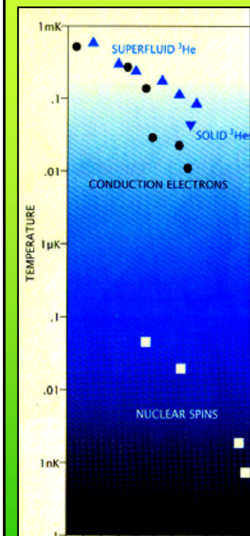
CONDENSED MATTER: towards Absolute Zero

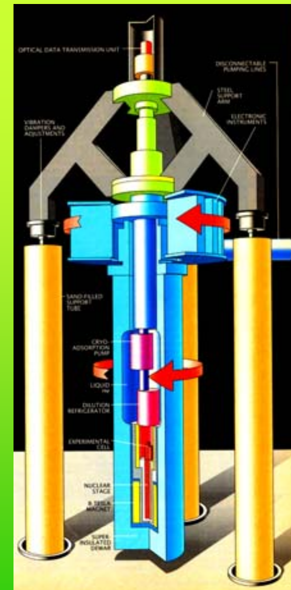


The lowest temperatures reached for bulk matter between 1970- 2000 AD.

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 (at which 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.



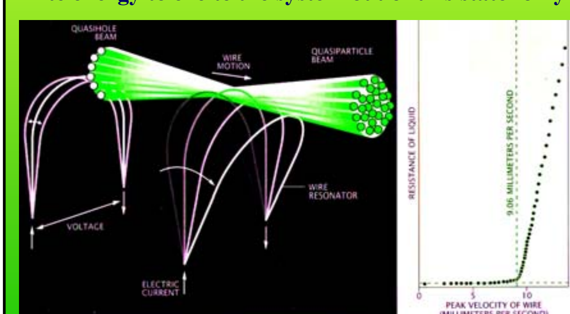
The 'ROTA 2' rotating cryostat. It cools to roughly 0.5 mK. The entire 500 kg apparatus can turn up to 6 times per second

CONDENSED MATTER: Superfluidity

Superfluidity is defined by 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).

Fountain effect

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 than v_c. He-3 (1 neutron instead of 2) is a fermion- but forms 'Cooper pairs' of atoms, which behave as bosons.'Pair-breaking' again occurs above a critical velocity (left).



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*).

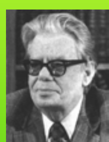
Wire in He-3 superfluid moves with zero resistance until a critical velocity, then emits 'wind' of 'broken pair'excitations

MACROSCOPIC WAVE-FUNCTIONS


F London


LD Landau (1908-1968)

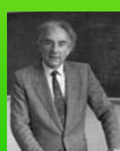
If all the particles in the system end up in the same state, we can write down a 'macroscopic wave-function' for the quantum state of the whole system! It was first seen by London in 1938 that this was the key to superfluidity & superconductivity. Later Landau gave a more complete theory (1941), and then finally in 1957 the BCS (Bardeen-Cooper-Schrieffer) theory, & an equivalent theory of Bogoliubov, gave a definitive explanation of these phenomena. The macroscopic quantum state is written in the form


Bogoliubov

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

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.

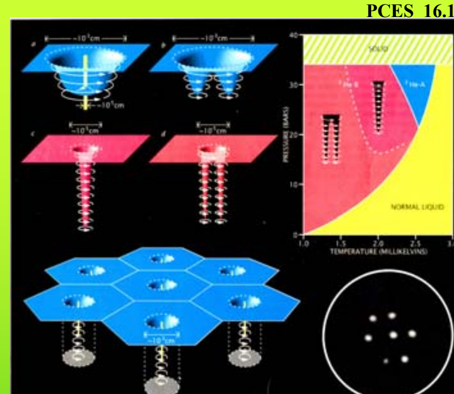

J Bardeen


LN Cooper


JR Schrieffer

Because all particles are in the same state, we can just talk about a single quantum state $\Psi(r)$ for the whole superfluid. This is the famous 'macroscopic wave-function' of London's. But it is still a probability amplitude! London's idea was disbelieved when proposed, but is now a central part of physics.

CONDENSED MATTER: Quantum vortices in Superfluids


Different vortex patterns in superfluid He-3

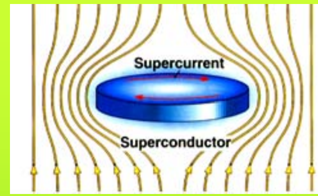
Suppose we look at a vortex in a superfluid- ie., fluid circulating around a core. From what we saw with atoms this tells us that we have probability waves circulating round the core with wavelength $\lambda = h/p = h/mv$, where v is the velocity of the atoms circulating around the core. But then we have the same situation as with the atom- 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 (see above).

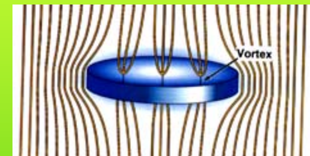
The vortices themselves are quantum excitations- so they also have a probability density! They have fascinating properties- one of the most interesting' is that they can form closed 'vortex rings', which are also probability waves.

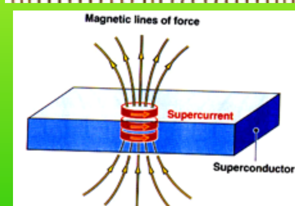

Circulating superfluid around core

CONDENSED MATTER: Quantum Vortices in Superconductors

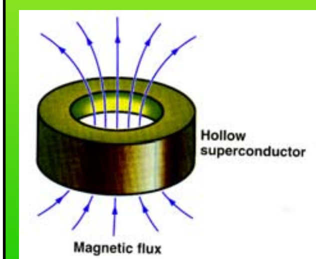
Superconductivity is a condensation of pairs of electrons, all into a single state. If we try to disturb this macroscopic quantum state by applying an external magnetic field, the supercurrents in the system, flowing without resistance, simply adjust to block the field from entering the superconductor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







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

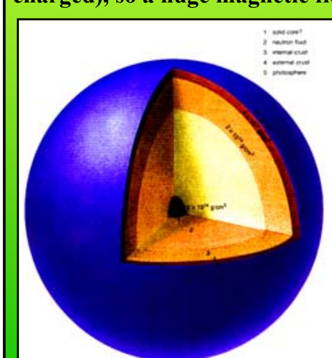


Magnetic Field through superconducting ring

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

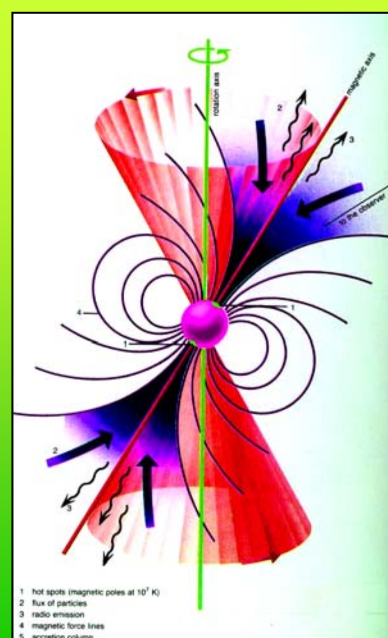
NEUTRON STARS: Stellar superfluids

Actually most 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. This is also a circulating electric current (the protons are charged), so a huge magnetic field is created.



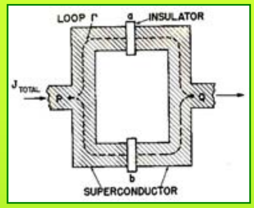
LEFT: structure of a neutron star. The inner dense parts (containing almost all mass) are neutron & proton superfluids

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

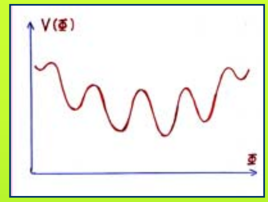


The 'SQUID'

As previously discussed (p. 12.6) 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).



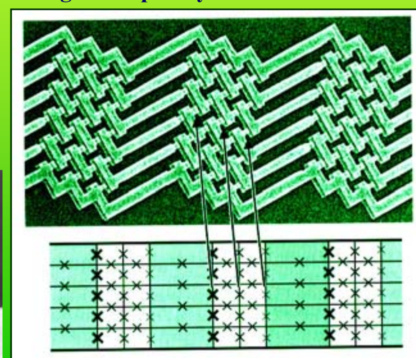
2-slit interference in SQUID



SQUID potential

One can also show how the energy V of the SQUID 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


Network of Josephson junctions and SQUIDs