A TEXTBOOK OF
NUCLEAR PHYSICS

BY

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PREFACE

THE main purpose of this book is to provide a general coverage of nuclear physics suitable for honours physics students. An attempt has been made to keep the subject matter as self-contained as possible and, for this reason, the first seven chapters deal with those parts of atomic physics, relativity, and quantum mechanics, which are a necessary prelude to the study of nuclear physics. It is, of course, impossible to give, for example, a comprehensive account of quantum mechanics in a single chapter, and it is hoped that the reader will already have some background to this most important aspect of modern physics, or be prepared to follow up the references given at the end of Chapter 6.

The second part of the book, Chapters 8 to 20 inclusive, is concerned with what may be described as "low energy nuclear processes and nuclear structure" the main field of study of nuclear physics in the post 1945 years. The penultimate chapter, on the other hand, deals with the rapidly developing subject of high energy nuclear physics and the light it throws on our knowledge of those peculiar objects we call "elementary particles". There is a growing inclination, an unfortunate one in the author's opinion, for the physics of finite nuclear matter to be divorced from the physics of elementary particles.† In an attempt to offset this tendency, a fairly long and detailed account of elementary particle physics is given in Chapter 21.

In the final chapter, an account is given of our present day knowledge of thermonuclear reactions in stars and also of one of the more successful theories of the origin of the elements. This chapter also illustrates the importance of not keeping the various branches of physics in rigidly separated compartments.

Throughout the book it has not always been possible to avoid the irritating phrase "it can be shown that"; but when this is inevitable, references to original sources have been given, and there is an adequate and up-to-date bibliography.

A few specific comments on some of the chapters may be helpful. Chapters 11 and 12 are devoted to the art of experimental techniques in nuclear physics: the range of detectors of nuclear radiation is continuously extending (the bubble chamber, the semiconduction counter, the spark chamber . . .); the chapter on "Electronic Techniques" does not attempt to give any detailed account of modern multi-channel pulse height analysers, nor does

† The importance of bearing in mind the properties of finite nuclei in studying elementary particles was the theme of Wilkinson's Rutherford Memorial Lecture (1962).

it include any discussion of the transistor equivalents of the thermionic vacuum tube circuits.

There is no attempt to cover any reactor physics; this is best regarded as a new brand of engineering physics, nor are current researches into laboratory controlled thermonuclear reactions mentioned.

Special emphasis should be made of parts of the subject matter of Chapter 16, "Nuclear Magnetism". Although the study of nuclear magnetic resonance in bulk matter is now mainly a sensitive tool for elucidating certain aspects of the solid and liquid state, the writer believes that it is worthwhile discussing such topics as spin–lattice and spin–spin relaxation effects. This chapter also includes a description of the elegant optical methods of determining nuclear magnetic moments. Finally, an account is given of one of the most refined experiments of recent years, the determination of the anomalous part of the gyromagnetic ratio of the muon at CERN.

The chapters need not be read in strict numerical order and it is possible to omit certain sections, such as that on "Angular Correlations in Nuclear Reactions" in Chapter 20, without any loss of understanding of the rest of the book.

Chapter 20, "Nuclear Reactions and Nuclear Models" attempts the wellnigh impossible task of covering an enormous field of "nuclear activity". For this reason, an extensive bibliography is given at the end of this chapter and the reader is urged to look at some of the review articles listed. The important section on the Nuclear Shell Model can be read separately, and it is probably wise to do this, for this model is referred to on several occasions in the earlier chapters.

There is no account included of cosmic ray physics and the remarkable high energy nuclear chain reactions known as extensive air showers. Here in the energy region from 10^{12} to 10^{20} electron volts we enter a domain which seems to be beyond the range of any foreseeable future advances in particle accelerators. These ultra-high energy reactions are omitted from the text,† as they belong to the province of the cosmic ray physicist. Another great problem of cosmic ray physics is also omitted from the book;—"where and how do the primary cosmic ray nuclei attain their enormous energies"?††

Two important contributions to nuclear physics in the past decade have been reluctantly omitted from the book because of the mathematical difficulties involved. The first is the theory of Brueckner‡ in which a determined attack has been made on the fundamental problem of the properties of nuclear matter, using a self-consistent field approach on the assumption that two-body interactions are dominant in the nucleus. The second is the

† The interested reader is referred to the book W. GALBRAITH, *Extensive Air Showers* Butterworth's, London, 1958.

†† P. MORRISON, *Rev. Mod. Phys.* **29**, 235, 1957.

‡ A useful introduction to Brueckner theory is given in the book D. J. THOULESS, *The Quantum Mechanics of Many Body Systems*, Academic Press, 1961.

method of dispersion relations, which has become the cornerstone of theoretical elementary particle physics. A very brief reference to this method is given in Chapter 21.

The author is greatly indebted to Dr. J. E. Evans of A.E.R.E., Harwell, for his encouragement in writing this book. He has read most of the chapters and has provided much helpful constructive criticism. Dr. Evans is also responsible for writing the Section on "Angular Correlations in Nuclear Reactions" in Chapter 20.

It is also a pleasure to acknowledge the help of many of my colleagues at the College of Technology, Oxford, who have read several of the chapters.

The photographic plates numbers I, II, IV, were kindly provided by the Rutherford High Energy Laboratory, Harwell. I should like to thank Mr. T. F. Gubbins for his help in obtaining permission to include these photographs.

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Questions from the Graduateship of the Institute of Physics examination papers.

Many figures are redrawn from *The Physical Review*, *Physical Review Letters*, and *Reviews of Modern Physics*.

CONTENTS

PREFACE xiii

ACKNOWLEDGEMENTS xvi

CHAPTER 1. INTRODUCTION

1.1 Kinetic Theory of Matter 1
Pressure of a Gas 1
Equipartition of Energy 2
The Distribution of Molecular Speeds 3
Mean Free Path and Molecular Cross Section 4
Determination of Avogadro's Number N 6
1.2 Cathode Rays and X-rays 8
X-rays 10
1.3 The Number of Electrons in an Atom, Z 11
1.4 Radioactivity 16
1.5 Isotopes 18
1.6 The Nuclear Model of the Atom 19
Geiger and Marsden's Experiment 23
Determination of Nuclear Charge 24

CHAPTER 2. THE QUANTUM THEORY

2.1 Planck's Radiation Law 27
2.2 The Photoelectric Effect 30
Einstein's Photoelectric Equation 32
Wave–Corpuscular Dual Nature of Light 33
2.3 Atomic Spectra 35
N. Bohr's Theory of the Atomic Spectrum of Hydrogen 36
Space Quantization 43
Electron Spin 45
2.4 Pauli Exclusion Principle and the Periodic Table 46
2.5 Experimental Determinations of Atomic Energy States 49
Lamb Shift 52

CHAPTER 3. THE THEORY OF RELATIVITY

3.1 Introduction 58
3.2 The Postulates of Special Relativity 59
The Michelson–Morley Experiment 61
The Absolute Velocity of Light 64
3.3 The Lorentz Transformation 65
3.4 Lorentz Contraction and Time Dilatation 69
3.5 The Doppler Effect 71

3.6 Relativistic Dynamics 73
Bucherer's Experiment 75
The Equivalence of Mass and Energy 77
Energy–Momentum Relations 80
The Centre-of-mass System 81
3.7 Polarized Light 84
3.8 The General Theory of Relativity 86

CHAPTER 4. X-RAYS

4.1 The Continuous X-ray Spectrum 89
Bremsstrahlung Cross Section σ_{rad} 92
4.2 Characteristic Line Spectrum 94
4.3 X-ray Absorption 97
4.4 The Refraction of X-rays 100
4.5 Measurement of X-ray Wavelengths by Ruled Gratings 102
4.6 X-ray Diffraction 103
The Bragg Law 107
Experimental Techniques of X-ray Crystallography 112
Intensity of Diffraction Spectra 117
Atomic Scattering Factor (Form Factor) 117
The Structure Factor F_{hkl} 122
4.7 The Compton Effect 124

CHAPTER 5. ELECTRON DIFFRACTION

5.1 The Wave Nature of Matter 131
5.2 Electron Diffraction 134
5.3 Accurate Verification of de Broglie's Equation 138
5.4 The Atomic Scattering Factor 140
5.5 Practical Applications 141

CHAPTER 6. QUANTUM MECHANICS

6.1 Introduction 143
6.2 Schrödinger's Wave Equation 145
6.3 The Probability Amplitude 149
6.4 The Time-independent Schrödinger Equation 150
6.5 One-dimensional Rectangular Potential Well 151
6.6 Probability Current 154
6.7 One-dimensional Rectangular Potential Barrier 155
6.8 Linear Harmonic Oscillator 160
6.9 Spherically Symmetric Potential 162
6.10 The Hydrogen Atom 167
The Two-body Problem 169
6.11 Parity 171
6.12 Quantum Statistics 174
6.13 The Commutation Laws 175
6.14 The Heisenberg Uncertainty Principle 176

6.15 Orthogonal Properties of Eigenfunctions 180
6.16 Elementary Perturbation Theory 181
6.17 Matrix Mechanics 184
Matrix Algebra 186
6.18 The Linear Harmonic Oscillator 190
6.19 Angular Momentum 193
6.20 The Relativistic Wave Equation 197

CHAPTER 7. THE DETERMINATION OF ATOMIC MASSES

7.1 Introduction 202
7.2 Basic Components of Mass Spectroscopes 204
Ion Sources 204
Energy Filters 205
Momentum (Magnetic) Filter 206
7.3 Mass Spectroscopes 207
Bainbridge and Jordan Mass Spectrograph (1936) 207
The Mass Doublet Method 209
Mass Spectrograph of Quisenberry, Scolman and Nier (1956) 210
The Mass Synchrometer 213

CHAPTER 8. GENERAL PROPERTIES OF ATOMIC NUCLEI

8.1 Charge, Mass, Size, and Constitution 217
8.2 Nuclear Stability, Binding Energy 219
8.3 Semi-Empirical Mass Formula 224
8.4 Nuclear Spin 227
Determination of Nuclear Spin 228
8.5 Nuclear Moments 230
Electric Dipole Moment 230
Electric Quadrupole Moment 231
Magnetic Moments 234
8.6 Nuclear Forces 235

CHAPTER 9. DETERMINATIONS OF NUCLEAR SIZE

9.1 Introduction 238
9.2 Electrical Methods 239
Mesonic X-Rays 239
Electron Scattering 242
Coulomb Energies of Mirror Nuclei 250
9.3 Nuclear Force Methods 253
Fast Neutron Cross Sections 253
Theory of Alpha Radioactivity 255
Alpha Particle Scattering 260
9.4 Neutron and Proton Surface Distribution 261
Conclusion 263

CHAPTER 10. RADIOACTIVE DECAY

10.1 Fundamental Laws of Decay 265
The Half-life T and the Mean-life τ 266
10.2 Decay of a Mixture of Two Unstable Isotopes 268
10.3 Radioactive Series 270
10.4 Radioactive Branching 274
10.5 Artificial Production of Radioactive Isotopes 276
10.6 Statistical Fluctuations in Radioactive Decay 279
Poisson Distribution 281
The Interval Distribution 284
10.7 Measurement of Decay Constants 286

CHAPTER 11. THE DETECTION OF NUCLEAR RADIATION

11.1 Introduction 298
11.2 The Ionization Chamber 305
11.3 The Proportional Counter 313
11.4 The Geiger Counter 317
11.5 The Scintillation Counter 321
11.6 Cherenkov Counters 329
11.7 Semiconductor Counters 335
11.8 Nuclear Emulsions 237
11.9 The Cloud Chamber 342
11.10 The Bubble Chamber 247
11.11 The Spark Chamber 351

CHAPTER 12. ELECTRONIC TECHNIQUES

12.1 Differentiation and Integration 354
Pulse Ionization Chamber 356
12.2 Pulse Amplifier 358
12.3 Voltage Discriminators 360
Single Channel Pulse Height Analyser 362
Multi-channel Pulse Height Analyser (Kick-sorter) 363
12.4 The Univibrator 363
12.5 Scaling Circuits 365
Gas-filled Counting Tube (Dekatron) 367
12.6 Coincidence Circuits 369
"Fast–Slow" Coincidence Method 371
Delayed Coincidence Method 373
Anticoincidence Circuit 375
12.7 Future Developments 375

CHAPTER 13. ALPHA AND GAMMA RADIATION

13.1 Summary of Properties of Alpha Radiation 378
13.2 Alpha Instability 379

13.3 Elementary Theory of Alpha Decay 381
13.4 The Fine Structure of Alpha Ray Energies 384
13.5 Multi-body Theories of Alpha Decay 388
(1) Statistical Model 388
(2) Nucleon Overlap Model 389
13.6 Alpha Decay of Spheroidal Nuclei 390
13.7 Gamma Radiation 392
13.8 Angular Correlations 398
13.9 Measurement of Gamma Ray Energies 403
13.10 Resonance Fluorescence 410
13.11 The Mössbauer Effect 414
Test of the Principle of Equivalence 416

CHAPTER 14. BETA DECAY

14.1 Introduction 420
14.2 Measurement of Beta Ray Energies 425
The Double Focusing Spectrometer 428
Magnetic Lens Spectrometers 430
14.3 Theory of Beta Decay 431
Fermi Theory (1934) 432
Fermi and Gamow–Teller Transitions 439
14.4 Muon Decay 441
14.5 Direct Evidence for the Antineutrino 443
The Davis Experiment 446
14.6 Double Beta Decay 446
14.7 Violation of Parity Conservation in Beta Decay 447
Beta Decay of Polarized Co^{60} Nuclei 448
14.8 The Helicity of Particles in Beta Decay 451
14.9 Internal Conversion 456

CHAPTER 15. THE NEUTRON

15.1 Discovery 461
15.2 Neutron Sources 463
Radioactive Sources 463
Photoneutron Sources 464
Charged Particle Sources 465
Ultrafast Neutrons 466
X-ray Sources 467
Reactor Sources 467
15.3 Neutron Detection 467
15.4 Basic Properties of the Neutron 471
Neutron Spin 471
Mass 472
Beta Decay of Free Neutron 473
Neutron–Electron Interaction 475

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15.5 Neutron Reactions—Resonances 476
The $1/v$ Law 480
Doppler Width 481
15.6 Measurements of Neutron Cross Sections as a Function of Energy 482
Crystal Spectrometer 482
Mechanical Velocity Selectors ("Choppers") 484
Electrically Pulsed Neutron Sources 486
15.7 Inelastic Scattering of Neutrons (n, n') 487
15.8 Neutron Optics 490
Neutron Refraction and Reflection 494
Neutron Filters 496
Neutron Polarization 496
15.9 The Slowing-Down of Fast Neutrons 498

CHAPTER 16. NUCLEAR MAGNETISM

16.1 Molecular Beam Resonance Methods 504
The Quadrupole Moment of the Deuteron 509
The Magnetic Moment of the Neutron 510
16.2 Nuclear Magnetic Resonance in Bulk Matter 512
16.3 Optical Detection of Nuclear Magnetic Resonance 519
16.4 The Magnetic Moment of the Muon 522

CHAPTER 17. NUCLEAR FISSION

17.1 Introduction 529
17.2 Mass Distribution of Fission Fragments 532
17.3 Distribution of Fission Energy 534
17.4 Spontaneous Fission 535
17.5 Average Number of Neutrons Released in Fission 536
17.6 Fission Cross Sections 536
17.7 Theory of Nuclear Fission 538
Theory of Spontaneous Fission 542
17.8 The Angular Distribution of Fission Fragments 543

CHAPTER 18. PARTICLE ACCELERATORS

18.1 Introduction 548
18.2 "Potential Drop" Accelerators 550
Voltage-multiplier Unit 550
Van de Graaff Accelerator 551
The Tandem Van de Graaff 553
18.3 The Cyclotron 556
18.4 The Synchrocyclotron 562
18.5 The Proton Synchrotron 565
18.6 The A—G Synchrotron 572
18.7 The Betatron 576
18.8 The Electron Synchrotron 578

18.9 The Linear Accelerator 580
The Travelling-wave Electron Accelerator 581
The Proton Linear Accelerator 583
18.10 Conclusion 585

CHAPTER 19. NUCLEAR FORCES

19.1 The Deuteron 588
Elementary Meson Theory of $V(r)$ 592
The Tensor Force 595
19.2 The Scattering of Neutrons by Protons 598
The Spin Dependence of the n–p Force 606
19.3 Proton–Proton Scattering 610
19.4 High Energy Nucleon–Nucleon Scattering 612

CHAPTER 20. NUCLEAR REACTIONS AND NUCLEAR MODELS

20.1 Introduction 617
20.2 General Limitations on Neutron Cross Sections 621
20.3 The Compound Nucleus 623
Ghoshal's Experiment 624
Breit–Wigner Dispersion Theory 626
20.4 The Experimental Study of Excited States of Nuclei 626
20.5 Energy Levels of Mirror Nuclei 630
20.6 The Optical Model 632
20.7 Stripping and Pick-up Reactions 638
20.8 Photonuclear Reactions 645
20.9 Heavy Ion Nuclear Reactions 652
20.10 Angular Correlations in Nuclear Reactions 656
20.11 Nuclear Shell Model 663
Empirical Evidence for the Shell Model 667
Nucleon Clusters 675
20.12 Collective Model and Nuclear Spectra 676
20.13 Nuclear Reactions at High Energies 678

CHAPTER 21. ELEMENTARY PARTICLES

21.1 Introduction 682
21.2 Conservation of Isospin 689
21.3 The Electromagnetic Interaction (Electron, Positron, and Photon) 692
Positronium 694
Helicity of Electron and Positron 695
The Photon 695
21.4 The Neutrino and Antineutrino 697
21.5 The Muon 700
$\pi \rightarrow \mu \rightarrow e$ Decay 702
Mean-life of Muon 702
Muon Spin and Magnetic Moment 703
Non-conservation of Parity in $\pi \rightarrow \mu \rightarrow e$ Sequence 703

Helicities of Leptons and Antileptons in $\pi \to \mu \to e$ Sequence 705
Negative Muon Orbital Capture 707
21.6 The Pion 707
Mean-life of the Charged and Neutral Pion 708
Intrinsic Spin of the π^+, π^-, and π^0 particles 710
Intrinsic Parity of the Negative Pion 711
The Scattering of Charged Pions by Protons 712
Photopion Production from Protons 716
21.7 Nucleons and Antinucleons 718
The Discovery of the Antiproton 719
Electric and Magnetic Structure of the Proton and Neutron 723
21.8 The Strange Particles: K Mesons and Hyperons 724
Parity Non-conservation in K Meson Decays 730
Isospin and Strangeness 732
21.9 Neutral K Meson as a Particle Mixture 737
21.10 Hypernuclei 739
21.11 The Resonance States of Elementary Particles: Y^* and K^* 742
21.12 The Two-Pion and Three-Pion Resonances 743
21.13 The Universal Weak Interaction 746
21.14 Conclusion 749

CHAPTER 22. THERMONUCLEAR REACTIONS IN STARS

22.1 Introduction 751
22.2 Astrophysical Background 753
22.3 Thermonuclear Reactions 759
22.4 Thermonuclear Reactions in the Sun 762
Carbon–Nitrogen Cycle 763
22.5 The Origin of the Elements 766
22.6 The Eight Synthesizing Processes 770
Helium Burning 771
The α-Process 772
The e-Process 773
22.7 Stellar Neutron Sources 774
The s-Process 774
The r-Process 774
Time Scale of Nuclear Synthesis 776
22.8 The Age of Our Galaxy 777
22.9 Conclusion 779

APPENDIX A. TABLE OF PHYSICAL CONSTANTS 782

APPENDIX B. PAULI SPIN OPERATORS AND ISOSPIN (ISOTOPIC SPIN) OPERATORS 784

APPENDIX C. RECENT ADDITIONS 789

ANSWERS TO PROBLEMS 793

NAME INDEX 797

SUBJECT INDEX 803

CHAPTER 1

INTRODUCTION

1.1. KINETIC THEORY OF MATTER

The atomic theory of matter discussed more than 2000 years ago by the Greek philosophers Democritus and Lucretius lay dormant until the beginning of the nineteenth century. John Dalton in 1808 pointed out that the quantitative laws of chemical compostion, derived from the gravimetric measurements of the substances involved in chemical reactions, could be explained in terms of an atomic theory. The fact, for example, that gases combine chemically in simple proportions, was interpreted in terms of atoms of certain elements combining to form molecules. Atoms of the same element were postulated to be identical in all respects: size, shape, weight, chemical affinity. In spite of the great advance in chemistry brought about by the Dalton atomic theory there existed as late as 1900 a school of scientists who were reluctant to accept the reality of atoms. Their main objection was the lack of direct evidence of individual atoms and at the time it seemed unlikely that such evidence would ever be found.

The molecular theory of matter was developed in physics in relation to the properties of gases. The fact that the common gases obey the simple laws of Boyle, Charles and Dalton is a reflection of the gaseous state rather than of the individual properties of the constituent molecules. Maxwell and independently Boltzmann, in the second half of the nineteenth century, developed with great skill the statistical theory known as the "Kinetic Theory of Gases". In dealing with the enormous number of molecules in one cubic centimetre of gas, about 10^{19} at S.T.P., a mathematical theory dealing with the motion of each individual molecule is impossible. The only hope of deriving any useful theoretical results is to deal with a large collection of molecules by statistical methods.

Pressure of a Gas

The pressure exerted by a gas on the walls of its containing vessel is a macroscopic manifestation of the rate at which momentum is communicated to unit area of the walls by the rebounding molecules. The pressure p of an ideal gas is given by the expression

$$p = \frac{1}{3} mn\overline{c^2} \qquad (1)$$

where m is the mass of a single molecule,
n is the number of molecules per unit volume,
$mn = \varrho$, where ϱ is the density of the gas.
$\overline{c^2}$ is the mean square speed of the molecules.

From equation (1), the root mean square speed, $c_{\text{R.M.S.}} = \sqrt{\overline{c^2}}$ is given by

$$c_{\text{R.M.S.}} = \sqrt{\frac{3p}{\varrho}} \tag{2}$$

Typical values at S.T.P. are 1,840 and 460 m per sec for hydrogen and oxygen respectively.

Equipartition of Energy

Combining equation (1) with the equation of state for 1 mole of ideal gas $PV = RT$, the average kinetic energy of a molecule can be expressed in terms of Boltzmann's constant k

$$\frac{1}{2}m\overline{c^2} = \frac{3}{2}kT \tag{3}$$

where $k = R/N$, N being Avogadro's number. Equation (3) is a special case of Boltzmann's Equipartition of Energy theorem which states that the average energy per degree of freedom of a molecule is equal to $\frac{1}{2}kT$. For a monatomic gas, each atom has three degrees of freedom corresponding to the three independent components of translational momentum of the centre of mass of the atom. Diatomic molecules in a gas have five degrees of freedom, the two extra degrees being associated with two independent internal rotations about axes perpendicular to the chemical bond joining the two atoms. Classical Physics cannot account for the absence of rotation of the molecule about the chemical bond or why, below 60°K, hydrogen gas molecules cease to rotate. This behaviour can only be explained in terms of the quantum theory. The equipartition theory is based on the assumption that as a result of many collisions between the particles of a system, a steady state is established with the total available energy equally divided between the individual degrees of freedom. A bold application of the theorem has been made by Fermi to explain the mechanism of acceleration of cosmic ray particles (mainly protons and other light atomic nuclei). There is strong astronomical evidence for the existence of moving clouds of gas in interstellar space. Statistically the protons and other cosmic ray nuclei gain energy in colliding with the magnetic fields of these clouds, until the total available energy is shared between the cosmic ray particles and the moving gas clouds† according to the equipartition principle.

† The "temperature" of the assembly of gas clouds is very high.

The Distribution of Molecular Speeds

The individual kinetic energies of the molecules of a gas are spread out over a wide range. This is not surprising in view of the fact that even if at some instant all the molecules had the same energy this state of affairs would not persist for long. At normal pressure and temperature a single molecule experiences about 10^9 intermolecular collisions per second. Some of the molecules will gain energy in collisions, some will lose energy, the average energy depending on the temperature. At each collision the energy of a molecule will in general change; nevertheless the number of molecules in

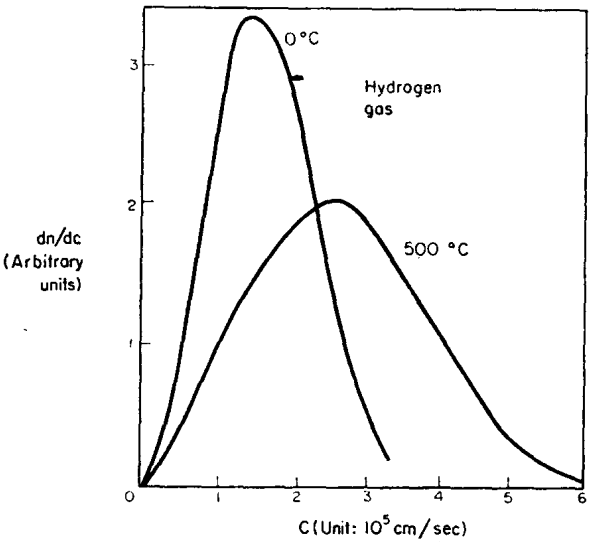

FIG. 1. Maxwell distribution of molecular velocities.

a definite small energy range will not alter, because, for every molecule scattered out of this narrow energy range one on average will be scattered into it. The steady state distribution of speeds amongst a large number of molecules in a gas at temperature T is given by the famous Maxwell law (1869).

The number of molecules dn out of a total number n, whose speed lies between c and $c + dc$ is given by

$$\frac{dn}{dc} = \frac{4n}{\sqrt{\pi}} \left(\frac{m}{2kT}\right)^{\frac{3}{2}} c^2 e^{-mc^2/2kT} \tag{4}$$

For small speeds, $mc^2/2kT \ll 1$, dn/dc is small as the term c^2 dominates the distribution; for high speeds the value of dn/dc is again small because the negative exponent of the exponential factor, which is the kinetic energy of a molecule of speed c divided by the thermal energy kT, is numerically

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