associated with the radioactivity. The $^{14}C$ resonance curve can be found by subtracting Curve 2 from Curve 1 and is shown as Curve 3 of Fig. 1, with a threshold value for resonance at about 500 kv. It

![Graph](image)

**Curve 1.** $^{14}C$ capture radiation; **Curve 2.** $^{14}C$ capture radiation (circles); **Thorium $\alpha$** radiation (crosses).

It is interesting to note that $^{14}C$ has such a large cross-section for proton capture that its yield is of the same order as that of $^{14}C$, though it is about 1 per cent abundant in natural carbon.

P. I. Dee.

Cavendish Laboratory, Cambridge. March 14.


The $\lambda$-Phenomenon of Liquid Helium and the Bose-Einstein Degeneracy

In a recent paper, Fröhlich has tried to interpret the $\lambda$-phenomenon of liquid helium as an order-disorder transition between $n$ holes and $n$ helium atoms in a body-centred cubic lattice of $2n$ places. He remarks that a body-centred cubic lattice may be considered as consisting of two shifted diamond lattices, and he assumes that below the $\lambda$-point the helium atoms prefer the places of one of the two diamond lattices. The transition is treated on the lines of the Bragg-Williams-Bethe theory as a phase transition of second order in close analogy to the transition observed with $\beta$-brass. Jones and Allen in a recent communication to *Nature* also referred to this idea. In both these papers, use is made of the fact, established by the present author, that with the absorbed abnormally great molecular volume of liquid helium (caused by the zero motion) the diamond-configuration has the lowest potential energy among all regular lattice structures.

In this note, I should like first to show that the mechanism proposed by Fröhlich cannot be maintained and then to direct attention to an entirely different interpretation of this strange phenomenon.

(1) According to Fröhlich, a diamond lattice of He atoms, when partly formed, should offer, to any other He atom, a preference for being attached at those points which belong to the same diamond lattice, that is, the binding energy at a diamond point should be greater than anywhere else. It is, however, easy to see that just the opposite, which according to Fröhlich should become less favourable for low temperatures, have an appreciably greater binding energy. It is true these holes have four nearest neighbours at exactly the same distance (3·08 A.), as the lattice points of the diamond lattice have, but in addition they possess six second neighbours at the distance of 3·57 A. which the diamond lattice points do not possess, and these second neighbours contribute considerably to the binding energy just at the hole-places (about 50 per cent to the potential energy). Therefore, actually no such co-operative phenomenon will appear as supposed by Fröhlich. The atoms would rather frequent the holes as much as the proper diamond lattice points, and this would signify that we have a body-centred lattice of $2n$ places for $n$ atoms, every place being occupied with the probability $\frac{1}{2}$ only—even at the absolute zero. In this configuration every atom has on the average four nearest neighbours at a distance of 3·08 A., as in the diamond configuration, but in addition there are here on the average three second neighbours at the distance of 3·57 A. In the diamond lattice there are twelve second neighbours but at a distance of 5·04 A., where there is almost no Van der Waals field. It might be mentioned, by the way, that a face-centred lattice of $2n$ places for $n$ atoms (on the average 6 first neighbours at a distance of 3·17 A.) has been found to have a still little lower energy than the configuration just discussed of the co-ordination number 4.

Complete numerical details cannot be given here; in any event it can be shown by such energetic discussions that a static spatial model of liquid He II of whatever regular configuration is certainly not possible. This has been previously suggested in consideration of the great zero point amplitude calculated for He$^4$. The determination of the most favourable co-ordination numbers of the first and second neighbours, however, maintains a good physical meaning: it may be considered as a rough Hartree calculus which yields the self-consistent field and the corresponding probability distribution of the atoms belonging to the minimum of energy.

(2) It seems, therefore, reasonable to imagine a model in which each He atom moves in a self-consistent periodic field formed by the other atoms. The different states of the atoms may be described by eigen functions of a similar type to the electronic eigen functions which appear in Bloch's theory of metals; and, as in Bloch's theory, the energy of the lowest states will roughly be represented by a quadratic function of the wave number $K$,

$$E = \frac{\hbar^2}{2m^*} K^2,$$

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the effective mass \( m^* \) being of the order of magnitude of the mass of the atoms. But in the present case we are obliged to apply Bose-Einstein statistics instead of Fermi statistics.

(3) In his well-known papers, Einstein has already discussed a peculiar condensation phenomenon of the 'Bose-Einstein' gas; but in the course of time the degeneracy of the Bose-Einstein gas has rather got the reputation of having only a purely imaginary existence. Thus it is perhaps not generally known that this condensation phenomenon actually represents a discontinuity of the derivative of the specific heat (phase transition of third order). In the accompanying figure the specific heat \( C_v \) of an ideal Bose-Einstein gas is represented as a function of \( T/T_0 \) where

\[
T_0 = \frac{h^2}{2\pi m^* k} \left( \frac{n}{2,615} \right)^{2/3}
\]

With \( m^* \) the mass of a He atom and with the mol. volume \( N_\lambda = 27.6 \, \text{cm}^3 \) one obtains \( T_0 = 3.09^\circ \). For \( T < T_0 \), the specific heat is given by

\[
C_v = 1.92 R \left( \frac{T}{T_0} \right)^{1/2}
\]

and for \( T > T_0 \) by

\[
C_v = \frac{3}{2} R \left( 1 + 0.231 \left( \frac{T}{T_0} \right)^{2/3} + 0.046 \left( \frac{T}{T_0} \right)^{3/2} \right)
\]

The entropy at the transition point \( T_0 \) amounts to 1.28 \( R \) independently of \( T_0 \).

(4) Though actually the \( \lambda \)-point of helium resembles rather a phase transition of second order, it seems difficult not to imagine a connexion with the condensation phenomenon of the Bose-Einstein statistics. The experimental values of the temperature of the \( \lambda \)-point (2.19°) and of its entropy (\( \approx 0.8 R \)) seem to be in favour of this conception. On the other hand, it is obvious that a model which is so far away from reality that it simplifies liquid helium to an ideal gas, cannot, for high temperatures, yield but, the value \( C_v = 3/2 R \), and also for low temperatures the ideal Bose-Einstein gas must, of course, give too great a specific heat, since it does not account for the gradual 'freezing in' of the Debye frequencies.

According to our conception the quantum states of liquid helium would have to correspond, so to speak, to both the states of the electrons and to the Debye vibrational states of the lattice in the theory of metals. It would, of course, be necessary to incorporate this feature into the theory before it can be expected to furnish quantitative insight into the properties of liquid helium.

The conception here proposed might also throw a light on the peculiar transport phenomena observed with He II (enormous conductivity of heat, extremely small viscosity, and also the strange fountain phenomenon recently discovered by Allen and Jones). A detailed discussion of these questions will be published in the Journal of Physique.

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March 5.


Cross-Sections of the Deuteron for the Electric and Magnetic Nuclear Photo-effect

The cross-section for the scattering of slow neutrons by protons leads to the assumption of a \( 1S \) level in the deuteron nucleus, with an energy of about 100,000 volts. Fermi showed that the capture of thermal neutrons by protons can be understood qualitatively as a magnetic dipole transition from a \( 1S \) level to the fundamental \( 3S \) level of the deuteron. The amount of the capture cross-section would still depend on the sign of the \( 1S \) level. For a virtual \( 1S \) level, the mean life of neutrons in water (not paraffin) should be \( \tau = 2.9 \times 10^{-24} \) sec. For a real level \( \tau = 6.3 \times 10^{-4} \) sec. The values for a virtual level are in good agreement with the recently obtained experimental values, \( \tau = 2.7 \times 10^{-4} \). The evidence obtained by the scattering of thermal neutrons by ortho- and para-hydrogen indicates as well a virtual level.

The photo-disintegration of the deuteron by \( \gamma \)-rays may take place by two transitions: the magnetic photo-effect is the inverse of the capture, a \( 3S-1S \) transition, and it leads to uniform angular distribution of the neutrons and protons. The photo-electric effect is due to a \( 3S-2P \) transition, and consequently the number of protons of neutrons emitted per unit solid angle should be proportional to the sine of the angle between the incident \( \gamma \)-ray and the photoparticles. The relative contribution of the two photo-effects depends on the sign of the \( 1S \) level. For 2-6 Mev. \( \gamma \)-rays the ratio of the number of neutrons or protons observed in the direction of the incident \( \gamma \)-ray to the number observed at 90° is expected to be

\[
\frac{I_\theta}{I_{90}} = 0.29 \quad \text{for a virtual level},
\]

\[
= 0.13 \quad \text{for a real level}.
\]

Chadwick, Feather and Bretschger observed the angular distribution of 65 photo-protons obtained by the \( \gamma \)-rays of thorium-C in a cloud chamber. The total angular distribution seems to show a contribution of the magnetic effect, which is still lower than the one expected for a real level.

I have measured the number of photo-neutrons emitted by a sphere of heavy water (diameter = 10 mm.) in the direction of the \( \gamma \)-rays and at 90° to this direction. As a source 450 mc. of mesothorium were used, the neutrons were detected by the artificial