and the new director of the Marine Biological Station at Plymouth, is secretary. The Committee met about two months ago and considered the grant of money necessary to carry out its plans; it applied for this grant to the Development Commission, which unanimously approved it. It then became possible to co-opt to the Committee two distinguished civil servants, namely, Mr. H. G. Maurice, assistant secretary of the Ministry of Agriculture and Fisheries, and Dr. E. S. Russell, chief scientific adviser on fishery matters. Needless to say, the assistance of these two members will be an invaluable addition to the powers of the Committee.

The staff to be appointed consists of Dr. Wheeler as director, a hydrologist, who will proceed to Woods Hole to be trained in the mathematical methods employed by that institute, and a director's assistant, who will be a naturalist.

It is perhaps vain to endeavour to lift the veil which shrouds the future, but it is to be remembered that the research work at Plymouth is really mainly oceanographical in character and with prophetic vision Dr. Kemp looks forward to the time when the Plymouth research will extend into mid-Atlantic and there meet in cordial co-operation with an eastward extension of the work of the Bermuda station.

Conduction of Electricity in Solids*

By Prof. N. F. Mott, F.R.S.

THE modern theory of the conduction of electricity in solids has already been applied to a large number of special problems; all that can be attempted here is a broad sketch of the fundamental ideas of the theory, together with an account of one or two of the most recent developments.

In the classical Drude theory, the conductivity of a metal depends on three quantities; namely, N , the number of free electrons per unit volume of the metal; v , their mean velocity, and l , their mean free path. Elementary considerations then give for the conductivity, σ ,

$$\sigma = \frac{1}{2}Ne^2l/mv \quad (1)$$

With certain slight modifications (in the quantum mechanical treatment v is actually the *maximum* electronic velocity) this formula may be transferred to the quantum mechanical treatment; the new theories are, however, important when we come to estimate N , l and v .

In monovalent metals we should expect that each atom would contribute just one to the total number of free electrons, so that N will be equal to the number of atoms per unit volume. For the alkali metals there is direct experimental evidence that this is the case. R. W. Wood¹ has shown that thin films of these metals deposited on glass are transparent to ultra-violet radiation below a certain wave-length, the transition from the opaque to the transparent region being rather sharp. Now as Zener² was the first to point out, one can apply to the reflection of light from a metal, provided that the absorption is neglected, the same formula as that used in the theory of

the reflection of wireless waves from the upper atmosphere, namely,

$$n^2 = 1 - Ne^2/\pi m v^2 \quad (2)$$

where n is the refractive index and v the frequency of the radiation. n is real only for short wave-lengths; for long wave-lengths the right-hand side of (2) is negative and n imaginary, so that total reflection of the radiation takes place. From the observed long wave-length limit of the transparent region, therefore, N can be determined; it turns out to be quite near to the number of atoms per unit volume for each of the alkali metals. Formula (2) cannot be applied to other metals owing to the existence of characteristic absorption bands, such as the band at 3100 Å. in silver.

As regards the mean velocity v of the metallic electrons, classical statistics, treating the electrons as a perfect gas, demand that their mean kinetic energy shall be $3kT/2$, corresponding to a velocity of 1.2×10^7 cm./sec. at room temperature. The application of Fermi-Dirac statistics, first made to this problem by Sommerfeld³, leads to the conclusion that the mean velocity has a very much greater value. The general ideas of the Fermi-Dirac statistics are most clearly seen by considering an idealized 'one-dimensional' metal, consisting of electrons free to move up and down a line of length L . We neglect first the interaction of the electrons, both with one another and with the atoms of the lattice. Now the velocity v of an electron is connected with its de Broglie wave-length λ by the well-known formula

$$\lambda = h/mv.$$

For an electron confined within a metal of length L , the de Broglie wave associated with the electron

* Substance of a course of lectures delivered at the Royal Institution on January 19, 26 and February 2.

must have the form of a standing wave. The wave-length must therefore have one of the values

$$\lambda = 2L/n, \quad (3)$$

where n is an integer, and the energy of an electron will be

$$E = \frac{1}{2}mv^2 = n^2h^2/8mL^2, \quad (4)$$

For values of L of the order of a centimetre, these values of the energy will be so close together as to be practically indistinguishable, so that to all intents and purposes the energy can take a continuous series of values. Nevertheless, our quantization of the energy is of importance for the following reason. According to the Pauli exclusion principle, not more than *two* electrons can be in any one quantized state. At the absolute zero of temperature, all the electrons will be in

compared with $E_{\max}$. up to the melting point, the change in the energy distribution of the electron is insignificant.

Experimental evidence that the conduction electrons have a series of energies lying in a range of several electron volts is provided by observations of the soft X-ray emission bands, of which those of O'Bryan and Skinner⁴ (Fig. 1) are typical. The X-ray quantum is emitted through one of the conduction electrons making a transition to the K - or L -level; since the energies of the conduction electrons are distributed in a wide range, an emission band instead of an emission line is observed. The sharp cut-off at the high frequency limit will be noticed.

THE MEAN FREE PATH

Using values of N and v obtained in these ways, one can, by using formula (1), deduce the mean free path from the *observed* electrical conductivity; the following are some values for silver:

Temperature (degrees Kelvin)	273	76	4.2
Conductivity (ohm-cm. $\times 10^3$) observed	6.8	36	(960) ⁵
l (cm. $\times 10^{-4}$)	1.14	6	(163)

Fig. 1.

K AND L_{III} -EMISSION BANDS FOR LIGHT METALS; THE WAVE-LENGTHS ARE SHOWN IN ELECTRON VOLTS, ACCORDING TO THE EQUATION $eV = hc/\lambda$.

states of as low energy as possible; thus according to formula (3) two electrons only will have the lowest energy, corresponding to a wave-length $2L$. If the total number of electrons is N , the electrons will have all wave-lengths from $2L$ down to a minimum $4L/N$. With one electron per atom, this is equal to four times the interatomic distance a . The velocities thus have all values from practically zero up to a maximum $h/4ma$; with $a = 2 \times 10^{-8}$ cm. this corresponds to $v = 9 \times 10^8$ cm./sec., or an energy of 2.3 electron volts. Similar results are obtained when the motion of the electrons in three dimensions is taken into consideration, the maximum energy being

$$E_{\max.} = \frac{h^2}{8m} \left(\frac{3N}{\pi\Omega} \right)^{2/3} \quad (5)$$

where Ω is the volume of the metal.

At finite temperatures a few of the electrons will be excited into higher states (these electrons give a small contribution to the specific heat, linear in the temperature), but since kT is small

The very long mean free paths, far greater than the interatomic distance, will be noticed. These values, quite inexplicable according to the classical theory, are easily understood for a crystalline metal in terms of wave mechanics, as follows:

The model which we have used to derive the energies of the conduction electrons is highly artificial, neglecting as it does the interaction of the electrons with each other and with the ions. To remedy this, in all recent work each electron is treated as moving in the field of all the positive ions together with the *average* field of the electrons. The approximation is exactly that used by Hartree⁶ in his calculation of the self-consistent fields in atoms. Thus, in a crystalline metal, if we use this model, we must think of the electrons as moving in a periodic field having the period of the lattice. In order to calculate the distance that an electron will move without being scattered we must apply the methods of wave mechanics, and picture a plane de Broglie wave moving through the metal with wave-length rather greater than the interatomic distance. We then obtain a result entirely at variance with classical ideas. Each metal ion scatters a wavelet, but since the metal is crystalline these wavelets build up a new plane wave front. There is therefore no resultant scattering of the wave. Hence, in a perfectly crystalline metal in which the ions are at rest in their positions of equilibrium, there is no scattering of the electrons and hence no resistance whatever.

Resistance in a pure metal arises from the fact that at any finite temperature the ions are not at rest in their positions of equilibrium, but are vibrating about them. The period of the atomic vibrations ($\sim 10^{-12}$ sec.) is very large compared with that of the de Broglie waves (10^{-16} sec.); the wave scattered by any displaced atom will therefore be slightly out of phase with that scattered by any other. A certain amount of incoherent scattering will take place. This incoherent scattering, and hence the resistance, will increase as the temperature is raised. Detailed calculations give good agreement with experiment both at high and low temperatures; though of course the model has proved totally unable to give an explanation of supraconductivity.

Although the periodic field of the crystal lattice does not lead to a finite mean free path, it has other effects; for example, the effective mass of an electron in a metal is found to be not exactly equal to that of a free electron. The further developments of the model, such as the explanation of the existence of insulators and semi-conductors by Wilson⁷, cannot be discussed here.

Some attempts have recently been made to demonstrate these long mean free paths experimentally by measuring the resistivities of very thin wires⁸, or of thin films deposited on glass⁹; obviously the mean free path cannot be greater than the thickness of the wire or film along which the current is flowing. We therefore expect the resistivity to increase for very small thicknesses. Such effects are in fact observed.

RESISTANCE OF ALLOYS

As first pointed out by Nordheim¹⁰, the large increase in the resistance of metals due to foreign atoms in solid solution finds a ready explanation in terms of the theory. A dissolved atom taking the place of one of the atoms of the lattice will not in general scatter an electron wave of the same amplitude as the solvent atoms. If the amplitudes of the waves are denoted by A and B , the increase in the resistance will clearly be proportional to $(A - B)^2$. Since the scattering power of an atom depends on the field within it, we should expect the resistance to increase with the horizontal distance between the two elements in the periodic table. This was first pointed out as an empirical rule by Norbury¹¹. More recently, Linde¹² has shown that the increase in the resistivity of copper or silver or gold due to one atomic per cent of any metal to the right of them in the periodic table is proportional to $(z - 1)^2$, where z is the number of electrons outside a closed shell (2 for zinc, 3 for gallium, 4 for germanium, 5 for arsenic). Such a simple rule is obviously susceptible of explanation in terms of this theory¹³.

The explanation of the resistance given here does *not* depend on the strained state of the metal round the impurity atom. In general, the surrounding atoms will certainly be displaced from their mean positions, and this will give rise to an increase in the resistance, but the effect of this is probably small compared with the effect considered above.

The theory of the conduction of electricity in alloys is certainly capable of further development. One phenomenon to which it may possibly be applied is that of age hardening. This is generally believed to be due to the precipitation of very small crystals of solute metal from a supersaturated solid solution⁴. The resistance of an alloy during age hardening usually shows an initial increase, followed by a marked fall. The initial increase has been ascribed to strain, but this does not seem to be the only possible explanation. Since the wave-length of the electron waves is rather larger than the diameter of the solute atoms, one would expect the initial stages of the precipitation, in which small crystals of 20-30 atoms are formed, to increase the resistance. It is only when the crystals become large compared with the wave-length that any decrease in the resistance is to be expected.

If this explanation be correct, the phenomenon has a certain analogy with the passage of light through moist air. The water vapour molecules, being smaller than the wave-length of light, do not scatter it much. If, however, they condense into small drops of size comparable with the wave-length, a more or less opaque fog is formed. If they condense still further into rain drops, the atmosphere becomes again transparent.

CONDUCTION IN INSULATORS

Some light on the very complicated phenomena of photoconductivity has been shed by the recent theoretical researches of Landau¹⁵, Frenkel¹⁶ and others¹⁷. Their ideas will be illustrated most clearly by considering the alkali halide crystals, which have been investigated in great detail from the experimental side by Pohl and his school. The alkali halide crystals are built up of positive metal ions and negative halogen ions. The electrons in both these ions have the rare gas configuration, and do not make any contribution to the conductivity. If, however, an electron is added to one of the metal ions, one would expect that it would be able to jump quite easily from one metal ion to the next, and theoretical calculations¹⁸ confirm this; such electrons ought to have a mobility of the same order of magnitude as the electrons in a metal.

If, however, a halide crystal is illuminated with ultra-violet light, a new absorption band is formed

in the visible (the *F*-band), the rock salt thereby acquiring a yellow and silvina (potassium chloride) a blue colour. The *F*-band is generally recognized to be due to electrons attached to metal ions, and can be produced in other ways; for example, by heating in alkali vapour, so that positive ions and electrons diffuse into the crystal. The coloured crystal is, however, an insulator at low temperatures, and shows photoconductivity only when illuminated with wave-lengths in the *F*-band. It is therefore often stated that these electrons are located at internal surfaces or cracks, which might be expected to play some role in rendering the electron immobile¹⁹. The work of Landau shows, however, that this hypothesis is unnecessary; this will now be explained.

The large dielectric constant of polar crystals is partly due to an actual displacement of the positive and negative ions from their mean positions by an external field. The time taken to polarize the medium is of the order 10^{-12} sec., and since the electron jumps from atom to atom in a time comparable with 10^{-15} sec., it will not in general have time to polarize the medium as it goes. If, however, the electron remains in the neighbourhood of one metal ion for a sufficiently long time, it will polarize the surrounding medium, the positive ions moving into new positions of equilibrium nearer to, and negative ions farther from, the electron. The electrostatic field round the electron falls from $-e/r^2$ to $-e/\kappa r^2$, where κ is the dielectric constant. Therefore, in the field of the polarized medium, the potential energy of the electron is

$$V(r) = -\left(1 - \frac{1}{\kappa}\right) \frac{e^2}{r}$$

In the 'potential hole' thus created, the electron will have a series of bound stationary states, similar to those for an electron in the field of a

hydrogen atom, for which $V(r)$ is $-e^2/r$. The absorption band (*F*-band) corresponds to the removal of the electron from this potential hole and is thus analogous to the ionization of a hydrogen atom; the electron is then free to move through the crystal, and the potential hole disappears.

These trapped electrons have, according to Frenkel¹⁸, a certain very small mobility, since the electron can jump from ion to ion and the surrounding ions move into displaced positions at the same time. Since by a well-known theorem of electrostatics a charged particle in a dielectric medium is repelled by any boundary of or hole in the medium, the most stable positions for trapped electrons will be as far as possible from any internal crack!

The theory of trapped electrons outlined here is quite general and can be applied to any polar solid; in future developments of the theories of the conduction of electricity in semi-conductors and insulators, it may prove of considerable importance.

¹ *Phys. Rev.*, **44**, 353 (1933).

² *NATURE*, **132**, 968 (1933).

³ *Z. Phys.*, **47**, 1 (1928).

⁴ *Phys. Rev.*, **45**, 370 (1934).

⁵ Meissner, *Z. Phys.*, **38**, 647 (1926). The value obtained depends mainly on the residual resistance.

⁶ *Proc. Camb. Phil. Soc.*, **24**, 89 (1928).

⁷ *Proc. Roy. Soc., A*, **133**, 458 (1931).

⁸ Eucken and Förster, *Göttingen Nachrichten, Math. Phys. Klasse* **1**, 43 (1934).

⁹ Lovell, *Proc. Roy. Soc., A*, **137**, 311 (1936).

¹⁰ *Ann. Phys.*, **9**, 641 (1931).

¹¹ *Trans. Far. Soc.*, **18**, 570 (1921).

¹² *Ann. Phys.*, **15**, 219 (1932).

¹³ Mott, *Proc. Camb. Phil. Soc.*, **32**, 281 (1936); Mott and Jones, "The Theory of the Properties of Metals and Alloys", 292 (Oxford, 1936).

¹⁴ Gayler, *J. Inst. Metals*, **4**, 55 (1937).

¹⁵ *Sov. Phys.*, **3**, 664 (1933).

¹⁶ *Sov. Phys.*, **9**, 158 (1936).

¹⁷ Blochinzev, *Sov. Phys.*, **10**, 431 (1937); von Hippel, *Z. Phys.*, **101**, 680 (1936).

¹⁸ Gurney and Mott, to be published.

¹⁹ Tamm, *Sov. Phys.*, **1**, 733 (1932).

Obituary Notices

Prof. A. R. Ling

ARTHUR ROBERT LING, whose death took place on May 14, owed his career as a research chemist to the inspiration of Prof. H. E. Armstrong, under whom he studied at the Finsbury Technical College in 1883 and thereabouts. He was encouraged to work on halogen derivatives of the nitrophenols, and he afterwards extended his investigations to similar derivatives of quinones, and in this began his long association with Julian Baker. The latter was continued when, as chemist to the London Beetroot Sugar Association, he carried out his routine work in the daytime, and in the evenings and at week-ends prosecuted with Baker his extensive investigations on the constitution of starch.

It is in the fields of starch and sugar chemistry and as an authority on brewing that Prof. Ling was best known. Ling's work during the decades preceding and succeeding the beginning of the century is recognized as being of sound character, and the interpretation of many of his results in the light of present-day knowledge and concepts adds materially to the known chemistry of starch and the mechanism of its degradation by diastase. It had among other things, the important effect of preventing a hasty acceptance of erroneous views which were widely held at the beginning of the century.

After leaving the Beetroot Sugar Association, Ling practised as a consulting chemist, his special fields being the brewing and sugar industries. From 1895,