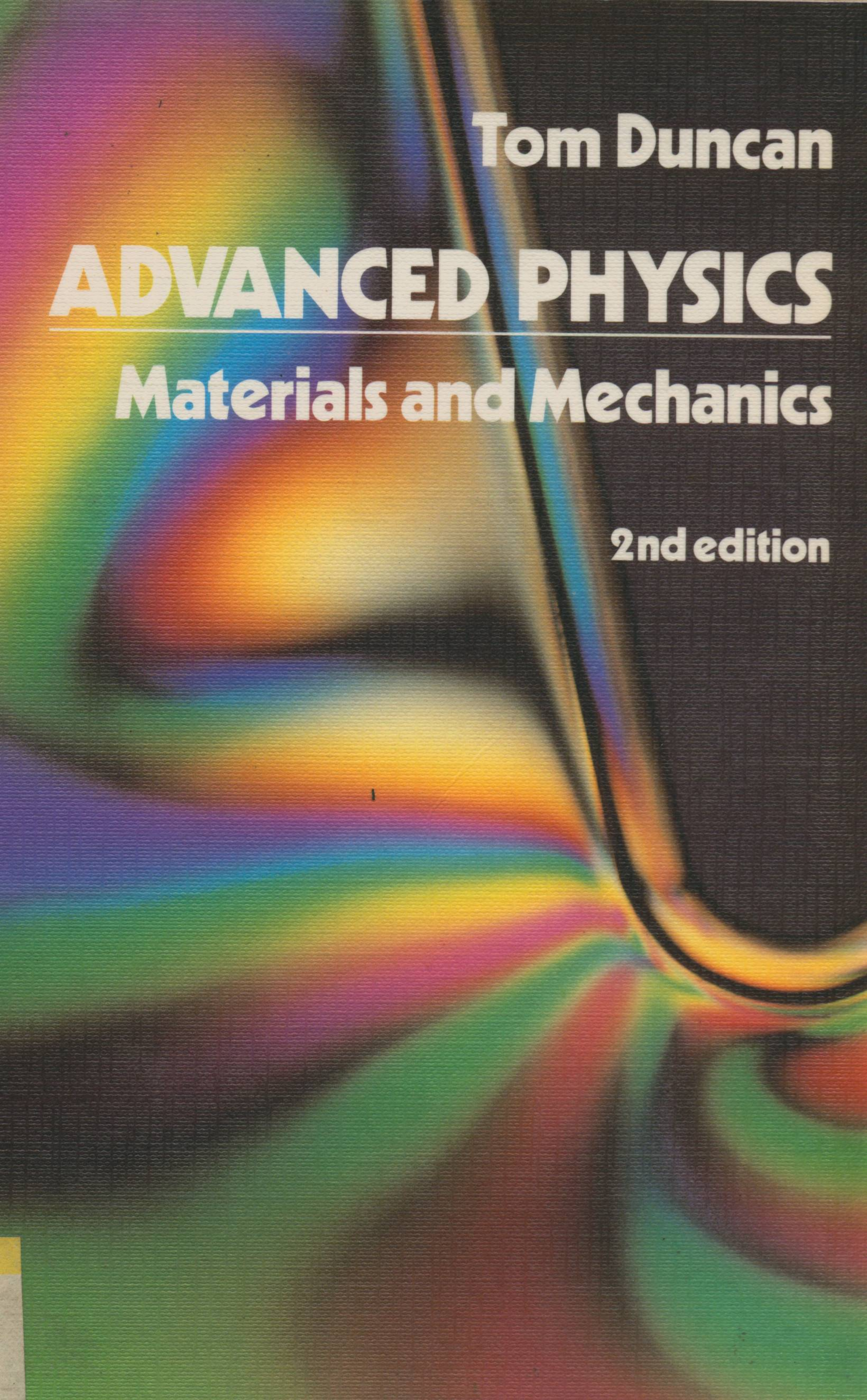
Tom Duncan

# ADVANCED PHYSICS

## Materials and Mechanics

2nd edition



# ADVANCED PHYSICS: Materials and Mechanics

### 2nd edition

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# ADVANCED PHYSICS: Materials and Mechanics

*By the same author*

Electronics and Nuclear Physics
Practical Modern Physics
Exploring Physics 1–5
Advanced Physics: Fields, Waves and Atoms
Physics for Today and Tomorrow
Adventures with Electronics
Adventures with Physics
Adventures with Microelectronics
Adventures with Digital Electronics

# Preface to first edition

This book provides a course which, it is hoped, will be suitable for students in sixth forms and colleges. In selecting and treating topics recent 'A' level syllabus revisions and current teaching trends have been kept in mind. Thus, an attempt has been made to regroup subjects so that greater emphasis is placed on explanations of the macroscopic behaviour of matter using atomic models. Also, detailed accounts of experimental methods of measuring quantities such as the gravitational constant, moments of inertia, expansivities, etc., have either been omitted or dealt with briefly. Many recent physics textbooks have been influenced by Nuffield and other courses and have drawn on their materials; this one is no exception.

The comparatively new subject of Materials Science—the modern version of Properties of Matter—is introduced and given, especially in Chapters 1 and 2, the rather fuller consideration required by those studying Nuffield 'A' level physics, engineering science, ONC physics and physical science.

To be in line with what is taught in more advanced courses a distinction is drawn between heat and internal energy. Heat, like work, is regarded as involving energy transfer. By internal energy is meant molecular kinetic *and* potential energy. The term thermal energy is avoided because in the past it has been used to mean heat or internal energy or both.

To cater for the individual preferences of teachers and to allow for the different 'O' level courses students may have taken, the treatment permits considerable flexibility in the order in which topics are followed. The chapters in Part 1 (Materials) may be taken in any sequence and need not all be covered before Part 2 (Mechanics) is started. If desired, some or all of Part 2 can precede Part 1.

An effort has been made to present numerical data consistently, a point which has been somewhat neglected in the past in examination and other questions. In general, answers to problems are given only to the number of significant figures justified by the data. (Occasionally the next figure is quoted in brackets, e.g. 2.4(3) kg.) When appropriate, powers of ten notation is used; thus, a length may be written as $1.53 \times 10^4$ m (rather than as 15 300 m), indicating three-figure accuracy. Similarly $1.80 \times 10^{-5}$ °C$^{-1}$ is used in preference to 0.000 018 0 °C$^{-1}$.

In examples worked out in the text, numbers *and* units are substituted for symbols in expressions. The *unit* of the required quantity as well as its value is then found (for example, see pp. 30 and 54). This procedure forms a useful check and is recommended.

I am much indebted to Dr J. W. Warren of Brunel University and to Mr J. Dawber of Wade Deacon Grammar School for Boys, Widnes, both of whom read the manuscript. They corrected numerous small errors and made many helpful suggestions. I must also thank Professor J. Stringer and Dr J. C. Gibbings of the University of Liverpool. The former very kindly commented on Chapters 1 and 2 and useful discussions were held with the latter on Chapter 10. Mr B. Baker of Chesterfield High School, Crosby, undertook the task of constructing and testing the objective-type questions at the end of the book. I am most grateful to him and also to my son-in-law and daughter, Mr and Mrs B. L. N. Kennett, who checked the numerical answers. Thanks are also due to my wife for preparing the typescript.

For permission to use questions from recent examinations grateful acknowledgement is made to the various examining boards, indicated by the following abbreviations: *A.E.B.* (Associated Examining Board); *C* (Cambridge Local Examination Syndicate); *J.M.B.* (Joint Matriculation Board); *L* (University of London); *O* (Oxford Local Examinations); *O and C* (Oxford and Cambridge Schools Examination Board); *S* (Southern Universities Joint Board); *W* (Welsh Joint Education Committee).

T.D.

# Preface to second edition

This edition is substantially the same as its predecessor but a few minor changes have been made. For example, the section on electric cells has been up-dated and rewritten, more has been made of the potential energy-separation curve for two atoms and treatment is given of bonding energy.

I am grateful to those students and teachers, particularly Mr J. V. Thornton of St Mary's College, Crosby, who have written to me with suggestions for improving the first edition.

T.D.

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Part 2 MECHANICS

# Part 1 MATERIALS

# 1 Structure of materials

## Materials science

Advances in technology depend increasingly on the development of better materials. This is especially true of those industries engaged in aircraft production, space projects, telecommunications, computer manufacture and nuclear power engineering. Structural materials are required to be stronger, stiffer and lighter than existing ones. In some cases they may have to withstand high temperatures or exposure to intense radioactivity. Materials with very precise electrical, magnetic, thermal, optical or chemical properties are also demanded.

A great deal has been known for many years about materials that are useful in everyday life and industry. For example, the metallurgist has long appreciated that alloys can be made by adding one metal to another or that heating, cooling or hammering metals changes their mechanical behaviour. Materials *technology* is a long-established subject. The comparatively new subject of materials *science* is concerned with the study of materials as a whole and not just with their physical, chemical or engineering properties. As well as asking *how* materials behave, the materials scientist also wants to know *why* they behave as they do. Why is steel strong, glass brittle and rubber extensible? To begin to find answers to such questions has required the drawing together of ideas from physics, chemistry, metallurgy and other disciplines.

The deeper understanding of materials which we now have has come from realizing that the properties of matter in bulk depend largely on the way the atoms are arranged when they are close together. Progress has been possible because of the invention of instruments for 'seeing' finer and finer details. The electron microscope, which uses beams of electrons instead of beams of light as in the optical microscope, reveals structure just above the atomic level. The field ion microscope and X-ray apparatus allow investigation at that level.

The scanning electron microscope, Fig. 1.1*a*, is a development from the electron microscope and 'scans' a surface with electrons in the way that a television screen is scanned. It gives higher magnifications and much greater depth of focus than optical microscopes using reflected light. It is useful for examining the surfaces of semiconductors, the hairlike fibres and 'whiskers' that are so important in the manufacture of the new generation of composite materials, man-made fibres, and corroded and fractured surfaces. A view of the end of a torn wire (× 75) is shown in Fig. 1.1*b* and of lead–tin telluride crystals (× 30) in Fig. 1.1*c*.

Materials science is a rapidly advancing subject with exciting prospects for the future. Its importance lies in the help it can give with the selection of materials for particular applications, with the design of new materials and with the improvement of existing ones. The strength of even a tea cup has been improved by research into ceramics, as Fig. 1.1*d* shows.

(b)

(a)

(c) (d)

*Fig. 1.1*

## Atoms, molecules and Brownian motion

The modern atomic theory was proposed in 1803 by John Dalton, an English schoolmaster. He thought of atoms as tiny, indivisible particles, all the atoms of a given element being exactly alike and different from those of other elements in behaviour and mass. By making simple assumptions he explained the gravimetric (i.e. by weight) laws of chemical combination but failed to account satisfactorily for the volume relationships which exist between combining gases. This required the introduction in 1811 by the Italian scientist, Amedeo Avogadro, of the molecule as the smallest particle of an element or compound capable of existing independently and consisting of two or more atoms, not necessarily identical. Thus, whilst we could only have atoms of elements, molecules of both elements and compounds were possible.

At the end of the nineteenth century some scientists felt that evidence, more direct than that provided by the chemist, was needed to justify the basic assumption that atoms and molecules exist. In 1827 the Scottish botanist, Robert Brown, discovered that fine pollen grains suspended in water were in a state of constant movement, describing small, irregular paths but never stopping. The effect, which has been observed with many kinds of small particles suspended in both liquids and gases, is called *Brownian motion*. It is now considered to be due to the unequal bombardment of the suspended particles by the molecules of the surrounding medium.

Very small particles are essential. If the particle is fairly large, the impacts, occurring on every side and irregularly, will cancel out and there will be no average resultant force on the particle. Only if the particle is small will it suffer impacts with a few hundred molecules at any instant and the chances of these cancelling out are proportionately less. It is then likely that for a short time most of the impacts will be in one direction; shortly afterwards the direction will have changed. The phenomenon can be observed in smoke in a small glass cell which is illuminated strongly from one side and viewed from above with a low-power microscope, Fig. 1.2. How would the random motion be affected by (*i*) cooling the air to a low temperature, (*ii*) using smaller smoke particles?

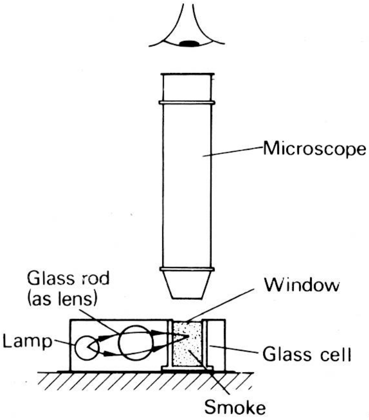

*Fig. 1.2*

The effect, on its own, does not offer conclusive proof for molecules but it clearly reveals that on the microscopic scale there is great activity in matter which macroscopically (on a large scale) appears to be at rest. The theory of the motion was worked out by Einstein and is found to correspond closely with observation. His basic assumption was that the suspended particles have the same mean kinetic energy as the molecules of the fluid and so behave just like very large molecules. Their motions should therefore be similar to those of the fluid molecules.

## The Avogadro constant: mole

*Atomic* and *molecular masses* (previously called *atomic* and *molecular weights*) give the masses of atoms and molecules compared with the mass of another kind of atom. Originally the hydrogen atom was taken as the standard with atomic mass 1 since it has the smallest mass. In 1960 it was agreed internationally, for various reasons, to base atomic and molecular masses on the atom of carbon (more precisely, on the carbon 12 isotope $^{12}_{6}C$). On the carbon scale the atomic mass of carbon 12 is taken as exactly 12 making that of hydrogen 1.008 and of oxygen 16.00. Nowadays atomic masses are found very accurately using a *mass spectrometer.*

It follows from the definition of atomic mass that any number of atoms of carbon will have, near enough, 12 times the mass of the *same* number of atoms of hydrogen. Therefore any mass of hydrogen, say 1 g, will contain the same number of atoms as 12 g of carbon. In general, the atomic mass of any element expressed in grams, contains the same number of atoms as 12 g of carbon. This number is thus, by definition, a constant. It is called the *Avogadro constant* and is denoted by $L$. Its accepted experimental value is $6.02 \times 10^{23}$.

The number of molecules in the molecular mass in grams of a substance is also (because of the way molecular masses are defined) the same for all substances and equal to the Avogadro constant. There are, therefore, $6.02 \times 10^{23}$ molecules in 2 g of hydrogen (molecular mass 2) and in 18 g of water (molecular mass 18). In fact, the Avogadro constant is useful when dealing with other particles besides atoms and molecules and a quantity which contains $6.02 \times 10^{23}$ particles is called, especially by chemists, a *mole.* We can thus have a mole of atoms, a mole of molecules, a mole of ions, a mole of electrons, etc.—all contain $6.02 \times 10^{23}$ particles. We must always have a mole of some kind of particle and so

$$L = 6.02 \times 10^{23} \text{ particles per mole}$$

It should be noted that the mole (abbreviation mol) is based on the gram and not the kilogram, which makes it an anomaly in the SI system of units. Sometimes, however, it is expressed in terms of the number of particles per kilogram-mole and its value then is $6.02 \times 10^{26}$.

The Avogadro constant has been measured in various ways. In an early method alpha particles emitted by a radioactive source were counted by allowing those within a small known angle to strike a fluorescent screen. Each particle produced one scintillation on the screen and if it is assumed that one particle is emitted by each radioactive atom an approximate value for $L$ can be obtained (see question 6, p. 24). Other methods give more reliable results—one involves X-ray crystallography.

## Size of a molecule

(*a*) *Monolayer experiments.* An experimental determination of the size of a molecule was made by Lord Rayleigh in 1899. He used the fact that certain organic substances, such as olive oil, spread out over a clean water surface to form very thin films.

A simple procedure for performing the experiment is to obtain a drop of olive oil by dipping the end of a loop of thin wire, mounted on a card, into olive oil, quickly withdrawing it and then estimating the diameter of the drop by holding it against a $\frac{1}{2}$ mm scale and viewing the drop and scale through a lens, Fig. 1.3*a*. If the drop is then transferred to the centre of a waxed tray overbrimming with water, the surface of which has been previously cleaned by drawing two waxed booms across it and then lightly dusted with lycopodium powder, Fig. 1.3*b*, it spreads out into a circular film pushing the powder before it. Assuming the drop is spherical, the thickness of the film can be calculated if its diameter is measured. It is found to be about $2 \times 10^{-9}$ metre, i.e. 2 nanometres (2 nm).

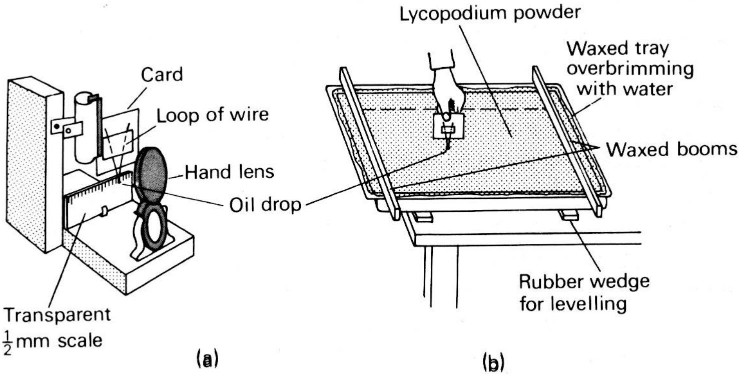

*Fig. 1.3*

Oil-film experiments do not necessarily prove that matter is particulate but from them we can infer that if molecules exist and if the film is one molecule thick, i.e. a monolayer, then in the case of olive oil one dimension of its molecule is 2 nm.

(*b*) *Predictions from kinetic theory of gases.* Information about the molecular world can sometimes be obtained from observations of the behaviour of matter in bulk, i.e. from macroscopic observations. Thus with the help of the kinetic theory of gases, expressions can be derived relating such properties as rate of diffusion with the size of the gas molecules involved.

(*c*) *Using the Avogadro constant.* Consider copper which has atomic mass 64 and density 9.0 g cm$^{-3}$. One mole of copper atoms, therefore, has mass 64 g and volume

64/9 $\text{cm}^3$; it contains $6.0 \times 10^{23}$ atoms. The volume available to each atom is $64/(9 \times 6 \times 10^{23})$ $\text{cm}^3$ and the radius $r$ of a sphere having this volume is given by

$$\frac{4}{3}\pi r^3 = \frac{64}{9 \times 6 \times 10^{23}}$$

$$\therefore \quad r = 0.14 \times 10^{-7} \text{ cm}$$

$$= 0.14 \times 10^{-9} \text{ m}$$

$$= 0.14 \text{ nm}$$

If copper atoms are spherical, would their radius be larger or smaller than this even if they were packed tightly? Why? A more accurate way of calculating the size of a copper atom is indicated in questions 10 to 13 on p. 25.

A word of caution is necessary regarding atomic dimensions. Nowadays atoms and molecules are no longer pictured as having hard, definite surfaces like a ball and there is, therefore, little point in trying to give their diameters too exact values; most are within the range 0.1 to 0.5 nm. Also, although we shall usually treat atoms and molecules as spheres, it is necessary on occasion to consider them as having other shapes.

## Periodic table

With the passage of time the early nineteenth-century picture of an indivisible atom came to be doubted in the light of fresh information. During the 1860s chemical knowledge increased sufficiently for it to be clear that there were elements with similar chemical properties. Moreover, atomic masses were being established with greater certainty and attempts were made to relate properties and atomic masses.

It was found that if the elements were arranged in order of increasing atomic masses then, at certain repeating intervals, elements occurred with similar chemical properties. Sometimes it was necessary to place an element of larger atomic mass before one of slightly smaller atomic mass to preserve the pattern. The first eighteen elements of this arrangement, called the Periodic table, are shown in Table 1.1. The third and eleventh (3 + 8) elements are the alkali metals lithium and sodium; the ninth and seventeenth (9 + 8) are the halogens fluorine and chlorine—here the repeating interval is eight. The serial number of an element in the table is called its *atomic number*.

*Table 1.1*

| *Group 1* | *Group 2* | *Group 3* | *Group 4* | *Group 5* | *Group 6* | *Group 7* | *Group 0* |
|---|---|---|---|---|---|---|---|
| 1<br>Hydrogen | | | | | | | 2<br>Helium |
| 3<br>Lithium | 4<br>Beryllium | 5<br>Boron | 6<br>Carbon | 7<br>Nitrogen | 8<br>Oxygen | 9<br>Fluorine | 10<br>Neon |
| 11<br>Sodium | 12<br>Magnesium | 13<br>Aluminium | 14<br>Silicon | 15<br>Phosphorus | 16<br>Sulphur | 17<br>Chlorine | 18<br>Argon |