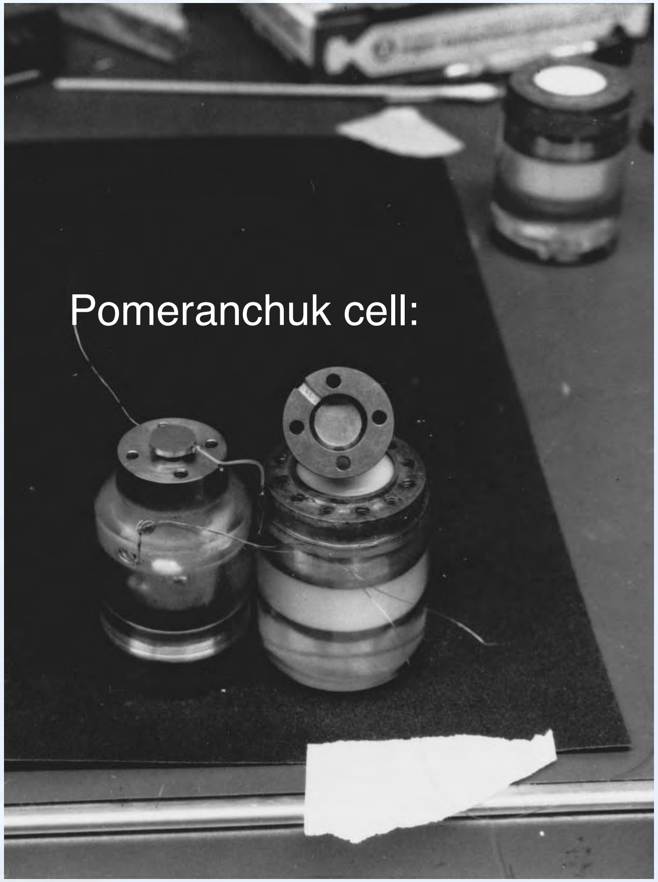
indications for several phase transitions in a pressure dependent measurement with a Pomeranchuk cell





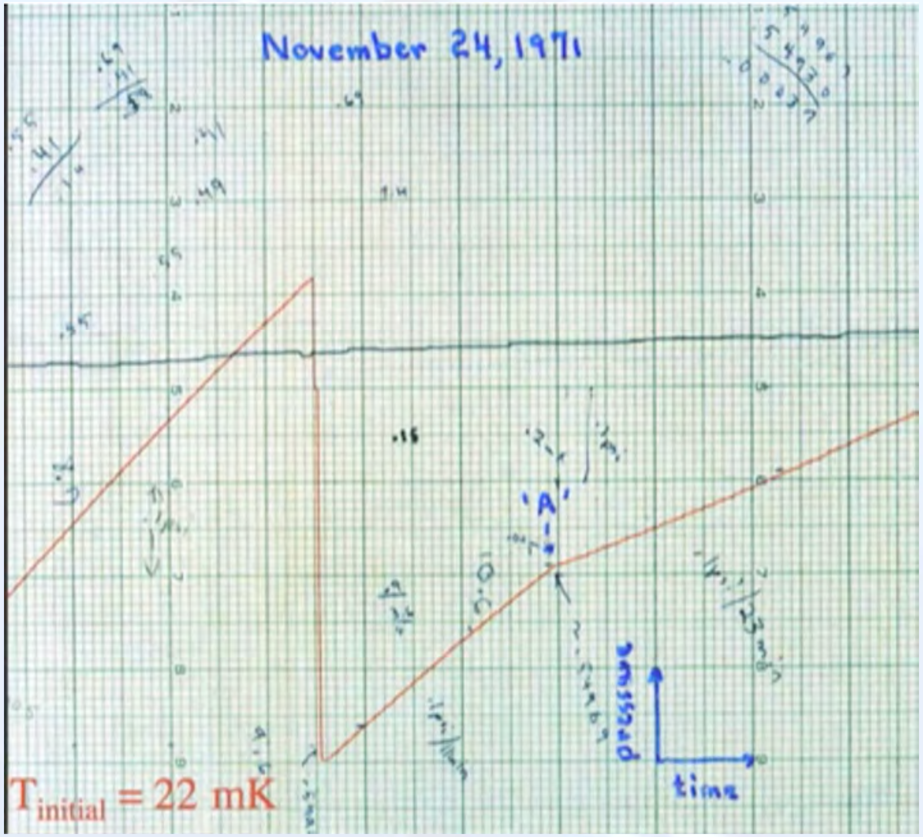
Discovery of superfluid ^{3}He

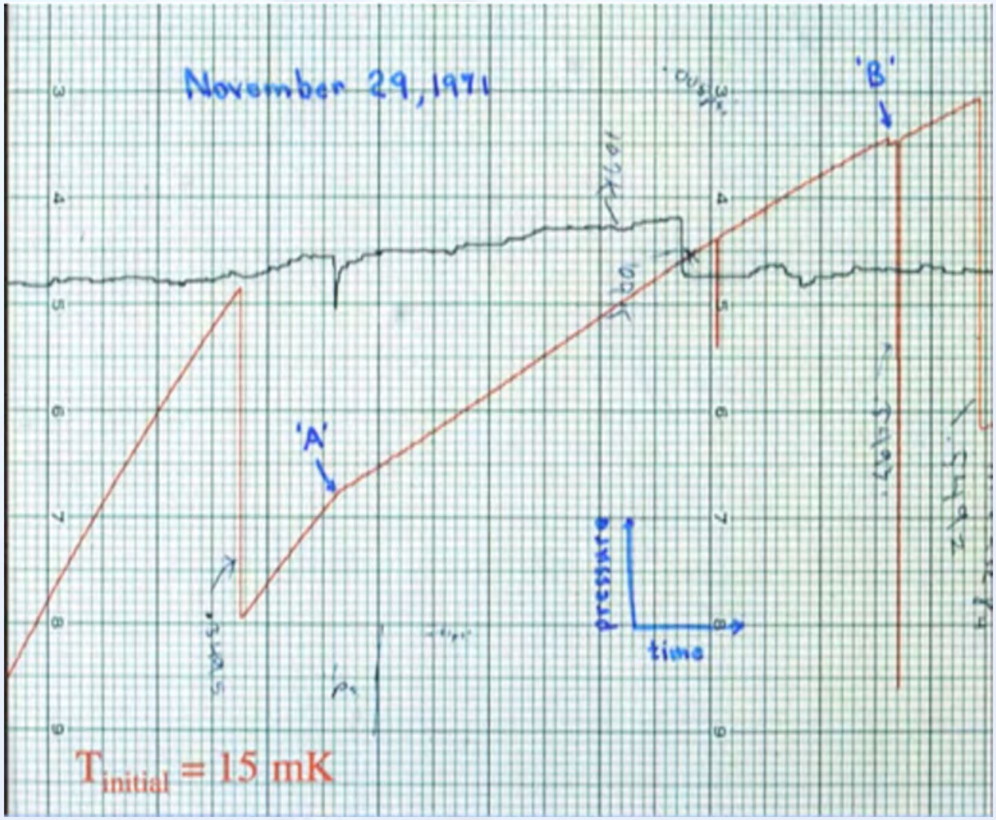




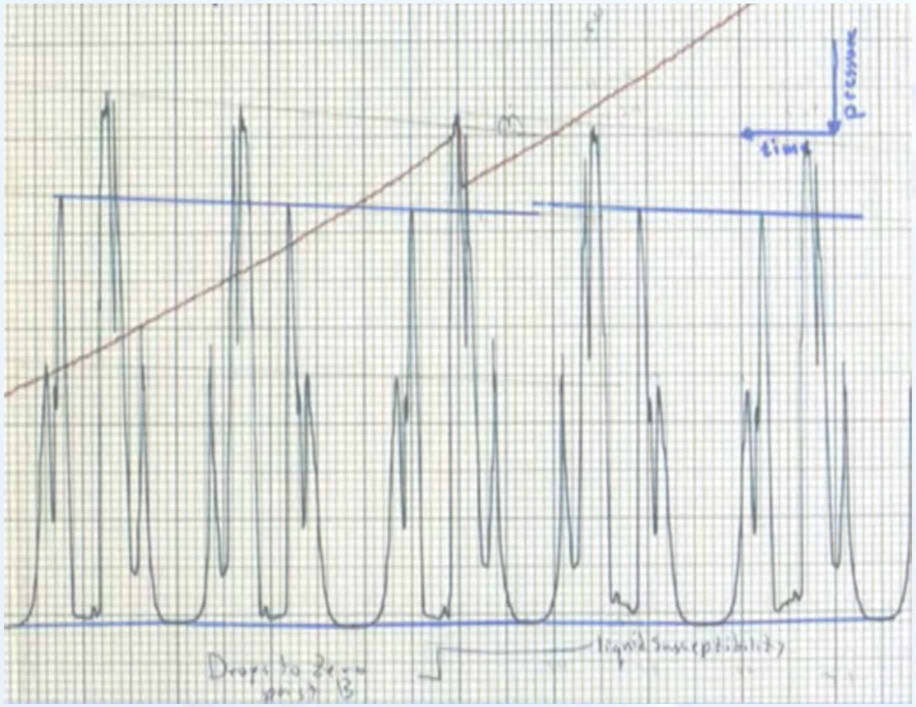
Discovery of superfluid ^3He

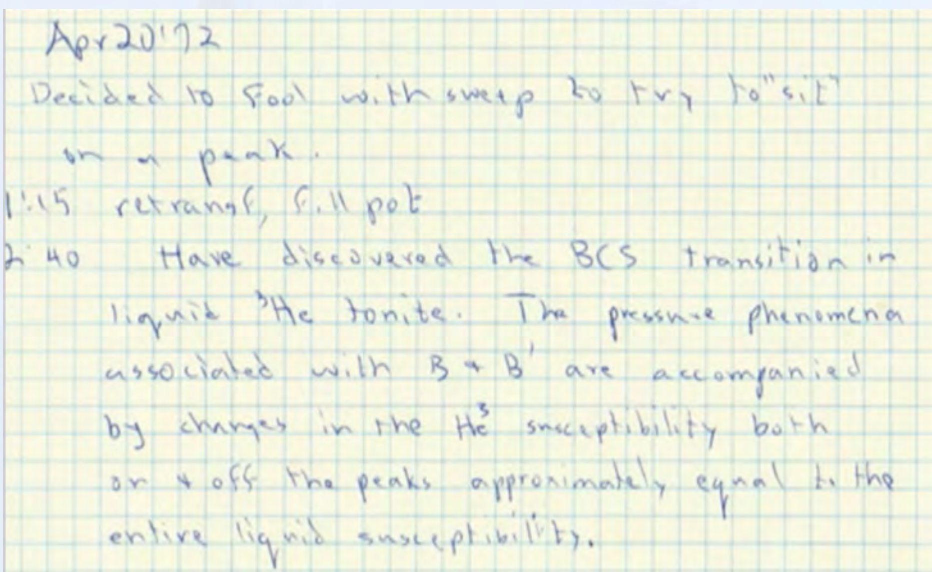
Original recordings:





Discovery of superfluid ^{3}He




Apr 20 '72
Decided to fool with sweep to try to "sit" on a peak.
1:15 retransf, fill pot
2:40 Have discovered the BCS transition in liquid ^{3}He tonite. The pressure phenomena associated with B + B' are accompanied by changes in the He^3 susceptibility both on + off the peaks approximately equal to the entire liquid susceptibility.

Lab book of Doug Osheroff

April 20, 1972

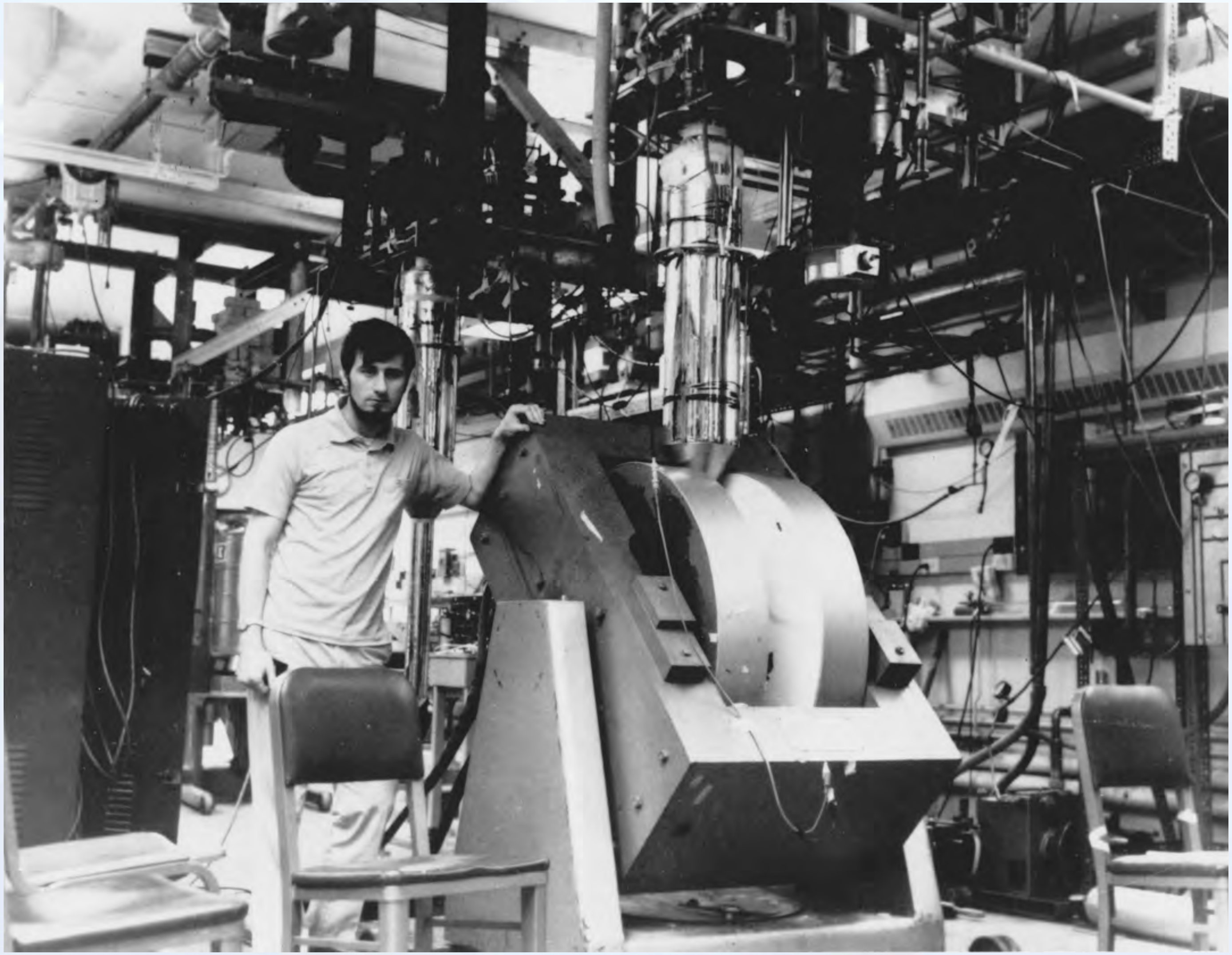
2:40 am: Have discovered the BCS transition in liquid ^{3}He tonite. The pressure pheonomena associated with B + B‘ are accompanied on + off the peaks approximately equal to the entire liquid susceptibility.

I checked all the other data I had taken, and then I looked around for someone with whom to share my good news. No one was anywhere to be found in the entire building.

At 4:00 am: I decided to call Dave Lee and Bob Richardson, perhaps a risky move for any graduate student. Both agreed that the identification was a strong one, and at 6:00 am Dave called back for more details.

Discovery of superfluid ^3He

morning after the discovery

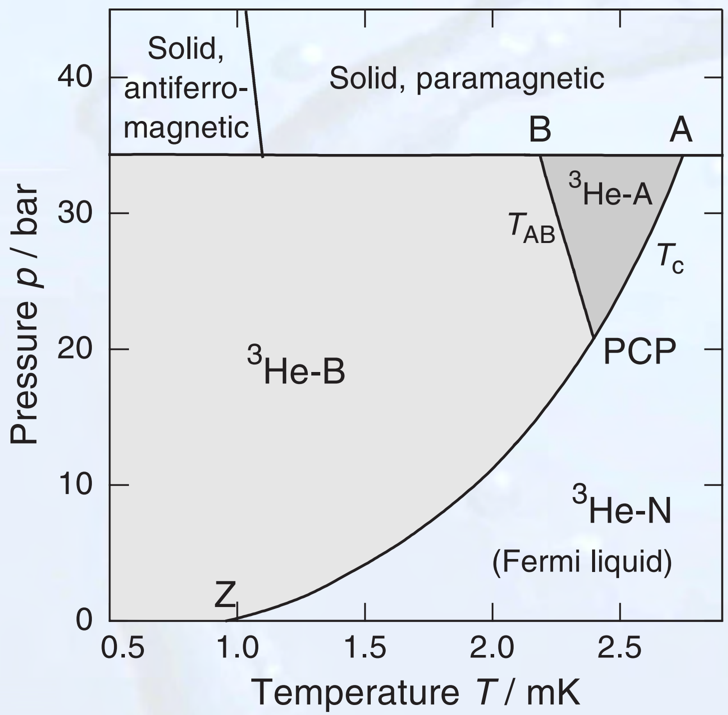


Discovery of superfluid ^3He

Heidelberg 2010

4.1 Basic Properties of superfluid ^3He

a) Phase diagram (at ultralow temperatures and without magnetic field)



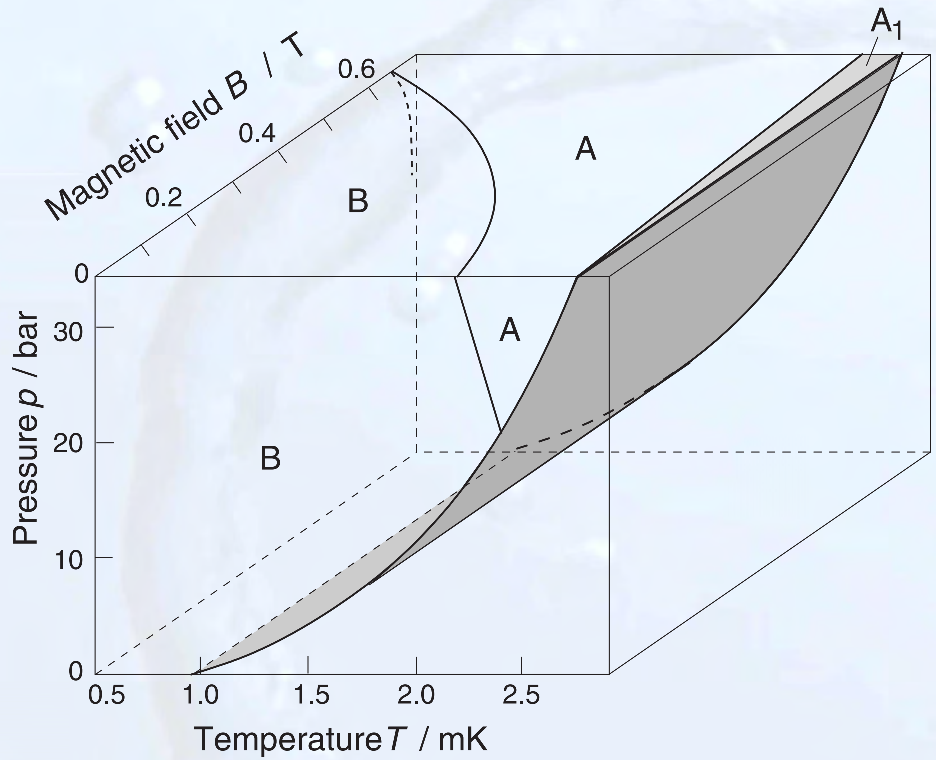
- PCP polycritical point
- ^{3}He-N → ^{3}He-A, ^{3}He-B A-PCP-Z
  ⟶ 2nd order phase transition
- ^{3}He-A → ^{3}He-B B-PCP
  ⟶ 1st order phase transition

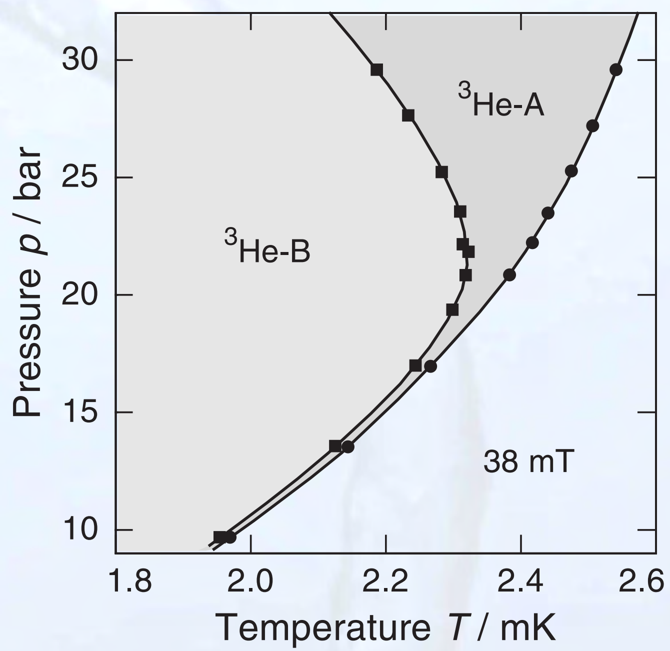
special points

	A	B	PCP	Z
pressure p (bar)	34.3	34.3	21.5	0
temperature T (mK)	2.44	1.90	2.24	0.92

4.1 Basic Properties of superfluid ^{3}He

with magnetic field

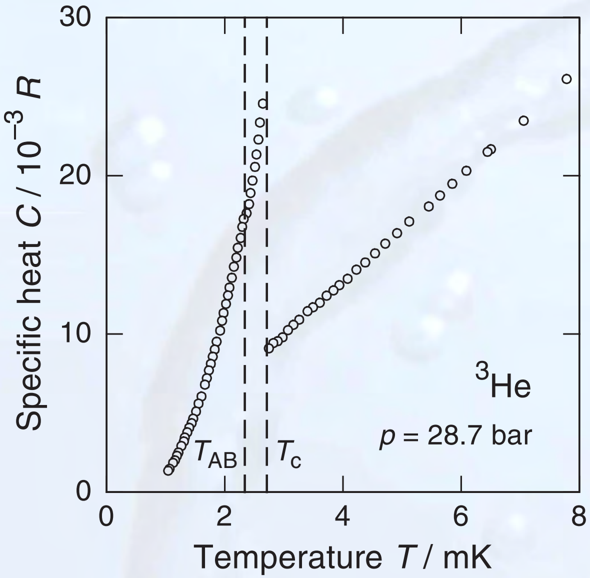




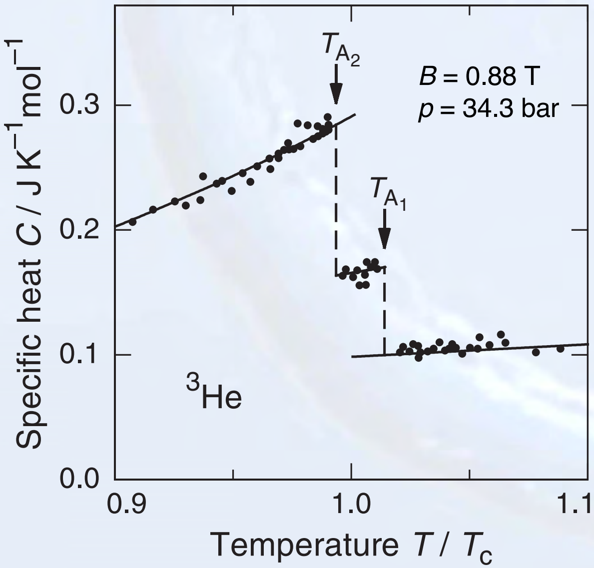
- A1 phase appears
- for $B > 0.65$ T no B phase
- PCP point disappears
- small corridor ~ 20 μK at 38 mT and 10 bar

4.1 Basic Properties of superfluid ^{3}He

b) Specific heat



- pressure 28.7 bar
- jump at T_c ^{3}He-N → ^{3}He-A
- jump $\Delta C/C_N \approx 1.4$ at $p = 0$
  $\Delta C/C_N \approx 2$ at $p = 34.3$ bar (melting pressure)
- anomaly at T_{AB} ^{3}He-A → ^{3}He-B
- Transition A → B: latent heat $L_{AB} \approx 1.54\,\mu J\,mol^{-1}$
  ⟶ 1st order phase transition



- splitting of A transition in magnetic field

  → A1

  → A2 ≙ A ($B = 0$)

4.1 Basic Properties of superfluid ^{3}He

c) Superfluidity

is ^{3}He a superfluid? ⟶ persistent flow experiments

A phase:

experiments are difficult

- only under pressure possible
- textures are important (more later on this)

⟶ persistent flow only meta stable and decays slowly

B phase:

persistent current experiments up to 48 h

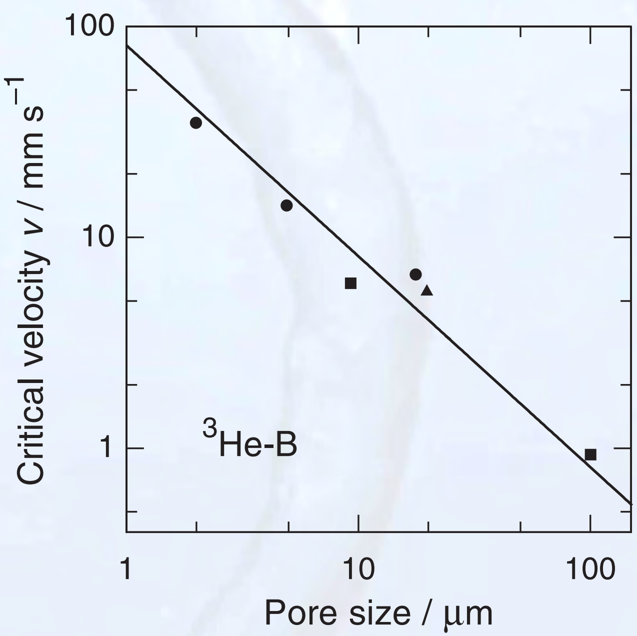
⟶ no reduction of flow

⟶ η drops by 12 orders of magnitude

critical velocity is extremely low: $v_c = 1 \ldots$ 100 mm/s

⟶ reasons: vortex rings and pair breaking

flow of ^{3}He-B through thin capillaries



- v_c drops linear with d : $v_c \propto d^{-1}$ as expected

compare He-II $v_c \propto d^{-1/4}$

4.1 Basic Properties of superfluid ^{3}He

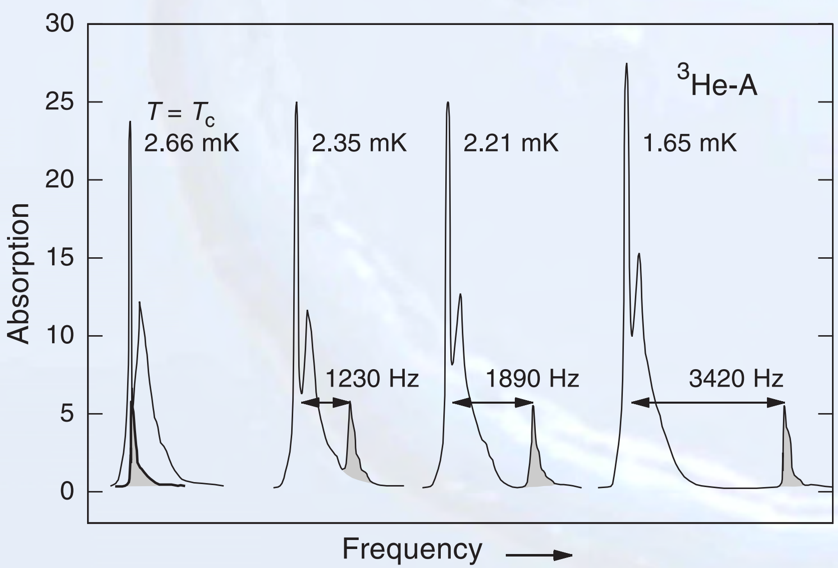
d) NMR experiments

no comparison with He-II possible ⟶ still revealing!

^{3}He: nuclear spin I =1/2, Lamor frequency $\omega_\mathrm{L} = \gamma|\boldsymbol{B}_0|$

- ^{3}He-N calculated Lamor frequency is observed
- ^{3}He-A, ^{3}He-B ⟶ very surprising effects

transverse rf field (normal geometry)



- measurement in Pomeranchuk cell by D. Osheroff
- double line because ^{3}He-A and solid ^{3}He are in cell
- NMR line shifts to higher frequencies with lower T
- empirical relation: $\omega_\mathrm{t}^2 = \omega_\mathrm{L}^2 + \Omega_\mathrm{A}^2(T)$