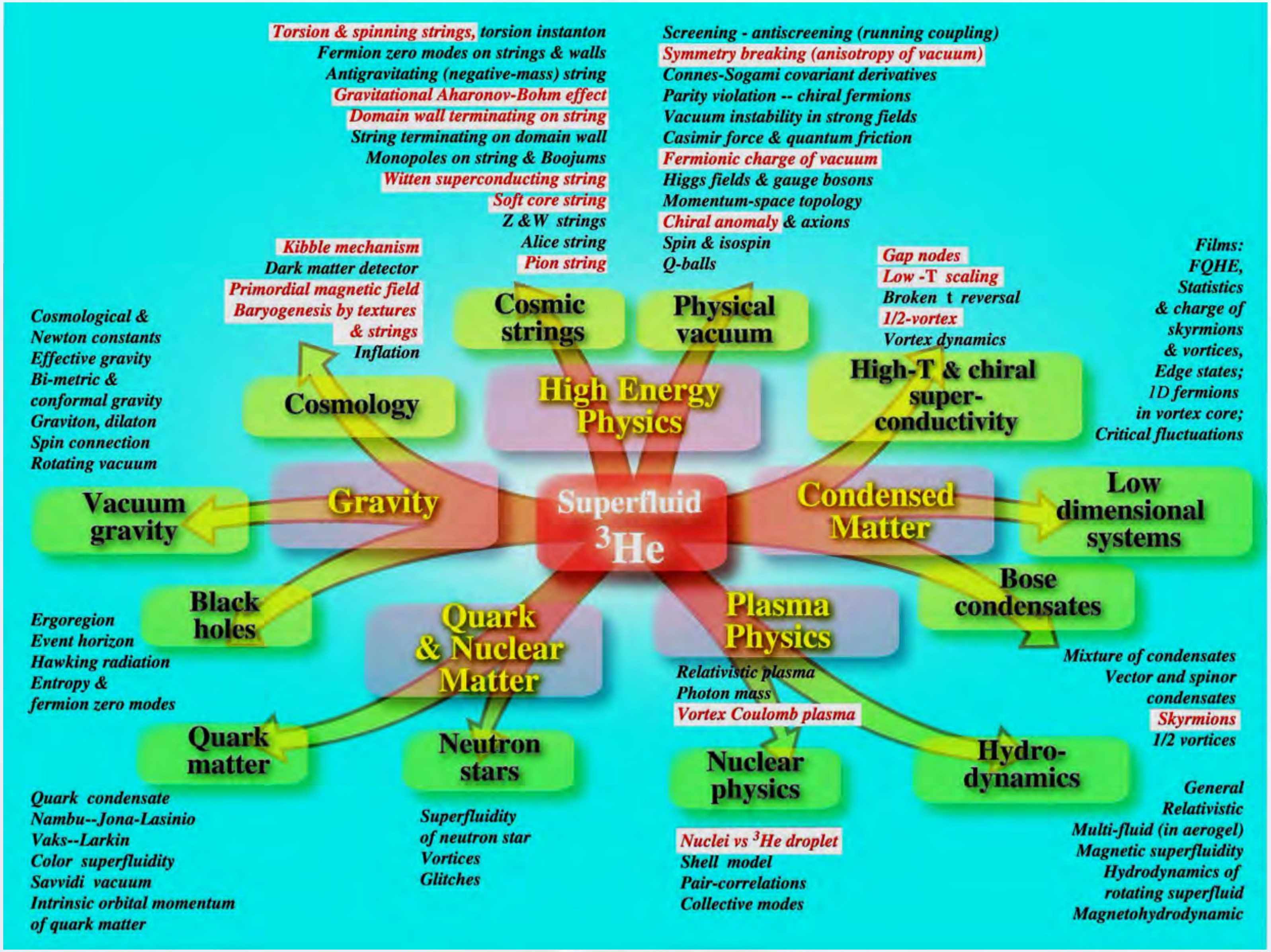
4. Superfluid ^{3}He

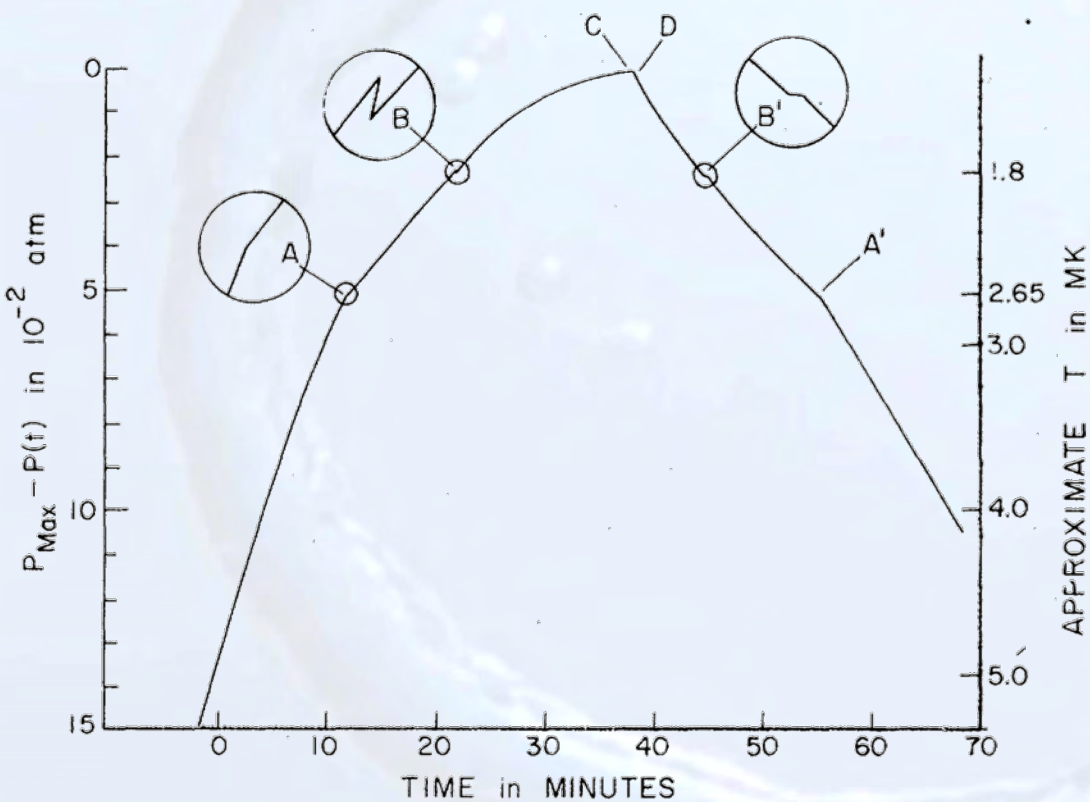
A model for all physics in our universe?

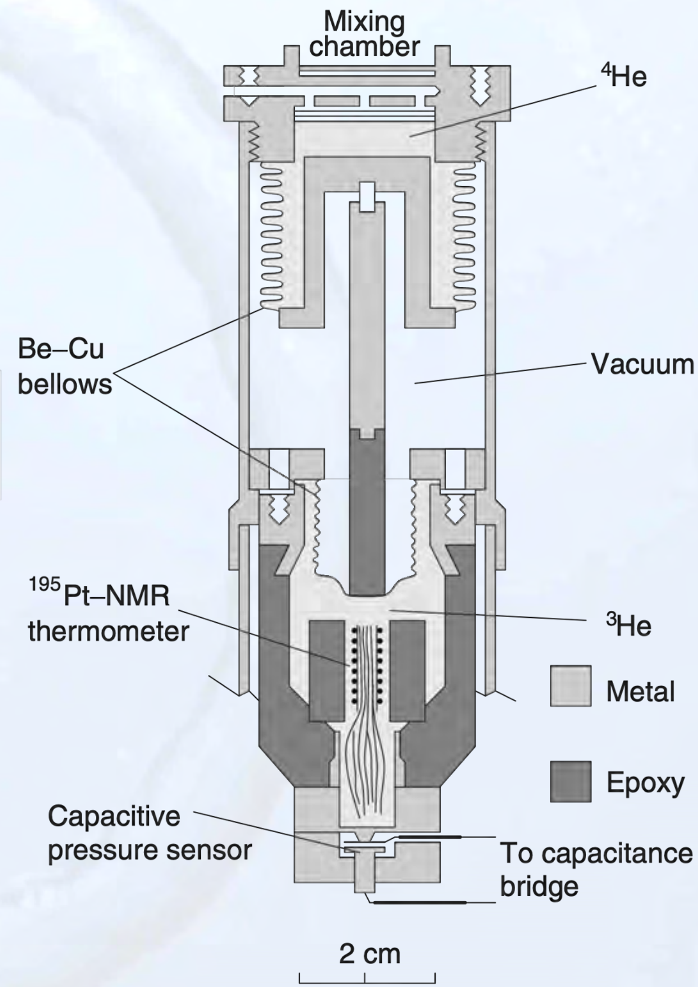


Discovery of superfluid ^{3}He

Douglas Osheroff, Bob Richardson, Dave Lee

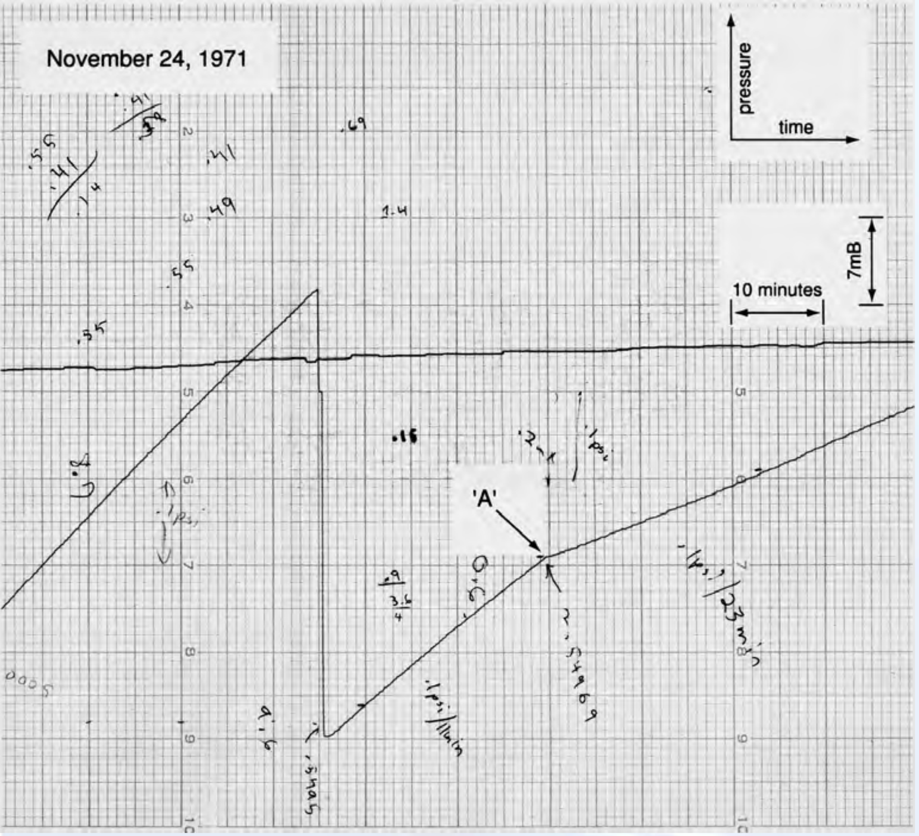
indications for several phase transitions in a pressure dependent measurement with a Pomeranchuk cell

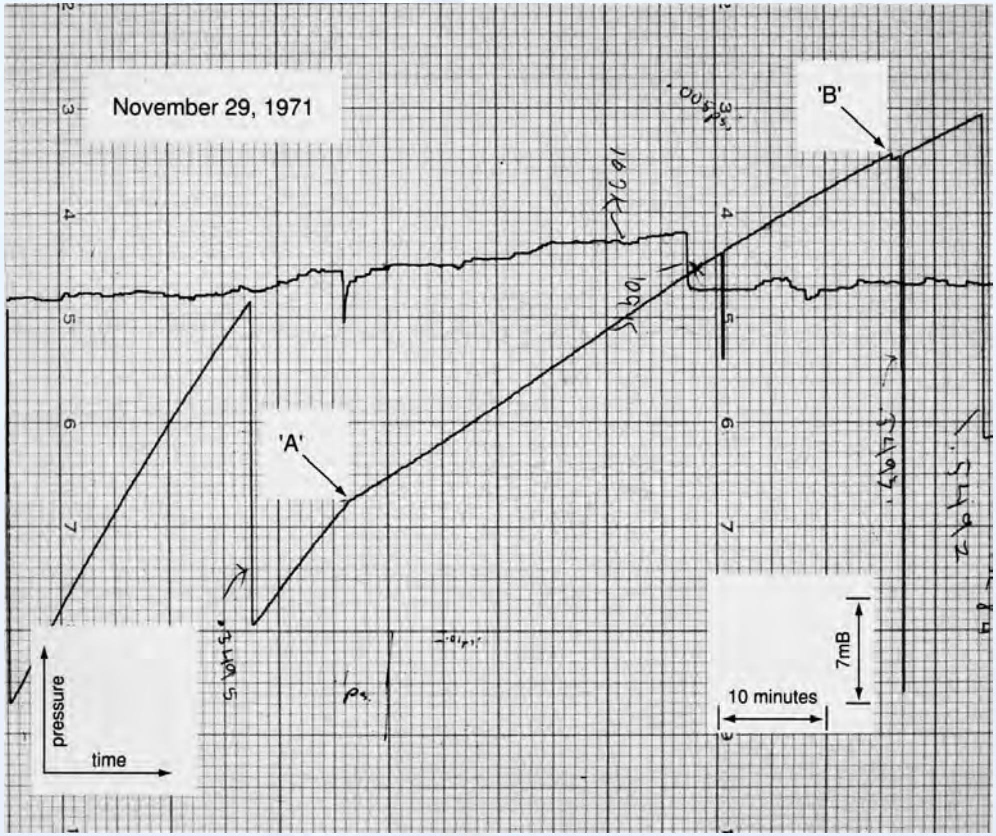




Discovery of superfluid ^{3}He

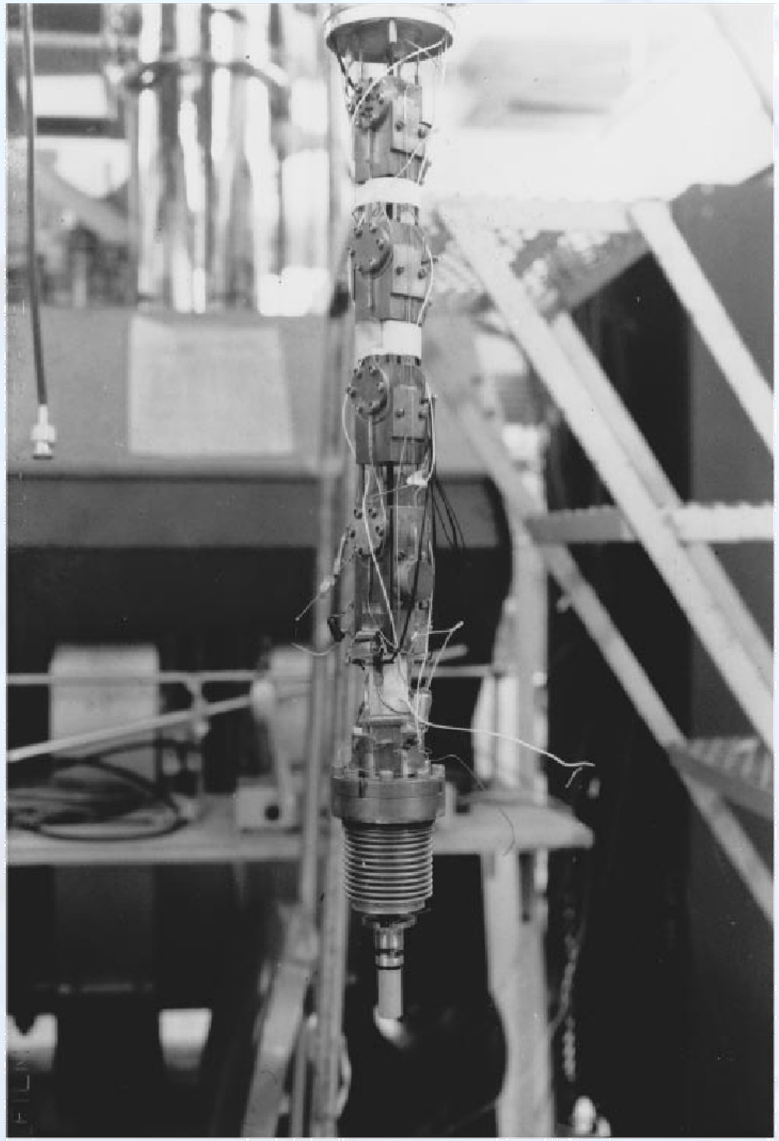
Original recordings:

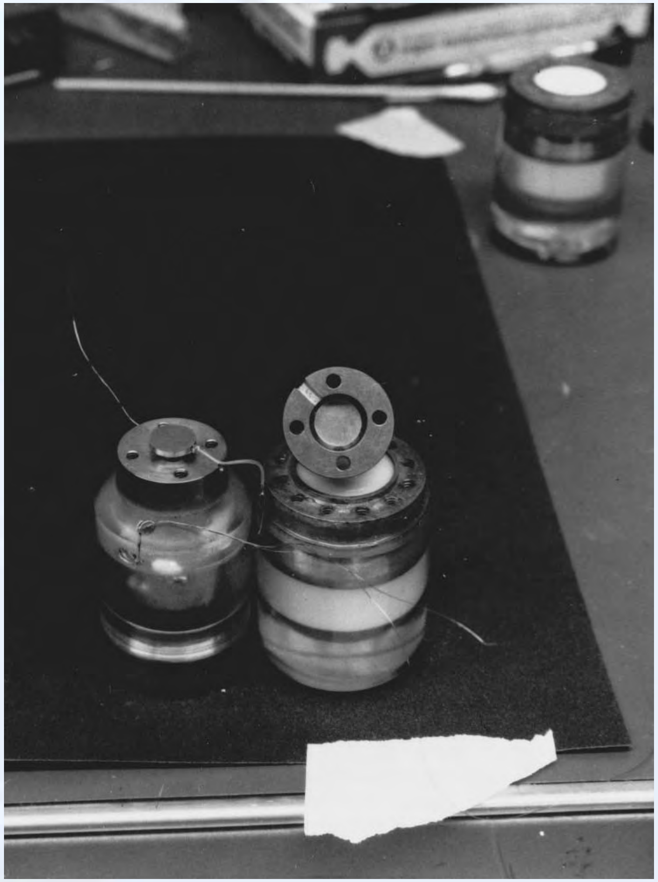




Discovery of superfluid ^3He

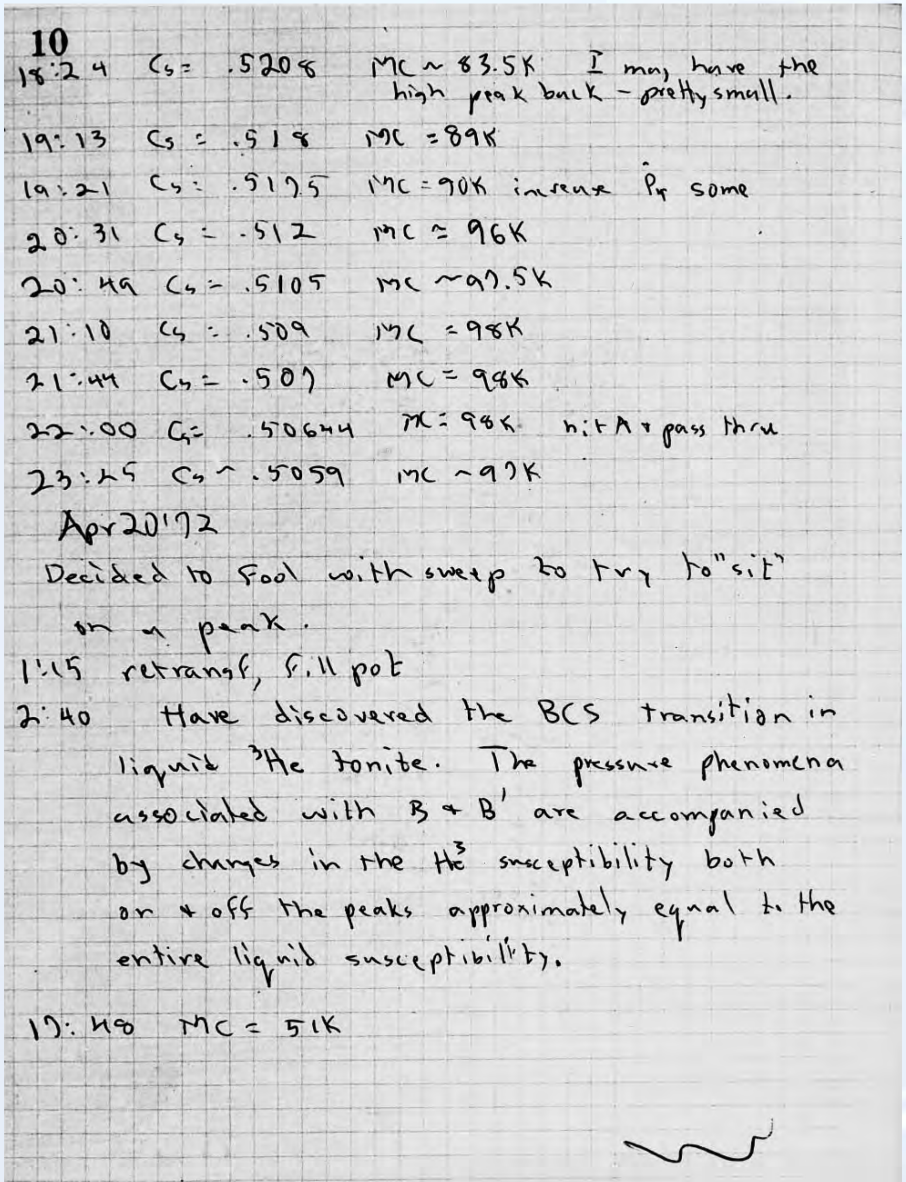
cryostat:





Discovery of superfluid ^{3}He

Lab book of Doug Osheroff


10

18:24 C_s = .5208 MC ~ 83.5K I may have the high peak back – pretty small.

19:13 C_s = .518 MC = 89K

19:21 C_s = .5175 MC = 90K increase $\dot{P}_F$ some

20:31 C_s = .512 MC ≃ 96K

20:49 C_s = .5105 MC ~ 97.5K

21:10 C_s = .509 MC = 98K

21:44 C_s = .507 MC = 98K

22:00 C_s = .50644 MC = 98K hit A + pass thru

23:45 C_s ~ .5059 MC ~ 97K

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.

17:48 MC = 51K

April 20, 1972

2:40 am: Have discovered the BCS transition in liquid ^{3}He tonight. 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.

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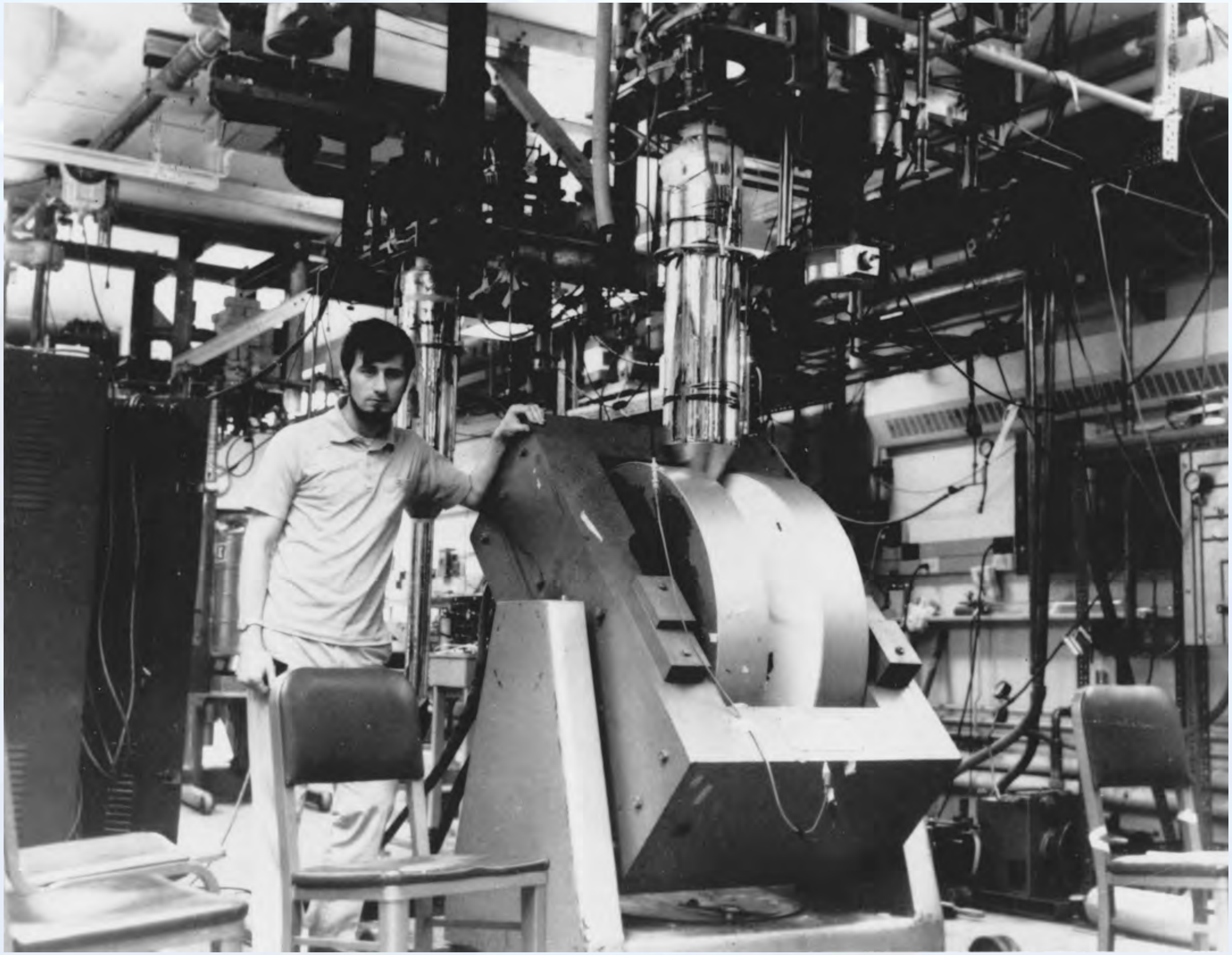
At 4:00 am: I decided to call Dave Lee and Bob Richardson, perhaps a risky move for any graduate student. Both agreed that the identification was a strong one, and at 6:00 am Dave called back for more details.

Discovery of superfluid ^{3}He

morning after the discovery

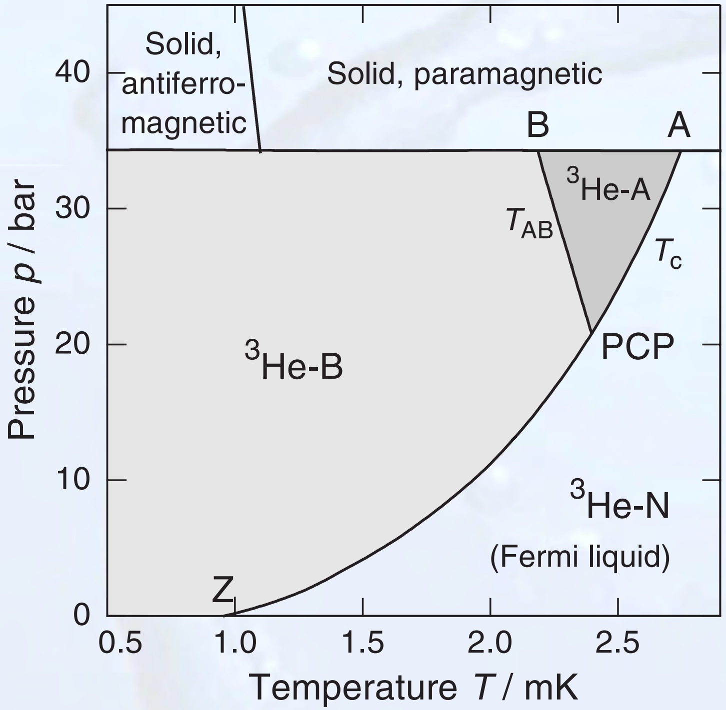


Discovery of superfluid ^{3}He

Heidelberg 2010

4.1 Basic Properties of superfluid ^{3}He

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



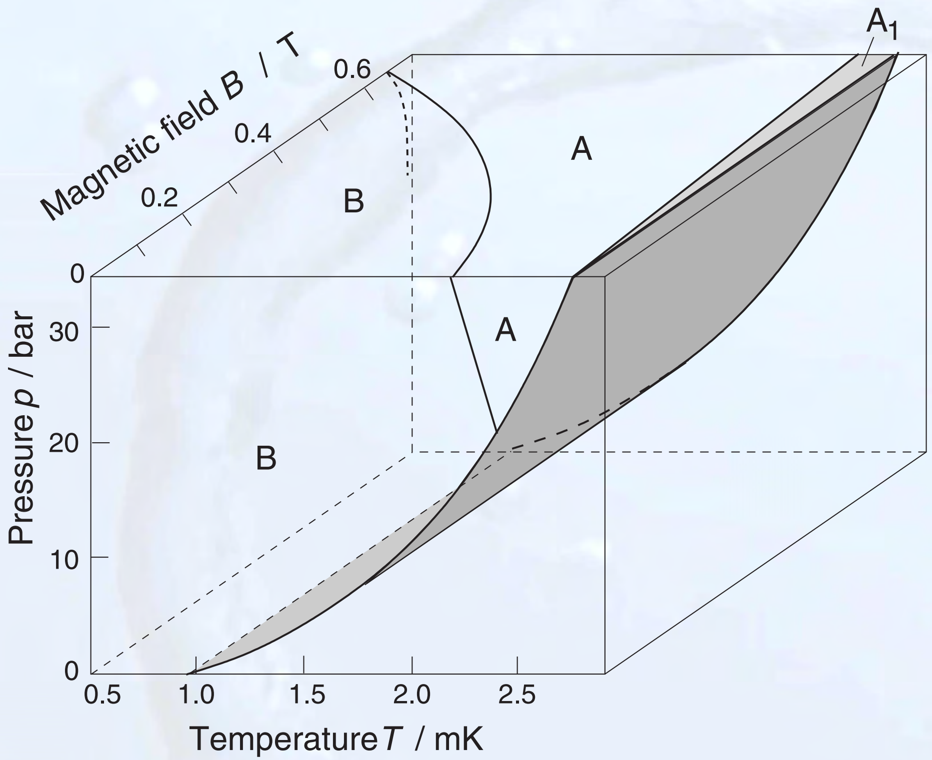
- PCP polycritical point
- ^{3}He-N → ^{3}He-A, ^{3}He-B   A-PCP-Z
  ⟶ 2nd order phase transition
- ^{3}He-A → ^{3}He-B   B-PCP
  ⟶ 1st order phase transition

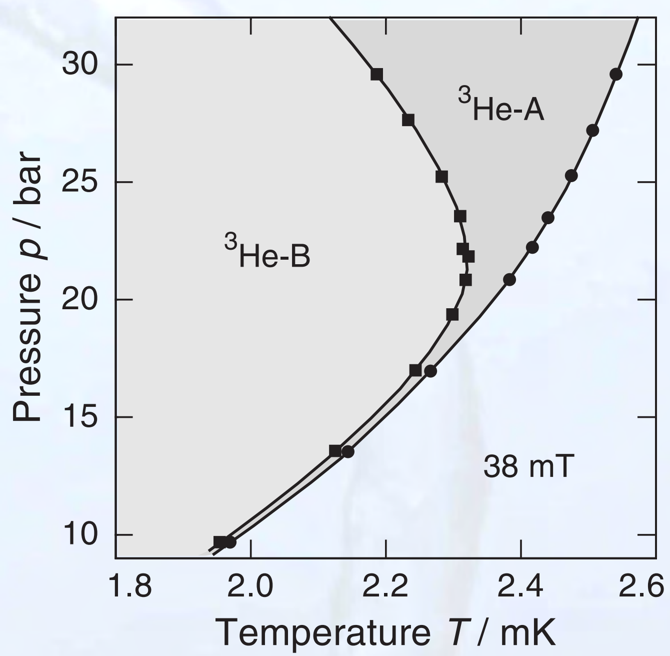
special points

	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

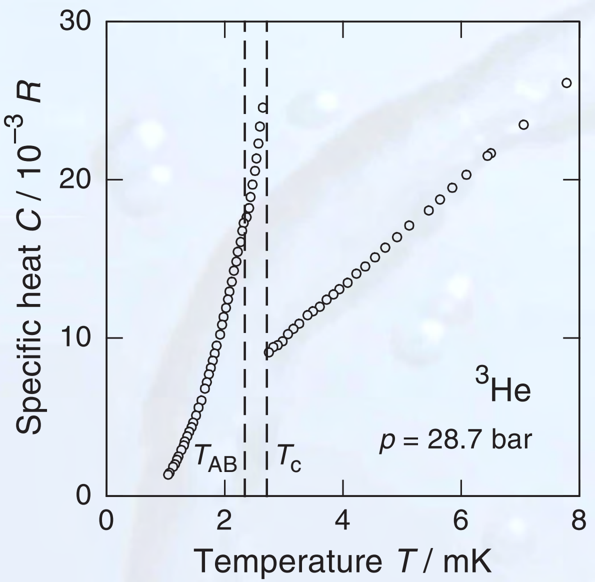




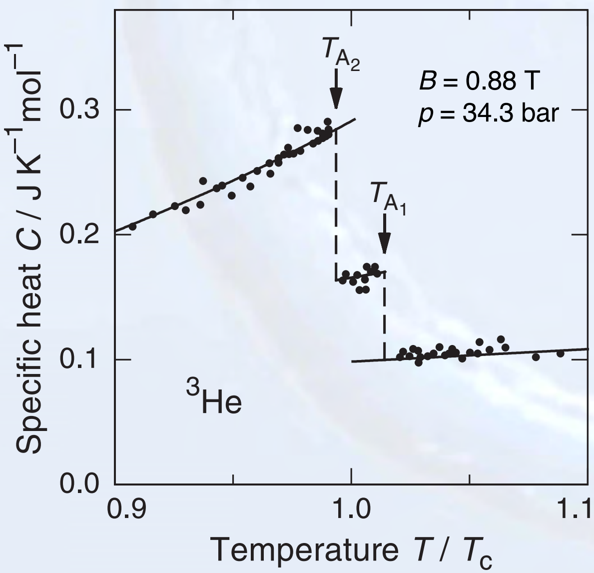
- A1 phase appears
- for $B > 0.65$ T no B phase
- PCP point disappears
- small corridor ~ 20 µK at 38 mT and 10 bar

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

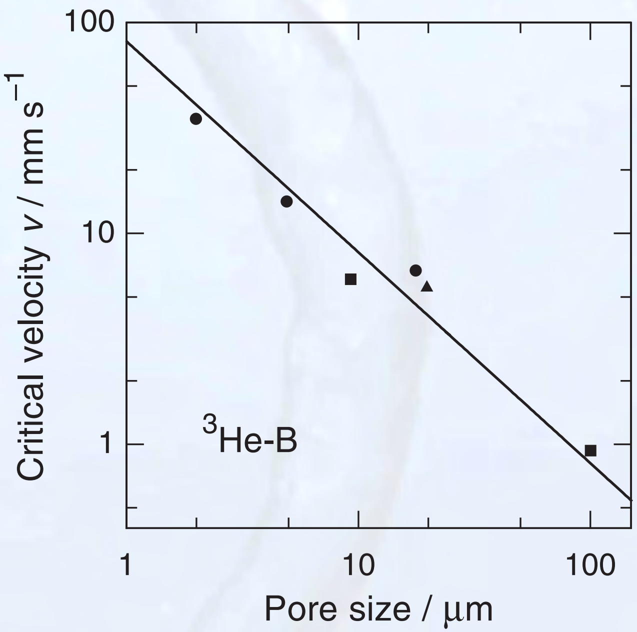
⟶ no reduction of flow

⟶ 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

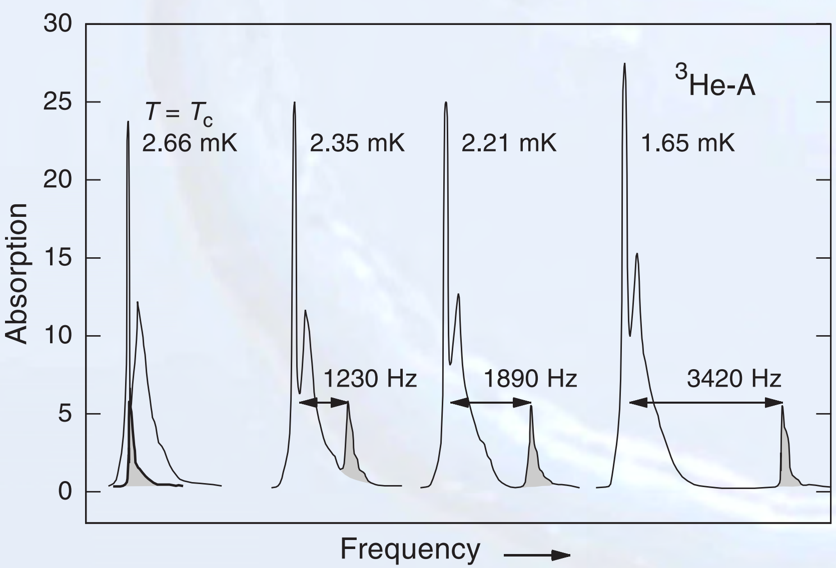
d) NMR experiments

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

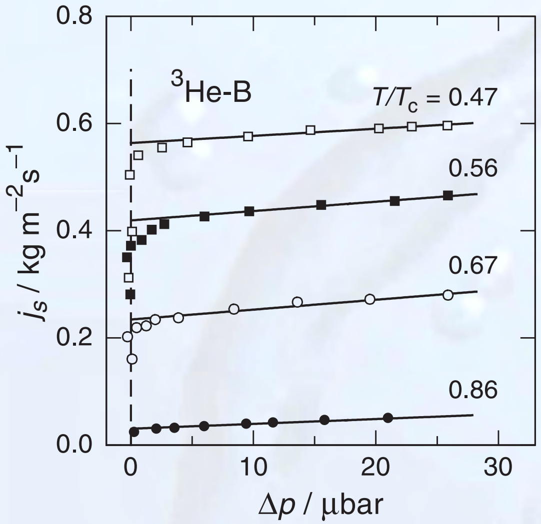
transverse rf field (normal geometry)



- ► 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: $\omega_\mathrm{t}^2 = \omega_\mathrm{L}^2 + \Omega_\mathrm{A}^2(T)$

4.2 Relevance of the Two-Fluid Model

a) Flow through thin capillaries



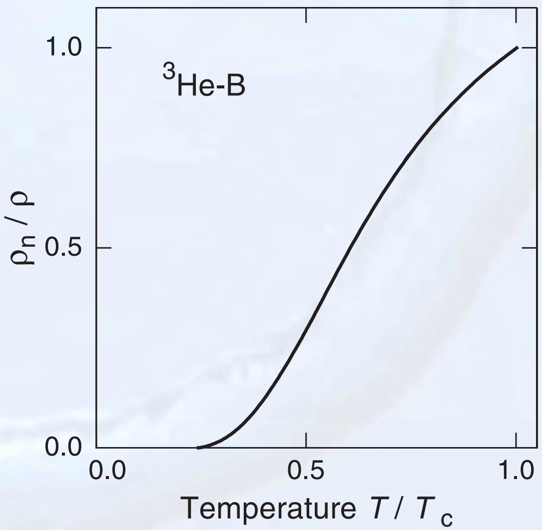
example: ^{3}He-B: flow through 1000 parallel channels, diameter $0.8\,\mu\mathrm{m}$, length $10\,\mu\mathrm{m}$

- significant flow without pressure
- j_s depends only weakly on pressure (as for He-II)
- j_s increases with decreasing temperature
  - → ϱ_s/ϱ rises with decreasing temperature (as for He-II)
  - → temperature dependence of the critical velocity $v_c(T)$

b) Normalfluid density

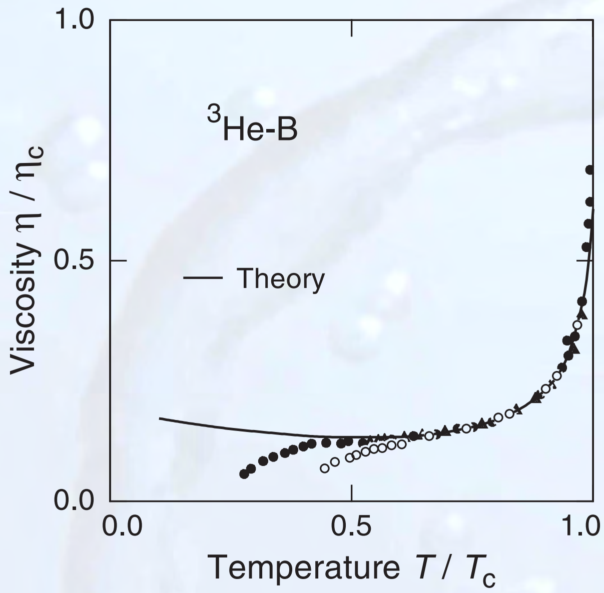
Andronikashvili-type experiment ^{3}He-B

- ϱ_n/ϱ increases with temperature (as for He-II)
- detailed temperature dependence different than for He-II

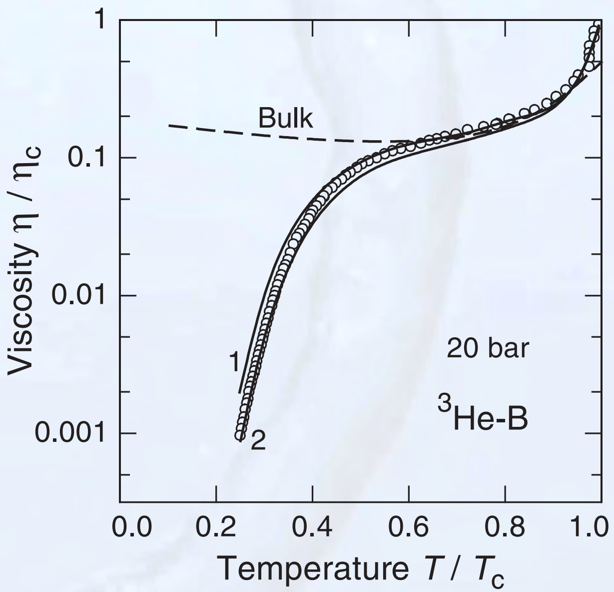


4.2 Relevance of the Two-Fluid Model

c) Viscosity



- theory for bulk ^{3}He-B fits well above 0.5 T/T_c
- deviations below 0.5 T/T_c



- --- theory for bulk ^{3}He-B
- (1) diffusive scattering
- (2) diffusive scattering and Andreev reflection

⟶ interaction with wall dominates

^{3}He-A: much more complicated behavior:
influence of magnetic fields, vessel geometry, textures, velocity fields, …

4.3 Quantum States of Superfluid ^3He

→ Cooper pairs: $S = 0$

→ ^3He pairs: strong magnetic exchange interaction (pairs of quasi particles)

→ $\underbrace{\boxed{S=1}}_{\text{symmetric}} \longrightarrow \underbrace{\boxed{L=1}, 3, \ldots}_{\text{anti-symmetric}}$

spin-triplet pairing $S = 1 \quad S_z = 0, \pm 1$

$$|S, S_z\rangle \longrightarrow \begin{aligned} |1,+1\rangle &= |\uparrow\uparrow\rangle\,, \\ |1,\ 0\,\rangle &= \frac{1}{\sqrt{2}}\Big[|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\Big] \\ |1,-1\rangle &= |\downarrow\downarrow\rangle\,. \end{aligned}$$

analog for orbital momentum $L = 1 \quad L_z = 0, \pm 1$

general wave function: linear combinations ⟶ $3 \times 3 = 9$ terms each with amplitude and phase

⟶ $2(2S+1)(2L+1) = 18$ real components

⟶ order parameter: 3×3 matrix with complex values