Physics and Electronics in Physical Medicine

by

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LONDON: G. BELL & SONS, LTD

First published 1959

Printed in Great Britain by
William Clowes and Sons Ltd, London and Beccles

To my wife

FOREWORD

By the time they qualify medical students have forgotten much of the detail of the chemistry, physics and mathematics which they learnt at the beginning of their long training. To a somewhat lesser extent the same applies to the other basic sciences of anatomy, physiology and pharmacology. However, the principles and their application to clinical work are remembered and the loss of detail is of little practical importance until reading for higher degrees or diplomas. Then relevant aspects of the basic sciences must be revised in preparation for acquiring additional and specialised knowledge. But it is not only a question of revision because when postgraduate students turn back to the basic sciences after a lapse of years they find such advances in knowledge have taken place that there is much fresh learning to be acquired as well as simple revision.

Postgraduate students are anxious to press on with their specialised studies and do not want to go back to the pre-clinical schools for a longer time nor to revise more detail than is strictly necessary. Yet adequate knowledge of the basic sciences is essential for sound clinical progress and this aspect must not be shirked. Unfortunately, not all teachers of the basic sciences seem to understand the need of postgraduate students for tuition designed to meet the practical requirements of a special field and, instead, expect a revival of interest in the wider and more academic aspects of their subjects, even to the extent of setting questions in the primary examinations for higher degrees and diplomas similar to those appearing in the pre-clinical or early professional examinations.

Dr. Nightingale has taught physics to undergraduate students of medicine, to students of physiotherapy and radiography and to postgraduate students of physical medicine and radiology. He understands the special needs and difficulties of undergraduate and postgraduate students. In particular, he has sympathy with students who find the subject difficult and he takes great pains to produce a text which is lucid, well illustrated by examples and diagrams, succinct yet in sufficient detail and a pleasure to read. Similar books dealing with the other basic sciences would be of inestimable value to clinicians trying to keep abreast of scientific progress in medicine as well as to postgraduate students. There are some such books but not enough.

This text book is intended primarily for those preparing for Part I of the Diploma in Physical Medicine. Its publication is timely because by a recent change in the Regulations attendance at a formal course of instruction is no longer obligatory. Candidates will find that the book provides the knowledge of basic and applied physics which will be required of them. Moreover, those practising physical medicine and advanced students of physiotherapy will find the physical basis of present practice, including electromyography, explained by a physicist who sets out to make physics interesting and of practical value to clinicians.

July, 1959 F. S. COOKSEY

ACKNOWLEDGEMENTS

I should like to thank Dr. P. Bauwens of St. Thomas's Hospital, London, for encouraging me to undertake the preparation of this book, and for advice on its form and scope. It is a pleasure to acknowledge the help given by Professor G. Stead, Professor C. B. Allsopp, and my colleagues in the Physics Department at Guy's Hospital Medical School, in many stimulating discussions on the best way to explain physics and electronics to doctors and physiotherapists. I am very grateful to my father, E. Nightingale, whose wide experience as an author of text-books has been invaluable, and who has borne the brunt of the proof reading. I owe a special debt to several 'generations' of my postgraduate diploma students who have made many useful and frank suggestions over the years about the improvement of the course.

In writing a text book of this sort the author must consult many specialised books and scientific papers, and acknowledgement is made to these in the Bibliography. The anatomical drawings in Figures 2,*8*, 2,*9*, 2,*10* and 2,*13* are adapted from the late Professor Whillis's *Elementary Anatomy and Physiology* (fourth edition revised and edited by Professor R. Warwick). My thanks are due to the publishers, Messrs. J. and A. Churchill Ltd., and to Professor Warwick for permission to use these drawings, and also to the Medical Illustration Department of Guy's Hospital Medical School who re-drew these figures and helped with a number of other diagrams in Chapter 2.

The following firms have been most helpful in providing detailed information about their equipment: Philips Electrical Ltd., Multitone Electric Co. Ltd., Hanovia Ltd., Stanley Cox Ltd., General Radiological Ltd., Sierex Ltd., Medical Supply Association Ltd. I should like to thank Mr. J. Webb of the Electrical Appliances Division of Philips for arranging a gift of Philips ultraviolet fluorescent tubes. The spectrum of the therapeutic type is given in the Frontispiece, and I am indebted to Mr. K. Twinn for his skill and patience in preparing this plate. I am very grateful to Miss J. Freegard for secretarial assistance throughout the preparation of the book.

Finally, a special word of thanks is due to Dr. F. S. Cooksey of King's College Hospital for his kindness in writing the Foreword, and for a number of valuable discussions during his visits to Guy's in his capacity as an examiner for the Diploma in Physical Medicine.

PREFACE

I have written this book because I felt there was a need for a fairly elementary but accurate account of the principles underlying the many physical methods of treatment and diagnosis employed in physical medicine. This need has come to my notice in the form of questions put to me over a period of many years by medical students, physicians, and neurologists, as well as physiotherapists and specialists in physical medicine.

My own interest in the subject stems partly from my work on a number of problems on which I have been asked from time to time to give advice in my capacity as an honorary adviser in physics to Guy's Hospital, and partly from two teaching courses in which I have taken part for many years. The first is for physiotherapists starting their training for the Preliminary Examination of the Chartered Society, and the second is for postgraduate students reading for the Diploma in Physical Medicine of the Royal College of Physicians and Surgeons.

These two courses have guided the arrangement of the book. The fundamental principles and an account of the more commonly used physical agents are given in Parts I and II, while the more difficult topics such as electromyography and the less commonly used methods like ultrasonic therapy are covered in Part III.* However, I have not by any means confined the subject matter to the syllabuses of these courses, but have taken certain topics further where I have felt that this is justified by their interest and importance, or where an accurate account cannot be given in very simple terms. I hope therefore that the book will be of value to all who are interested in medical physics. First year medical students in particular will find here much that is relevant to their physics course.

The book is written by a physicist and is not a clinical textbook. I have given details of clinical techniques where these are necessary for an understanding of the principles and where they affect the design of equipment, but I have tried to avoid giving opinions on the clinical value of the different methods of treatment. Such opinions can only be given by clinicians. However, I am convinced that the correct evaluation and improvement of methods both old and new depend upon a clear understanding of the physical as well as the medical problems, and I hope that in this way the book will make a useful contribution to the science of physical medicine. A.N.

* This Part also contains some notes on mathematical techniques which are used throughout the book, and which should be read first by those whose knowledge of mathematics is small or 'rusty'.

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PART II: APPLICATIONS

PART III: APPENDICES

PART 1: FUNDAMENTALS

CHAPTER 1

THE STRUCTURE OF MATTER

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2. The structure of the atom
3. Chemical bonds
4. The order of magnitude of the size, mass, and charge of electrons, nuclei, and atoms
5. Properties of electrons
6. The importance of electrons in interpreting physical phenomena

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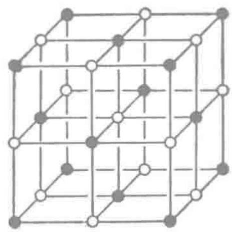
1. Atoms, molecules, and ions

A piece of carbon can be subdivided into smaller and smaller particles of carbon which have the same properties as the original lump, but this process cannot be continued without limit. A stage is eventually reached when the particles cannot be further subdivided by simple means, and if more drastic methods are applied the particles lose the characteristics of carbon and become something different. The smallest particles which retain the properties of the parent carbon are called *atoms*. Substances like carbon whose smallest particles are simple atoms are called *elements*. Each element has its own type of atom which is different from the atoms of other elements. There is a limited number (about 100) of such elements from which all materials on earth are constructed. It is convenient to represent an atom of each element by a symbol; e.g. C stands for one atom of carbon, and O for one atom of oxygen.

More complicated materials, called *compounds*, consist of particles containing more than one type of atom. Compounds can be broadly subdivided into two classes, *molecular* and *ionic*. For example, carbon dioxide is a molecular compound; it is made up of *molecules* each of which consists of one atom of carbon in chemical combination with two atoms of oxygen, and its chemical symbol is CO_2. Ionic compounds on the other hand contain ions. An ion is an atom which has associated with it a positive or negative electric charge, and so differs from an ordinary atom which is electrically neutral. For example, common salt (NaCl) contains equal numbers of positively charged sodium (Na^+) and negatively charged chlorine (Cl^-) ions, held together by the attraction between the opposite charges. Ionic compounds, like nearly all substances, form crystals in the solid state, and ionic crystals should be regarded as a regular arrangement of ions rather than as an assembly of molecules. One cannot assign a special partnership to any particular pair of sodium and chlorine ions in salt; each sodium ion is surrounded in the crystal by several chlorine ions and vice versa (Fig. 1, *1*). When ionic compounds are dissolved in water the ions

Fig. 1, *1*. Showing arrangement of sodium and chlorine ions in a crystal of common salt. (○ = Na^+, ● = Cl^-)



separate and can move about in the solution, making it a conductor of electricity.

We have mentioned above that ionic compounds form crystals in the solid state. It should be realised that molecular compounds and elements also form crystals. For example, water (H_2O) is a molecular compound and when frozen forms crystals of ice or snow, and copper is an element and like other metals is crystalline when solid. In crystals there is an attraction between the individual particles which constrains them to settle into a regular pattern. In the ionic compounds this attraction is easy to understand as it depends on a familiar phenomenon —the force acting between opposite electric charges. In the elements and molecular compounds the nature of the forces is beyond the scope of this book. The regularity of the arrangement of the basic particles in the crystal is the cause of the regularity of its shape when it is seen under the microscope.

The properties of compounds are of course quite different from those of its constituent elements. Common salt, an essential constituent of the human body, is derived from sodium, a highly reactive metal, and chlorine, a poisonous gas. This difference between the properties of a compound and its elements is accounted for by the electronic theory of chemical change which will be outlined later in this chapter.

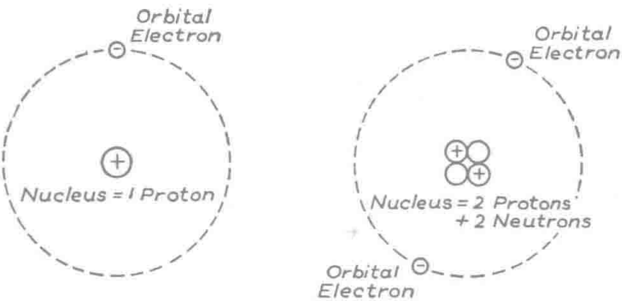
2. The structure of the atom

An atom can be further split by suitably drastic methods, and every atom has been found to contain a *nucleus* surrounded by a certain number of *electrons*. The nucleus is relatively heavy and carries a definite positive electric charge. The electrons are relatively light and carry a definite negative charge. They can be considered to be revolving at high speed round the nucleus in 'orbits' like the planets round the sun. The tendency of a revolving particle to fly off at a tangent (a sensation familar to patrons of fast-moving roundabouts) is opposed by the attraction between the negative charge of the electron and the positive charge of the nucleus. The number of orbital electrons is equal to the number of positive charges on the nucleus so that the atom as a whole is electrically neutral.

The nucleus itself can also be 'split' and contains even simpler units, the *protons* and *neutrons*. These are particles which are almost equal in mass but differ in their electrical properties; the neutron is uncharged whilst the proton carries a positive charge equal in magnitude to the negative charge on one electron.

Some examples will help to show how every atom can be considered to be constructed from these particles. The simplest element of all is hydrogen; each atom contains only one proton and one orbital electron. The next element, helium, has a nucleus containing two protons and two neutrons, with two orbital electrons. Fig. 1, *2* is an

Fig. 1, *2*



Hydrogen Atom   Helium Atom

attempt to 'draw a picture' of these two atoms, and this is a good opportunity to warn the reader that while such pictures are of great value in helping us to correlate the known properties of atoms, they remain mere pictures and can only correspond roughly to the true state of affairs inside the atom. Modern theories have developed and extended these simple ideas, but are still inadequate. It appears that the more we know, the more clearly we realise how little we know, so that we must beware of attributing 'truth' or 'reality' to such mental pictures.

The mass and charge of protons and electrons are so small that it is inconvenient to measure them in the usual units such as grams or coulombs, and therefore much smaller 'atomic' units are employed. On this atomic scale the mass of the proton and neutron is taken to be unity* and that of the electron is then about $\frac{1}{2000}$ (see Table 1, *1*).

TABLE 1, *1*

	MASS		*CHARGE*	
Particle	*Atomic Scale*	*Grams*	*Atomic Scale*	*Coulombs*
Proton	1	$1{\cdot}7 \times 10^{-24}$	+1	$+1{\cdot}6 \times 10^{-19}$
Neutron	1	$1{\cdot}7 \times 10^{-24}$	0	0
Electron	1/1840	$9{\cdot}1 \times 10^{-28}$	−1	$-1{\cdot}6 \times 10^{-19}$

The magnitude of the charge on the electron is taken as the unit of electrical charge on the atomic scale; this has a more fundamental physical meaning since all charges ever measured have turned out to be multiples of the electronic charge, and no smaller charge has ever been found.

The *atomic mass* of an element can now be defined as the total number of protons and neutrons in its nucleus, whilst the *atomic number* is the number of protons (equal to the number of orbital electrons). Thus hydrogen has atomic mass 1 and atomic number 1, helium mass 4 and atomic number 2, and so on.

3. Chemical bonds

Chemical changes are brought about by the sharing or transfer of electrons between two or more atoms. Generally speaking, sharing produces a molecular compound, transfer an ionic compound. For example, a *molecule* of hydrogen gas consists of a pair of hydrogen nuclei (i.e. protons) round which the two *shared* electrons, originally belonging to the two separate protons, perform more complicated orbital paths. The *ionic* crystalline compound, sodium chloride, contains positive sodium and negative chlorine *ions*, formed by the transfer of an electron from a sodium to a chlorine atom.

* Strictly speaking the mass scale is based on the atomic weight of oxygen, taken to be 16. On this basis the mass of the proton and neutron is not precisely unity; this difference is unimportant for our present purposes, although it is vital in the study of nuclear energy and radioactivity.

Since the electrons in the outer orbits of an atom play such an important part in forming chemical bonds, and since the number of such electrons available for this purpose depends on the atomic number, it turns out that the chemical properties of an element are closely related to its atomic number. Those who wish to follow up this fascinating subject should read *An Introduction to the Modern Theory of Valency* by J. C. Speakman (Arnold).

4. The order of magnitude of the size, mass, and charge of electrons, nuclei, and atoms

At this stage it is worth getting some idea of the small size of the particles of which we and our surroundings are composed. The diameter of an electron has been estimated at approximately 6×10^{-13} cm. The diameter of a neutron or proton is about the same. Even quite a large nucleus such as that of aluminium, which contains several neutrons and protons, has a diameter of less than 10×10^{-13} cm. The diameter of an atom is about 2×10^{-8} cm, that is some 50,000 times greater than that of its nucleus; this means that an atom itself is mostly empty space. One gram of water contains about 4×10^{22} molecules, that is forty thousand million million millions. A current of one ampere corresponds to the rate of flow of about six million million million electrons per second. These particles are so small that we cannot hope to see them, even with the aid of the most powerful microscope, since visible light is far too coarse in its structure. Using visible light waves to detect an atom is like trying to detect a thin vertical post set up in the sea by observing the change it produces in the waves of a long ocean swell. However, knowledge of the properties of these minute particles has been built up gradually by using indirect methods. The description of such methods for the nucleus is beyond the scope of this course, but the electron enters into so many phenomena associated with physical medicine that it is worth while considering some of the experiments used to discover its properties.

5. Properties of electrons

Figs. 1, *3* to 1, *6* show some experimental arrangements for demonstrating the existence and properties of electrons. In the first a high electrical potential difference is applied between electrodes in an evacuated glass tube. A green fluorescent glow is seen along the walls of the tube. Fig. 1, *4* shows a similar experiment in which the positive electrode is taken out of the way into a side tube. The glow is seen on the end of the tube PQ provided the electrode A is made positive, but not when A is negative. It is inferred that something is given off by the negative electrode (the cathode) which causes the fluorescence.

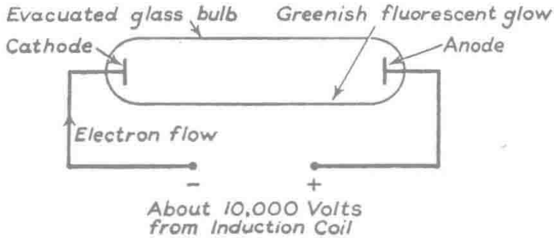
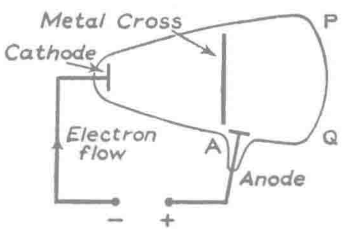


Fig. 1, *3*



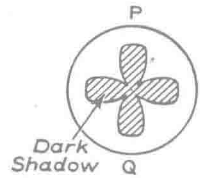


Fig. 1, *4*. *a*

b. Appearance of end of tube, showing well-defined shadow of metal cross surrounded by fluorescent glow

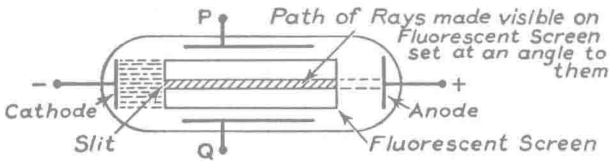


Fig. 1, *5a*. Elevation view

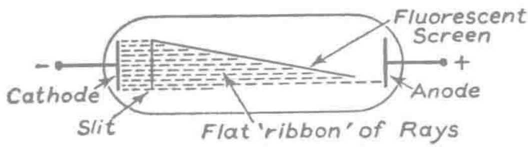


Fig. 1, *5b*. Plan view

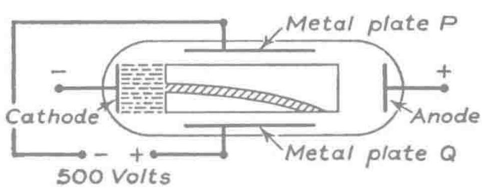


Fig. 1, *5c*. Elevation view. Electric field applied between plates P and Q

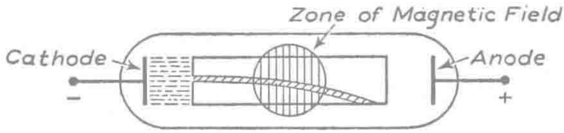


Fig. 1, *6a*. Elevation view. Magnetic field applied by magnet. Zone of magnetic field is downwards into page

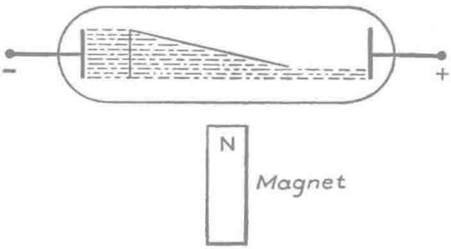


Fig. 1, *6b*. Plan view. Magnetic field causes deflexion of rays downwards into page

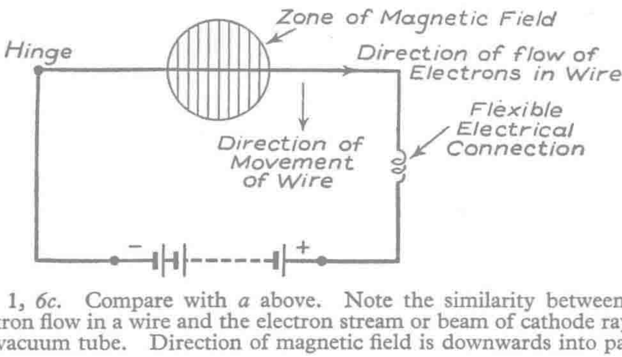


Fig. 1, *6c*. Compare with *a* above. Note the similarity between the electron flow in a wire and the electron stream or beam of cathode rays in a vacuum tube. Direction of magnetic field is downwards into page

This 'something' was termed 'cathode rays' by the early experimenters. An obstacle placed in the path of the rays forms a well defined shadow. Hence the rays travel in straight lines from the cathode. Figs. 1, *5a*, *b* show a tube containing a slit and fluorescent screen set at an angle; the rays impinging on the screen produce a light line so that their path is made visible. A high potential difference applied between metal plates P and Q above and below the rays causes the rays to be deflected, away from the negative plate and towards the positive (Fig. 1, *5c*). This indicates that the rays carry a negative electric charge. Rays can also be deflected by a magnetic field, but in this case the deflection is at right angles to the direction of the magnetic field (Figs. 1, *6a*, *b*). This is similar to the effect produced by a magnetic field upon a metal wire carrying an electric current (Fig. 1, *6c*), which is the basis of the electric motor and of the moving-coil galvanometer. Again, the direction of deflection of the cathode rays shows that they carry a negative charge.

By measuring the deflection due to electric and magnetic fields applied simultaneously in a special cathode ray tube J. J. Thomson at the turn of the century was able to confirm the view that cathode rays consist of streams of negatively charged particles of a definite mass and electric charge, which he termed electrons. Furthermore it was found that electrons are produced by many different materials and can be regarded as a common constituent of all matter.

6. The importance of electrons in interpreting physical phenomena

This section is a general survey which it is hoped will be useful in drawing together different phenomena to be discussed in more detail in later chapters. Beginners should read it realising that some of the terms may not be understood at this stage. It should be read again at the end of the course.

(*a*) *Electrification by friction* can now be explained as a transfer of electrons from one surface to another. Amber when rubbed with flannel becomes negatively charged, having gained electrons at the expense of the flannel, which is left with a positive charge. On the other hand glass rubbed with silk becomes positively charged, so the glass must have lost some of its electrons to the silk. It is interesting that the names positive and negative were adopted arbitrarily long before the discovery of the electron, and that these 'two kinds of electricity' are now attributed, in the case of frictional charges, to a deficit or excess of only one kind of particle. Electricity produced by frictional machines was used in the early days of electric treatment, and although it is no longer so used it is still of more than academic importance, since it is used in large machines for producing highly penetrating X-rays, also it may be unintentionally generated in awkward situations. In the operating theatre it can cause sparks which initiate explosions of inflammable anaesthetic vapours. Less seriously, it can cause shocks to patient and therapist during vigorous massage treatment, if the floor, couch, and therapist's shoes are excessively bad conductors so that the electrons cannot leak away to 'earth'.

(*b*) *The conduction of electricity in metals* is due to the flow of electrons. Good conductors contain plenty of relatively free electrons, only very lightly bound to the parent atoms and able to move from one to another