The Nobel Prize In Physics – 1996

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The Nobel prize in Physics for 1996 has been awarded to Lee, Osheroff, and Richardson, working in Cornell, for the discovery of superfluid phases in ^{3}He, an isotope of helium, in 1972. This discovery confirmed earlier theoretical speculation for the existence of the superfluid state in this isotope of helium and also brought to light many new phenomena.

Superfluidity is the phenomenon in which, under certain conditions, a liquid can flow through narrow channels without viscous resistance. This phenomenon was first discovered in liquid ^{4}He, when it was cooled below 2.17 K, by Keesom in 1927. Kapitza was awarded the Nobel prize for his work on superfluidity in liquid ^{4}He. One can understand the behaviour of the superfluid state by assuming that the liquid is made of two components, the normal component with a density ρ_n, which has normal viscosity, and a superfluid component with a density ρ_s which has no viscosity. The total density of the liquid is the sum of the densities of the normal and superfluid components with the ratio ρ_s/ρ, where ρ is the total density, increasing from zero at 2.17 K to unity as the temperature approaches absolute zero. ^{4}He nucleus has two protons and two neutrons and its total spin is zero. A nucleus with zero or integral spin obeys Bose-Einstein (BE) statistics in which there is no restriction on the number of particles occupying a given quantum state. One of the consequences of this condition is that, below a temperature dependent on the number density of the particles, a macroscopic fraction of the total number of particles start occupying the ground state. This is called Bose-Einstein condensation (see *Resonance* in Suggested Reading). In the condensed state the particles have zero entropy. The superfluid component in ^{4}He is identified with this condensed state.

Helium has an isotope, ^{3}He, which has two protons and one neutron. This nucleus has a total spin of 1/2. All particles having half-integral spin obey the Fermi-Dirac (FD) statistics and are referred to as Fermions. Electrons in metals are characteristic examples of such particles. In the FD statistics each quantum state can be either unoccupied or can be occupied by only one particle. One would not expect particles obeying FD statistics to show superfluidity since there can be no condensation of the particles in the ground state. However some metals show superconductivity which is the resistanceless flow of electrons. Bardeen, Cooper and Schreiffer (BCS) pointed out that if two electrons have a weak attractive interaction between them, arising out of lattice deformation in their presence, then they may pair together with a total zero linear momentum and with their spins aligned in opposite directions. Since the total spin of the bound pair is zero, the angular momentum quantum number of the pair can only be an even number. In many metals this is zero. Such paired electrons can then condense into a state in which they will show no frictional resistance to motion.

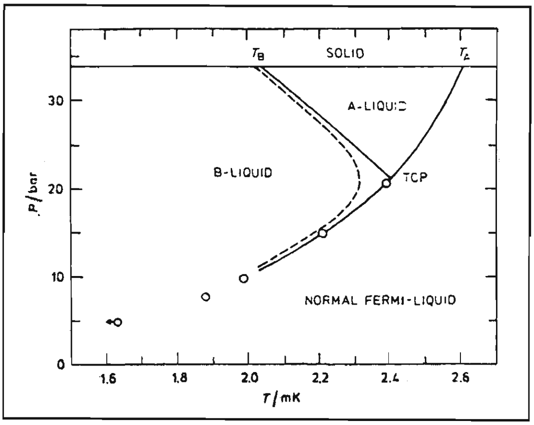
The isotope ^{3}He has an extremely low abundance in naturally occuring helium gas and so it has to be produced artifically in a nuclear reactor. This isotope became available in sufficient quantities by 1958 and extensive experiments were done on the properties of liquid ^{3}He till about 1970. These experiments established that liquid ^{3}He behaved like a normal Fermi liquid(FL)(ie) a liquid containing interacting Fermions. The interaction between the particles arises from spin fluctuations and is attractive at large distances and strongly repulsive at short distances. It is obvious that if a BCS like pairing should occur between two ^{3}He particles, they should be at large distances. The only way this is possible is for the two particles to rotate around each other with large enough angular momentum in the attractive centripetal force between the two particles. Also because of the magnetic interaction between the nuclei, in liquid ^{3}He, there are clusters of atoms with parallel spins. Pitaevskii in 1959, and other authors in 1960, predicted that one could have a pairing in which the two nuclei will have parallel spins. The total spin of the pair becomes 1 and the pair will obey BE statistics. Liquid ^{3}He should exhibit interesting anisotropic superfluid properties at low enough temperatures. The estimates of the temperature for the onset of superfluid behaviour were always lower than the lowest temperature attainable with the existing cryogenic techniques at that time.

But with the development of the dilution refrigerator, Pomeranchuk cooling and adiabatic nuclear demagnetization (techniques to be described in Parts III and IV of the series article titled *The approach to absolute zero* in this journal), it became possible in 1972 to study the behaviour of ^{3}He at temperatures a few millikelvin above absolute zero.

In a Pomeranchuk cell one applies a high pressure (about 33.5 bars) on liquid ^{3}He when its temperature is a few millikelvin. When such a pressure is applied, under adiabatic conditions, on liquid ^{3}He at a temperature below 100 mK, the liquid cools with the gradual conversion of the liquid into solid. Osheroff, Richardson and Lee were looking at the pressure on the liquid as a function of time as the liquid was compressed. They observed two very small but reproducible effects at 2.6 mK and 2 mK. At the higher temperature the slope of pressure versus time graph changed abruptly, while at the lower temperature of 2 mK there was a sudden discontinuous fall in pressure after which the pressure again continued increasing. At first they thought that these changes were associated with some transitions in the solid ^{3}He phase. But NMR experiments, in which they were able to look at the NMR signal from different sections of the cell with a technique similar to magnetic resonance imaging, clearly showed that these changes were occurring in the liquid and not in the solid. It immediately occurred to them and their co-workers that these may reflect transitions from the normal to the superfluid states expected by theorists since 1959.

Three groups, one at Cornell, the other at San Diego, USA, and the third at Helsinki, Finland, started intensive studies on various properties of liquid ^{3}He in these states. Within two years they were able to establish the phase diagram of the transition from a ^{3}He FL phase to a phase called A and then to a phase called B (see *Figure 1*) as a function of pressure, temperature and magnetic field. In the presence of a magnetic field the temperature for the A-B transition decreases. Also there is no tricritical point (TCP) at which the three phases can co-exist. In the presence of a magnetic field there is a narrow region of A phase between B and FL phases. The A phase itself splits into two regions A1 and A2. When the two nuclei pair to have a spin $S = 1$, there are three possible values of M_s, namely 1,0 and –1 . There is evidence to show that phase A consists of pairs with $M_s =$ 1 and –1 (Anderson-Morel state) and phase B contains $M_s = 0$ pairs also (Balian-Werthamer state).

Figure 1 The phase diagram of ^{3}He below 3mK. Dashed line shows the boundary between the A - and B- liquids in an external magnetic field of 38mT (see Lounasmaa in Suggested Reading).



The three main experiments to clearly demonstrate the superfluidity of A and B phases were (a) measurement of specific heat jump at the transition (b) the velocity of fourth sound below the transition and (c) direct determination of viscosity through the transition. The first measurement showed that there is a sudden jump in the specific heat at the transition FL-A, exactly what one sees in a normal to superconducting transition in a metal. When a superfluid fills a porous medium with narrow pores, the normal component is clamped because its viscosity is high. However the superfluid component can carry a pressure wave. This is called fourth sound. The velocity of fourth sound is different from the velocity of ordinary (or first) sound. There will be no fourth sound propagation in the absence of a superfluid. The density of the superfluid component is proportional to the square of the fourth sound velocity and was found to increase linearly with decreasing temperature below FL to A transition. Finally the viscosity was measured by a vibrating wire technique. The square of

the amplitude of vibration at resonance is inversely proportional to the viscosity. It was found that as the temperature passes through FL-A transition, there is a small fall in viscosity. But at the A-B transition the viscosity drops discontinuously and continues to fall as the temperature is reduced. The measured viscosity entirely arises from the normal component, the density of which decreases as one lowers the temperature below the superfluid transition.

Since the discovery of superfluidity in ^{3}He considerable work has been done over the last twenty five years, on elucidating the properties of superfluid helium, the effect of magnetic field on the phases and on the flow properties of the liquid.

One of the fall-outs of these investigations is the realization that one may have in certain metals a pairing of electrons similar to that in ^{3}He (ie) p wave pairing. Some compounds containing the heavy rare earth elements or the actinide elements, such as $CeCu_2Si_2$, UPt_3, become superconductors at very low temperatures. In these materials specific heat and magnetic susceptibility measurements indicate that the effective mass of the electrons is very high, of the order of a few hundred electron masses. These materials show unusual superconducting properties. They are called Heavy Fermion Superconductors. It is believed that the pairing of electrons in these materials is like the pairing in liquid ^{3}He .

The discovery of superfluidity in ^{3}He is a classic example of theory anticipating experiment, the development of techniques and ingenuity in experimentation going hand in hand to carry out successfully difficult experiments at very low temperatures, and the experiments in turn leading to frenetic theoretical activity which has wide repercussion in other areas of work.

Suggested Reading

- **O V Lounasmaa. Experimental Principles and Methods below 1 K. *Contemporary Physics*. Vol 15. p 353, 1974.**
- **R Nityananda. Research News. *Resonance*. Vol. 1. No. 2. p 111, 1996.**

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