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# Transition temperature for $^4$He liquid adsorbed in disordered media

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For pure $^4$He liquid the superfluid fraction starts having a finite value at and below the λ-transition temperature 2.176K, whereas for $^4$He in a disordered media the superfluid fraction starts having a finite value at 2.168K, a temperature that is lower compared to the temperature at which superfluidity appears in pure $^4$He. Relations for transition temperatures for both cases that are in agreement with experimental values have been obtained. Adsorption, which normally leads to a decrease in the degrees of freedom, consequently results in a release of heat, which destroys superfluidity. Hence for the liquid $^4$He flowing into a disordered medium, the transition temperature is expected to be lower.

[**Keywords:** Transition temperature, Superfluid, Disordered media]

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## 1 Introduction

In absorption, the solute molecules diffuse from the bulk of a gas phase to the bulk of a liquid phase while in adsorption molecules diffuse from the bulk of the liquid to the surface of the solid adsorbent, forming a distinct adsorbed phase. The adsorption may result from the influence of Van der Waal's forces. In that case, it is essentially a physical phenomenon. If the forces are not strong, then the adsorption can be easily reversed. In some cases additional forces may bind adsorbed molecules to the solid surface.

When molecules move from the bulk fluid to the adsorbed phase, they lose degrees of freedom and the free energy is reduced. Adsorption is always accompanied by the liberation of heat. For physical adsorption, the magnitude of the heat is of the same order as that of the heat of condensation.

It is often convenient to think of adsorption as occurring in three stages as the adsorbent concentration increases. First, a layer of molecules builds-up over the surface of the solid. This monolayer may be associated with the change in free energy, which is characteristic of the forces, which hold it. As the fluid concentration is further increased, second, third, etc. layers form from the physical adsorption. The number of layers, which can form may be limited by the size of the pores.

Though the three stages are described as taking place in sequence, in practice all three may be occurring simultaneously in different parts of the adsorbent because conditions are not uniform throughout. Generally, concentrations will be higher at the outer surface of an adsorbent pellet than in the centre; at least until equilibrium conditions have been established. The distribution of liquid molecules will depend on the pore structure and distribution of pore sizes.

Measurements[1,2] of superfluid density and heat capacity of $^4$He in a 94% porous aerogel show that, as in the case of pure $^4$He, the superfluid density vanishes at the same temperature at which one finds a maximum in the heat capacity. This property emphasizes the fact that the transition in the $^4$He/aerogel system is a genuine phase transition.

The ability of $^4$He to undergo phase transition in different media is not affected by the degree of porosity of the medium into which it flows[3,4]. But the phase transition occurs at different temperatures for the two systems, one system being pure liquid $^4$He and the other being $^4$He adsorbed into a porous medium. This implies that the degree of randomness affects the magnitude of the transition temperature and superfluid fraction, but the nature and shape of the transition remains the same. Hence the fundamental characteristics of $^4$He liquid, namely, the phase transition and the λ-transition, are independent

of the degree of randomness of the medium into which $^4$He flows and subsequently stays.

Adsorption also results in the increase in the velocity of flow and this velocity is more than the critical velocity resulting in disappearance of superfluidity, as we had shown earlier[5]. As the coverage is increased, further adsorption decreases or stops. The velocity of the collective (i.e. the $^4$He atoms flowing into the disordered medium) may be less than the critical velocity and the transition from the Bose insulator to a superfluid phase is observed.

In this manuscript, we have explained why the phase transition occurs at different temperatures for the case of pure $^4$He and $^4$He in a disordered medium like Aerogel or Vycor glass.

## 2 Theory for Disordered Media.

Let $N$ be the number of $^4$He atoms being adsorbed into the disordered medium with $n$ available sites. Since the distribution of the $n$ sites is not known, we shall assume that their distribution law may be the same as if $n$ bosons are being distributed among the available energy levels. Therefore the number of bosons to be distributed among the energy levels will be $(N+n)$ and this may result from the interaction of $N$ helium atoms and $n$ sites of the adsorbent.

Now we consider the $N$ helium atoms and $n$ sites of the adsorbent as one system and study its condensation. Then the number of particles in the lowest condensed state (Zero-Momentum State ZMS) can be written as,

$$N_O = (N+n)\left[1-\left(\frac{T}{T_O}\right)^{\frac{3}{2}}\right] \qquad \ldots(1)$$

where $T_o$ is the transition temperature for the $(N+n)$ system, and will be given by

$$T_o = \frac{T}{\left(1-\frac{N_o}{N+n}\right)^{\frac{2}{3}}} \qquad \ldots.(2)$$

If $T_c$ is the transition temperature for normal to supefluid liquid helium without the effects of adsorption, then

$$T_c = \frac{T}{\left(1-\frac{N_o}{N}\right)^{\frac{2}{3}}} \qquad \ldots(3)$$

## 3 Numerical Results

Combining Eqs (2) and (3) we get,

$$T_o = T_c \frac{\left(1-\frac{N_o}{N}\right)^{\frac{2}{3}}}{\left(1-\frac{N_o}{N+n}\right)^{\frac{2}{3}}} \qquad \ldots(4)$$

Eq. (4) gives the transition temperature $T_o$ for the superfluid$^4$He in a disordered medium in terms of the transition temperature $T_c$ for the normal to superfluid phase for pure $^4$He liquid. Since $T_c$ = 2.176K, we can calculate $T_o$. For this calculation we assume that near the transition temperature or just below it, $N_o \cong 0.8N$. If the porosity of the vycor glass or aerogel is 97%, then $n$ = 0.03N. Substituting these values in Eq. (4) we get

$$T_o = 2.023\text{K} \qquad \ldots(5)$$

If we assume $N_o \cong 0.9N$, the value of $T_o$ = 1.864K. If the porosity of the aerogel is 94%, then $n = 0.06N$, and for $N_o \cong 0.8N$, $T_o$ = 1.9K. Similarly for $N_o \cong 0.9N$ and $n = 0.06N$, $T_o$ = 1.654K.

All the values for $T_o$ are less than $T_c$ = 2.176K and quite close to the experimental value for $T_o$ which is 2.168K. Results obtained are given in Table 1. The variation of $T_o$ with n is plotted in Fig. 1. For $T_o$ = 2.168K and $n = 0.06N$, we obtain the occupancy of the ZMS level as $N_o = 0.099N$, and this value is very small as it should be. Now $F = N_o/N$, is the condensate fraction. We obtain values of $T_o$ for different $F$ as shown in Table 2. Fig. 2 gives a plot of $F$ versus $T_o$ for porosity of 94%.

Table 1 — Values of transition temperature $T_o$ for different values of $N_o$ and $n$.

| $N_o$ | Porosity (%) | $n$ ($N$) | $T_o$ |
|---|---|---|---|
| ≅ 0.6N | 90 | 0.1 | 1.999 |
| | 92 | 0.08 | 2.029 |
| | 94 | 0.06 | 2.062 |
| | 96 | 0.04 | 2.097 |
| | 97 | 0.03 | 2.116 |
| ≅ 0.7N | 90 | 0.1 | 1.915 |
| | 92 | 0.08 | 1.957 |
| | 94 | 0.06 | 2.004 |
| | 96 | 0.04 | 2.056 |
| | 97 | 0.03 | 2.084 |
| ≅ 0.8N | 90 | 0.1 | 1.77 |
| | 92 | 0.08 | 1.831 |
| | 94 | 0.06 | 1.9 |
| | 96 | 0.04 | 1.979 |
| | 97 | 0.03 | 2.023 |
| ≅ 0.9N | 90 | 0.1 | 1.461 |
| | 92 | 0.08 | 1.549 |
| | 94 | 0.06 | 1.654 |
| | 96 | 0.04 | 1.786 |
| | 97 | 0.03 | 1.864 |

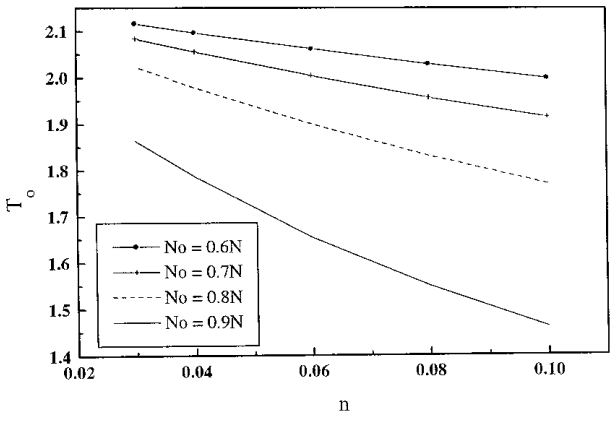


Fig. 1 — Variation of $T_o$ with $n$ for different $N_o$

## 4 Discussion

Since the denominator in Eq. (2) is bigger than the denominator in Eq. (3), $T_o < T_c$, and this means that the adsorbed helium will become superfluid at a temperature lower than $T_c$, and this is what is observed experimentally[1-4].

Table 2 — Values of transition temperature $T_o$ for different values of the condensate fraction $F$

| Condensate fraction $F$ | $T_o$ |
|---|---|
| 0.5 | 2.099 |
| 0.6 | 2.062 |
| 0.7 | 2.004 |
| 0.8 | 1.9 |
| 0.9 | 1.654 |

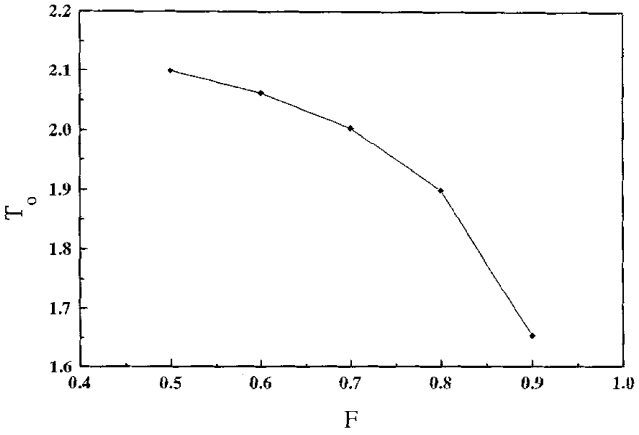


Fig. 2 — Plot of transition temperature $T_o$ against condensate fraction $F$ for $n = 0.06N$

Fig. 1 shows that the transition temperature $T_o$ for the superfluid $^4$He in a disordered medium decreases as the value of $N_o$ increases. This fact is also apparent in Fig. 2 that shows that $T_o$ decreases as $F$ increases.

It is also observed experimentally that superfluid helium, when adsorbed in a disordered medium like Vycor glass, is no longer superfluid[6,7]. Now if the disordered helium with reduced degrees of freedom has to become superfluid, it will occur at a temperature lower than $T_c$. Moreover, when the subsequent layers are not adsorbed, superfluidity reappears. The fact that superfluidity disappears when $^4$He liquid flows into a disordered medium can be verified by an experiment in which two balls of the same mass and size, but one made of normal glass and the other made of vycor glass, are allowed to move through $^4$He superfluid in long glass beakers. The ball made of normal glass will experience no friction and will move faster than the ball made of vycor glass

since it will experience friction due to disappearance of superfluidity due to adsorption of helium into it.

## References


1 Chan H W, Blum K I, Murphy S Q, Wong G K S & Reppy J D, *Phys Rev Lett*, 61 (1988) 1950.

2 Wong G K S, Crowell P A, Cho H A & Reppy J D, *Phys Rev*, B48 (1993) 3858.

3 Reppy J D, *J Low Temp Phys*, 87 (1992) 205.

4 Pekala R W & Hrubesh L W, *Proceedings of the Fourth International Symposium on Aerogel*, NorthHolland, Amsterdam (1995) 30.

5 Khanna K M & Sakwa W T, *Indian J Pure & Appl Phys*, 38 (2000) 530.

6 Valles J M, Dynes R C & Garno J P, *Phys Rev*, B40 (1989) 6680.

7 Finatello D, Gills K A, Wong A & Chan W H M, *Phys Rev Lett*, 61 (1988) 1954.