

**OXFORD CAMBRIDGE AND RSA EXAMINATIONS  
ADVANCED GCE**

**G495**

**PHYSICS B (ADVANCING PHYSICS)**

**Unit G495: Field and Particle Pictures**

**INSERT**

**FRIDAY 18 JUNE 2010: Morning**

**DURATION: 2 hours**

**SUITABLE FOR VISUALLY IMPAIRED CANDIDATES**

**INSTRUCTIONS TO CANDIDATES**

- **This insert contains the article required to answer the questions in Section C.**

**INSTRUCTION TO EXAMS OFFICER/INVIGILATOR**

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# Developing a Model for Electrical Current

Electrical current can be understood as the flow of charged particles. This model has proven to be very robust and successful for well over a century now, but it took many years to develop. We owe the success of the model to the contributions of various physicists from across the world whose independent work in different areas of science was brought together into one theory of electrical conduction. 5

## AMBERISATION AND CHARGE 10

It was known in ancient Greece that rubbed amber attracted small objects, like hair and dust. The phenomenon was given a name by the Englishman Francis Gilbert in 1600, who called it *amberisation*, and then *electrification* from *electron*, the Greek word for amber. Further investigations by the French scientist Charles Du Fay led to the idea that there were two types of electrification which, towards the middle of the 18th century, the American Benjamin Franklin called 'positive' and 'negative'. Franklin also asserted that a glass rod rubbed with a silk cloth becomes as positive as the cloth becomes negative. 15 20

This idea of the rod losing as much charge as the cloth gains was experimentally proven in London by Michael Faraday in 1837. Meanwhile, a theory had emerged that in matter there existed two fluids where a positively charged body had an excess of positive fluid, whilst a negatively charged body had an excess of negative fluid. Franklin himself, though, believed in the existence of an electrical particle, even though this was at odds with the fluid theory. 25 30

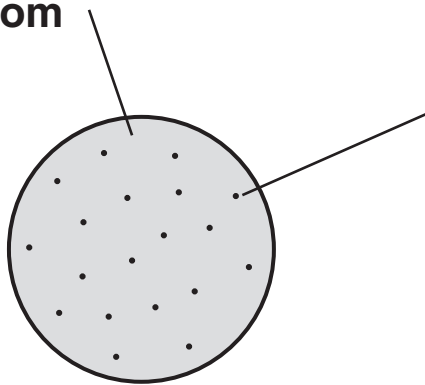
**Faraday's experiments on electrolysis provided evidence for an atomic hypothesis for electricity. The idea of charges as separate entities became established but physicists were still reluctant to believe in a model of charge flow in solid conductors.** 35

## **THE ELECTRON**

**In 1871, in Germany, Wilhelm Weber explained several electrical phenomena, including thermoelectricity, by assuming that there were two types of *electrical atom*, one of which was more mobile than the other. Furthermore, the Irish physicist G Johnstone Stoney, in a lecture given in 1874, described a clear picture of a particle theory of electricity and even went on to obtain a value of the elementary electrical charge. It was he, indeed, in 1891, who first used the word electron as a name for the basic unit of electricity, but the notion of electrical current in solids as a flow of charged particles had still not evolved.** 40  
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**This changed, however, in 1897 when J J Thomson demonstrated that cathode rays are streams of tiny, electrical particles – the electrons of Stoney's theory. This inevitably led to new theories on the nature of matter itself, including Thomson's own 'Plum Pudding Model' and, later, Rutherford's nuclear atom. However, it also opened the door for new models of electrical conduction.** 55

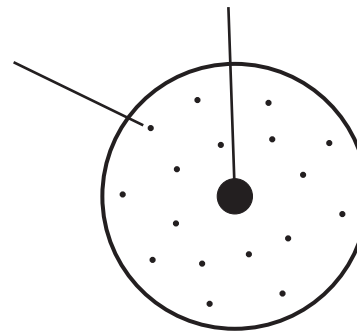
all of the positive charge evenly spread throughout the atom



Thomson's model

all of the positive charge and most of the mass concentrated in one place

electron



Rutherford's model

**FIG. 1** Early models of the atom

## **DRUDE'S THEORY AND BASIC CONDUCTION**

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Sure enough, in 1900, a theory for electrical conduction in metals was proposed by the German Paul Drude. He based the theory on the idea that the metal consisted of a sea of mobile electrons in a lattice of positive ions. It was the movement of these electrons which constituted the electric current in the metal and the large numbers of mobile electrons in metals explained why metals were such good conductors. Consider copper, for example: knowing the density of copper and the mass of a copper atom and allowing for one free electron per atom, it can be shown that the number of free electrons per cubic metre (the number density,  $N$ ) is of the order of  $10^{29} \text{ m}^{-3}$ .

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The success of Drude's model was to be found in the explanations it offered of well-known properties of metals, electrical and otherwise. A useful quantity to consider in this context is the current density,  $j$ , which is the current per unit cross-sectional area. For electrons moving with a speed,  $u$ , through the lattice, it can be shown that

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$$j = N e u \quad \text{EQUATION 1}$$

where  $N$  is the number density of the electrons and  $e$  the charge on an electron. Copper has a conductivity of about  $6 \times 10^7 \text{ S m}^{-1}$ . So, for instance, a copper wire 1.0 metre long, with a circular cross-section of  $0.5 \text{ mm}^2$  and a p.d. of 1.5V across it, would have in it a current density of nearly  $10^8 \text{ A m}^{-2}$ , i.e. a current of almost 50 A. Even this huge current implies a drift velocity of only a few  $\text{mm s}^{-1}$ . This is at odds with what might be expected, suggesting that the underlying picture behind the model is far from complete.

**85****90**

Inspired by the kinetic theory for ideal gases, developed by Lord Kelvin and others, Drude assumed that electrons are free to move around the whole volume of the metal, like molecules of a gas in a container. In the absence of any electric field and at non-zero temperatures, the electrons would move around in random directions, colliding from time to time with defects in the lattice.

**95****100**

In this way, it is possible to estimate the average 'thermal' speed ,  $v$ , using

$$\frac{1}{2} mv^2 = \frac{3}{2} kT \quad \text{EQUATION 2} \quad 105$$

in which  $m$  is the mass of the electron,  $k$  is the Boltzmann constant and  $T$  is the absolute temperature.

For the electrons in a copper wire at room temperature, this suggests an average thermal (random) speed of around  $10^5 \text{ m s}^{-1}$ . This is much larger than the speed of, say, a nitrogen molecule in air at the same temperature, but, more significantly, considerably larger than the drift velocity calculated earlier. 110 115

To appreciate the reason for the enormous difference between the drift and thermal speeds of the electron, a closer look at the motion of the electron through the lattice is required.

## DRUDE RELAXATION 120

Placing a potential difference across a metal wire produces an electric field within it. Being charged, the electrons experience a force and accelerate in a direction parallel to the field. However, they do not accelerate indefinitely, for, as already noted, from time to time they are scattered by defects in the lattice. 125

Drude's theory considered the momentum gained by an electron accelerating for a time  $\tau$  (the relaxation time) before being scattered; the theory confirmed Ohm's Law, among other things, which made it very convincing. 130

## DERIVATION OF DRUDE THEORY

An electron in an electric field  $E$  experiences a force  $eE$  and accelerates in a direction parallel to the field. Accelerating for a time  $\tau$  (the *relaxation time*) before being scattered, the electron gains momentum  $p$  given by:

$$p = eE\tau \quad \text{EQUATION 3}$$

and so a drift velocity of

$$u = \frac{eE\tau}{m} \quad \text{EQUATION 4}$$

Combining Equation 4 with Equation 1 (line 83 in the main text), gives

$$j = \frac{Ne^2E\tau}{m} \quad \text{EQUATION 5}$$

or

$$j = \sigma E \quad \text{EQUATION 6}$$

where  $\sigma$  is the electrical conductivity, and is given by

$$\sigma = \frac{Ne^2\tau}{m} \quad \text{EQUATION 7}$$

Equation 6 is, in fact, an alternative statement of Ohm's Law.

## FURTHER IMPLICATIONS OF THE DRUDE MODEL

Substituting data quoted earlier in the passage into Equation 7,  $\tau$  is shown to be about  $10^{-14}$  s. The drift speed of the electron,  $u$ , typically  $10^{-3}$  m s<sup>-1</sup>, is superimposed on its much higher, random thermal speed,  $10^5$  m s<sup>-1</sup>. This is a similar notion to that of considering the speed of an air particle in a steady breeze, for which the wind speed is much less than the particle's thermal speed. It also becomes apparent that in time  $\tau$  an electron can travel a considerable distance on the atomic scale before being scattered.

Equation 7, shows that the conductivity is proportional to  $N$  and  $\tau$ . In a given metal,  $N$  will be constant, but  $\tau$  can vary. For temperatures greater than about 5 K, the conductivity (and therefore  $\tau$ ) decreases as the absolute temperature increases. This is because the electrons are scattered by concentrations of positive charge produced by lattice vibrations and the lower the temperature, the less the lattice vibrates so the less likely it is that a scattering concentration will occur. Below 5 K scattering by static defects, such as impurity atoms and grain boundaries, starts to dominate. This scattering, and therefore the conductivity, is independent of temperature, though it does depend on the sample.



## THE DRUDE MODEL AND THE ABSORPTION OF LIGHT

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One interesting effect related to the Drude relaxation time is the reflection or absorption of light. If electromagnetic radiation of frequency  $f$  is shone on a metal surface, what happens to it (whether it is reflected or absorbed) depends upon how the value of  $f$  compares with that of  $1/\tau$ . If  $f$  is much less than  $1/\tau$ , then an electron, being oscillated by the electric field of the electromagnetic wave, can make many energy-losing collisions in one cycle of the wave and so the radiation is absorbed. If  $f$  is much greater than  $1/\tau$ , then many cycles of radiation occur before energy is lost. So, the metal will be transparent to high frequency radiation, which for a value of  $\tau$  of  $10^{-14}$  s equates to ultraviolet and x-rays, but opaque to lower frequencies such as visible light, infrared and radio waves.

Drude's relaxation time can be used to account for the opacity and reflectivity of metals.

## SUPERCONDUCTIVITY

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In 1911, not long after Drude developed his model, the Dutch physicist Kamerlingh Onnes investigated how the electrical resistivity of the metal mercury was affected by temperature. When it was cooled to 4.2 K, using liquid helium, he found that the resistivity disappeared altogether. This implied an infinite value of  $\tau$ : electrons passing through the lattice without experiencing any scattering at all. Onnes had discovered what is known today as superconductivity and in order to explain this, physicists needed to radically refine the Drude model and looked to a new branch of physics emerging at the time: quantum theory.

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And that's another story.

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