Chapter 4

Scintillations in Liquid Helium

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Scintillations in liquid helium due to the passage of a charged particle were first observed by Simmons and Perkins in 1961.[1] Subsequent investigations have revealed that the intensity of the scintillations as a function of temperature is different from that for scintillators near room temperature and is almost certainly connected with the superfluid nature of liquid helium below the λ point. This temperature effect is discussed in terms of current theories of liquid helium and in the light of the present state of knowledge relating to the scintillation phenomenon.

Both α and β particles have been used to excite the liquid helium and it is significant that the effect of temperature on the scintillations depends on the particle producing the scintillation. The most thorough investigation of α-induced scintillations has been carried out by the University of Virginia group[2] who have observed scintillations down to 0.3°K. Their results are shown in Fig. 1. The scintillation intensity drops steadily from 4.2°K to the λ point (2.18°K) where it drops sharply. Below the λ point the intensity decreases by about 15% to what appears to be a constant value. The decrease from 4.2°K to 2.18°K can be explained by a change in the density of the liquid which causes a decrease in the α-path length and hence an increase in the fraction of scintillation light absorbed on the source holder. The sharp drop at the λ point is probably due to the cessation of internal boiling in the liquid. The superfluid nature of helium below the λ point gives rise to a very large thermal conductivity which prevents enough heat being localised to form a bubble. The fit to the data below the λ point produced by the authors of reference 2 is discussed later. They noted in this experiment that if all the emitted photons were collected then no decrease was observed below the λ point. These observations clearly require an explanation in terms of a mechanism which delays photon emission to a degree that depends on the temperature of the liquid.

A similar investigation of the effect of temperature on the scintillation intensity induced by β-particles gave the results shown[3] in Fig. 2. It can be seen here that the intensity remains constant with temperature apart from a discontinuity at the λ point. As the path length of electrons is about two orders of magnitude greater than that of

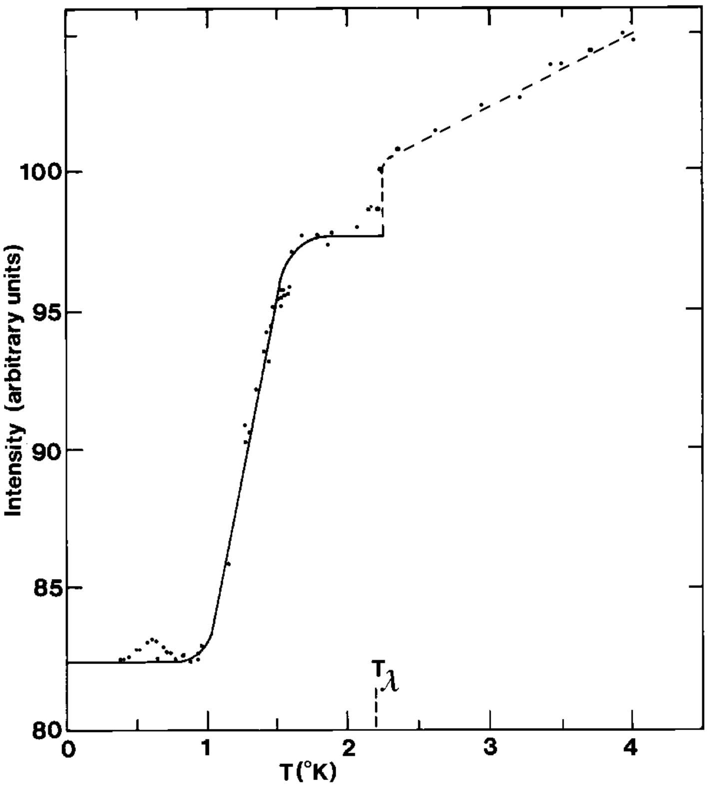
Intensity (arbitrary units)
80
85
90
95
100
0
1
2
3
4
T(°K)
T_λ

Fig. 1

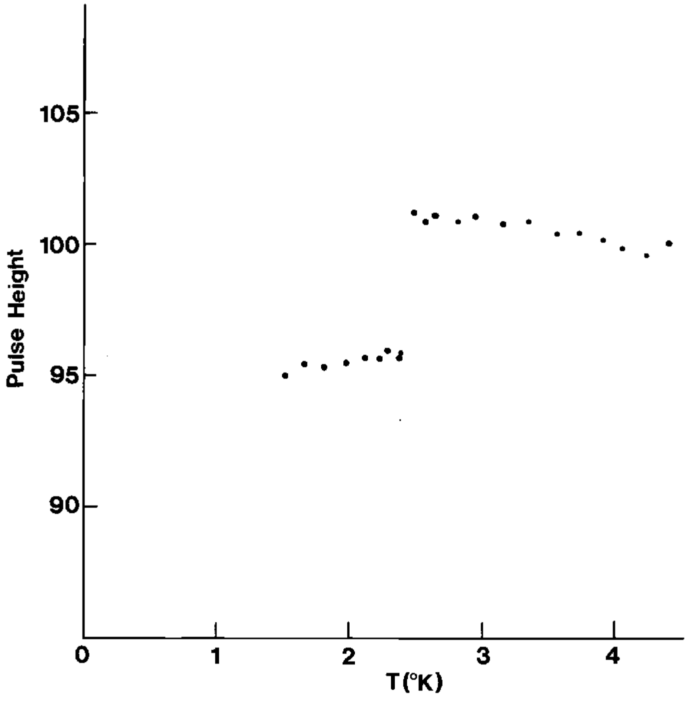
Pulse Height
90
95
100
105
0
1
2
3
4
T(°K)

Fig. 2

α-particles no detectable light absorption effects are expected. The discontinuity at the λ point is again probably due to the cessation of internal boiling.

Before attempting to discover the cause of these effects the results of two more experiments which may be relevant should be discussed.

The first experiment[4] was designed to determine the proportion of scintillation light that is due to ion recombination processes. This was carried out by applying an electric field to the region around an α source to draw off the ions and correlate the current with the decrease in scintillation intensity. The conclusion reached here is that about 60% of the light is due to recombination processes. These authors also concluded that the recombination luminescence is not temperature dependent. In the light of reference 2 this conclusion is not justified from their experiment.

The second experiment[5] was designed to determine the spectrum of light emitted from liquid helium following bombardment with electrons. A broad continuum was observed with its maximum centred on 800 Å. The emission is due to the radiative dissociation of the ground vibrational level, $A'\Sigma_u{}^+$, of He_2. The afterglow period was examined by using a pulsed electron beam but the rather qualitative results make an interpretation difficult. It is possible however, that an effect due to the increased mobility of ions as the temperature is reduced was seen in this experiment. A similar investigation[6] has indicated that the broad peak may, in fact be made up from two peaks at 825 Å and 755 Å.

A spectroscopic study in the longer wavelength region[7] has shown that the metastable state $a^3\Sigma u^+$ is populated at a rapid rate when liquid helium is excited by electrons. The significance of this will become clear.

No studies of the spectrum produced by α-induced excitation have been carried out but there is no reason to expect that the molecular processes will be different from those induced by electrons. In fact the metastable state mentioned above, the $a^3\Sigma u^+$ state, may have been observed in quite a different way by Surko and Reif.[8] Measurements on this neutral excitation indicate that below 0.5°K its lifetime could be quite long (10^{-4} s) but above this temperature the increasing number of thermal excitations in the liquid would cause its rapid decay.

Fischbach *et al.*[2] have proposed that the effect of temperature on α-induced scintillations is due to the formation of metastable states whose decay rate will depend on the density of excitations (phonons and rotons) in the helium. With this theory they have obtained a good fit to the α-data. The question still remains however, as to why a similar effect is not observed for β-induced scintillations. There is no evidence that the molecular states involved are different for the two methods of excitation. In fact the metastable state most likely to be responsible for an effect of this kind, the $a^3\Sigma u^+$ state, is known to be present in the excitation produced by electrons.

In order to investigate the effect further it will be necessary to know something about the physics of liquid helium.

If the pressure above liquid helium is reduced and the liquid is thus cooled it is found that at 2.18°K (the λ point) a phase transition takes place. This is similar to a second order phase transition but may not rigorously satisfy the requirements for one.

Below the λ point some strange effects occur which give rise to the two fluid model of liquid helium. First, if helium is passed through a narrow channel (10^{-4} cm width) it is found that up to a certain critical velocity the flow-rate is independent of the pressure-head and depends in a complicated way on the width of the channel such that the phenomenon bears no resemblance to the usual concept of viscosity. A disc rotating in liquid helium will however be subject to a frictional drag.

The explanation of these two apparently contradictory observations is that there are two components in helium below the λ point. The super-fluid component is capable of flowing through very narrow channels with little or no drag; and the normal component which is responsible for the viscous effect observed in the rotating disc experiment. Thus the total density is made up from these two components.

$$\rho = \rho_s + \rho_n$$

A theory to explain this effect is based on the assumption that the weakness of the interatomic forces in helium allow it to be treated in a similar way to a gas of bosons. While this theory must have its limitations it does show that below a certain temperature a finite number of atoms will be in a zero energy state.

Another approach to the liquid state is to regard it as a type of solid in which the atoms are free to move from their lattice sites. Landau, using this approach, showed that two types of excitation could exist in the liquid. The phonon corresponds to longitudinal motion while the roton is associated with rotational motion. These phonons and rotons which comprise the normal fluid are embedded in an unexcited background, the superfluid. Thus a calculation of the density of phonons and rotons should yield the relative proportions of the normal and superfluid components.

It has become apparent recently that another type of excitation can exist in helium below the λ point. Excitations of this kind are called vortices and are associated with the superfluid component. Vorticity is a classical idea but in the case of liquid helium it can be shown that the angular momentum of the helium atoms about the core is quantised giving the following relation between the velocity of the atom, v, and its distance from the vortex core, r.

$$v = n \frac{\hbar}{m} \frac{1}{r}$$

where n is an integer and m is the mass of the helium atom. This quantisation arises from the orderliness of the atoms in the superfluid component. The atomic wavefunctions are not perturbed by interactions with phonons and rotons and hence will be single valued for a closed trajectory. These vortices are similar to whirlpools in a stream (for example).

The significance of vorticity in the present problem is that it can trap ions. The mass and size of an ion in liquid helium is however far greater than that of the free ion. The positive ion, which is likely to be He_2^+, gives rise to a polarisation of the atoms in its vicinity. This effectively increases its mass to about 100 helium mass and its radius to about 6.4 Å. The negative ion, which is probably the electron, exists in a 'bubble' in the liquid. Its polarising effect gives it an effective mass of 100 helium masses and a radius of 14.5 Å.

The trapping of ions can be explained using hydrodynamical arguments[9] that involve the reduction in energy when an ion is substituted for a portion of the vortex. In this way lifetimes of the trapped ions have been calculated and it is now known that positive ions escape very easily from vortices at temperatures above about 0.7°K. Negative ions however can remain trapped for times of the order of minutes below 1.6°K and so escape for these can be neglected.

Once an ion is trapped in a vortex line there is less chance of it being scattered by phonons and rotons and hence it can move quickly through the liquid.

The possible connection between vorticity and the scintillation effect was first realised by Agee *et al.*[10] who carried out experiments to attempt to prove the connection. In their first experiment[10] they produced vorticity by rotating the liquid helium. No effect was observed but as the authors point out the amount of vorticity produced was so small that no effect could reasonably be expected. Their second experiment[11] was designed to produce vorticity by passing a large heat current through the liquid. The effect they observed was explained in a later publication[12] in terms of the effect on the path length of bubbles formed in the liquid by the large heat flow. Thus the connection between vorticity and the scintillation process has neither been established nor refuted.

If any connection between the two does exist it may be possible to explain why the scintillation effects produced by α-particles and electrons are different. The α-particles in the experiments mentioned above originated from a source immersed in the helium and as their path length is only 0.2 mm it is reasonable to expect the liquid to be perturbed in the region of the source. This perturbation would take the form of the production of rotons, phonons and vortices near the source. As the decay time of the vorticity would be of the order of seconds[13] some equilibrium density of vortices would be set up and this would depend on the fraction of superfluid in the liquid, ρ_s/ρ_n, and hence on the temperature.

The situation for an electron however would be quite different as its path length is much longer than that of an alpha particle of similar energy. This would result in a much lower vortex density and any interaction between the vortex and the ions would be small compared to that for ions produced in the α-particle track.

With this high density of vorticity in the α-particle track it is possible that below about 1.7°K the negative ion complex can be trapped in a vortex line and move rapidly out of the region of high ion concentration. This process will inhibit recombination and could give rise to the reduced intensity observed for α induced scintillations.

Another possibility is that the neutral metastable excitation mentioned above is trapped in a vortex and hence protected from collisions with phonons and rotons which would cause its decay. This would give rise to an excitation that would be longer lived in the region of the α source than that in an electron track. There is no direct evidence however for the trapping of these neutral excitations available at the present time.

In conclusion it would seem that there is strong evidence for a connection between the temperature dependence of the scintillation intensity and the production of vortices, although the precise mechanism is still open to speculation. Until more is known about the production of vorticity by an energetic charged particle, it is unlikely that a meaningful fit to the data will be obtained or the mechanism involved exactly understood.

It is proposed to establish if a connection between vorticity and the decrease in scintillation intensity exists by using a low energy β source in the region of the α particle tracks such that ions produced by either particle will be exposed to the same density of vorticity and hence any effect of vorticity on the scintillation intensity should be similar for excitations produced by the two particles.

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