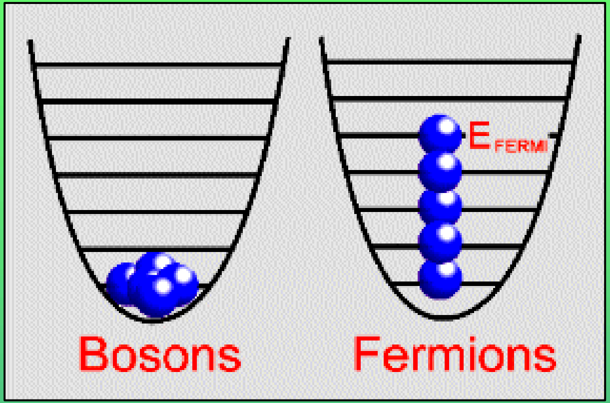
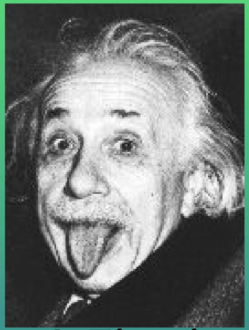
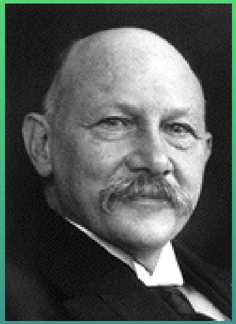
QUANTUM FLUIDS & SUPERFLUIDS

All the advances in our understanding of the structure of matter discussed so far depend on quantum mechanics only insofar as quantum theory explains the structure of the basic units, & how they bind together. However there is a much more radical possibility- that completely new kinds of structure might exist, which are intrinsically quantum-mechanical AS A WHOLE.

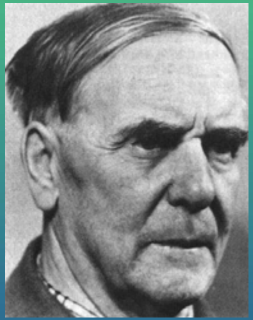


At first glance the idea that quantum correlations could be maintained between vast numbers of particles, in the face of thermal fluctuations and external perturbations, seems impossible. But this is not true if all particles can 'Bose condense' into the same state. It was first realised by Einstein in 1924 that this could happen


A. Einstein (1879-1955)


H K Onnes (1853-1926)

Superconductivity was found in 1911 by Kammerlingh Onnes in Leiden, in Al at 1.3K. Superfluidity in ^{4}He at 2.2K was not discovered until 1938, by Allen & Misener in Cambridge, & Kapitza in Moscow (who then did very complete investigations of its properties).


PL Kapitza (1894-1984)


DD Osheroff (1945-)


RC Richardson (1937-)


DM Lee (1931-)

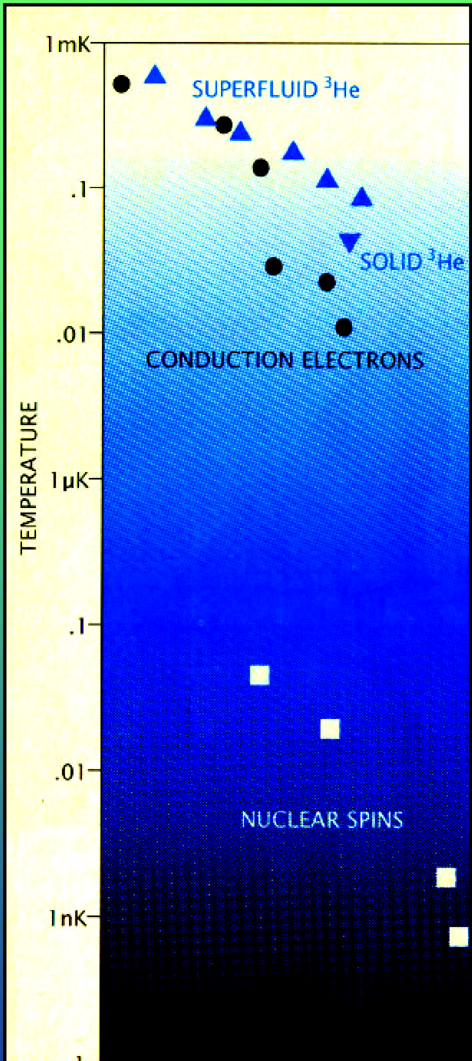
Theoretical understanding only came gradually, & required several key ideas- Bose-Einstein condensation (BEC), the macroscopic wave-function, and fermion pairing to give fermionic BEC. These ideas are described on slide 4.92. As experiments went to ever lower temperatures, more & more systems were seen to go superfluid/superconducting – a major triumph was the long-awaited discovery of superfluid ^{3}He at 2.7 mK (Osheroff + al)

CONDENSED MATTER: towards Absolute Zero

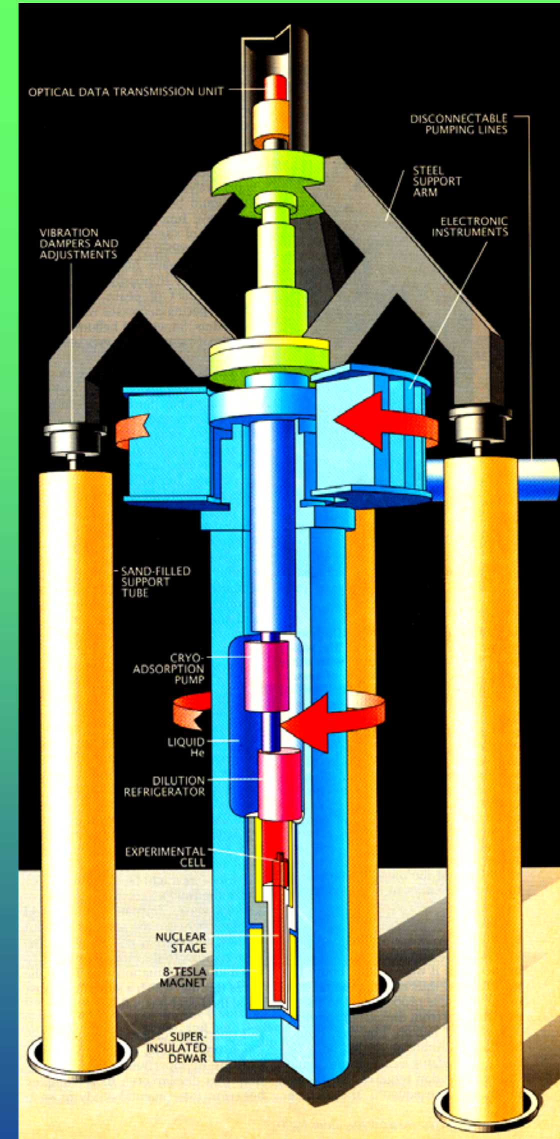
How does one go to such low temperatures? We have seen the voyages to inner & outer space in physics. There is also a voyage to the ultra-cold, which is now within 10^{-10} K of absolute zero (see left). One can never reach absolute zero (where all random thermal motion stops), since no cooling device is perfectly reversible- something always leaks back.

The fascination of ultralow T is that more & more complex kinds of 'quantum order' develop, undisturbed by the thermal motion. This has led to some of the most extraordinary phenomena in physics.

The experimental techniques which get to such temperatures are equally remarkable. Cooling is done in stages– one first cools by pumping on gases to liquify them. This works down to 0.3K, after which one mixes superfluids & polarizes spins with strong fields. One can then remove the fields – the spins then 'suck up' thermal energy to randomize their directions.



The lowest temperatures reached for bulk matter between 1970- 2000 AD.



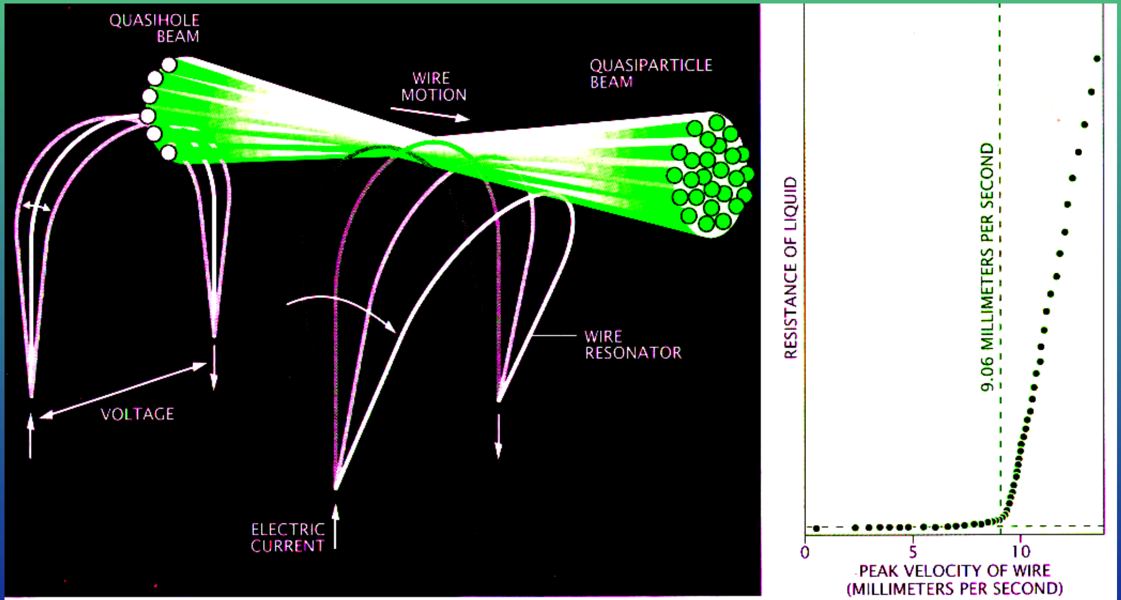
The 'ROTA 2' rotating cryostat. It cools to roughly 0.5 mK. The entire 500 kg apparatus can turn up to 6 times per second

CONDENSED MATTER: Superfluidity

Superfluidity is seen, eg., in the absence of viscous resistance to the flow of a fluid. The superfluid flows freely, ad infinitum, through holes hardly larger than atomic size. The 'fountain effect' at right shows free flow of He-4 liquid through packed 'jeweller's rouge' (rather like lipstick).

The ultimate explanation of this is in the Bose statistics of the particles. He-4 atoms are bosons (with 2 electrons, 2 protons, & 2 neutrons). At low T they all 'Bose condense' into the same quantum state. The superfluidity then arises because it takes a finite energy to excite the system out of this state- only possible if it flows faster than a 'critical velocity' v_c, or if some object moves through it faster than v_c .

Fountain effect



SUPERCONDUCTING WIRE LOOP set in motion by current and magnetic field breaks up superfluid Cooper pairs to create beams of quasiparticles and quasiholes (*left*). A second loop can detect the resulting quasiparticle wind, whose motion yields data on the structure of the superfluid. Pair breaking increases rapidly as the wire exceeds a critical velocity (*right*).

He-3 (1 neutron instead of 2) is a fermion- but 2 such fermions form 'Cooper pairs' of atoms, which behave as bosons.'Pair-breaking' again occurs above a critical velocity (left), which again excites the superfluid. Thus under small perturbations, superfluidity is stable

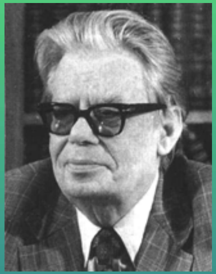
Wire in He-3 superfluid moves with zero resistance until a critical velocity, then it emits a 'wind' of 'broken pair'excitations

MACROSCOPIC WAVE-FUNCTIONS

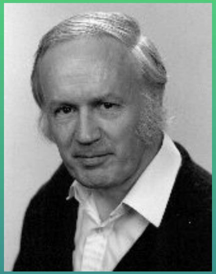
F London
(1900-1954)

LD Landau
(1908-1968)

If all the particles Bose condense in the same state, we can write down a 'macroscopic wave-function' for the quantum state of the whole system! It was first seen by London in 1937-8 that this was the key to superfluidity & superconductivity. Landau gave a phenomenological theory in 1941 for superfluid ^4He, & then finally in 1957 the BCS (Bardeen-Cooper-Schrieffer) theory, & an equivalent theory of Bogoliubov, gave a definitive explanation of superconductivity (where fermionic electrons 'pair' to form bosons which then go superfluid). The generalisation to superfluids with rotating pairs with spin was given by Leggett & others. The BCS macroscopic quantum state for a set of bosons is written in the form



N Bogoliubov
(1909-1992)

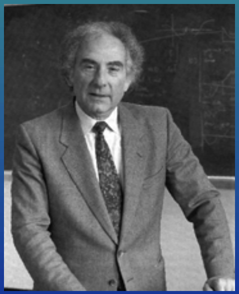


AJ Leggett
(1938-)

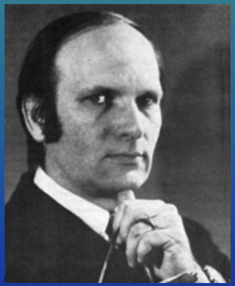
$$\Psi (r_1, r_2, \ldots r_N) = \Sigma_{perm} \, \phi(r_1) \, \phi(r_2) \ldots \phi(r_N)$$

where the sum is over all possible swaps of the particles (remember the particles are indistinguishable). This formula may look terrible, but it just says that all particles are in the same quantum state ϕ .

J Bardeen
(1908-1991)



LN Cooper
(1930-)

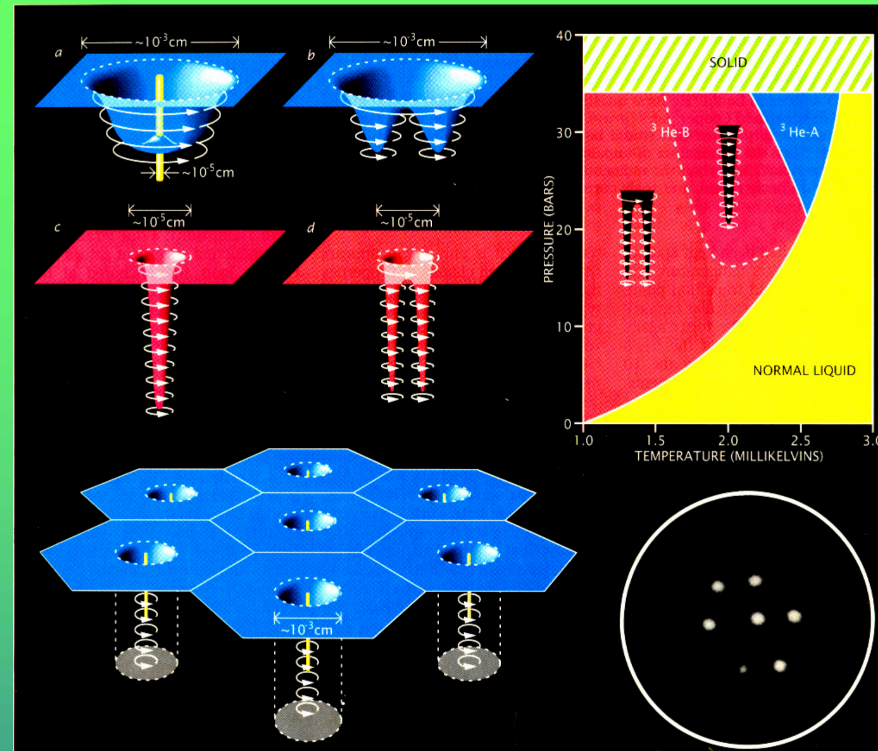


JR Schrieffer
(1931-)

All particles are in the same state, so we can talk about a single quantum state $\Psi (r)$ for the whole superfluid. This is London's famous 'macroscopic wave-function'. Note: it is still a probability amplitude! London's idea was initially disbelieved when, but is now a central part of physics. Thus we see a new kind of 'quantum emergence' beginning to appear – not yet based on macroscopic entanglement, but on Bose condensation. Nevertheless it has spectacular macroscopic effects….

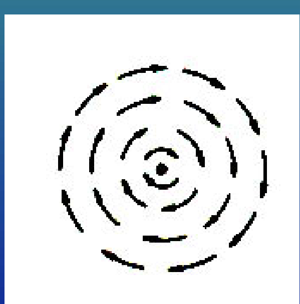
Quantum Vortices in Superfluids

Suppose we look at a vortex in a superfluid- ie., fluid circulating around a core. From what we saw with atoms this tells us we have probability waves circulating round the core with wavelength $\lambda = h/p = h/mv$, where v is the velocity of the atoms circulating round the core. But then, as noted by Onsager in 1950, as in atoms, only certain velocities are allowed, if we are to fit the waves around the core. Hence we find that the total circulation is quantized- we have '**quantized vortices**'. In this simple picture the core is like a string- in fact it has a finite diameter. In He-4 this is very small (only about **1 Angstrom**!), but in other superfluids like He-3 it is much larger (**~150 Angstroms**), & so the core is itself very complex.

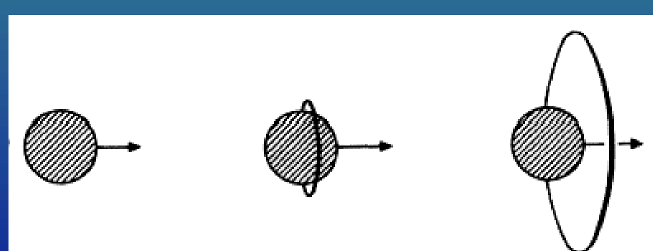


Different vortex patterns in superfluid He-3

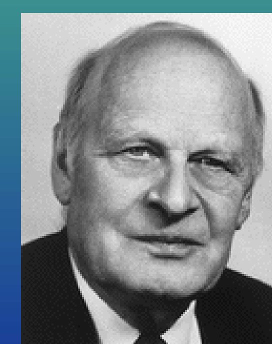
The vortices themselves are quantum excitations- so they also have a probability density! They have fascinating properties- eg, they can form closed 'vortex rings', which are also probability waves.



superfluid moving around vortex core



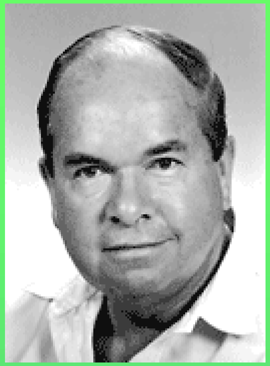
The nucleation of a vortex ring by a microscopic object moving through He.



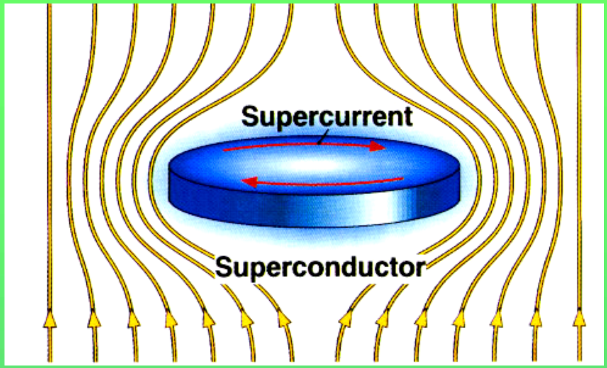
L Onsager (1903-1976)

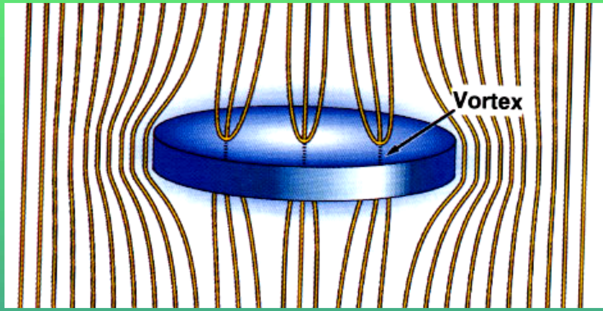
Quantum Vortices in Superconductors

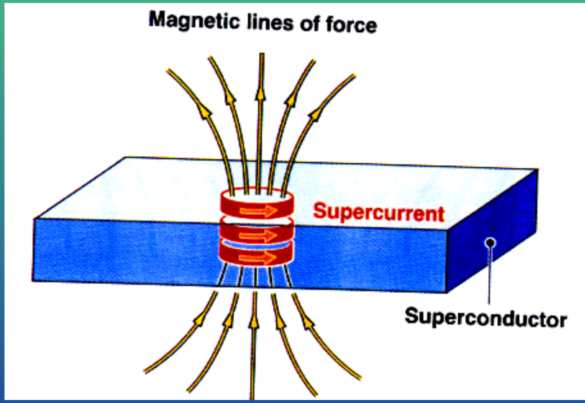
Superconductivity is a condensation of pairs of electrons, all into a single state. If we try to disturb this quantum state by applying an external magnetic field, the supercurrents in the system, flowing without resistance, simply adjust to block the field from entering the superconductor (the ‘Meissner effect’). However, as shown by Abrikosov in1957, in some materials the field can get in via vortices, like those in superfluids- again, the circulating current is quantised.



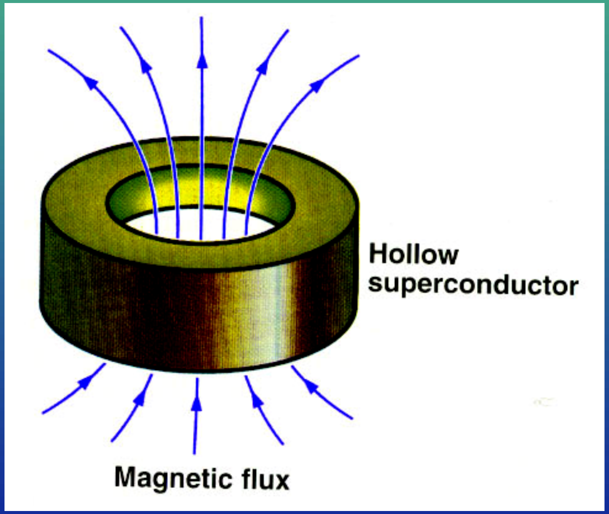
AA Abrikosov (1928-)







TOP: magnetic field lines around a superconductor
MIDDLE: vortices penetrate
BOTTOM: close-up of vortex in superconductor

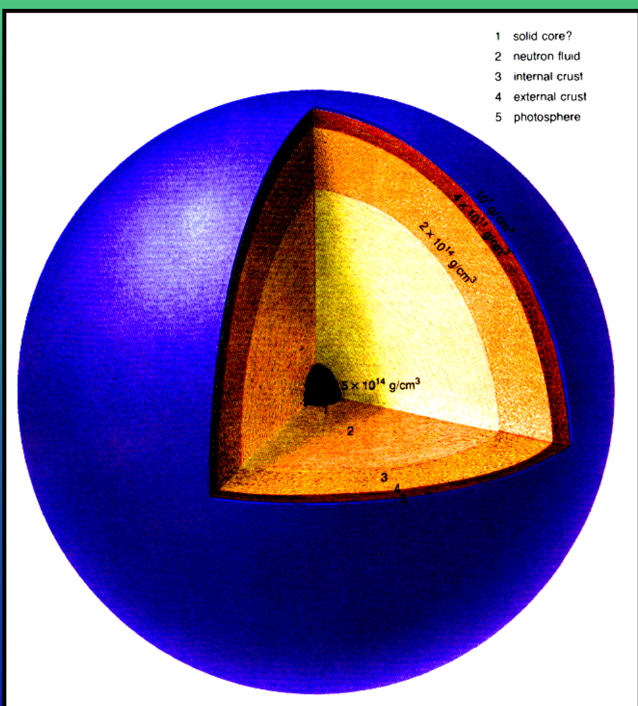


Magnetic Field through superconducting ring

If we have a loop of superconducting material we can trap magnetic flux inside it- this is kept out of the superconductor by currents in it, as before. Again, the circulating current is quantised, and thus so is the flux- in units of a flux quantum **h/e**

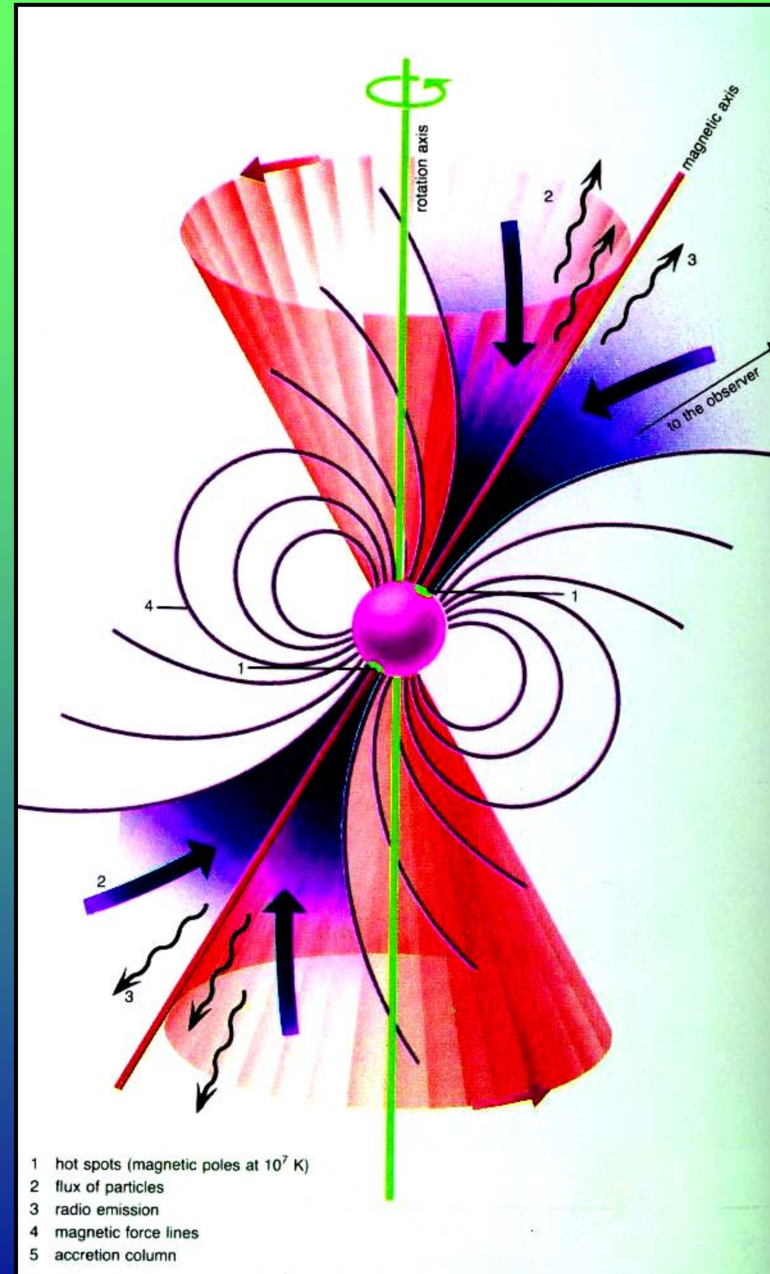
NEUTRON STARS:
Stellar superfluids

Actually a lot of the matter in the universe is in superfluid form. Neutron stars, left after a supernova explosion, are actually like giant nuclei, and they are superfluid. The neutron star & the superfluid in it are rapidly rotating, hence full of vortex lines. There is also a circulating electric current (the protons are charged), so a huge magnetic field is created.

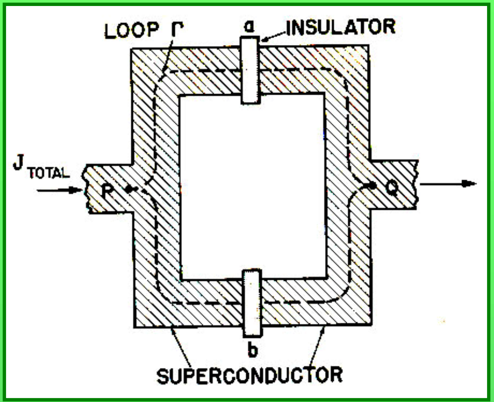


LEFT: structure of a neutron star. The inner dense parts (containing almost all mass) are neutron & proton Superfluids

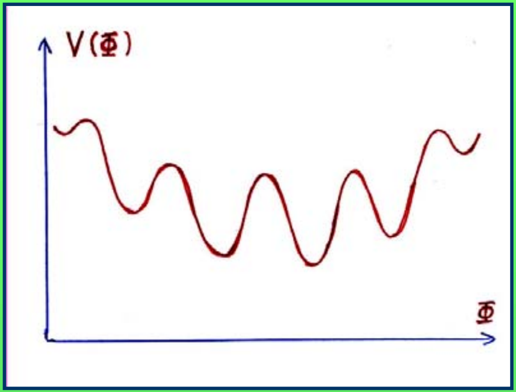
RIGHT: magnetic field around neutron star- high energy particles are ejected along magnetic poles



The ‘SQUID’



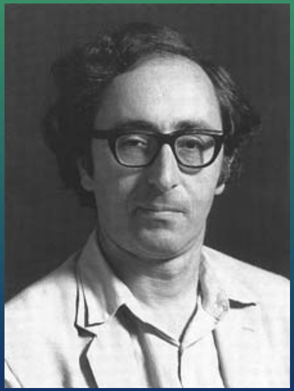
2-slit interference in SQUID



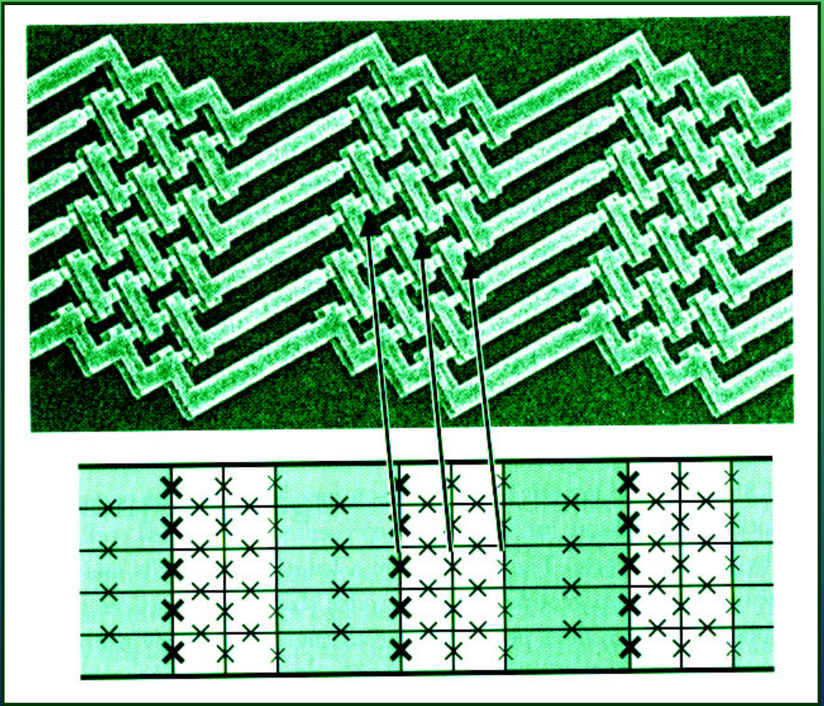
SQUID potential

As previously discussed (p. 4.26) we can set up a 2-slit experiment in superconductors using a “SQUID” (Superconducting QUantum Interference Device) ring. It depends crucially on the existence of 2 ‘Josephson junctions’ which allow flux to move in and out of the ring. The SQUID is a fantastically sensitive detector of magnetic field- its interference pattern changes completely if a single quantum of flux moves in or out of the ring (assuming the electron waves are coherent around the ring), as shown theoretically by Josephson in 1962.

The energy V of the SQUID also depends on the total magnetic flux Φ through it (top right). Moving a flux quantum in or out means pushing the system between 2 adjacent potential wells. The current circulating in the SQUID changes by a large amount when this transition occurs.

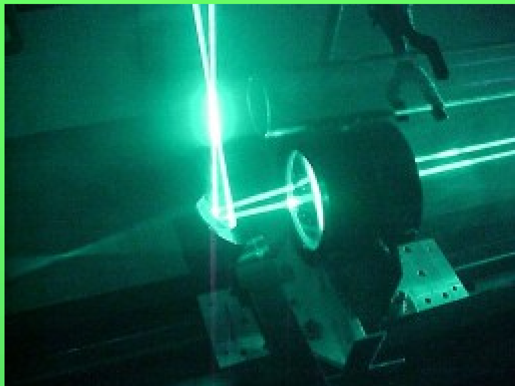


BD Josephson (1940-)

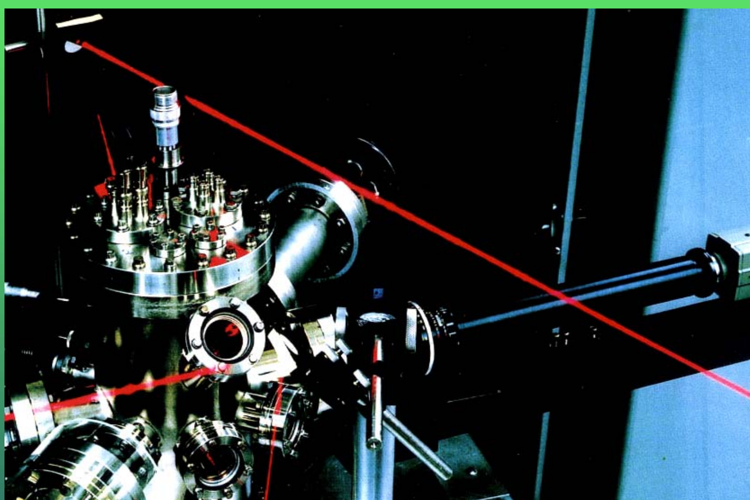


Network of Josephson junctions and SQUIDs

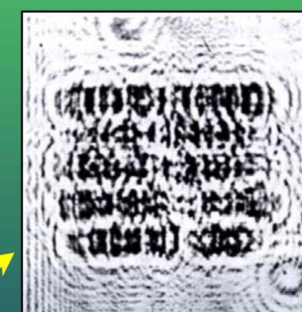
COHERENT LIGHT & LASERS

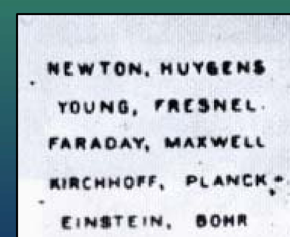


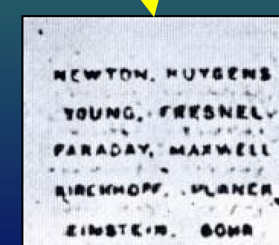
The basic idea of the laser was already implicit in papers by Einstein written before the 1st World War. As we have seen, light is essentially a collection of photons, and in principle these can all be put in the same state – ie., they can Bose condense just like Helium. To actually do this turned out to be not so easy – it was first done with microwaves, to produce the 'Maser' (an acronym for 'Microwave Amplification by Stimulated Emission of Radiation'), The idea is to put a large number of identical atoms in the same excited state, and then when they start to decay, emitting photons, they set the others off, producing a sudden intense beam of photons all in the same state. We now know that masers exist naturally in interstellar gas clouds. Lasers (with microwaves replaced by light) were first made in the 1960's in Russia and the USA, and are now in use everywhere.



The uses of lasers are so diverse In industry now that it would take pages to describe them all – but most of these only require very intense & highly-controlled radiation.



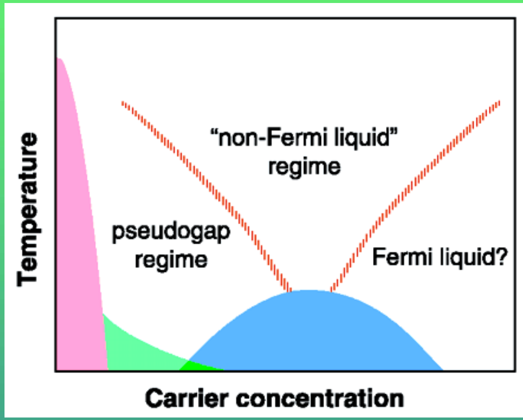




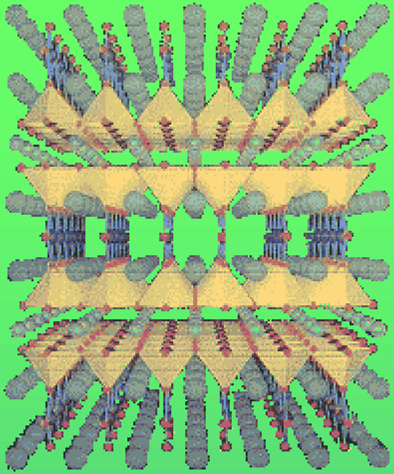
Coherent photon states are nevertheless of growing importance in more sophisticated devices. Perhaps the 1st of these (which only relies on the existence of coherent radiation) was the hologram, in which all the wave information is encoded in an interference pattern. In recent years the use of small numbers of coherent photons has become important in opto-electronic devices; and future quantum information processing technology will require coherent photons

New Kinds of Superfluid & Superconductor

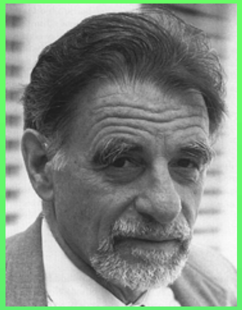
A new superconductor is discovered at least once every day in physics, & most go completely un-noticed. Great excitement surrounded the discovery in 1986 of '*high-temperature*' superconductors by Bednorz & Muller, undergoing transitions to superconductivity at temperatures T_C as high as 120K (this is still -153 C!). High-T_C materials are complex, & the mechanism of superconductivity is clearly connected to the magnetic properties of the systems. We do not yet have a good picture of the underlying physics in these systems, which is clearly connected to the strong interactions between the electrons, & this is still a very active area of research.



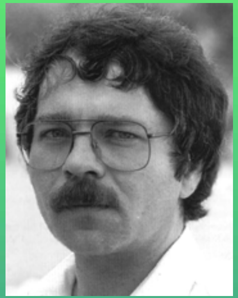
Phase diagram of the YBCO superconductor; blue area is superconducting



Structure of the high-Tc superconductor YBCO



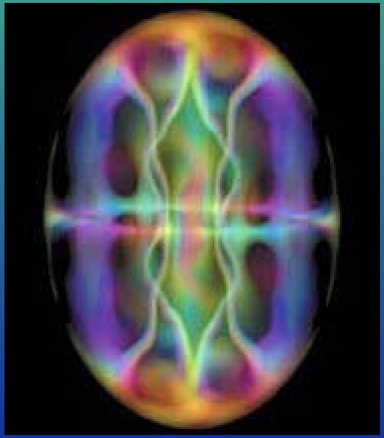
KA Muller (1927-)



JG Bednorz (1950-)

The hope is that one day we will have room-temperature superconductors. The high-Tc superconductivity itself is not radically different from that in other systems, involving electron pairs which rotate around each other (in a way quite similar to that in ^{3}He superfluid)

In the early 1990's atomic physicists cooled small collections of atoms to very low temperatures, only about 100 nK above absolute zero (NB: 1 nK is 10^{-9} K). This was done by trapping them in 'magnetic bottles', slowing their thermal motion using lasers, and further cooling them by evaporation, using a method devised theoretically by Cohen-Tannoudji. In this way Cornell & Wieman finally prepared BEC's of atomic gases, which have since shown very interesting properties. Again, however, the basic structure of the superfluidity, and the mechanism responsible for it, is essentially that discussed in the old work of Einstein, London, Landau, & BCS, and already seen in ^{4}He & ^{3}He.



A rotating cold atomic gas BEC, with vortex lines in the middle

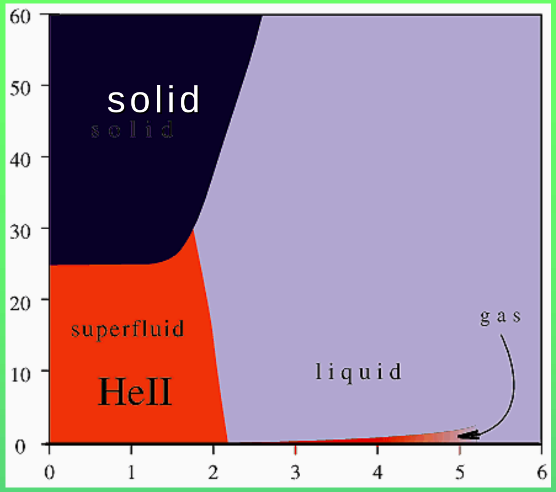
C Wieman (1951-
E Cornell (1961-)

LEFT: C Cohen-Tannoudji (1931-

SUPERSOLIDS

In 2004 a remarkable discovery was made by a group under M Chan. It was found that a sample of solid He-4, under very high pressures, behaved as if some fraction of it was superfluid. In other words, even though the system remained rigid, and the crystalline order in it was maintained, nevertheless some part of it could 'superflow', ie., flow without resistance.

This remarkable behaviour has been seen in several ways. The original discovery rotated the solid in a sealed 'bucket'-shaped container – part of the contents did not rotate but stayed stationary in the lab frame. In a second experiment, superfluid He flowed through the solid – this was even filmed on video.



The phase diagram of He-4

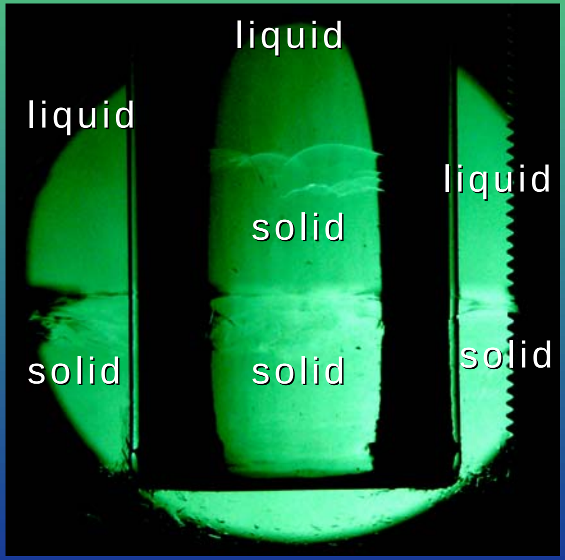
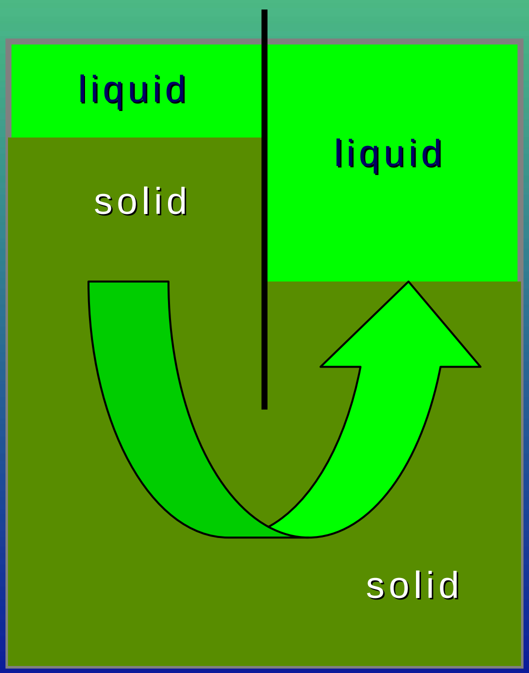
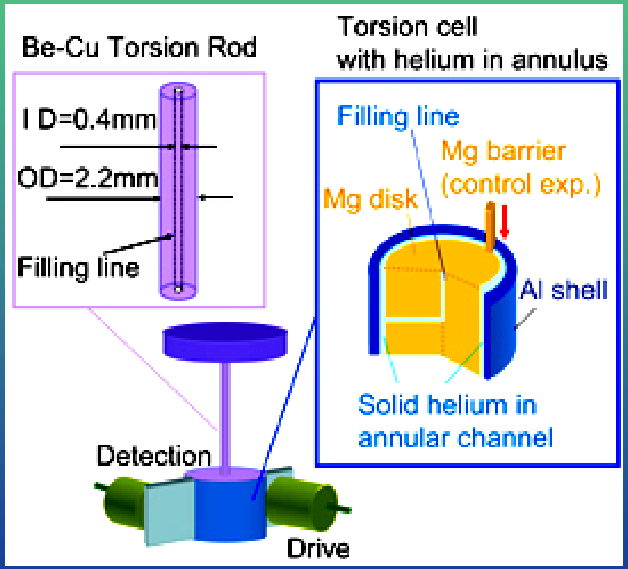


Photo (taken from video) of the liquid & solid phases, with fluid flowing through the solid (shown schematically at right





The experiment in which part of the solid inside a closed rotating Container di dnot rotate with the Container.