MODERN ATOMIC PHYSICS: FUNDAMENTAL PRINCIPLES

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Preface

Atomic physics was responsible for the birth and development of quantum theory and indeed is still closely linked with it; one can go further and say that atomic physics cannot exist without quantum mechanics. A course on quantum mechanics that emphasised the experimental consequences of the mathematics would amount to a good course on atomic physics. However, experience has shown that students find great difficulty in coping with the mixture of terminologies that is inevitable when constantly switching from theoretical calculation to experimental description. Thus in order to facilitate the assimilation of new ideas, it would seem desirable to separate the whole subject into two distinct courses. These would comprise (a) the experimental justification of the principles of quantum mechanics and the consequences of these principles as they concern atomic structure, and (b) an account of quantum mechanics arranged, once the basic principles have been described, almost entirely on logical and deductive lines. It is to the first of these tasks that this volume is dedicated; the second task is undertaken in *Quantum Theory and its Applications*.

Our approach concentrates on describing experiments and comparing them with theoretical results; it has the objects of: (a) establishing the experimental basis of the fundamental principles of quantum mechanics, by describing the crucial experiments that demonstrate the limitations of classical theory and provide unchallengeable results which the theory must explain; (b) setting out the fundamental laws governing the internal structure of atomic systems, knowledge of which is indispensable now that they have such wide application; (c) surveying the experimental work currently being conducted in physics laboratories and thus appreciating its aims.

In discussing the experimental foundations of the principles of quantum mechanics, we think that the device of rediscovery is to be avoided. This device involves following the path of history from the beginning of the century with the object of proving for ourselves that the only way to progress would be to invent quantum mechanics. Quantum mechanics is now so solidly based and supported by such a wide range of experiments that further persuasion is unnecessary. Besides, the path of history has been winding and uneven and the course which it has taken is far from being the simplest and most direct. Certain ideas suddenly appeared during very prolific periods in the form of very complex deductions from work carried out simultaneously in different fields.

However, a certain amount of detailed and wide-ranging experimental evidence appears indispensable for an understanding of the significance of the essential ideas of quantum mechanics and for easing their assimilation; this is what we have tried to include. We have not forgotten some of the older experiments that are still of fundamental importance, but we have added many other more recent experiments; moreover it seemed sensible to group them in the same part of the book, even in the same chapter, without regard to their chronological order, as long as they supported the same essential idea.

It is a fact that when considering specific experiments different ideas often overlap, and the plan that we have adopted gives prominence to certain ideas at the expense of others. We have chosen to give general concepts priority over particular phenomena, and since the explanation of certain phenomena requires the use of several general concepts, we have often had to discuss the same phenomenon from different aspects. Optical resonance, for example, is a phenomenon involving an atom–photon collision, the explanation of which involves the principle of the conservation of energy (chapter 1), of the conservation of momentum (chapter 2) and the notion of transition probability or cross-section (chapter 3). To take another example, the interpretation of magnetic resonance brings into play the gyromagnetic ratio (chapter 9), spatial quantisation (chapter 10) the angular momentum associated with circular polarisation (chapter 11), and so on.

Our presentation has been guided by our concern both to graduate the difficulties and to allow for the possibility of a partial reading of the book. So we have gathered together in volume 1 those simple concepts that can be understood without any knowledge of the formal mathematics of quantum mechanics. Volume 1 is devoted to the description of experiments and to the development of those quantum mechanical ideas with the most straightforward experimental basis. It can be read before an explanation of quantum mechanics. Some more theoretically inclined readers might object that this first volume makes too much use of the language of classical physics; but it should not be forgotten that classical terminology remains indispensable for a rapid and convenient description of physical processes, and that the experimental physicist should develop the ability to change continually from quantum to classical language. Apart from which, it is precisely on the classical nature of measuring apparatus that the quantum theory of measurement is based. In any case, our concern to make the connection with quantum mechanics permeates this volume. It is this in particular which has led us to emphasise the chapters devoted to angular momentum; they promote a better understanding of the importance given in quantum mechanics to the theory of angular momentum.

We have, on the other hand, collected together ideas in the second volume, even some very old ones, that can be satisfactorily understood only by using quantum-mechanical calculations or their results. This volume can be read to best advantage by those who have already taken a course in quantum mechanics, and this assumption accounts for the alteration in pace and style. Nevertheless the first four chapters of the second volume do not make use of quantum mechanical formalism, a familiarity with the general ideas of quantum mechanics being the only prerequisite. It is only in the second volume that the description of atomic structure is actually completed. The final chapter surveys some experimental problems that are currently under consideration.

Writing this book has involved a number of compromises. The essential aim has been to give the reader the most precise and accurate review possible of the problems of atomic physics; it is this goal which has determined our choice of topics. The extent of the subject is obviously greater than an average student can absorb in a year in which he is taking courses in quantum mechanics and nuclear physics, perhaps in addition to being taught, for example, field theory or electronics. Our presentation makes a number of chapters relatively independent, so that the reader can design his own course and select accordingly. Also, by using small print, we have singled out certain passages in each chapter that are not essential to its understanding; they may be omitted on the first reading.

Another aim of this course is to show the reader how to work out the results of an experiment for himself and to give him a sense of orders of magnitude, necessary for justifying those approximations without which few calculations in physics would be possible. This prevented us from putting (in the way theoreticians do): $\hbar = c = 1$, and so we had to confront the irritating problem of units. Since French students have for several years used rationalised MKS units, we did not want to interfere with this practice, and we have used rationalised formulae. However, most publications and major works in atomic physics, even the most recent, use the non-rationalised gaussian system and one should be able to convert from one to the other. To this end we have introduced into our formulae a coefficient κ defined by the relation

$$\kappa = \epsilon_0 \mu_0 c^2$$

(a) In the MKS system, $\kappa = 1$. The coefficient κ can be simply disregarded in all the formulae, which then become normal rationalised formulae, and the numerical values of the constants are

$$4\pi\epsilon_0 = \frac{1}{9 \times 10^9}; \qquad \frac{\mu_0}{4\pi} = 10^{-7}$$

(b) In the gaussian system, where electrical units from the electrostatic c.g.s. system and magnetic units from the electromagnetic c.g.s. system are used simultaneously, the coefficients are determined thus

$$4\pi\epsilon_0 = 1; \qquad \frac{\mu_0}{4\pi} = 1 \quad \text{and} \quad \kappa = c$$

Appendix 1 gives a set of electromagnetic formulae showing how the classical formulae should be modified to take account of the coefficient κ. We have taken these modified formulae as our starting point for all our calculations in atomic physics (see p. 301).

Before starting the course, we would like to thank all the staff and research workers in our laboratories, both in Paris and Grenoble, who have helped us to prepare this new presentation of atomic physics. Above all we must thank Professor Kastler and Professor Brossel for their inspiration, both in their teaching and in the everyday life of the laboratory.

B. Cagnac
J.-C. Pebay-Peyroula

Preface to the English Edition

The English edition of Cagnac and Pebay-Peyroula's *Physique Atomique* has been prepared with the aim of retaining as faithfully as possible both the spirit and the letter of their work. However, certain changes have been made.

(1) Wherever it was felt that English-speaking students would be unfamiliar with the French terminology, preference was given to the accepted English practice: for example, hyperfrequency transitions are always referred to as microwave transitions.

(2) The French edition is divided into two volumes, with the chapters numbered continuously throughout; the appendixes appear at the end of the second volume only. For the English edition it has been decided to publish two books that are as far as possible independent of one another. To this end, each book has been given a distinctive title—'Fundamental Principles' corresponding to volume 1 and 'Quantum Theory And Its Applications' corresponding to volume 2. The numbering of the chapters in the two volumes is independent and decimal notation has been used to subdivide each chapter. Reference to other chapters always imply the current volume unless otherwise stated. Each book now contains its own appendixes, some of which appear in both books.

(3) In consultation with the authors, some sections have been amplified to avoid any possible misunderstanding. Additionally, in an effort to ensure that the book is up to date at the time of writing, major developments in the past three years have been included where they have an important bearing on

the subject matter. Alterations, other than corrections and those due to changes of terminology, have been inserted as translator's footnotes.

(4) SI units (rationalised MKS) have been used throughout, though the coefficient κ (see preface to French edition) is retained in relevant formulae. Thus, despite some spectroscopists' aversion to changing, for example, from ångström units to a subunit of the metre or from gauss to tesla, numerical values are nearly always given in SI.

(5) Important names and dates are given for their historical interest only and accordingly precise references are usually omitted, as in the French edition. Where the French edition refers to textbooks that have not been translated into English, an English substitute has been given.

I should like to express my thanks to Dr M. H. Tinker for reading and commenting upon the entire translated manuscript, to my wife who sacrificed much of her time for several months in preparing the final typescript version, and finally to the publishers for their continued encouragement and helpfulness.

J. J. Thomson Physical Laboratory J.S.D.
Reading
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Glossary

1 Latin Alphabet

a	acceleration semi-major axis of an ellipse, or other length
A	magnetic vector potential amplitude of a sinusoidal function magnetic moment coupling constant probability of spontaneous emission atomic mass number
$\mathscr{A}$	atomic mass (approximately equal to A in CGS, or to $A/1000$ in MKS)
b	impact parameter in collision problems semi-minor axis of an ellipse, or other length
B	magnetic induction vector, usually called magnetic field (the excitation vector $\boldsymbol{H} = (1/\mu_0 \mu_r)\,\boldsymbol{B}$ is hardly ever used) absorption and induced emission probability coefficients (Einstein notation) amplitude of a sinusoidal function
$\mathscr{B}$	magnetic field vector
c	velocity of light

C
- constant in a Coulomb law of force ($W(r) = C/r$)
- Curie constant of magnetic susceptibilities
- capacitance
- torsion constant of a wire

d — differential

d — symbol for the quantum number $l = 2$ (total orbital angular momentum of an electron)

D
- electric induction vector
- probability density
- distance
- symbol for the quantum number $L = 2$ (total orbital angular momentum of an atom)

$\mathscr{D}$ — intensity of a beam of particles per unit cross-sectional area ($N = \mathscr{D}tS$)

e — base of napierian logarithms $\mathrm{e} = 2{\cdot}7183$

e — elementary positive charge $e = 1{\cdot}6 \times 10^{-19}$ C

E
- electric field vector
- algebraic value of the total energy of an atomic state

$\mathscr{E}$ — complex function associated with the electric field of a wave

f
- a function
- force vector
- oscillator strength
- symbol for the quantum number $l = 3$ (orbital angular momentum of an electron)

F
- resultant vector for a system of forces
- symbol for the quantum number $L = 3$ (orbital angular momentum of an atom)

g
- Landé factor
- symbol for the quantum number $l = 4$ (orbital angular momentum of an electron)

G
- statistical weight or order of degeneracy
- symbol for the quantum number $L = 4$ (total orbital angular momentum of an atom)

h — Planck's constant ($\hbar = h/2\pi$)

H — hamiltonian operator

$\mathscr{H}$ — hamiltonian function

i — square root of -1, the base of imaginary numbers

i
- index number
- angle of incidence

I
- magnitude of an electric current
- moment of inertia
- nuclear spin quantum number and the corresponding vector

j	the electric current density vector index number quantum number of angular momentum and the corresponding vector
J	total angular momentum quantum number of an atom, and the corresponding vector
k	Boltzmann's constant wave vector an integer
K	contact potential difference absorption coefficient symbol for the principal quantum number $n = 1$
l	a length orbital angular momentum quantum number and the corresponding vector
L	luminance the total orbital angular momentum quantum number of an atom and the corresponding vector symbol for the principal quantum number $n = 2$
$\mathscr{L}$	lagrangian function
m	mass, especially mass of the electron magnetic quantum number
M	molecular mass mass, especially the mass of an atom or a nucleus intensity of magnetisation vector symbol for the principal quantum number $n = 3$
$\mathscr{M}$	magnetic moment vector
n	number of particles per unit volume principal quantum number
N	an integer (dimensionless) unit normal vector symbol for the principal quantum number $n = 4$
$\mathscr{N}$	Avogadro's number
O	symbol for the principal quantum number $n = 5$
p	momentum or impulse vector electric dipole moment vector index number population of an energy level symbol for the quantum number $l = 1$ (orbital angular momentum of an electron)

P — power; polarisation vector of a dielectric; symbol for the quantum number $L = 1$ (total orbital angular momentum of an atom); symbol for the principal quantum number $n = 6$

$\mathscr{P}$ — generalised impulse vector

q — algebraic electric charge (especially charge on the electron $q = -e$)

Q — electric charge; quality factor of a resonant cavity or a resonant circuit; reduced quadrupole moment

Q — components of the quadrupole tensor

r — radius vector, distance between two points

R — distance between two points; electric resistance; Rydberg constant for atomic spectra; gas constant for a perfect gas

$\mathscr{R}$ — radial wave function

s — spin quantum number and the corresponding vector; screening coefficient; symbol for the quantum number $l = 0$ (orbital angular momentum of an electron

S — area; total spin quantum number of an atom and the corresponding vector; symbol for the quantum number $L = 0$ (total orbital angular momentum of an atom)

t — time

T — absolute temperature; period; spectral term

$\mathscr{T}$ — work

u — energy density; unit vector; transverse component of the magnetisation M in a rotating frame

U — internal energy; electrostatic potential

v — velocity vector; transverse component of the magnetisation M in a rotating frame

V — electrostatic potential or electromotive force; exceptionally, velocity vector

$\mathscr{V}$	volume
w	a small energy
W	energy in general, and especially potential energy $W(\boldsymbol{r})$
x, X	co-ordinate
y	co-ordinate
Y	co-ordinate angular wave functions of hydrogen (spherical harmonics)
z	co-ordinate
Z	co-ordinate atomic number of an element statistical partition function

2 Greek Alphabet

α	fine structure constant ($\alpha = e^2/4\pi\varepsilon_0\hbar c$) angle direction cosine name of a type of particle
β	Bohr magneton angle direction cosine name of a type of particle (β^- and β^+ rays)
γ	gyromagnetic ratio direction cosine name of a region of the electromagnetic spectrum
Γ	moment of a force or resultant moment of a system of forces
δ	increment, difference
Δ	laplacian operation
$\varDelta$	width of a line correction applied to an energy value following a perturbation calculation
ε	constant depending on units, ε_0, (in CGS ε_0 is replaced by $1/4\pi$) dielectric constant ε_r a conical eccentricity any very small quantity
η	efficiency, or other dimensionless fraction
θ	angle, especially latitude in spherical co-ordinates

Θ	angular wave function Debye temperature
κ	constant depending on units: $\varepsilon_0 \mu_0 c^2 = \kappa^2 \begin{cases} \kappa = 1 \text{ in MKSA system} \\ \kappa = c \text{ in gaussian system} \end{cases}$
λ	wavelength
Λ	Compton wavelength ($\Lambda = h/mc$)
μ	constant depending on units, μ_0, (in CGS, μ_0 is replaced by 4π) magnetic permeability reduced mass
ν	frequency
ξ	co-ordinate
ϖ	pressure probability
π	3·1416 . . . symbol for a polarisation of a wave (parallel to a magnetic field)
Π	product
ρ	density electric charge density particular values of a radius vector
σ	angular momentum vector cross section symbol for a polarisation of a wave (circular or perpendicular to a field)
Σ	summation
τ	time constant (lifetime, relaxation time)
ϕ	angle, especially longitude in spherical co-ordinates
Φ	magnetic flux angular wave function
χ	angle magnetic susceptibility
ψ	angle total wave function
ω	angular velocity of rotation angular frequency of a sinusoidal function
Ω	solid angle exceptionally, angular velocity of rotation