Contents

1 Introduction 1
1.1 The Constituents and Basic Structure of Atomic Nuclei 1
1.2 Properties of Particles Relevant to Nuclear Physics 2
1.3 The Role of Various Forces 6
1.4 Useful Physical Quantities 7
1.5 Species of Nuclei 8
1.6 Column: QCD Phase Diagram of Nuclear Matter 11
References 12

2 Bulk Properties of Nuclei 13
2.1 Nuclear Sizes 13
2.1.1 Rutherford Scattering 13
2.1.2 Electron Scattering 17
2.1.3 Mass Distribution 25
2.2 Number Density and Fermi Momentum of Nucleons 28
2.2.1 Number Density of Nucleons 28
2.2.2 Fermi Momentum: Fermi-Gas Model, Thomas–Fermi Approximation 28
2.3 Nuclear Masses 31
2.3.1 The Binding Energies: Experimental Data and Characteristics 32
2.3.2 The Semi-empirical Mass Formula (The Weizsäcker–Bethe Mass Formula)—The Liquid-Drop Model 42
2.3.3 Applications of the Mass Formula (1): The Stability Line, the Heisenberg Valley 43
2.3.4 Applications of the Mass Formula (2): Stability with Respect to Fission 46
2.3.5 Application to Nuclear Power Generation 57
2.3.6 Fission Isomers 60
References 64

3 The Nuclear Force and Two-Body Systems 65
3.1 The Fundamentals of Nuclear Force 65
3.1.1 The Range of Forces—A Simple Estimate by the Uncertainty Principle 65
3.1.2 The Radial Dependence 66
3.1.3 The State Dependence of Nuclear Force 67
3.2 The General Structure of Nuclear Force 71
3.2.1 Static Potentials (Velocity-Independent Potentials) 71
3.2.2 Velocity-Dependent Potentials 73
3.3 The Properties of Deuteron and the Nuclear Force 74
3.3.1 The Effect of Tensor Force: The Wave Function in the Spin–Isospin Space 74
3.3.2 The Radial Wave Function: Estimate of the Magnitude of the Force Between Proton and Neutron 77
3.4 Nucleon–Nucleon Scattering 78
3.4.1 Low-Energy Scattering: Effective Range Theory 78
3.4.2 High-Energy Scattering: Exchange Force 81
3.4.3 High-Energy Scattering: Repulsive Core 83
3.4.4 Spin Polarization Experiments 85
3.5 Microscopic Considerations: Meson Theory, QCD 85
3.6 Phenomenological Potential with High Accuracy: Realistic Potential 88
3.6.1 Hamada–Johnston Potential 89
3.6.2 Reid Potential 91
3.7 Summary of the Nuclear Force in the Free Space 91
3.8 Effective Interaction Inside Nucleus 92
3.8.1 *G*-Matrix 92
3.8.2 Phenomenological Effective Interaction 94
References 96

4 Interaction with Electromagnetic Field: Electromagnetic Moments 97
4.1 Hamiltonian of the Electromagnetic Interaction and Electromagnetic Multipole Moments 97
4.1.1 Operators for the Dipole and Quadrupole Moments 98
4.1.2 Various Corrections 100
4.1.3 Measurement of the Magnetic Moment: Hyperfine Structure 100
4.2 Electromagnetic Multipole Operators 102
4.3 Properties of the Electromagnetic Multipole Operators 103
4.3.1 Parity, Tensor Property and Selection Rule 103
4.3.2 Definition of the Electromagnetic Moments 104
References 106

5 Shell Structure 107
5.1 Magic Numbers 107
5.2 Explanation of the Magic Numbers by Mean-Field Theory 109
5.2.1 The Mean Field 109
5.2.2 Energy Levels for the Infinite Square-Well Potential 110
5.2.3 The Harmonic Oscillator Model 111
5.2.4 The Magic Numbers in the Static Potential Due to Short Range Force 112
5.2.5 Spin–Orbit Interaction 114
5.3 The Spin and Parity of the Ground and Low-Lying States of Doubly-Magic ± 1 Nuclei 117
5.4 The Magnetic Dipole Moment in the Ground State of Odd Nuclei: Single Particle Model 119
5.4.1 The Schmidt Lines 120
5.4.2 Configuration Mixing and Core Polarization 121
5.4.3 [Addendum] The Anomalous Magnetic Moments of Nucleons in the Quark Model 123
5.5 Mass Number Dependence of the Level Spacing $\hbar\omega$ 124
5.6 The Magnitude and Origin of Spin–Orbit Interaction 125
5.7 Difference Between the Potentials for Protons and for Neutrons: Lane Potential 125
5.8 The Spin and Parity of Low-Lying States of Doubly-Magic ± 2 Nuclei and the Pairing Correlation 127
5.8.1 The Spin and Parity of the Ground and Low Excited States of $^{210}_{82}$Pb 127
5.8.2 The Effect of δ-Type Residual Interaction: Pairing Correlation 128
5.9 Column: Superheavy Elements (SHE) 130
References 133

6 Microscopic Mean-Field Theory (Hartree–Fock Theory) 135
6.1 Hartree–Fock Equation 135
6.1.1 Equivalent Local Potential, Effective Mass 136
6.1.2 Nuclear Matter and Local Density Approximation 137
6.1.3 Saturation Property in the Well-Behaved Potential, Constraint to the Exchange Property 140
6.2 Skyrme Hartree–Fock Calculations for Finite Nuclei 141
6.2.1 Skyrme Force 141
6.2.2 Skyrme Hartree–Fock Equation 143
6.2.3 Energy Density and Determination of Parameters 144
6.2.4 Comparison with the Experimental Data 147
6.2.5 The Equation of State, Saturation, Spinodal Line, Surface Thickness 148
6.2.6 Beyond the Hartree–Fock Calculations: Nucleon–Vibration Coupling; ω-Mass 154

6.3 Relativistic Mean-Field Theory ($\sigma\omega\rho$ Model) . . . 155
6.3.1 Lagrangian . . . 156
6.3.2 Field Equations . . . 157
6.3.3 The Mean-Field Theory . . . 158
6.3.4 Prologue to How to Solve the Mean-Field Equations . . . 158
6.3.5 Non-relativistic Approximation and the Spin–Orbit Coupling . . . 160
6.3.6 Parameter Sets . . . 161
6.4 Pairing Correlation . . . 162
6.4.1 Overview . . . 162
6.4.2 Multipole Expansion of the Pairing Correlation, Monopole Pairing Correlation Model and Quasi-Spin Formalism . . . 163
6.4.3 BCS Theory . . . 164
6.4.4 The Magnitude of the Gap Parameter . . . 168
6.4.5 The Coherence Length . . . 169
References . . . 170

7 The Shapes of Nuclei . . . 171
7.1 The Observables Relevant to the Nuclear Shape: Multipole Moments and the Excitation Spectrum . . . 171
7.2 Deformation Parameters . . . 174
7.3 The Deformed Shell Model . . . 177
7.4 Nucleon Energy Levels in a Deformed One-Body Field: Nilsson Levels . . . 180
7.5 The Spin and Parity of the Ground State of Deformed Odd Nuclei . . . 182
7.6 Theoretical Prediction of Nuclear Shape . . . 182
7.6.1 The Strutinsky Method: Macroscopic–Microscopic Method . . . 182
7.6.2 Constrained Hartree–Fock Calculations . . . 184
7.7 Column: Superdeformed States . . . 187
References . . . 188

8 Nuclear Decay and Radioactivity . . . 191
8.1 Alpha Decay . . . 191
8.1.1 Decay Width . . . 192
8.1.2 The Geiger–Nuttal Rule . . . 200
8.2 Fission . . . 200
8.3 Electromagnetic Transitions . . . 203
8.3.1 Multipole Transition, Reduced Transition Probability . . . 203
8.3.2 General Consideration of the Selection Rule and the Magnitude . . . 205
8.3.3 Single-Particle Model Estimate: Weisskopf Units and Experimental Values . . . 206

8.3.4 Connection Between Electromagnetic Transitions and the Shapes and Collective Motions of Nuclei 209
References 212

9 Synthesis of Elements 215
9.1 The Astrophysical S-Factor and Gamow Factor 215
9.2 Gamow Peak 217
9.3 Neutron Capture Cross Section 218
9.4 Synthesis of Heavy Elements: S-Process and R-Process 219
9.5 Column: Overview of the Synthesis of Elements 220
References 221

Appendix A: Important Formulae and Their Derivation 223

Index 261

http://www.springer.com/978-4-431-55377-9

Fundamentals of Nuclear Physics

Takigawa, N.; Washiyama, K.

2017, XV, 269 p. 86 illus., 6 illus. in color., Hardcover
ISBN: 978-4-431-55377-9