

# Contents

|  |          |
|--|----------|
| <b>1. Nuclear Concepts .....</b>                           | <b>1</b> |
| 1. Introduction.....                                       | 1        |
| 2. Terrestrial Nuclear Energy.....                         | 2        |
| 3. Space Exploration and Nuclear Power .....               | 3        |
| 4. Medicine and Nuclear Principles .....                   | 4        |
| 5. Nuclear Principles for Homeland Security .....          | 6        |
| 6. Book Content .....                                      | 7        |
| <br>   |          |
| <b>2. Atomic Theory .....</b>                              | <b>9</b> |
| 1. Introduction.....                                       | 9        |
| 2. Atomic Models .....                                     | 10       |
| 2.1 The Cannonball Atomic Model .....                      | 10       |
| 2.2 The Plum Pudding Atomic Model .....                    | 12       |
| 2.3 Millikan’s Experiment .....                            | 14       |
| 2.4 The Planetary Atomic Model.....                        | 15       |
| 2.4.1 Disproof of Thomson’s Plum Pudding Atomic Model..... | 15       |
| 2.4.2 Idea of a Nucleus in the Center of an Atom.....      | 18       |
| 2.4.3 Rutherford’s Scattering Formula .....                | 24       |
| 2.4.4 Stability of the Planetary Atomic Model .....        | 27       |
| 2.5 The Smallness of the Atom.....                         | 28       |
| 2.6 The Quantum Atomic Model.....                          | 29       |
| 2.6.1 Quantum Leap.....                                    | 29       |
| 2.6.2 Absorption and Emission of Photons.....              | 30       |
| 2.6.3 The Bohr Model of the Hydrogen Atom.....             | 31       |
| 2.7 Atomic Spectra .....                                   | 34       |
| 2.7.1 The Balmer–Rydberg Formula .....                     | 35       |

|  |           |
|--|-----------|
| 2.7.2 Properties of the Hydrogen Atom According to Bohr's Atomic Model ..... | 37        |
| 2.7.3 Ionization and Excitation .....  | 40        |
| 2.7.4 Hydrogen-Like Ions .....   | 42        |
| 2.7.5 Empirical Evidence of Bohr's Theory .....                              | 44        |
| 2.8 Atoms of Higher $Z$ .....  | 47        |
| 2.8.1 Quantum Numbers .....  | 47        |
| 2.8.2 The Pauli Exclusion Principle .....                                    | 50        |
| 2.8.3 The Aufbau Principle .....   | 52        |
| 2.8.4 Screening Effect .....   | 52        |
| 2.9 The Periodic Table and Properties of the Elements .....                  | 53        |
| 2.9.1 Ground States of Atoms .....   | 55        |
| 2.9.2 Excited States of Atoms .....  | 56        |
| 2.9.3 Atomic Radius .....  | 57        |
| 2.9.4 Ionization Energy .....  | 59        |
| 2.9.5 Independent Particle Approximation for Electrons .....                 | 61        |
| 2.10 Atomic Parameters .....   | 63        |
| Applications .....   | 66        |
| Problems .....   | 67        |
| <b>3. Nuclear Theory .....</b>   | <b>71</b> |
| 1. Introduction .....  | 71        |
| 2. The Nucleus .....   | 72        |
| 2.1 Size, Shape and Density of Nucleus .....                                 | 73        |
| 2.2 Equivalence of Mass and Energy .....                                     | 74        |
| 2.3 Binding Energy of a Nucleus .....  | 78        |
| 2.4 Stability of the Nucleus .....   | 81        |
| 2.5 Protons and Neutrons .....   | 82        |
| 2.5.1 Protons and Proton Decay .....   | 83        |
| 2.5.2 Neutrons and Neutron Decay .....                                       | 84        |
| 2.6 Nuclear Forces .....   | 88        |
| 2.7 The Pauli Exclusion Principle and the Symmetry Effect .....              | 90        |
| 2.8 Excited States of Nuclei .....   | 92        |
| 2.9 Independent Particle Approximation for Nucleons .....                    | 93        |
| 3. Nuclear Models .....  | 95        |
| 3.1 The Liquid Drop Model and the Semi-empirical Mass Formula ...            | 96        |
| 3.2 The Shell Model .....  | 101       |
| Applications .....   | 104       |
| Problems .....   | 111       |

|  |            |
|--|------------|
| <b>4. Duality of Nature .....</b>                              | <b>115</b> |
| 1. Planck's Theory of Quanta .....                             | 116        |
| 1.1 Black Body Radiation .....                                 | 117        |
| 1.2 Wein's Displacement Law .....                              | 119        |
| 1.3 The Stefan–Boltzmann Law .....                             | 119        |
| 1.4 The Rayleigh–Jeans Law .....                               | 120        |
| 1.5 Planck's Law .....   | 121        |
| 2. The Wave–Particle Duality .....                             | 121        |
| 2.1 De Broglie's Hypothesis .....                              | 122        |
| 2.2 Double-Slit Experiment .....                               | 125        |
| 2.3 Experimental Evidence for the Wave–Particle Duality .....  | 130        |
| 2.4 The Uncertainty Principle .....                            | 133        |
| 3. Schrödinger Equation .....                                  | 138        |
| 3.1 Interpretation of Quantum Mechanics .....                  | 138        |
| 3.2 Standing Waves .....                                       | 140        |
| 3.3 Quantum Waves .....  | 142        |
| 3.4 General Characteristics of the Quantum Wave Function ..... | 143        |
| 3.5 Wave Function for a Particle in an Infinite Well .....     | 145        |
| 3.6 A Wave Function for a Free Non-Relativistic Particle ..... | 147        |
| 3.7 Tunneling Phenomena .....                                  | 148        |
| 3.8 Hydrogenic Wave Functions .....                            | 151        |
| 3.9 Quantization of Angular Momentum .....                     | 151        |
| Applications .....   | 156        |
| Numerical Example .....  | 162        |
| Problems .....   | 162        |
| <br>   |            |
| <b>5. Radioactive Decay .....</b>                              | <b>169</b> |
| 1. Introduction .....  | 169        |
| 2. Mechanism of Radioactive Decay .....                        | 171        |
| 3. Kinetics of Radioactive Decay .....                         | 174        |
| 3.1 Decay Constant .....                                       | 174        |
| 3.2 Radioactive Decay .....                                    | 174        |
| 3.3 Activity .....   | 175        |
| 3.3.1 Definition .....   | 175        |
| 3.3.2 Units .....  | 176        |
| 3.4 Half-Life .....  | 176        |
| 3.5 Radioactive Decay Equilibrium .....                        | 179        |
| 3.6 Production of Radioisotopes .....                          | 185        |
| 4. Alpha Decay .....   | 187        |
| 4.1 Mechanism of Alpha Decay .....                             | 187        |
| 4.2 Kinetics of Alpha Decay .....                              | 192        |
| 5. Beta Decay .....  | 193        |

|   |            |
|---|------------|
| 5.1 Mechanism of Beta Decay .....   | 193        |
| 5.2 Kinetics of Beta-Minus Decay .....  | 197        |
| 5.3 Kinetics of Beta-Plus Decay .....   | 199        |
| 5.4 Kinetics of Orbital Electron Capture .....  | 201        |
| 5.5 Kinetics of Internal Conversion .....   | 203        |
| 5.6 Auger Electrons .....   | 204        |
| 6. Gamma Decay .....  | 205        |
| 6.1 Mechanics of Gamma Decay .....  | 205        |
| 6.2 Kinetics of Gamma Decay .....   | 206        |
| 7. Natural Radioactivity .....  | 207        |
| 8. Nuclear Isomerism .....  | 211        |
| Numerical Example .....   | 211        |
| Problems .....  | 213        |
| <b>6. Interactions of Radiation with Matter .....</b>                                       | <b>217</b> |
| 1. Introduction .....   | 217        |
| 2. Interactions of Charged Particles .....  | 218        |
| 2.1 Types of Interactions .....   | 218        |
| 2.1.1 Elastic Scattering of Charged Particles .....   | 218        |
| 2.1.2 Inelastic Scattering of Charged Particles with Electrons ...                          | 222        |
| 2.1.3 Inelastic Scattering of Charged Particles with a Nucleus ..                           | 222        |
| 2.2 Loss of Energy .....  | 225        |
| 2.2.1 Stopping Power ( $-dE/dx$ ) .....   | 225        |
| 2.2.2 Relative Stopping Power .....   | 227        |
| 2.2.3 Secondary Electrons .....   | 228        |
| 2.2.4 Specific Ionization and Ion Pairs .....   | 230        |
| 2.2.5 Range of Interactions .....   | 231        |
| 3. Alpha Particles and Protons .....  | 234        |
| 3.1 Mechanism of Energy Loss .....  | 234        |
| 3.2 Range–Energy Relationship .....   | 235        |
| 4. Beta Particles (Electrons and Positrons) .....   | 240        |
| 4.1 Mechanism of Energy Loss .....  | 240        |
| 4.2 Range–Energy Relationship .....   | 246        |
| 5. Photons (Gamma and X-rays) .....   | 250        |
| 5.1 Exponential Absorption Law .....  | 250        |
| 5.2 Mechanism of Energy Loss .....  | 255        |
| 5.2.1 Photoelectric Effect ( $\gamma + \text{atom} \rightarrow e^- + \text{ion}$ ) .....    | 256        |
| 5.2.2 Compton Effect ( $\gamma + \text{Atom} \rightarrow \gamma + e^- + \text{Ion}$ ) ..... | 264        |
| 5.2.3 Correction for Bound Electrons and Coherent<br>(Rayleigh) Scattering .....            | 270        |
| 5.2.4 Pair Production ( $\gamma + \text{Atom} \rightarrow e^+ + e^- + \text{Atom}$ ) .....  | 272        |
| Numerical Example .....   | 275        |
| Problems .....  | 276        |

|  |                |
|--|----------------|
| <b>7. Neutron Physics .....</b>  | <b>281</b>     |
| 1. Introduction.....   | 282            |
| 2. Nuclear Interactions .....  | 282            |
| 3. Neutron Sources and Neutron Classification .....                        | 286            |
| 4. Neutron Attenuation .....   | 289            |
| 4.1 Concept of the Cross Section.....                                      | 289            |
| 4.2 Probability of Neutron Interactions .....                              | 296            |
| 4.3 Neutron Mean Free Path.....  | 298            |
| 4.4 Reaction Rate and Concept of Neutron Flux<br>and Neutron Current ..... | 299            |
| 4.5 Neutron Interactions .....   | 312            |
| 4.5.1 Elastic Scattering ( $n, n$ ).....                                   | 315            |
| 4.5.2 Inelastic Scattering ( $n, n'$ ).....                                | 317            |
| 4.5.3 Radiative Capture ( $n, \gamma$ ) .....                              | 320            |
| 4.5.4 Charged Particle Emission ( $n, \alpha$ ), ( $n, p$ ) .....          | 324            |
| 4.5.5 Hydrogen and Deuterium.....  | 326            |
| 4.5.6 Cross Sections for Different Neutron Interactions.....               | 328            |
| 4.5.7 Breit–Wigner Formula and Resonance Width .....                       | 332            |
| 4.6 Maxwell–Boltzmann Distribution .....                                   | 338            |
| 4.7 Doppler Broadening.....  | 344            |
| 4.8 Neutron Beam Attenuation and Neutron Activation.....                   | 346            |
| 5. Fission.....  | 350            |
| 5.1 Mechanism of the Fission Process.....                                  | 350            |
| 5.2 Fission Rate and Reactor Power .....                                   | 355            |
| 5.3 Fission Neutrons .....   | 357            |
| 5.4 Fission $\gamma$ Rays .....  | 359            |
| 5.5 Fission Products.....  | 360            |
| 5.5.1 Fission Yield .....  | 360            |
| 5.5.2 Formation and Removal of Fission Products in a Reactor.....          | 362            |
| 5.6 Energy Released in Fission.....  | 365            |
| 5.7 Spontaneous Fission .....  | 366            |
| Applications.....  | 367            |
| Numerical Example .....  | 370            |
| Problems .....   | 371            |
| <br><b>8. Neutron Transport.....</b>                                       | <br><b>377</b> |
| 1. Introduction.....   | 377            |
| 2. Concept of Time-Independent Neutron Transport.....                      | 378            |
| 2.1 The Nuclear Chain Reaction.....  | 378            |
| 2.2 Fick’s Law .....   | 379            |
| 2.3 Diffusion Coefficient and Diffusion Length.....                        | 381            |
| 2.4 Neutron Diffusion Theory .....   | 387            |

|   |     |
|---|-----|
| 2.4.1 One-Speed Neutron Diffusion Equation .....  | 387 |
| 2.4.2 Solution to One-Speed Neutron Diffusion<br>Equation from a Point and Plane Source in Infinite<br>Medium ..... | 390 |
| 2.4.3 Solution to One-Speed Neutron Diffusion Equation<br>in Finite Medium.....                                     | 394 |
| 2.4.4 Neutron Diffusion in Multiplying Medium .....   | 399 |
| 2.4.5 Solution to One-Speed Neutron Diffusion<br>Equation in Infinite Slab Bare Reactor .....                       | 403 |
| 2.4.6 Solution to One-Speed Neutron Diffusion<br>Equation in Rectangular Bare Parallelepiped Reactor .....          | 408 |
| 2.4.7 Solution to One-Speed Neutron Diffusion Equation<br>in Spherical Bare Reactor .....                           | 411 |
| 2.4.8 Solution to One-Speed Neutron Diffusion Equation<br>in Cylindrical Bare Reactor.....                          | 413 |
| 2.4.9 Two-Group Neutron Diffusion Theory .....  | 416 |
| 2.4.10 Multi-Group Neutron Diffusion Theory .....   | 420 |
| 3. Slowing Down of Neutrons .....   | 421 |
| 3.1 Elastic Scattering in the Moderating Region .....   | 422 |
| 3.2 Energy Distribution in Elastic Scattering –<br>Logarithmic Energy Decrement.....                                | 428 |
| 3.3 Average Cosine of the Scattering Angle.....   | 432 |
| 3.4 Slowing Down of Neutrons in Infinite Medium .....   | 433 |
| 3.4.1 Slowing Down Density (Neutron Moderation)<br>Without Absorption .....   | 433 |
| 3.4.2 Lethargy .....  | 436 |
| 3.4.3 Slowing Down Density (Neutron Moderation)<br>with Absorption .....  | 438 |
| 3.5 Spatial Distribution of the Slowing Down Neutrons .....   | 440 |
| 3.5.1 Fermi Model.....  | 440 |
| 3.5.2 Migration Length .....  | 445 |
| 4. Neutron Transport in Thermal Reactors .....  | 446 |
| 4.1 Neutron Lifetime in Thermal Reactors .....  | 446 |
| 4.2 Homogeneous and Heterogeneous Reactors.....   | 450 |
| 4.3 Bare and Reflected Reactors .....   | 454 |
| 5. Concept of the Time-Dependent Neutron Transport.....   | 455 |
| 5.1 Neutron Lifetime and Reactor Period Without<br>Delayed Neutrons .....   | 456 |
| 5.2 Delayed Neutrons and Average Neutron Lifetime .....   | 459 |
| 5.3 Diffusion Equation for Transient Reactor.....   | 462 |
| 5.3.1 Time-Dependent Infinite Slab Reactor .....  | 462 |
| 5.3.2 Derivation of the Point Kinetics Equations.....   | 466 |

|  |            |
|--|------------|
| 5.3.3 Solution of the Point Kinetics Equations .....                                       | 469        |
| 5.3.4 The Inhour Equation .....  | 471        |
| 5.4 The Prompt Jump Approximation and Inhour Formula.....                                  | 473        |
| Numerical Example .....  | 477        |
| Problems .....   | 485        |
| <b>9. Nuclear Reactor Control.....</b>   | <b>491</b> |
| 1. Methods of Reactor Control .....  | 491        |
| 1.1 Control Rods .....   | 491        |
| 1.1.1 Effect of Fully Inserted Control Rod on Neutron<br>Flux in Thermal Reactors.....     | 492        |
| 1.1.2 Control Rod Worth in Fast Reactors.....  | 494        |
| 1.1.3 Effect of Partially Inserted Control Rod on<br>Neutron Flux in Thermal Reactors..... | 495        |
| 1.2 Chemical Shim.....   | 498        |
| 2. Fission Product Poisoning .....   | 499        |
| 2.1 Xenon Poisoning.....   | 501        |
| 2.1.1 Production and Removal of $^{135}\text{Xe}$ During<br>Reactor Operation .....        | 501        |
| 2.1.2 Xenon Poisoning After Reactor Shutdown.....  | 506        |
| 2.2 Samarium Poisoning .....   | 508        |
| 2.2.1 Production and Removal of $^{149}\text{Sm}$ During<br>Reactor Operation .....        | 508        |
| 2.2.2 Samarium Poisoning After Reactor Shutdown .....                                      | 509        |
| 3. Temperature Effects on Reactivity .....   | 510        |
| 3.1 Temperature Coefficients .....   | 510        |
| 3.2 Fuel Temperature Coefficient (Nuclear Doppler Effect).....                             | 512        |
| 3.3 The Void Coefficient .....   | 513        |
| 3.4 The Moderator Coefficient .....  | 514        |
| 3.4.1 Moderator Temperature Coefficient .....  | 514        |
| 3.4.2 Moderator Pressure Coefficient .....   | 515        |
| Numerical Example .....  | 515        |
| Problems .....   | 516        |
| <b>Appendix 1: World Wide Web Sources on Atomic<br/>and Nuclear Data.....</b>              | <b>519</b> |
| <b>Appendix 2: Atomic and Nuclear Constants.....</b>                                       | <b>521</b> |
| <b>Appendix 3: Prefixes .....</b>  | <b>523</b> |
| <b>Appendix 4: Units and Conversion Factors .....</b>                                      | <b>525</b> |

**Appendix 5: Neutron Angular Momentum and Spin.....527**

**Appendix 6: Gradient ..... 531**

**Appendix 7:  $k_{eff}$  in Two-Group Diffuion Theory .....533**

**Bibliography..... 537**

**Index.....541**