Helium-3, Phase diagram

High temperatures

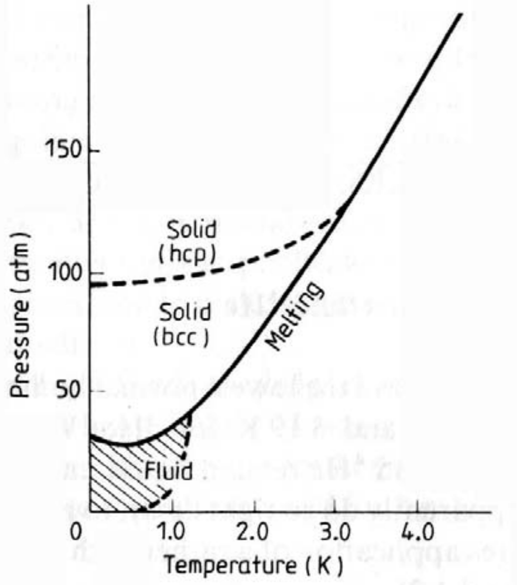
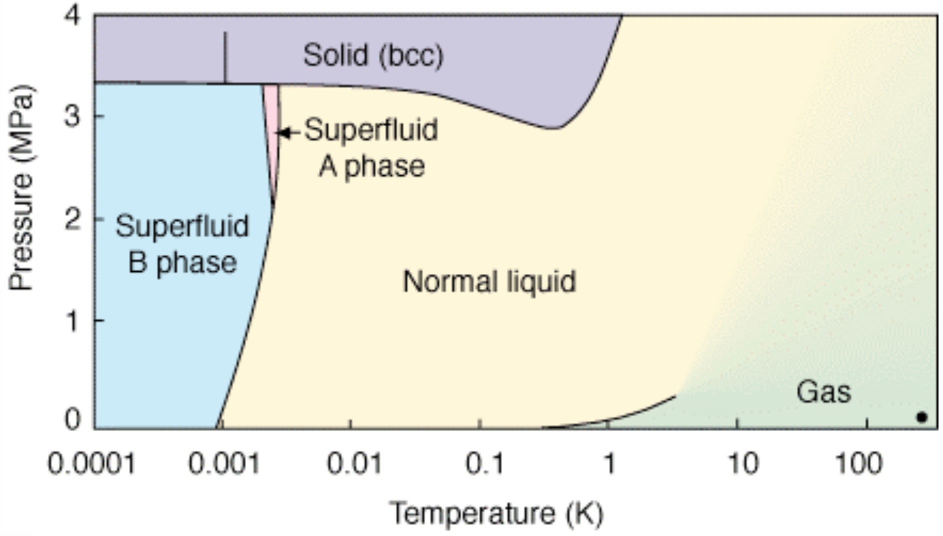


Figure 1.2 Phase diagram of ^{3}He (adapted from Grilly and Mills 1959). Hatched area shows region of negative expansion coefficient.

Logarithmic temperature scale



the polycritical point

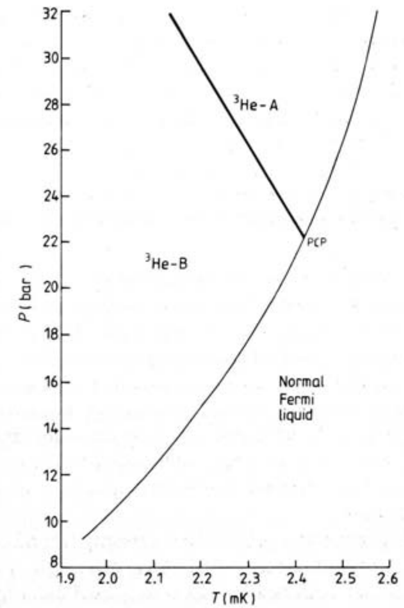


Figure 1.26 Phase diagram of liquid ^{3}He in zero magnetic field. —— second-order phase transition, —— first-order phase transition. The phase transition lines meet at the *polycritical point* PCP.

Differences compared to He-4:

He-3 atoms are fermions, i.e. no ordinary BEC
No super fluid transition at “high” temperature
Lower T_{boil}, higher P_{melt}, due to lower mass larger zero point fluctuations.
Melting curve is non-monotonous.
Super fliud transition around 1mK.

Fermi liquid theory

Start with a noninteracting Fermi gas and turn on interactions slowly, then you get a Fermi liquid.
Developed by **Landau** in the 50ies

Describes quasiparticles which can be thought of as dressed helium atoms with an effective mass m*
A mean time between collisions τ_c is defined.

Helium 3 has two properties which is different from ordinary Fermi gases

1. At low temperature the specific heat has the unusual form

$$C_V = aT + bT^3 \ln T$$

the logarithmic term can be explained by so called para magnons: fluctuations where the neighboring atoms are aligned. The fluctuation will have a long life time.

2. Strongly paramagnetic
Below 300 mK the liquid has lower entropy than the solid

$$S_{liquid} \propto T$$

$$S_{solid} = R \cdot \ln 2 = \text{constant}$$

c.f. Pomeranchuck cooling

What can be expected

Helium-3 is lighter than Helium-4 => Stronger zero point fluctuations
Atoms further apart

Helium-3 are fermions => Fermi Dirac statistics
No Bose condensation
More similar to superconductors
More BCS like behavior expected

Compared to superconductors the potential is much stronger, 1/r^12 rather than 1/r
This favors p- or d-state rather than s-state, i.e. states where the spins are not pointing in opposite directions.

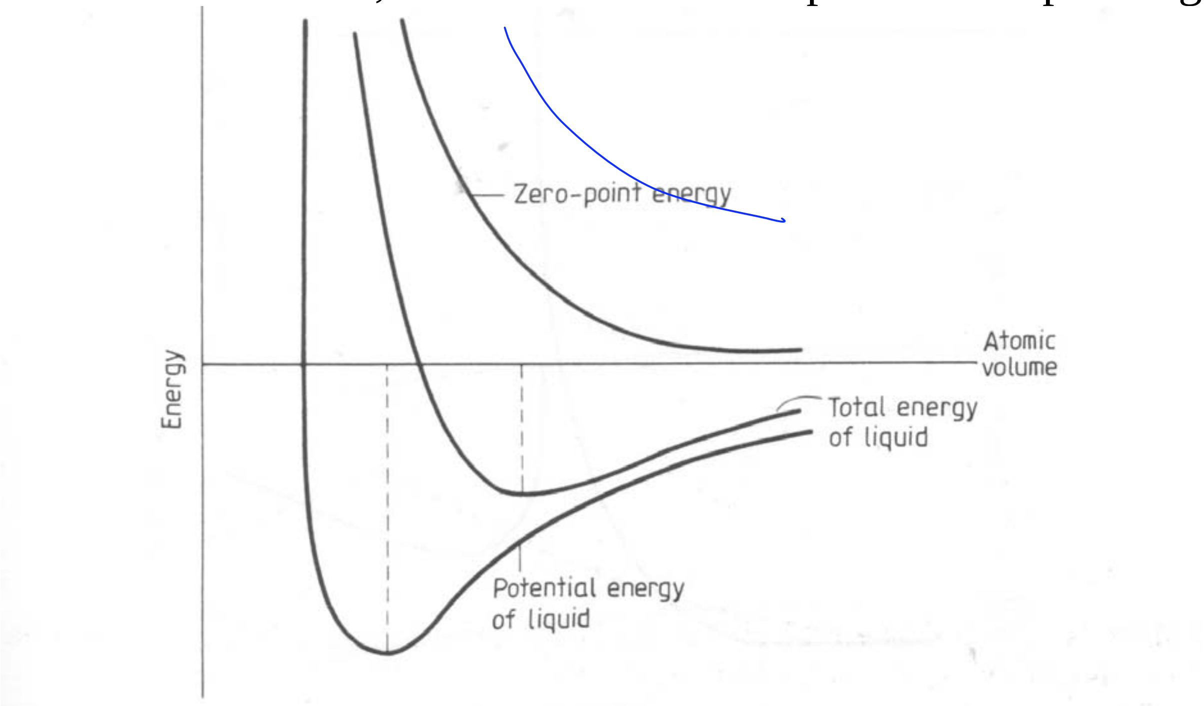


Figure 1.3 Energy of liquid helium. Total energy is sum of potential energy and zero-point energy.

Different phases, Predictions

Theory came before experiments, spin triplet p-wave pairing

Cooper pairing, p state (total spin=1) with less "weight" at r=0.

The ABM phase

Anderson and Morel (1961)

S=1

$$\Psi_{AM} = |\uparrow\uparrow\rangle, \text{ or } \Psi_{AM} = |\downarrow\downarrow\rangle$$

First suggested

Anisotropic

No gap along x-axis

The BW phase

Balian and Werthamer (1963)

S=1

$$\Psi_{BW} = \frac{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle}{\sqrt{2}}$$

Lower energy

Isotropic

Same gap for different directions

Energy lowered by paramagnetic interactions via so called paramagnons

Anderson and Brinkman (1973)

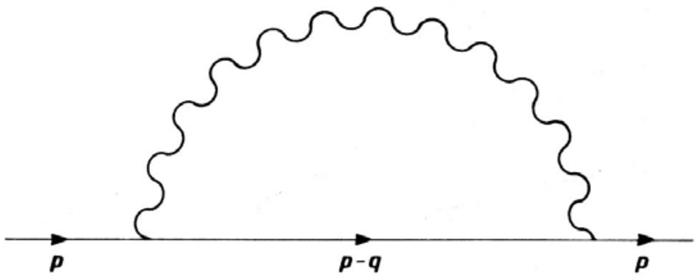


Figure 9.3 Paramagnon modification of single particle energy.

PW Anderson

The observation of Superfluidity

Lee, Osheroff and Richardson studied Helium three in a Pomeranchuck cell (1972). Nobel Prize (1996)

1.3 **BASIC PROPERTIES OF SUPERFLUID ^{3}HE** 27

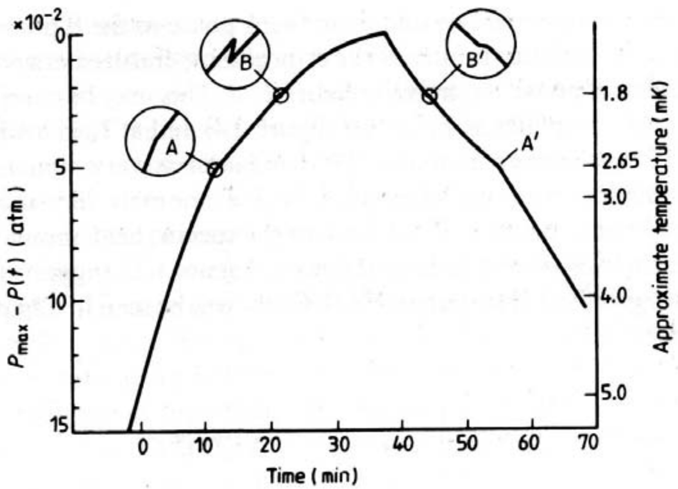


Figure 1.25 Time evolution of melting pressure of ^{3}He during compression and subsequent decompression. A, A′ anomalies showing discontinuity in slope, indicative of second-order transitions. B anomaly with hysteresis; B′ anomaly with flat portion of curve, both indicative of first order transitions. (After Osheroff *et al* 1972a.)

They observed very small kinks and steps during cooling, similar kinks and steps occurred at the same temperature also on warming

Did something happen in the liquid or in the solid ?

$$\omega^2 = \omega_0^2 + \Omega_A^2(T)$$

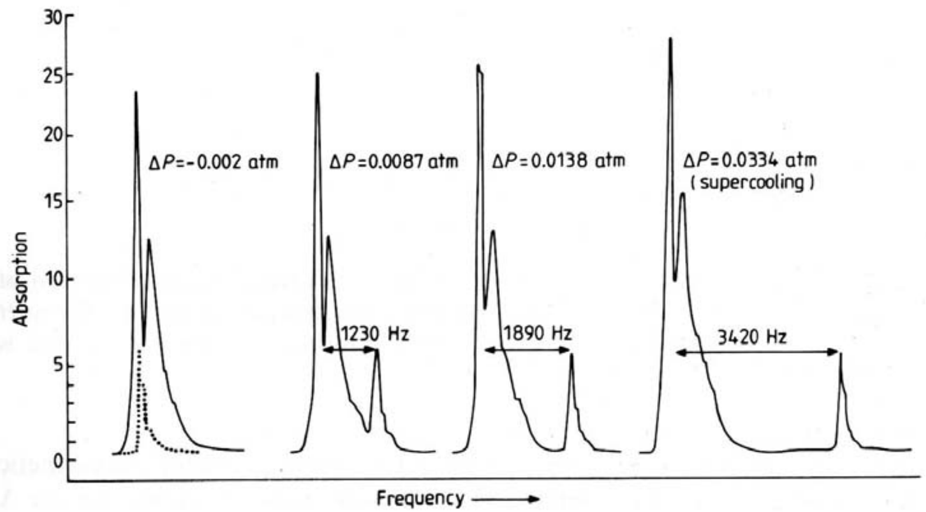


Figure 9.7 NMR absorption in the A phase in the absence of a magnetic field gradient at successively lower temperatures. Dotted curve corresponds to initial all liquid profile. (After Osheroff *et al* 1972b.)

Nuclear Magnetic resonance measurements of the A phase. Note the shifted peak as a function of pressure.

Confirmation of the superfluidity

Specific heat versus temperature

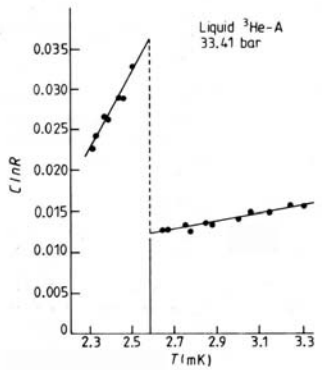


Figure 1.27 Specific heat discontinuity at the A transition. (After Webb *et al* 1973.)

Note the strong similarity to BCS superconductors

Viscosity from vibrating wire

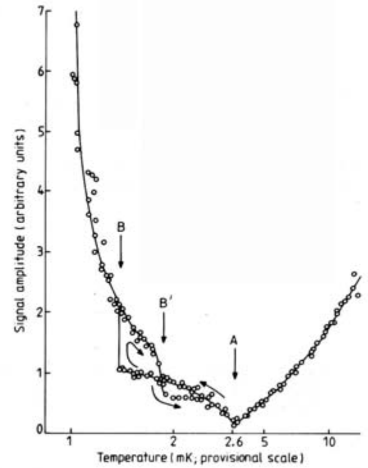


Figure 9.10 Vibrating wire amplitude W as a function of temperature. (After Alvesalo *et al* 1974.)

Later allowed independent measurement of density and viscosity. Super fluid densities could be extracted.

Note kink at A transition but discontinuity at B transition

Attenuation of sound

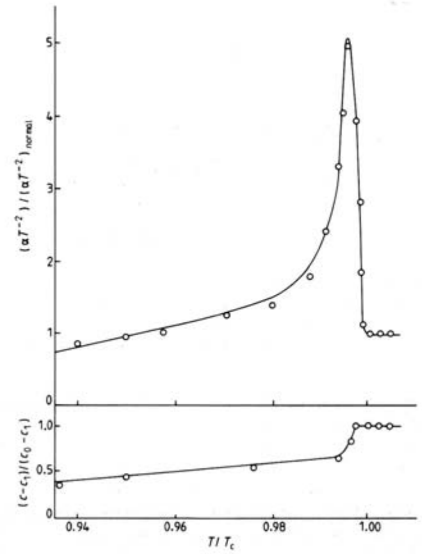


Figure 9.13 Sound attenuation and velocity shift at 15.15 MHz in ^{3}He-B at a pressure of 19.6 bar. C_0 and C_1 are the normal stage zero- and first-sound velocities. Solid curves: theory of Wölfle (1975). Data points from Paulson *et al* (1973).

Strong attenuation at the transition temperature

The A1 phase

A new phase was discovered at finite magnetic field.

A magnetic superfluid exist in a very narrow range of magnetic field. Symmetry is broken since $|\uparrow\uparrow\rangle$ is favored over $|\downarrow\downarrow\rangle$

Specific heat shows two transitions in an applied magnetic field

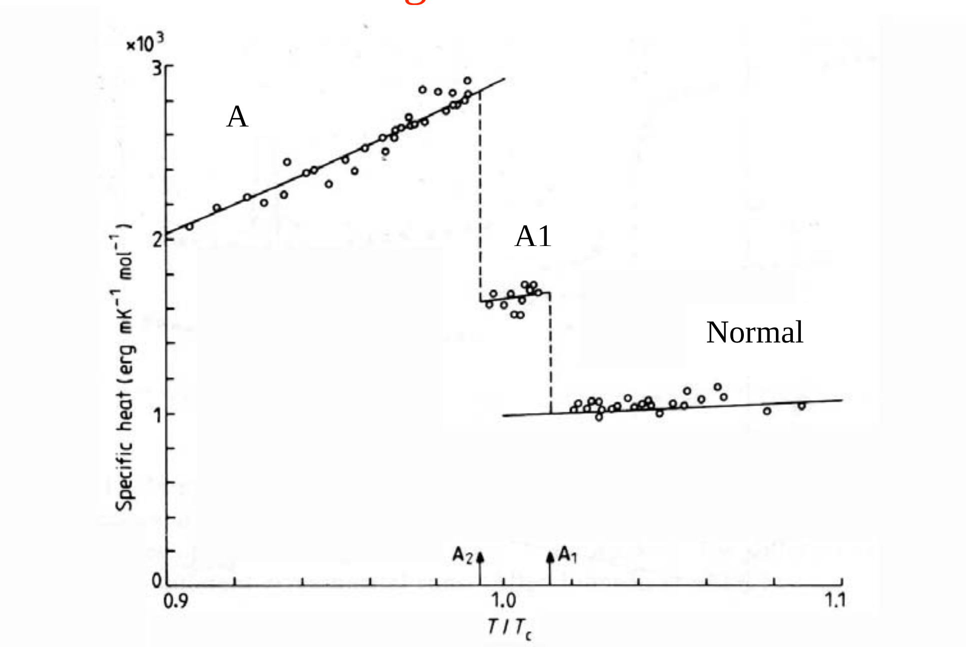
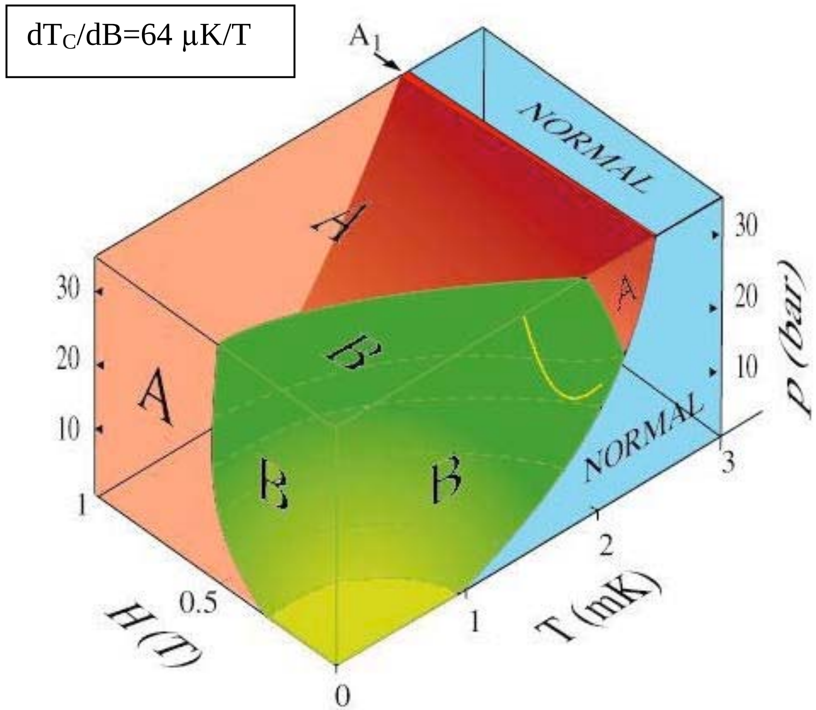


Figure 9.14 Specific heat at the melting pressure in a magnetic feld of 8.8 kOe. (After Halperin *et al* 1976.)

A three dimensional phase diagram



Ambegaokar and Mermin (1973)

Always two phases at any magnetic field

The explanation of Anthony Leggett (Nobelprize 2003)
Different kinds of symmetry breaking

- **Breaking of guage invariance gives a well defined phase as in superconductors**
- **Breaking of rotational symmetry of spin gives a spontaneous field as in magnets**
- **Breaking of orbital rotation symmetry gives a preferred direction as in liquid crystals.**

Each atom (quasiparticle) can be seen as carrying two vectors, one for spin and one for orbital momentum.

The wave function can be described by 3 orbital sub-states, $L_Z=0,\pm1$, and three spin sub-states $S_Z=0,\pm1$. All in all there are 3x3=9 sub-states, i.e. you need 18 parameters (real and imaginary part) to describe the system.

Possible situations of different broken symmetries

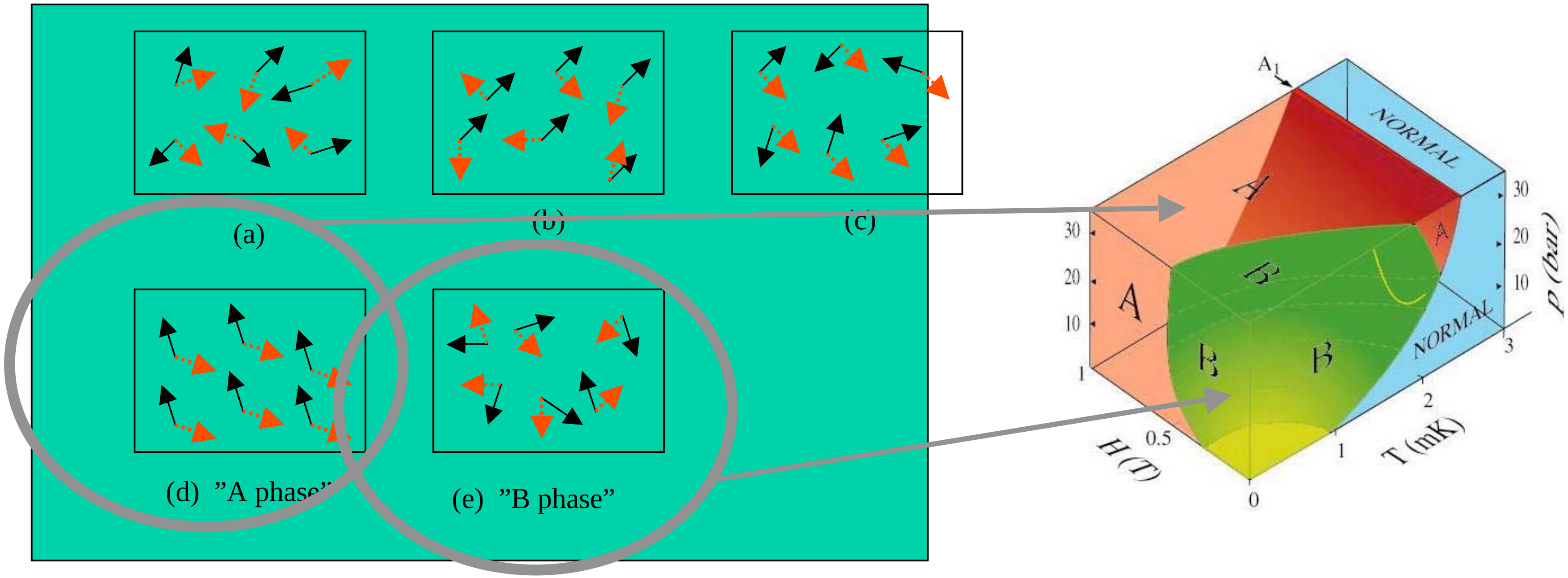
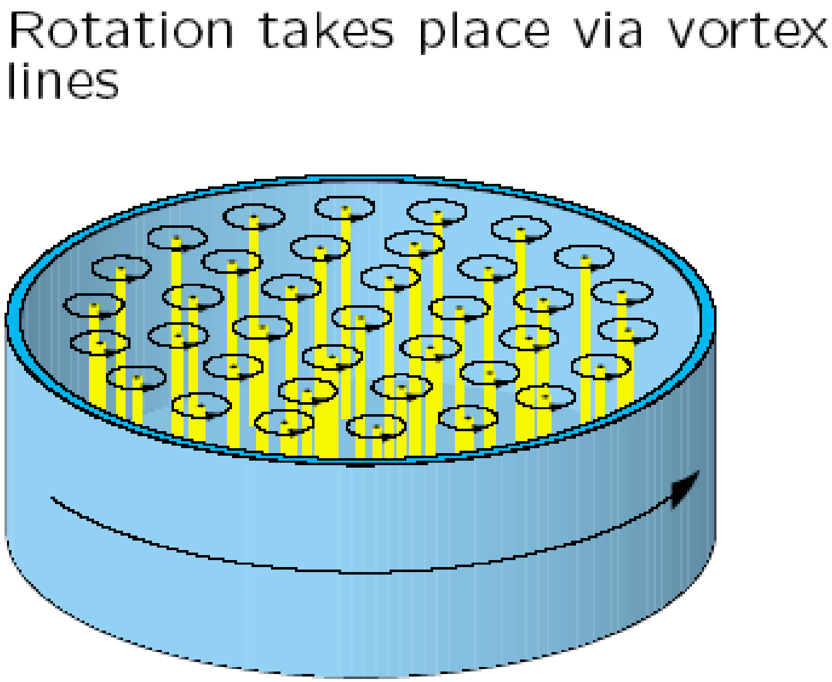


Figure 1. The possible states in a two-dimensional model liquid of particles with two internal degrees of freedom: spin (full-line arrow) and orbital angular momentum (broken-line arrow). (a) Disordered state: isotropic with respect to the orientation of both degrees of freedom. The system is invariant under separate rotations in spin and orbital space and has no long range order (paramagnetic liquid). (b)–(e) States with different types of long range order corresponding to all possible broken symmetries. (b) Broken rotational symmetry in spin space (ferromagnetic liquid). (c) Broken rotational symmetry in orbital space (“liquid crystal”). (d) Rotational symmetries in both spin and orbital space *separately* broken (as in the A phase of superfluid ^{3}He). (e) Only the symmetry related to the *relative* orientation of the spin and orbital degrees of freedom is broken (as in the B phase of superfluid ^{3}He). Leggett introduced the term spontaneosuly broken spin-orbit symmetry for the broken symmetry leading to the ordered states in (d) and (e).

Studying vortices in Helium-3

Rotating a cryostat that reaches 1 mK (Helsinki)



Persistant angular momentum

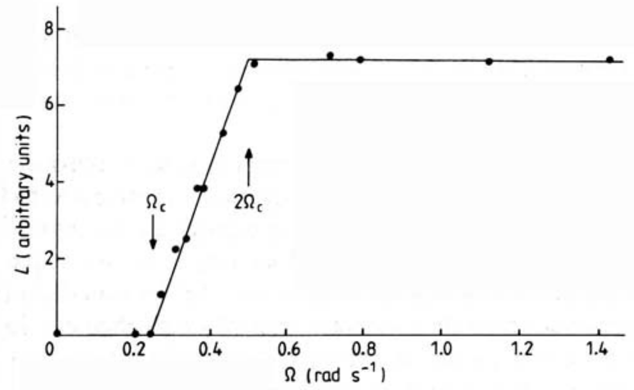


Figure 9.29 Persistent angular momentum L versus preparation angular velocity Ω at $P = 8$ bars. (After Pekola *et al* 1984.)

Nothing happens until the angular frequency reaches Ωc≈1 rad/s.
No degradation of the persistant current over 48 hours, from this it can be concluded that the viscosity is at least 12 orders of magnitude higher in the superfluid phase than in the normal phase.

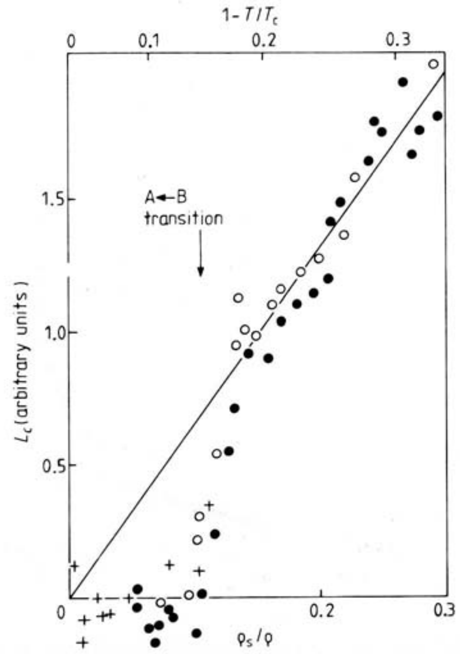
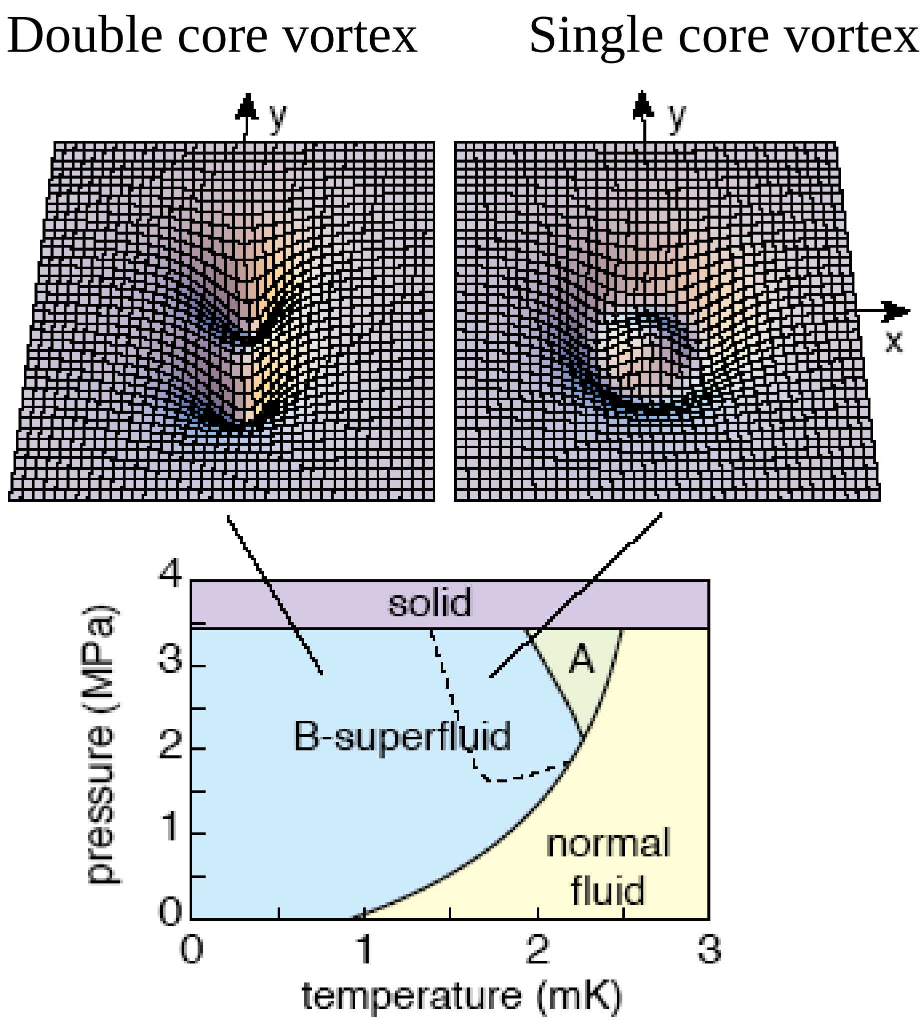


Figure 9.30 L_c versus ρ_s/ρ around the B to A transition at $P = 29.3$ bars. Preparation angular velocities Ω were: ○ 1.16 rad s^{-1}, ● 0.86 rad s^{-1}, + 0.57 rad s^{-1}. (After Pekola *et al* 1984a.)

Note there is no persistant angular momentum in the A phase since it has a node in the gap, and thus excitations can be created.



Double core vortex
Single core vortex
y
y
x
solid
A
B-superfluid
normal
fluid
pressure (MPa)
temperature (mK)
0
1
2
3
4
0
1
2
3

Summary of phases

	B-phase	A phase	A1-phase
Conditions	**At lowest T and P**	**T ~ 2 mK P > 20 bar**	**T ~ 2 mK P > 20 bar B≠0**
Wave function	$\lvert\uparrow\downarrow\rangle + \lvert\downarrow\uparrow\rangle$	$\lvert\uparrow\uparrow\rangle\ ,\ \lvert\downarrow\downarrow\rangle$	$\lvert\uparrow\uparrow\rangle$
Gap	**Isotropic**	**Anisotropic, Δ=0 in some directions**	**Anisotropic Δ=0 in some directions**
Symmetry	**Angle between L and S fixed for each atom (quasi particle)**	**All L alliged and all S alligned**	**All L alligned and all S alligned**