# ERRATUM NOTICE

**ADVANCED GCE**

## PHYSICS B (ADVANCING PHYSICS) G495

Unit G495: Field and Particle Pictures **June 2010**

### FOR THE IMMEDIATE ATTENTION OF THE EXAMINATIONS OFFICER AND THE HEAD OF SCIENCE DEPARTMENT

**TO BE OPENED IMMEDIATELY**

**This erratum concerns G495 Advance Notice Article,** which is published on the OCR website (www.ocr.org.uk).

Please note the following clarifications regarding the already released **ADVANCE NOTICE ARTICLE** and **bring them to the attention of all candidates.**

Please turn to **Page 4, Box 1:**

**Line 4** currently reads:

$p = eEt$ **Equation 3**

This should read:
$p = eE\tau$ **Equation 3**

**Line 7** currently reads:

'Combining (ii) with Equation 1 (line 60 in the main text), gives….'

This should read:

'Combining Equation 4 with Equation 1 (line 47 in the main text), gives….'

**Please ensure that all candidates amend their copy of the Advance Notice Article. A corrected version of the Advance Notice Article will be issued as an insert to the question paper on the day of the exam.**

Any enquiry about this notice should be referred to the Customer Contact Centre on 01223 553 998 or general.qualifications@ocr.org.uk

Ref: JUN10/erratum

THIS IS A NEW SPECIFICATION

RECOGNISING ACHIEVEMENT

ADVANCED GCE

# PHYSICS B (ADVANCING PHYSICS) G495

Unit G495: Field and Particle Pictures

ADVANCE NOTICE ARTICLE

**To be opened on receipt**

**Friday 18 June 2010**
**Morning**

**Duration:** 2 hours

*OCE/15571*

## INSTRUCTIONS TO CANDIDATES

- Take the article away and read through it carefully. Spend some time looking up any technical terms or phrases you do not understand. You are not required to research further the particular topic described in the article.
- For the examination in June 2010 you will be given a fresh copy of this article, together with a question paper. You will not be able to take your original copy into the examination with you.
- The values of standard physical constants will be given in the Advancing Physics Data, Formulae and Relationships booklet. Any additional data required are given in the appropriate question.

## INFORMATION FOR CANDIDATES

- Questions in Section C of paper G495 Field and Particle Pictures will refer to this Advance Notice material and may give additional data related to it.
- Section C will be worth about 40 marks.
- Sections A and B of paper G495 will not be based on the material in the Advance Notice.
- There will be 2 marks for quality of written communication (QWC) assessed in Section C.
- This document consists of **8** pages. Any blank pages are indicated.

# 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.

## Amberisation and Charge

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.

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. 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.

## 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.

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.

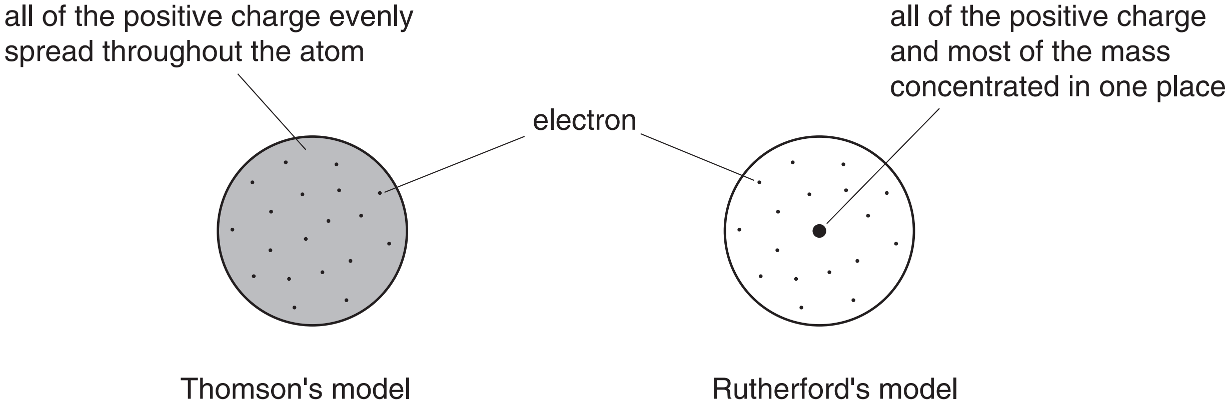

**Fig. 1** Early models of the atom

## Drude's Theory and basic conduction

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 $10^{29}$ $m^{-3}$.

**Fig. 2** The German physicist Paul Drude

## Electrons and the Ideal Gas law

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

$$j = N e u \qquad \textbf{Equation 1}$$

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

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.

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

$$½\, mv^2 = 3/2\, kT \qquad \textbf{Equation 2}$$

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 $10^5$ 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.

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

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. 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 (see Box 1).

**Box 1**

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:

$$p = eEt \qquad \textbf{Equation 3}$$

and so a drift velocity of

$$u = \frac{eE\tau}{m} \qquad \textbf{Equation 4}$$

Combining (ii) with Equation1 (line 60 in the main text), gives

$$j = \frac{Ne^2E\tau}{m} \qquad \textbf{Equation 5}$$

or

$$j = \sigma E \qquad \textbf{Equation 6}$$

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

$$\sigma = \frac{Ne^2\tau}{m} \qquad \textbf{Equation 7}$$

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, Box 1, $\tau$ is shown to be about $10^{-14}$ s. The drift speed of the electron, $u$, typically $10^{-3}\,\mathrm{m\,s^{-1}}$, is superimposed on its much higher, random thermal speed, $10^{5}\,\mathrm{m\,s^{-1}}$. 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, Box 1, 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

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.

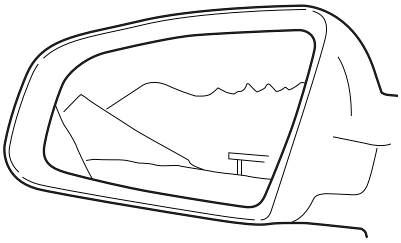

Fig. 3

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

### Superconductivity

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.

And that's another story.

**END OF ARTICLE**

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