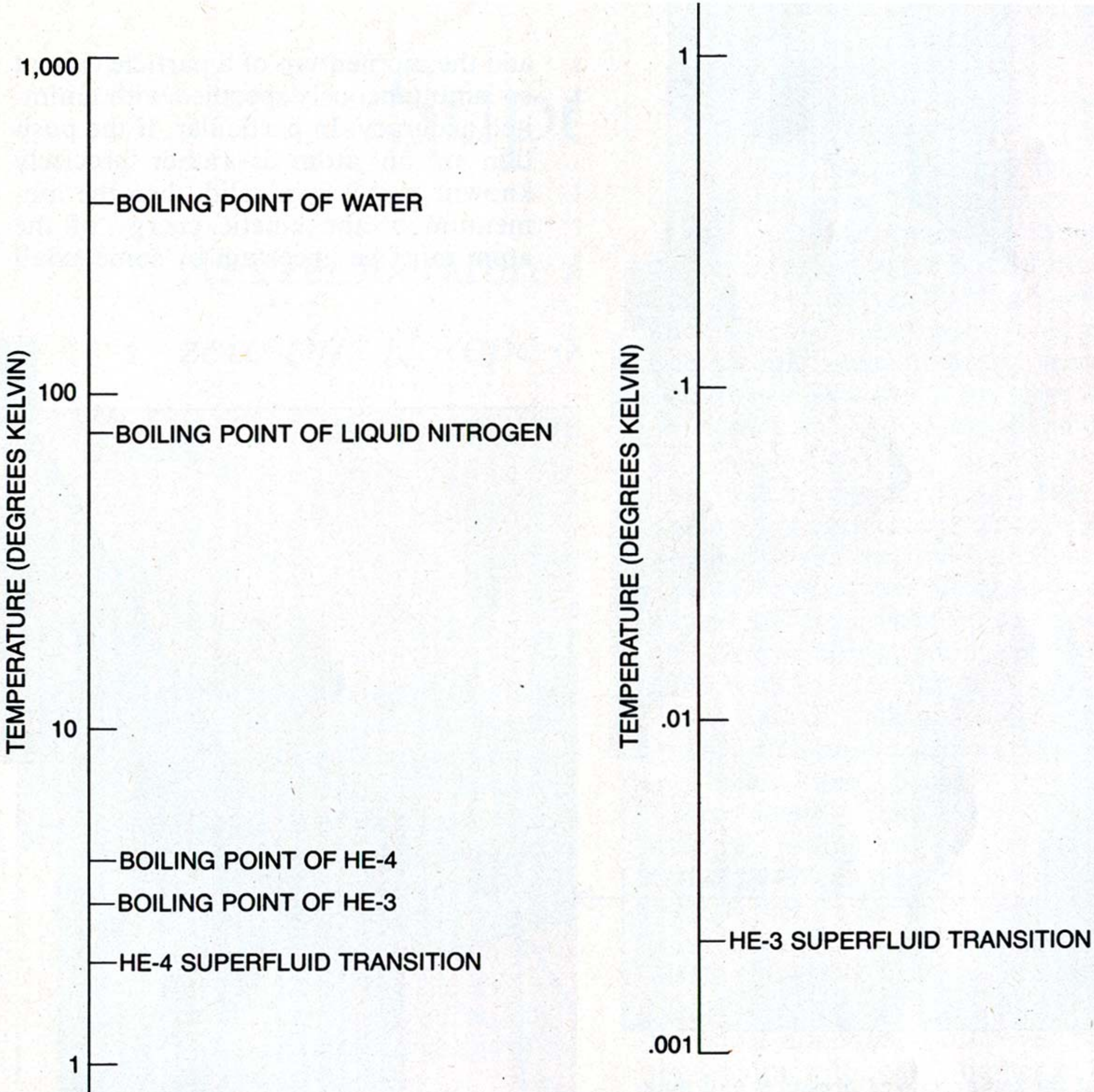
The Magic of Superfluids

David M Lee

Department of Physics and Astronomy

Texas A&M University

Quantum Fluids
Superfluid ^{4}He
Persistent Current
Fountain effect and Creeping film
Superfluid Wave Function
Quantum Vortices
Superconductivity
Levitation


TEMPERATURE (DEGREES KELVIN)
1,000
BOILING POINT OF WATER
100
BOILING POINT OF LIQUID NITROGEN
10
BOILING POINT OF HE-4
BOILING POINT OF HE-3
HE-4 SUPERFLUID TRANSITION
1
TEMPERATURE (DEGREES KELVIN)
1
.1
.01
HE-3 SUPERFLUID TRANSITION
.001

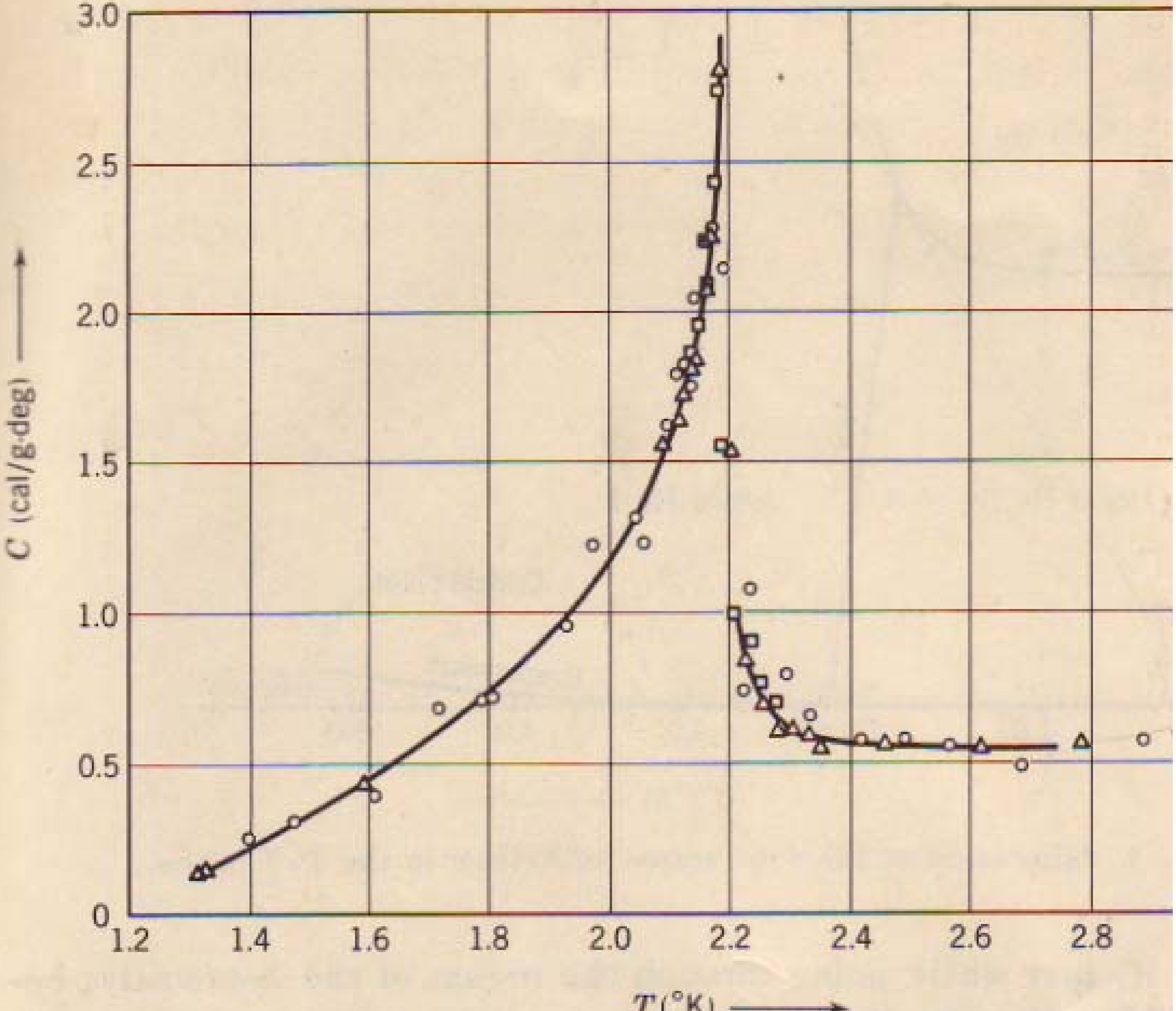


Fig. 2. Specific heat of liquid helium under its own vapor press
(after Keesom and Clusius[4] and Keesom and Keesom[4]).

Quantum Fluids

Quantum Theory

1. Uncertainty Principle - Heisenberg

$$\Delta(mv_X)\Delta x \geq h/2\pi = 10^{-34} \text{ joule} - \text{sec.}$$

<u>Consequence:</u> If you try to confine an atom in a small space, it acquires a large momentum and thus a large kinetic energy.

<u>Explains:</u> Low density of liquid helium.
—needs 25 atmospheres to solidify!

---

2. Matter waves – de Broglie wavelength λ.

$$\lambda = h/p = h/mv$$

Slow particles have long wavelengths.

<u>Consequence</u>: At very low temperatures λ becomes greater than mean inter-particle spacing $\rightarrow$ QUANTUM FLUID BEHAVIOR.

Two Fluid Model

Liquid helium below T lambda consists of two interpenetrating fluids!

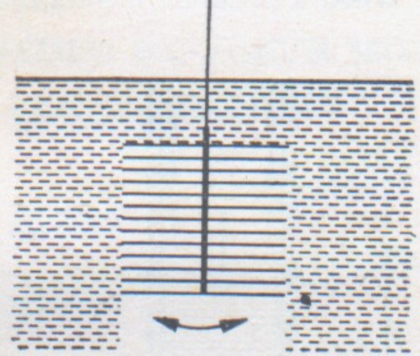
Normal Fluid – Acts like ordinary liquid. Carries heat, viscous.

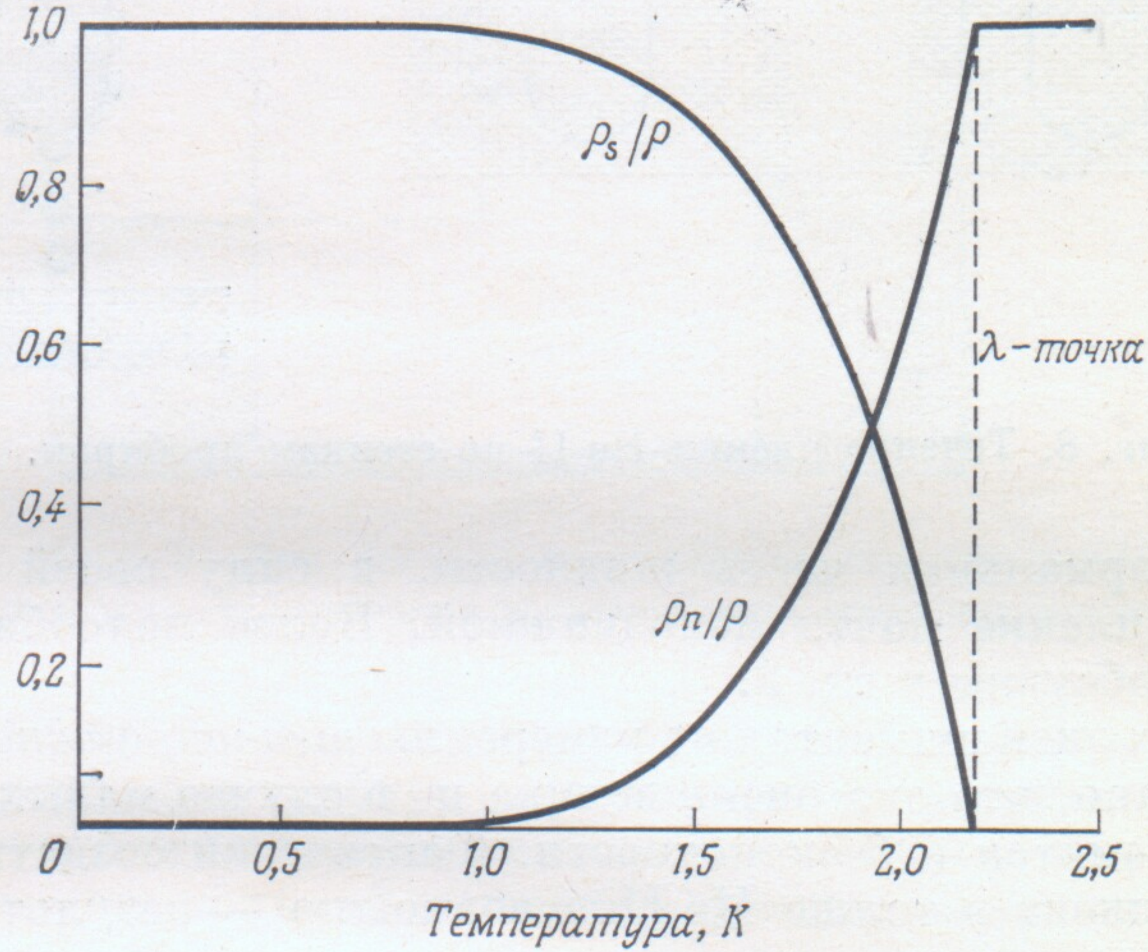
Superfluid Component – Does not carry heat. Flows through fine channels without resistance.

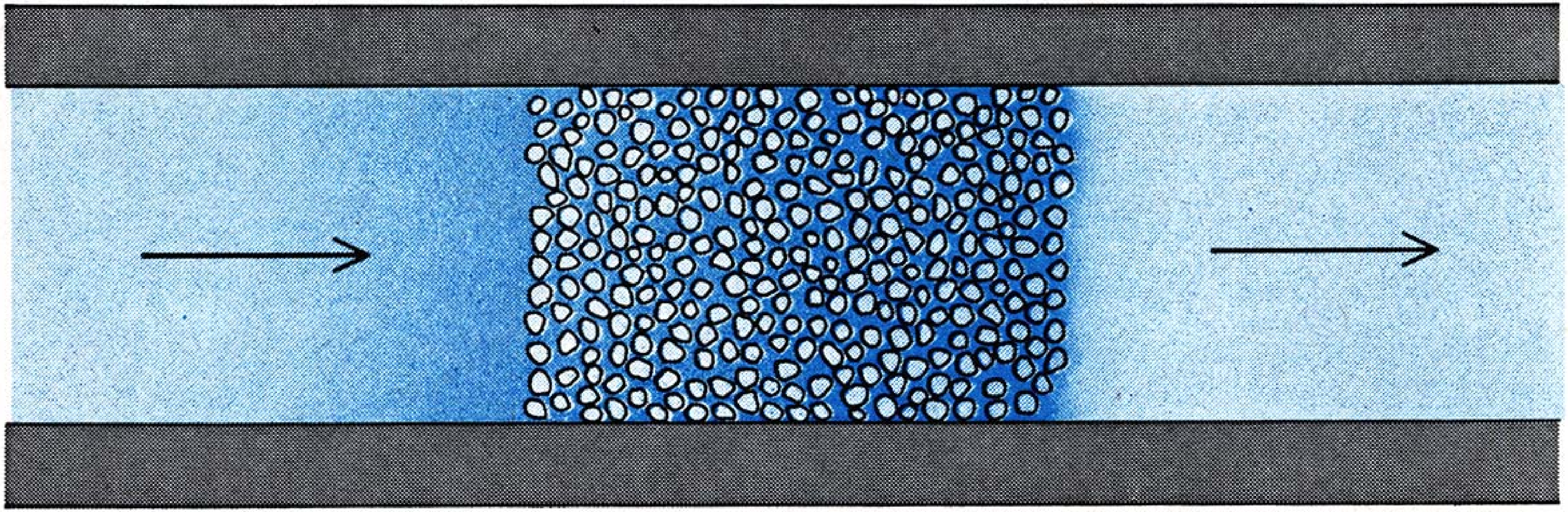
L.D. Landau – Normal Fluid Component consists of excited quantum states.

e.g. Phonons – quanta (particles) of sound. Analogous to Photons

Fine channels filter out the excited states.
Superflow



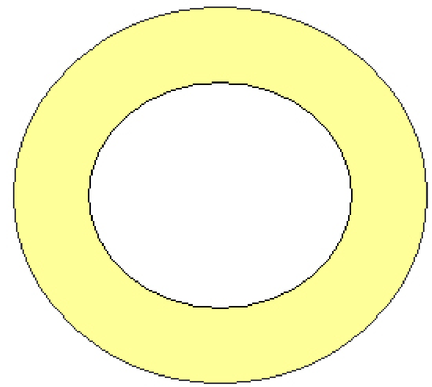

1,0
0,8
0,6
0,4
0,2
0
0,5
1,0
1,5
2,0
2,5
ρs/ρ
ρn/ρ
λ-точка
Температура, K



FRICTIONLESS FLOW OF HELIUM 3 provides convincing evidence that the new phases of the liquid are in fact superfluids. Powder is packed tightly into a tube, making it nearly impervious to fluid flow above the superfluid transition. In the superfluid phase, however, some of the liquid flows freely through the powder. In practice the experiment is performed with an oscillating current of superfluid, which thus moves back and forth through the powder.

Persistent Currents are a Hallmark of Superfluidity

Liquid Helium



- An annulus filled with a packed powder and liquid helium is rotated and cooled below the lambda temperature.
- The annulus and powder are stopped.
- A long-lasting persistent current in the liquid helium is still present.
- Detected Gyroscopically.
- Similarly, a persistent electrical current can be induced in a Superconducting ring by placing it in a high magnetic field and reducing the field to zero.

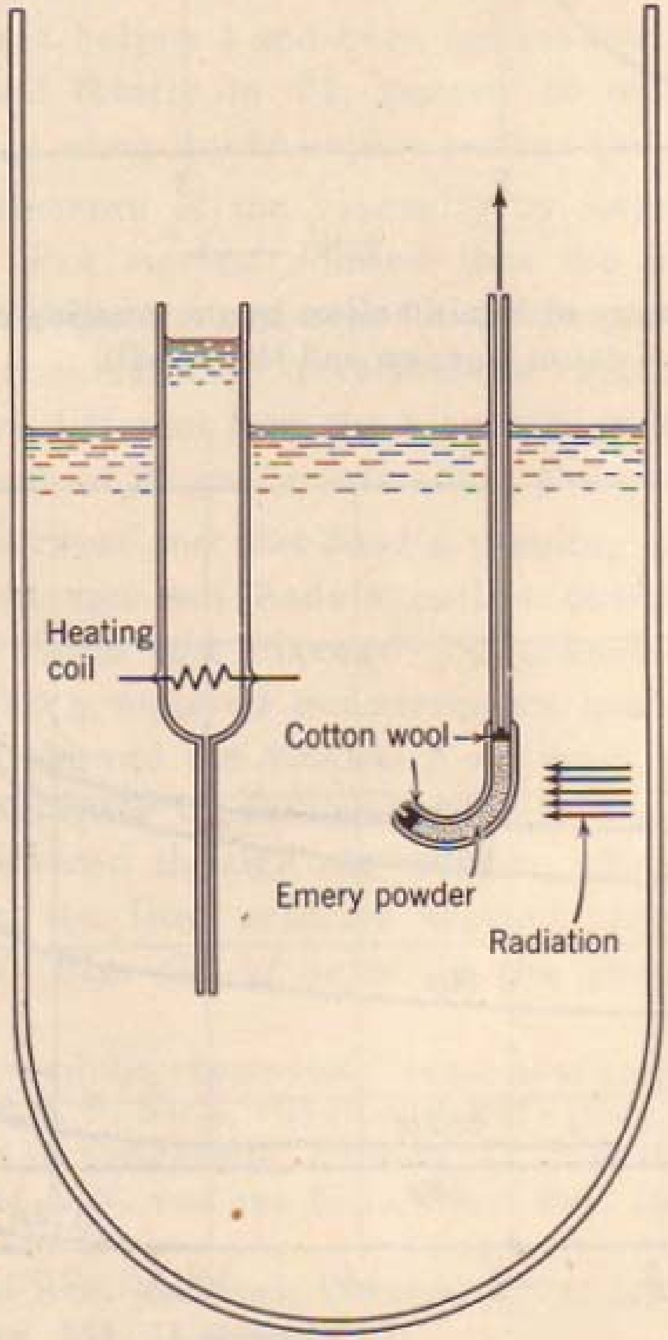
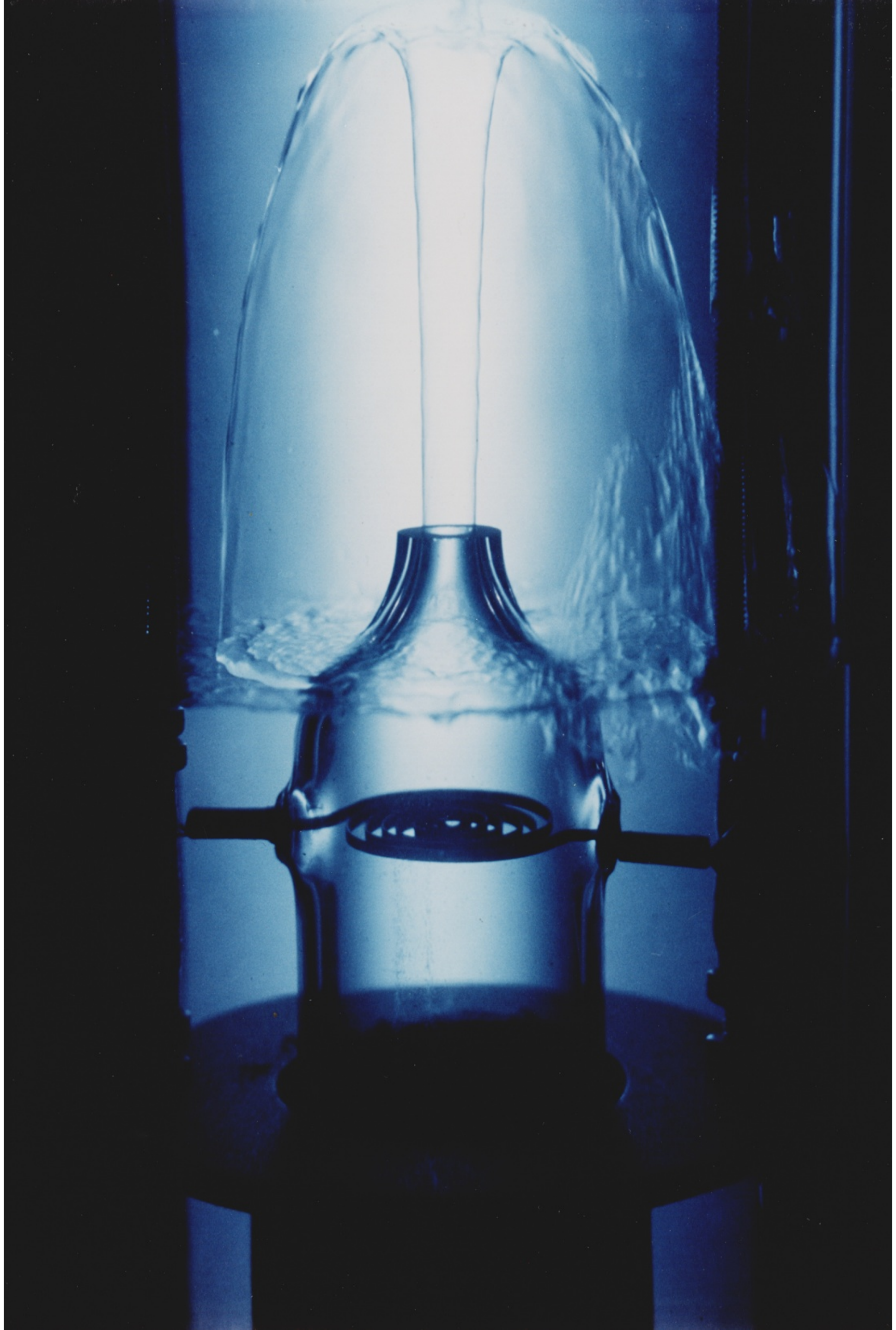


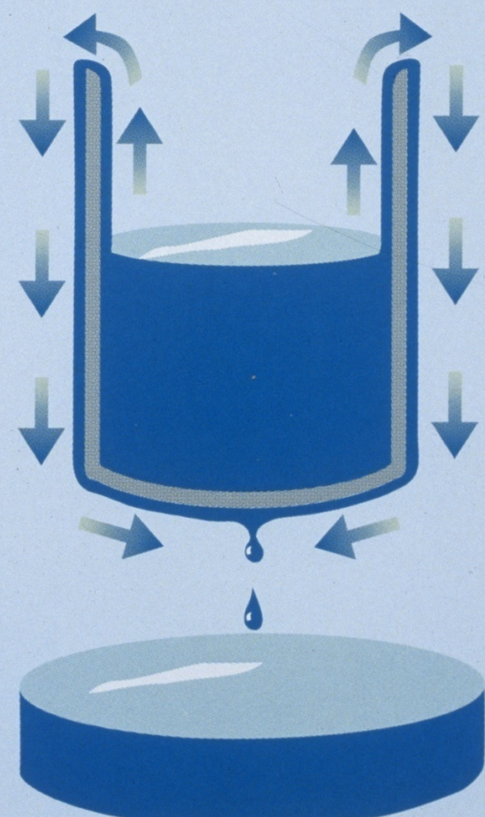
Fig. 9. Fountain effect.

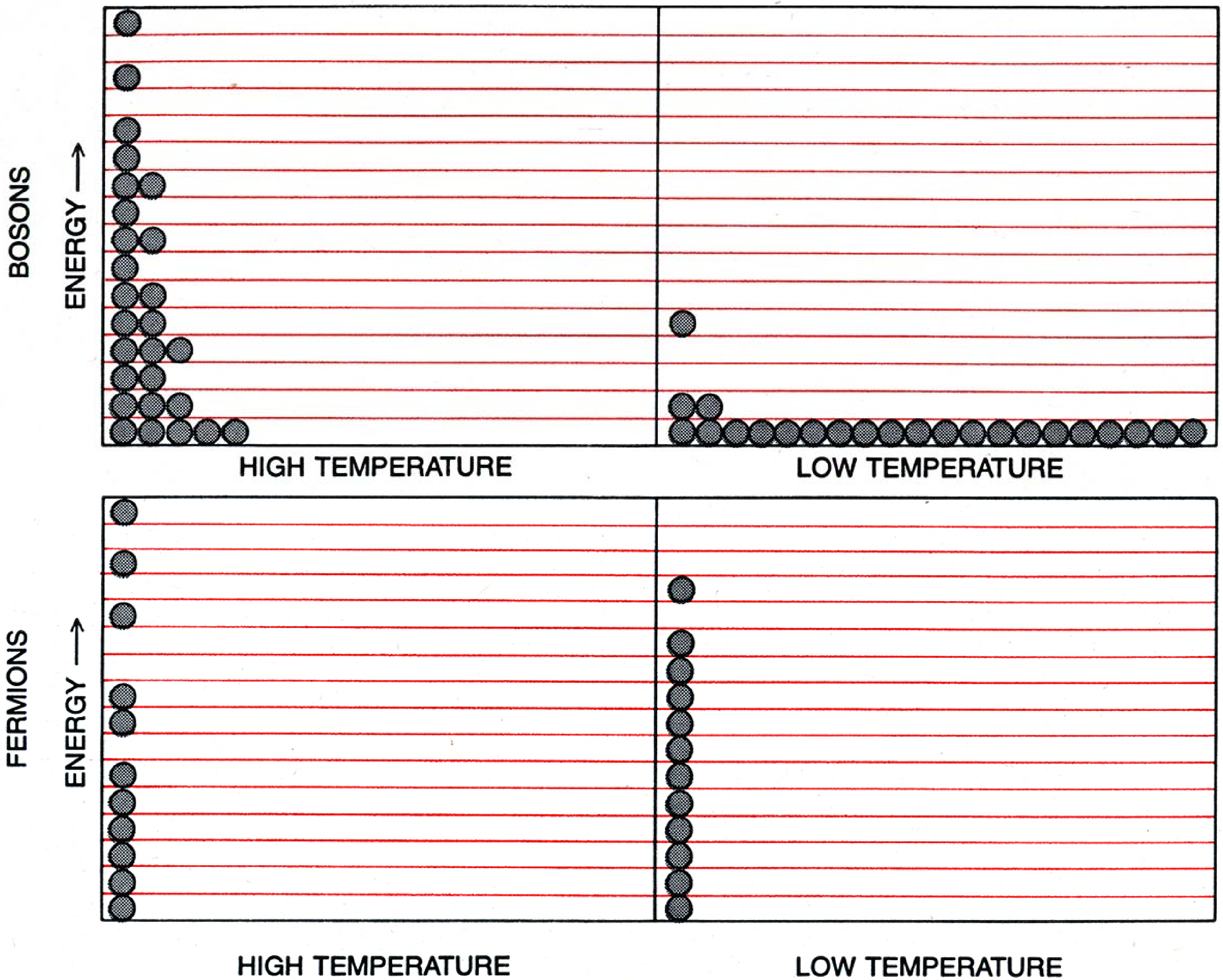


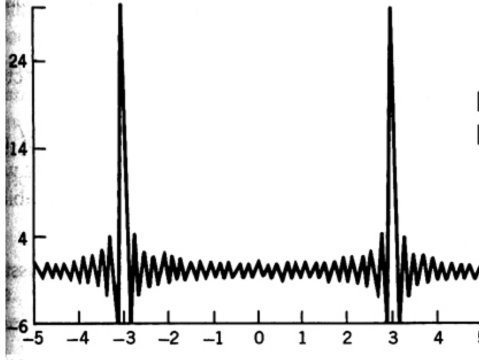
Superfluidity

Pjotr Kapitza* discovered that liquid helium flows without friction when cooled below 2.17 K. This phenomenon is termed **superfluidity**. A superfluid shows several spectacular effects. For example, superfluid helium cannot be kept in an open vessel because then the fluid creeps as a thin film up the vessel wall and over the rim.

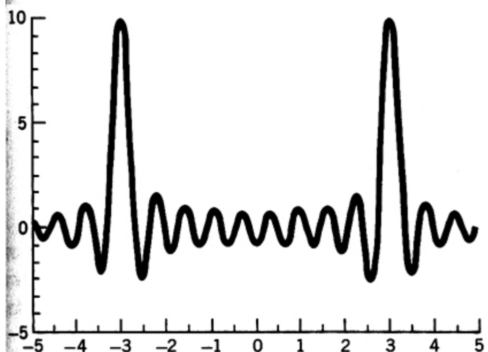
*Nobel Prize 1978

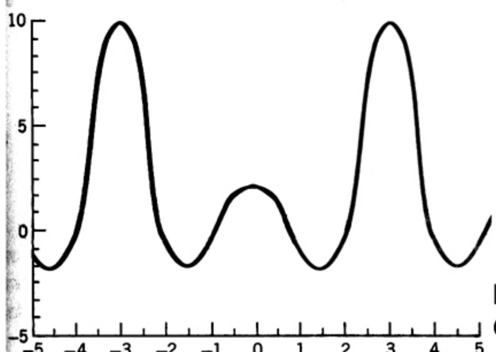



BOSONS
ENERGY →
HIGH TEMPERATURE
LOW TEMPERATURE
FERMIONS
ENERGY →
HIGH TEMPERATURE
LOW TEMPERATURE

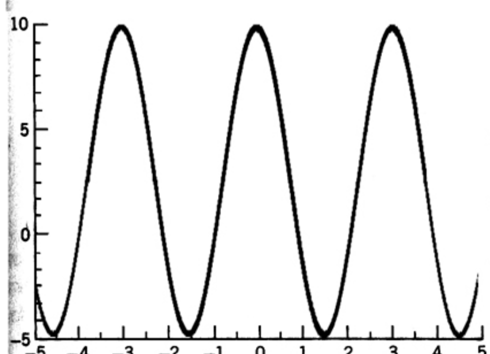


High temperature. $\lambda = h/mv$ is short.
No overlap.





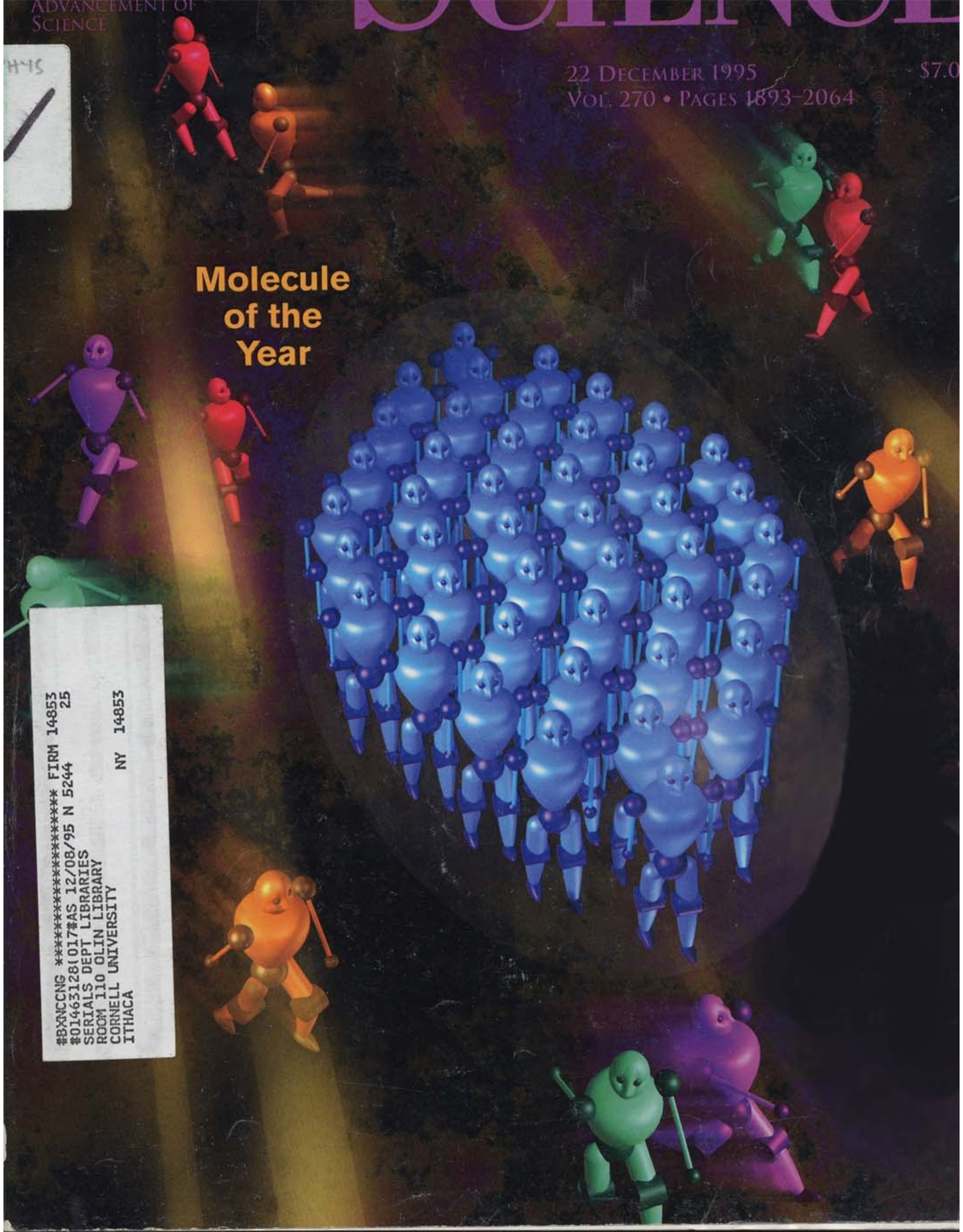
Low temperature. $\lambda = h/mv$ is long.
Overlap of indistinguishable particles, which lose their identities and become delocalized.



A macroscopic wave function to represent the whole superfluid sample:

$$\psi = \psi_0 e^{i\phi}$$

ψ_0 = Amplitude, ϕ = Phase

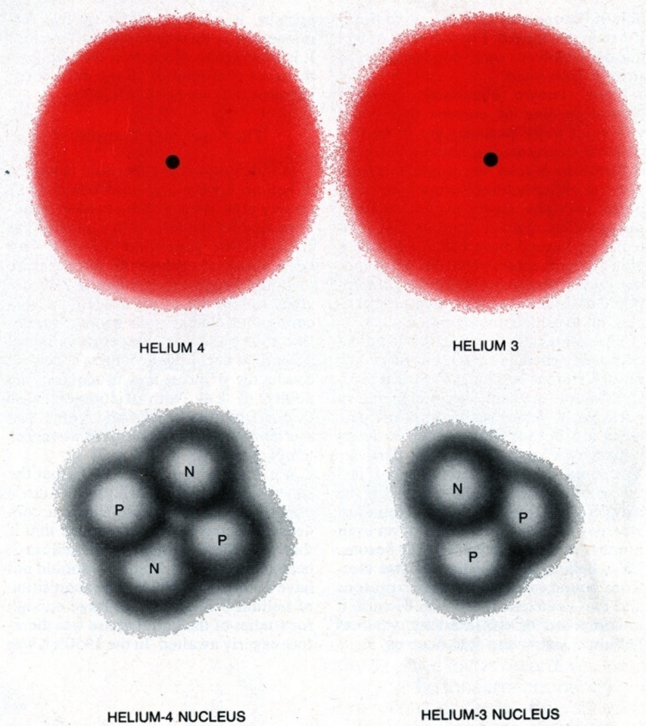

Advancement of
Science
22 December 1995
Vol. 270 • Pages 1893–2064
$7.0
Molecule
of the
Year

Fritz London

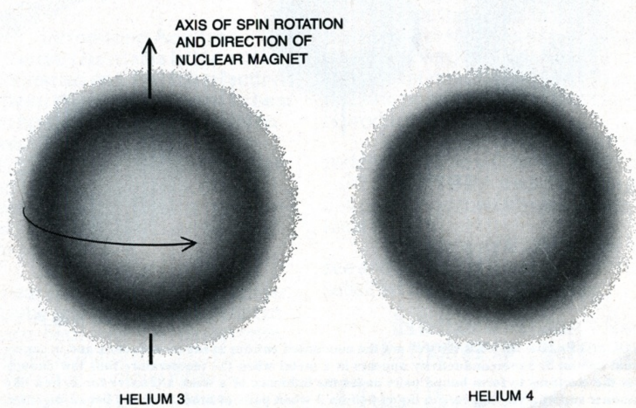
The whole sample is characterized by a single MACROSCOPIC wave function

$$\psi = \psi_0 e^{i\phi}$$

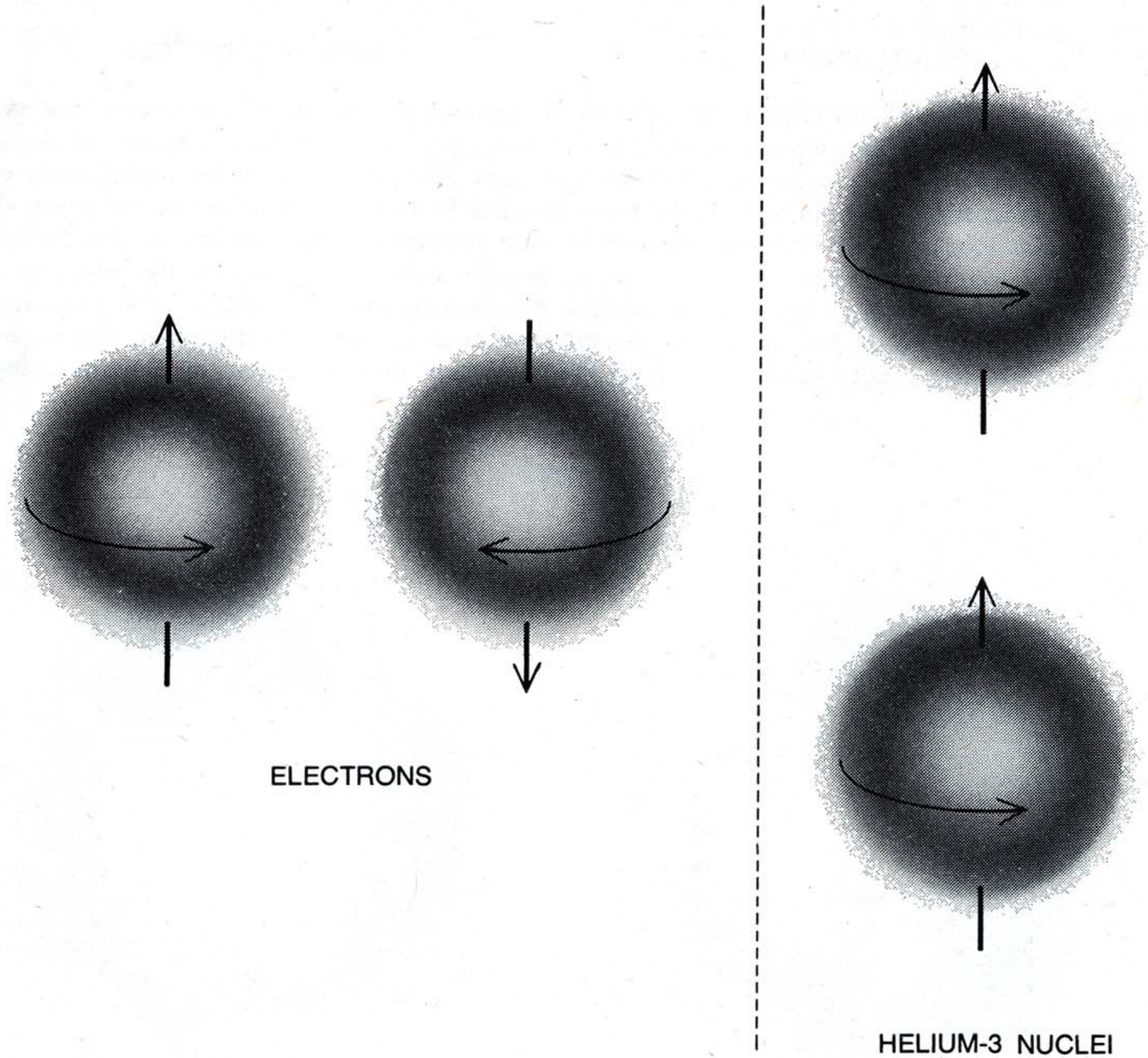
Quantum mechanics on a Macroscopic Scale!



ELECTRONIC STRUCTURES OF HELIUM ISOTOPES are almost precisely the same. The atoms of both helium 4 and helium 3 have two electrons, which form a spherical cloud of negative electric charge surrounding the nucleus (*top*). The two atoms differ significantly only in their nuclei, which are about 100,000 times smaller in diameter than the surrounding electron clouds. The helium-4 nucleus consists of two protons and two neutrons; the helium-3 nucleus has two protons but only one neutron (*greatly enlarged at bottom*). The physical and chemical properties of all other materials are determined almost entirely by the electronic structure of their atoms, but in helium the differences in nuclear structure give rise to many pronounced differences in behavior of both the liquid and the solid forms of the two isotopes.



NUCLEAR PROPERTIES of helium 3 and helium 4 differ. The helium-3 nucleus spins like a gyroscope and behaves magnetically as if it were a permanent bar magnet oriented along the axis of spin rotation. The vertical arrow indicates the direction of a magnetic pole; the equatorial arrow indicates the spin. The helium-4 nucleus possesses neither spin nor magnetism.

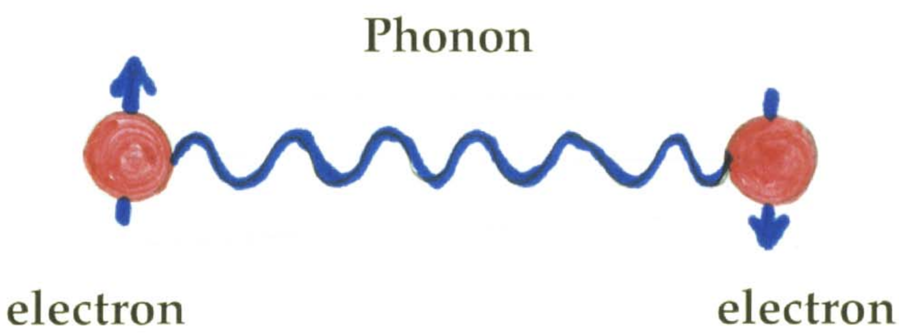


BOUND PAIRS OF FERMIONS are the condensed entities in superconductors and in superfluid helium 3. Superconductivity appears in a metal when the temperature falls low enough for the electrons to form bound pairs under the influence of a weak attractive force. In a like manner superfluidity appears in liquid helium 3 when pairs of atoms become bound together. In a bound electron pair in a superconductor the elementary magnets oppose each other, and the pair has no net intrinsic magnetism. The electrons also spin in opposite directions. The bound pairs of helium-3 atoms are quite different. The magnets reinforce each other, and as a result the pair possesses a net magnetism. Helium-3 nuclei also have same direction of spin.

1957 - BCS Theory

Basic Ingredients $T < T_c$

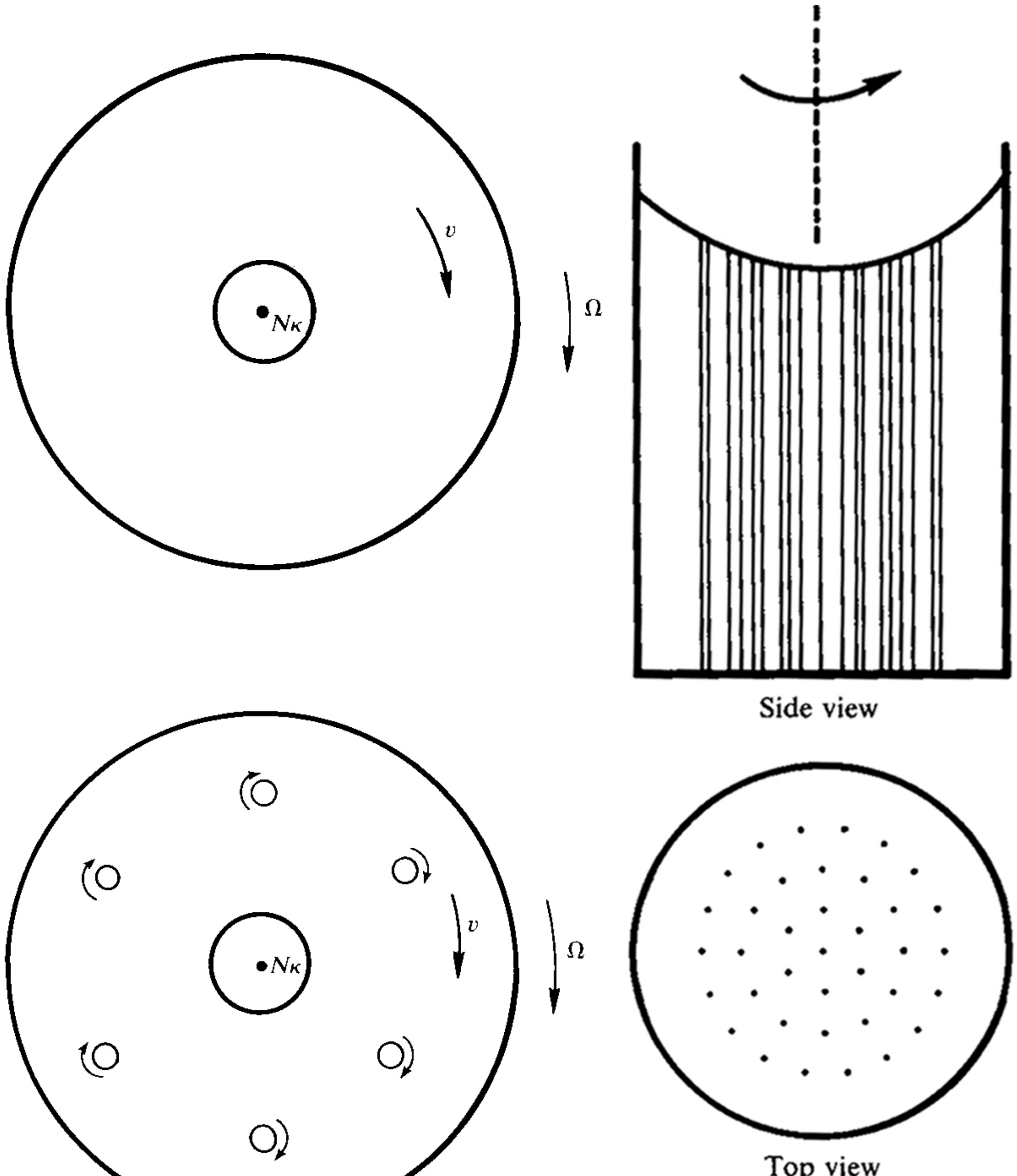
1. Net attractive interaction between e^- via phonons leads to Cooper pair.

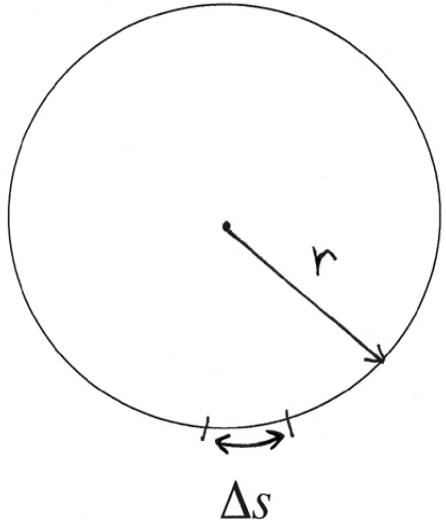


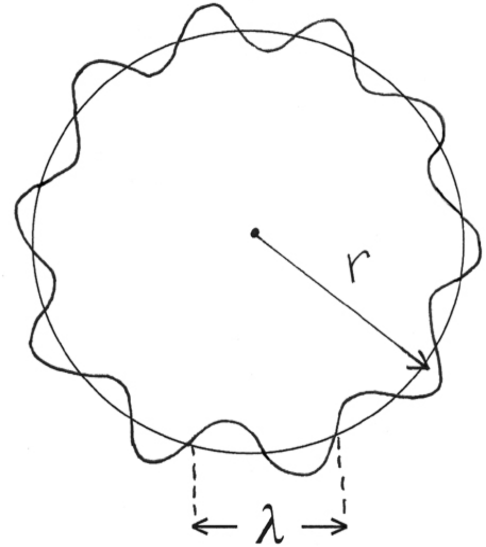
2. Formation of order parameter ψ: Wave fcn. like entity - correlates motion of e^- over long range.

3. Energy gap develops at Fermi surface - separates ground state order parameter from excited quasi-particles.

4. S wave superconductors $\rightarrow$ isotropic gap.


v
Nκ
Ω
Side view
v
Nκ
Ω
Top view





Quantized Vortices

$s = 2\pi r$ = Sum of all the elements Δs

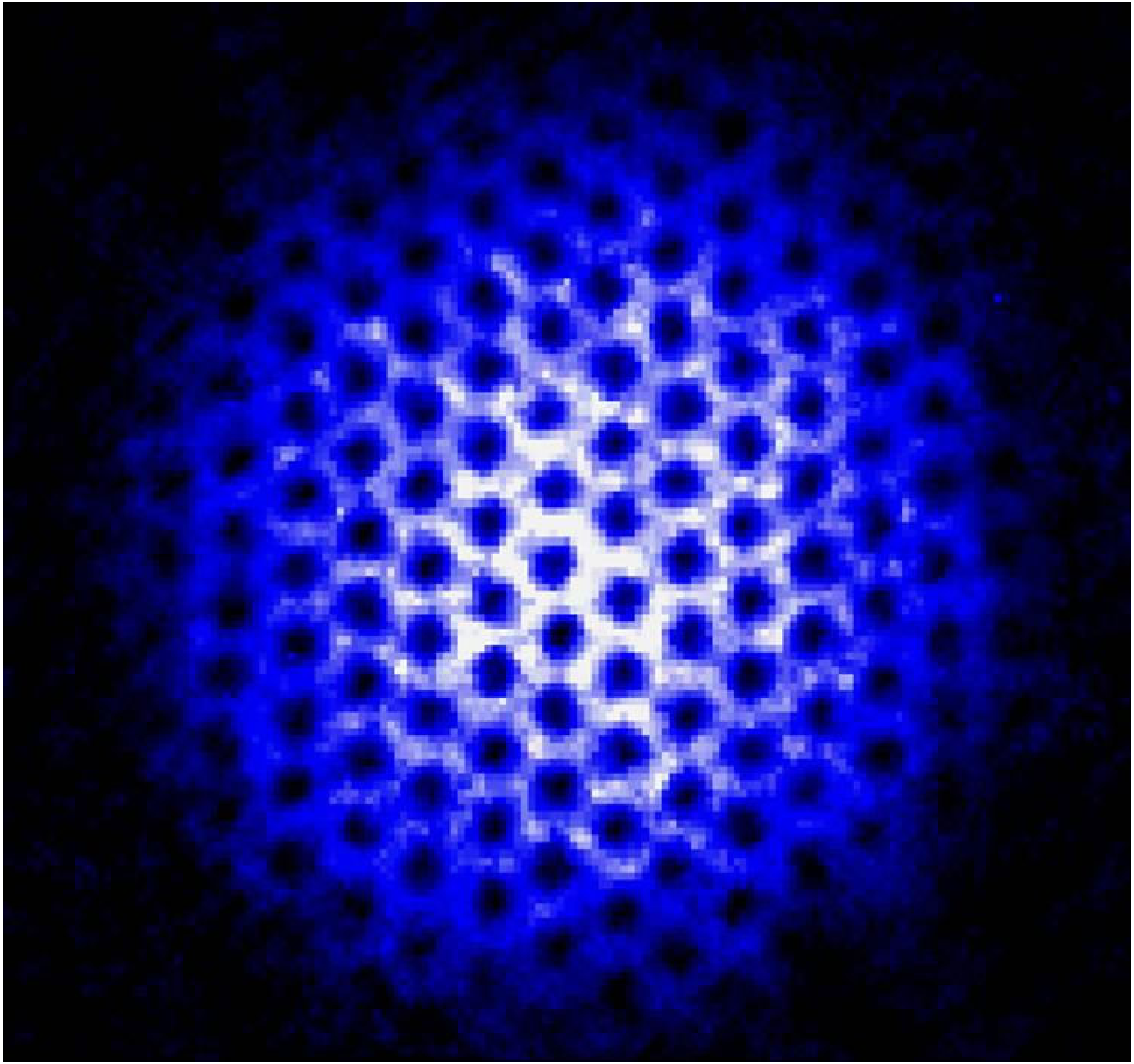
Integral No. of Wavelengths around ring

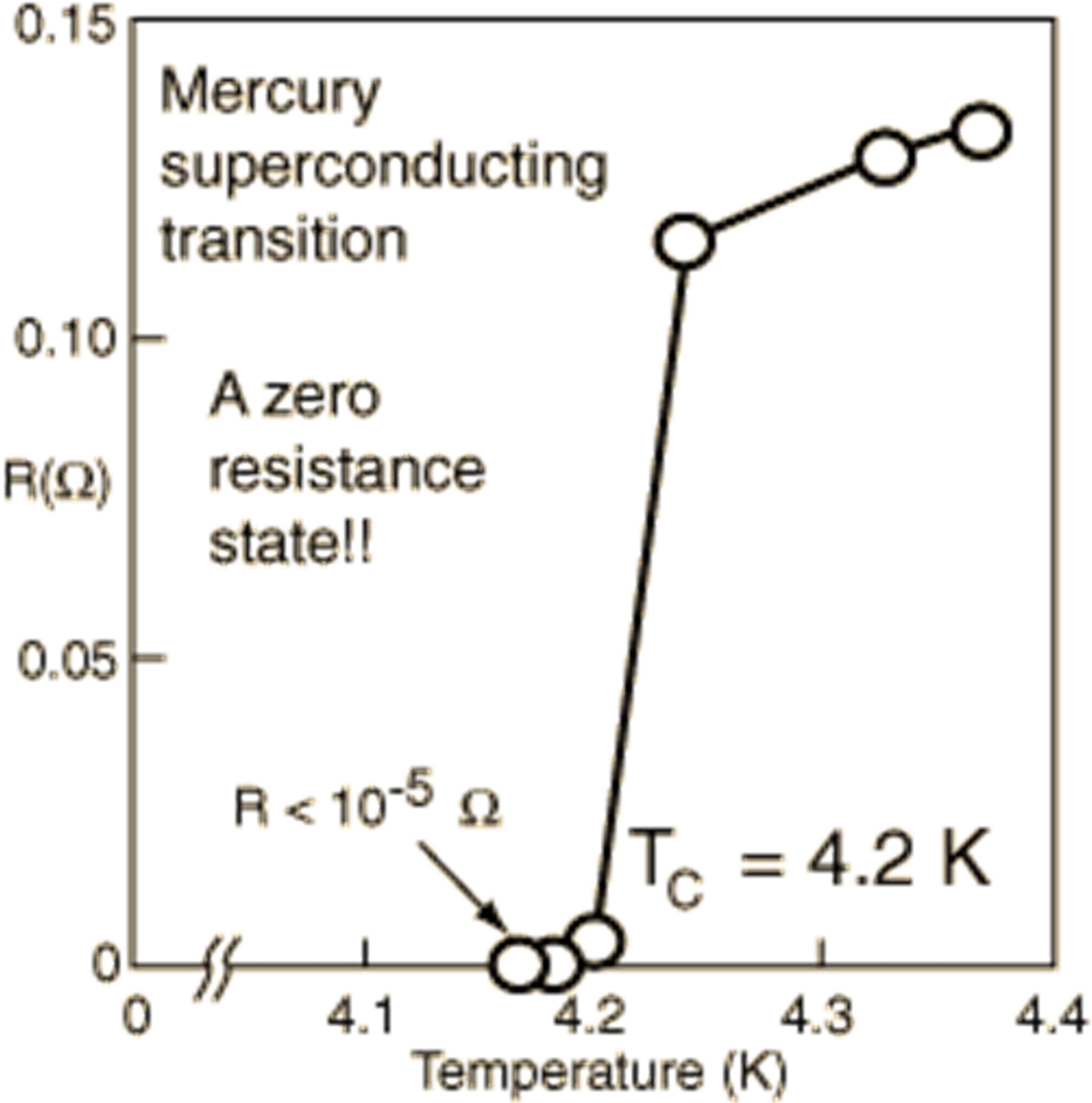
$$\rightarrow \qquad \frac{2\pi r}{\lambda} = n$$

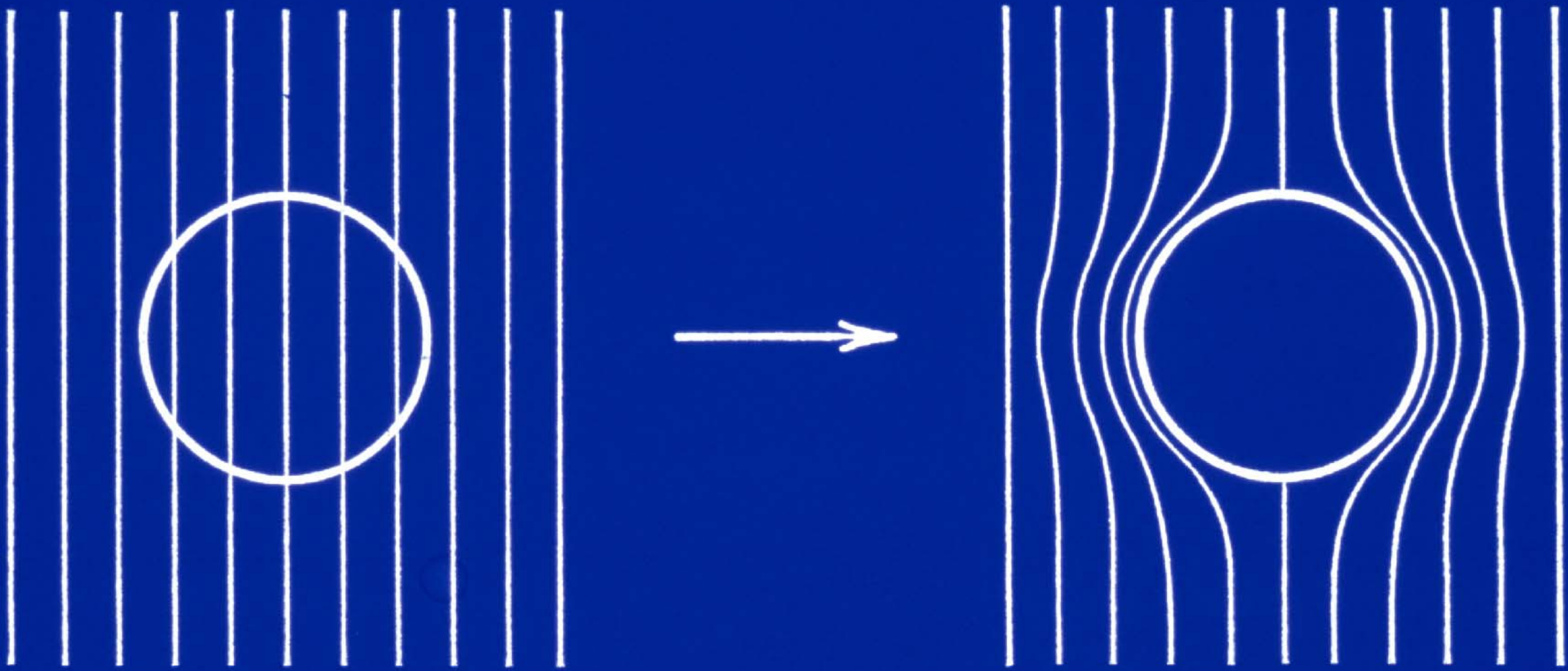
$$\text{so} \qquad 2\pi r \frac{h}{\lambda} = s \frac{h}{\lambda} = nh$$

But de Broglie says $mv = p = h/\lambda$

Circulation $K = vs = \frac{nh}{m}$

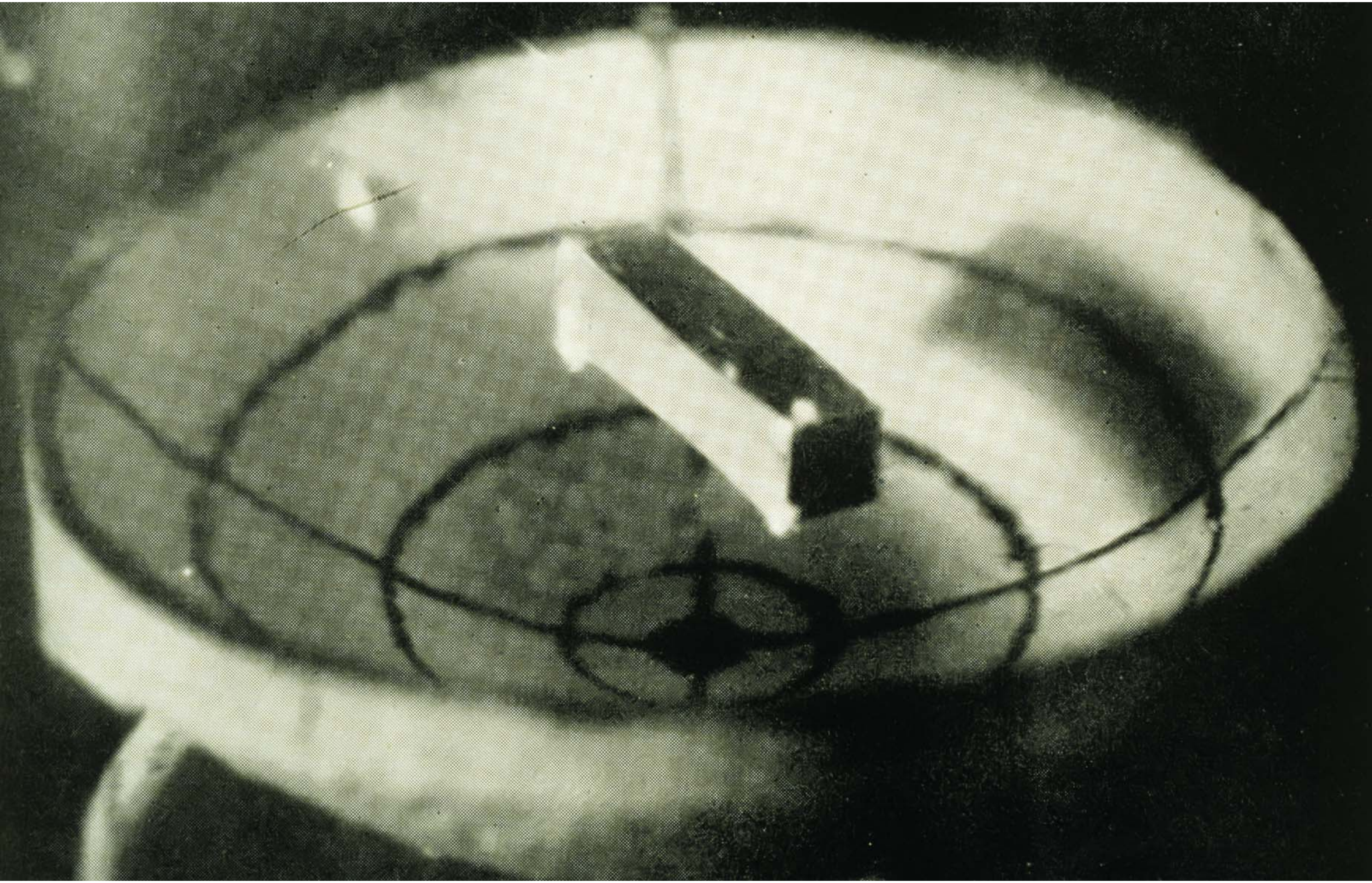



0.15
Mercury
superconducting
transition
0.10
A zero
resistance
state!!
R(Ω)
0.05
R < 10-5 Ω
TC = 4.2 K
0
0
4.1
4.2
4.3
4.4
Temperature (K)



The magnetic field is applied while the specimen is in the normal state;

the field is pushed out when the specimen is cooled below its transition temperature.



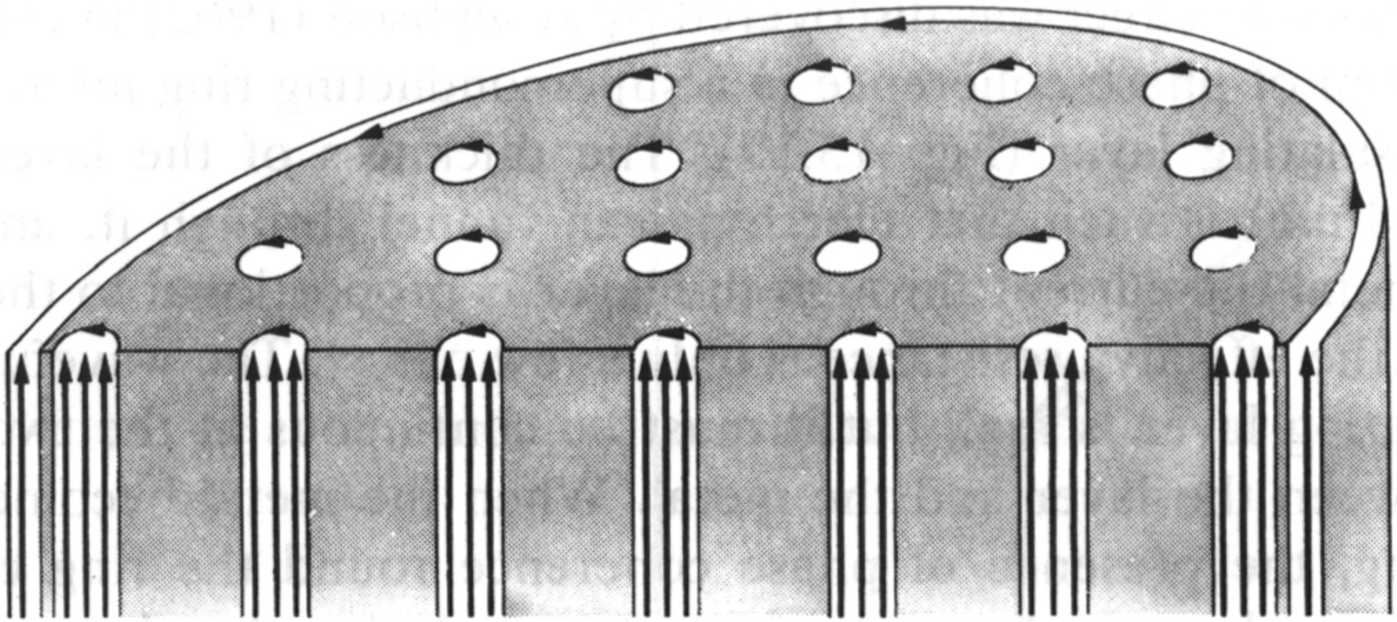


FIG. 13.16. The 'vortex state' in a superconductor between B_{c1} and B_{c2}. At the centre of a vortex there is 'normal' metal carrying lines of magnetic flux, around which flow circulating currents out to a distance equal to the penetration depth λ. The total flux through each vortex is just equal to one quantum Φ_0, and in a perfect crystal the vortices are equally separated in a triangular array.

SUPERCONDUCTING LEVITATION TRAIN