

Contents

Part I Nuclear Reactions

1	Introduction: Role of Nuclear Reactions in Nuclear and Particle Physics	3
1.1	Nuclear Reactions in Nuclear Spectroscopy	3
1.2	Extension of Nuclei	3
1.3	Typical Energies	5
1.3.1	Binding Energies of Nuclei	5
1.3.2	Coulomb Barrier	6
1.3.3	“Optical” Argument	7
1.4	Nuclear Reaction Models	8
1.4.1	Hierarchy of Excitations	8
1.5	Exercises	10
	References	11
2	Classical Cross Section	13
2.1	Deflection Function	13
2.2	Rutherford Scattering	15
2.2.1	Rutherford Scattering Cross Section	15
2.2.2	Minimal Scattering Distance d	16
2.2.3	Trajectories in the Point-Charge Coulomb Field	17
2.2.4	Consequences	18
2.2.5	Consequences of the Rutherford Experiments and Their Historic Significance	19
2.2.6	Quantum-Mechanical Derivation of Rutherford’s Formula	19
2.2.7	Deviations from the Rutherford Formula	20
2.3	Scattering, Density Distributions, and Nuclear Radii	21
2.3.1	Nuclear Radii from Deviations from Rutherford Scattering	21
2.3.2	Coulomb Scattering from an Extended Charge Distribution	21

2.3.3	Ansatz for Models	26
2.3.4	Expansion into Moments	26
2.3.5	Results of Hadron Scattering	28
2.4	Electron Scattering	29
2.4.1	Matter-Density Distributions and Radii	33
2.4.2	Special Cases—Neutron Skins and Halo Nuclei	33
2.5	Exercises	36
	References	37
3	Role of Conservation Laws and Symmetries in Nuclear Reactions	39
3.1	Generalities	39
3.1.1	Discrete Transformations	41
3.1.2	Continuous Transformations	41
3.2	Conserved Quantities in Nuclear Reactions	42
3.2.1	Energy Conservation	42
3.2.2	Momentum Conservation	42
3.2.3	Reaction Kinematics	43
3.2.4	Conservation of Angular Momentum	43
3.2.5	Conservation of Parity	44
3.2.6	Nuclear Reactions Under Parity Conservation	45
3.2.7	Nuclear Reactions Under Parity Violation	46
3.3	Isospin in Nuclear Reactions	48
3.3.1	Formalism	48
3.3.2	Isospin as Conserved Quantity	50
3.3.3	Isospin Breaking	51
3.4	Exchange Symmetry in Nuclear Reactions of Identical Particles	52
3.4.1	Identical Bosons with Spin $I = 0$	54
3.4.2	Identical Fermions with Spin $I = 1/2$	54
3.5	Time-Reversal Invariance	54
3.5.1	Time Reversal, Reciprocity, and Detailed Balance	56
3.5.2	Other Nuclear Observables of Possible Time Reversal Violation TRV	58
3.6	Exercises	59
	References	59
4	Cross Sections	61
4.1	General Appearance of Cross Sections	61
4.1.1	Neutral Particles—Elastic Scattering (n, n)	61
4.1.2	Neutral Particles—Inelastic Neutron Scattering	62
4.1.3	Neutral Particles—Exothermic Reactions with Thermal Neutrons (n, γ), (n, p), (n, f) etc.	63
4.1.4	Neutral Incident Particles—Endothermic Reactions ($Q < 0$) with Charged Exit Channel	63
4.1.5	Charged Particles in the Entrance and Exit Channels	64
4.1.6	Threshold Effects	64
4.1.7	Other Phenomena	65

4.2	Formal Description of Nuclear Reactions	67
4.2.1	Wave Function and Scattering Amplitude	67
4.2.2	Scattering Amplitude and Cross Section	68
4.2.3	Schrödinger Equation	69
4.2.4	The Optical Theorem	73
4.3	Remark and Exercise	74
	References	75
5	Polarization in Nuclear Reactions—Formalism	77
5.1	Polarization Formalism	77
5.2	Expectation Value and Average of Observables in Measurements	78
5.3	Density Operator, Density Matrix	78
5.3.1	General Properties of ρ	79
5.3.2	Density Matrix of the General Mixed State	79
5.3.3	Examples for Density Matrices	80
5.3.4	Complete Description of Spin Systems	84
5.3.5	Expansions of the Density Matrix, Spin Tensor Moments	85
5.4	Rotations, Angular Dependence of the Tensor Moments	97
5.4.1	Generalities	97
5.4.2	The Description of Rotations by Rotation Operators	97
5.4.3	Rotation of the Density Matrix and of the Tensor Moments	99
5.4.4	Practical Realization of Rotations	101
5.4.5	Coordinate Systems	101
5.5	Exercises	102
	References	103
6	Nuclear Reactions of Particles with Spin	105
6.1	General	105
6.2	The M Matrix	106
6.3	Types of Polarization Observables	108
6.4	Coordinate Systems	110
6.4.1	Coordinate Systems for Analyzing Powers	110
6.4.2	Coordinate Systems for Polarization Transfer	111
6.4.3	Coordinate Systems for Spin Correlations	112
6.5	Structure of the M Matrix and Number of “Necessary” Experiments	115
6.6	Examples	118
6.6.1	Systems with Spin Structure $1/2 + 0 \longrightarrow 1/2 + 0$	118
6.6.2	Systems with Spin Structure $1/2 + 1/2 \longrightarrow 1/2 + 1/2$	119
6.6.3	Systems with Spin Structure $\vec{1}/2 + \vec{1}$ and Three-Nucleon Studies	120
6.6.4	Systems with Spin Structure $\vec{1} + \vec{1}$ and $\vec{1}/2 + \vec{1}/2$ and the Four-Nucleon Systems	121

6.6.5	Practical Criteria for the Choice of Observables	121
6.7	Exercises	122
	References	122
7	Partial Wave Expansion	125
7.1	Neutral Particles	125
7.2	Charged Particles	128
7.3	Exercises	129
	References	130
8	Unpolarized Cross Sections	131
8.1	General Features	131
8.2	Inelasticity and Absorption	133
8.3	Low-Energy Behavior of the Scattering	136
8.3.1	Scattering Length a	137
8.3.2	Analytically Solvable Models for the Low-Energy Behavior	139
8.4	Exercises	141
	References	143
9	The Nucleon-Nucleon Interaction	145
9.1	The Observables of the NN Systems	145
9.1.1	NN Observables	146
9.1.2	NN Scattering Phases	148
9.1.3	NN Interaction as Exchange Force	149
9.2	Few-Nucleon Systems	152
9.2.1	The Two-Nucleon System	153
9.2.2	The Three-Nucleon System	154
9.2.3	Elastic Scattering in the Three-Nucleon System	154
9.2.4	Kinematics of Three-Nucleon Breakup Reactions	154
9.2.5	Results for the Three-Nucleon Breakup Reaction	159
9.2.6	Recent Progress in Few-Nucleon Reactions	159
9.2.7	Other Few-Nucleon Systems	162
9.3	Exercises	162
	References	165
10	Models of Reactions—Direct Reactions	167
10.1	Generalities	167
10.2	Elastic Scattering	167
10.3	Optical Model	168
10.4	Direct (Rearrangement) Reactions	169
10.5	Stripping Reactions	171
10.6	T Matrix and Born Series	174
10.6.1	Integral Equations	174
10.7	Born Approximation	175
10.7.1	First Born Approximation = PWBA = Plane Wave Born Approximation	175

10.7.2 Distorted Wave Born Approximation = DWBA	176
10.8 Details of the Born Approximations	176
10.9 Exercises	179
References	180
11 Models of Reactions—Compound-Nucleus (CN) Reactions	181
11.1 Generalities	181
11.2 Theoretical Shape of the Cross Sections	182
11.3 Derivation of the Partial-Width Amplitude for Nuclei (s Waves Only)	184
11.4 Role of Level Densities	185
11.4.1 Induced Nuclear Fission	187
11.5 Single Resonances	188
11.5.1 General Features	188
11.5.2 Alternative Description of Resonances	189
11.5.3 Overlapping Resonances	192
11.5.4 Ericson Fluctuations	192
11.5.5 Analysis of Ericson Fluctuations	196
11.5.6 Results for Level Widths	197
11.6 Complete Averaging over the CN States	197
11.6.1 Generalities	197
11.6.2 Hauser-Feshbach Formalism	199
11.7 Exercises	202
References	204
12 Intermediate Structures	207
12.1 Heavy-Ion Scattering and Molecular Resonances	207
12.2 Structures in Neutron Reactions	209
12.2.1 Neutron-Nucleus IS	209
12.2.2 Single-Particle Neutron Resonances	209
12.3 Giant Resonances	210
12.4 Fission Doorways	213
12.5 Isobaric Analog Resonances (IAR)	213
12.6 Exercises	217
References	218
13 Heavy-Ion (HI) Reactions	221
13.1 General Characteristics of HI Interactions	221
13.2 Semi-Classical Phenomena and Description	223
13.2.1 Elastic Scattering	224
13.2.2 Other HI Reaction Models	225
13.2.3 Molecular Resonances	225
13.2.4 Heavy-Ion Reactions and Superheavies SH	225
13.3 Nuclear Spectroscopy and Nuclear Reactions	226
13.4 Heavy-Ion Reactions as Special Tools for Nuclear Spectroscopy	226
13.4.1 Coulomb Excitation	226

13.4.2	Fusion-Evaporation Reactions	227
13.5	Exercises	228
	References	229
14	Nuclear Astrophysics	231
14.1	Reaction Rates	231
14.2	Typical <i>S</i> -Factor Behavior	232
14.2.1	Calculation of Reaction Rates in Plasmas	234
14.3	Exercises	239
	References	240
15	Spectroscopy at the Driplines, Exotic Nuclei, and Radioactive Ion Beams (RIB)	241
15.1	Use of RIB	241
15.1.1	Nuclear Radii and Neutron vs. Proton Distributions	241
15.1.2	Nuclear Models for Exotic Nuclei	242
15.1.3	Giant Resonances of Exotic Nuclei	242
15.2	Production of Radioactive-Ion Beams	242
15.2.1	The ISOL Principle	242
15.2.2	IFF and Post-Accelerating Schemes	243
15.3	Nuclear Reactions and the Way to Superheavies	244
	References	246
Part II Tools of Nuclear Reactions		
16	Accelerators	251
16.1	Electrostatic Accelerators	251
16.1.1	The Cockroft-Walton Accelerator	251
16.1.2	The Van-de-Graaff (VdG) Accelerator	252
16.2	RF Accelerators	255
16.2.1	The Linear Accelerator (LINAC)	255
16.2.2	The Cyclotron	255
16.2.3	Betatron and Synchrotron	258
16.3	Beam Forming and Guiding Elements	260
16.3.1	Electrostatic Lenses	262
16.3.2	Magnetic Lenses	263
16.3.3	Strong Focusing	265
16.4	Ion Sources	266
16.4.1	Unpolarized Beams	266
16.4.2	Polarized Beams and Targets	269
16.5	Physics and Techniques of the Ground-State Atomic Beam Sources ABS	271
16.5.1	Production of H and D Ground-State Atomic Beams	271
16.5.2	Dissociators, Beam Formation and Accommodation	272
16.5.3	State-Separation Magnets—Classical and Modern Designs	273
16.5.4	RF Transitions	275

16.6	Ionizers	279
16.6.1	Ionizers—Electron-Bombardment and Colliding-Beams Designs	279
16.6.2	Sources for Polarized ${}^6,{}^7\text{Li}$ and ${}^{23}\text{Na}$ Beams	283
16.6.3	Optically Pumped Polarized Ion Sources (OPPIS)	283
16.7	Physics of the Lambshift Source LSS	284
16.7.1	The Lamb Shift	284
16.7.2	Level Crossings and Quench Effect	285
16.7.3	Enhancement of Polarization	286
16.7.4	Production and Maximization of the Beam Polarization	288
16.8	Spin Rotation in Beamlines and Precession in a Wien Filter	293
16.8.1	Spin Rotation in Beamlines	294
16.8.2	Spin Rotation in a Wien Filter	295
16.9	Exercises	297
	References	299
17	Detectors, Spectrometers, and Electronics	301
17.1	Ionization Chambers	301
17.2	Scintillation Detectors	302
17.3	Solid-State Detectors	303
17.3.1	Si Detectors	304
17.3.2	Particle Identification	306
17.3.3	Magnetic Spectrographs	306
17.3.4	Ge Detectors	307
17.4	Neutrons	309
17.4.1	Production of Neutrons	309
17.5	Neutron Detectors	310
17.5.1	Neutron-Induced Reactions	311
17.5.2	Neutrons as Reaction Products	311
17.5.3	Different Neutron Detection Methods Depending on Neutron Energies	311
17.6	Polarized Neutrons	313
17.6.1	Magnetized Materials	313
17.6.2	Polarized ${}^3\text{He}$ as Spin Filter	314
17.7	γ Spectroscopy	315
	References	318

Part III Applications of Nuclear Reactions and Special Accelerators

18	Medical Applications	321
18.1	Particle (Hadron) Tumor Therapy	321
18.2	Isotope Production	323
18.3	Exercises	324
	References	325

19	Nuclear-Energy Applications	327
19.1	Fusion-Energy Research	327
19.1.1	Fusion Basics	327
19.1.2	Nuclear Cross Sections	327
19.2	Five-Nucleon Fusion Reactions	328
19.2.1	“Polarized” Fusion	329
19.3	Four-Nucleon Reactions	331
19.3.1	Suppression of Unwanted DD Neutrons	332
19.3.2	Possible Reaction-Rate Enhancement for the DD Reactions by Polarization?	334
19.4	Other Fusion Reactions	334
19.5	Present Status of “Polarized” Fusion	334
19.6	New Calculations for Few-Body Systems	335
19.6.1	Theoretical Approaches	336
19.7	New Aspects of Polarized Fusion	337
19.7.1	Effect of Electron Screening	337
19.7.2	Rate Enhancement and Electron Screening	337
19.7.3	Pellet Implosion Dynamics	338
19.7.4	Technical Questions	338
19.7.5	Preservation of Polarization on Injection	339
19.8	Future of Polarized Fusion	339
19.9	Transmutation of Nuclear Waste	339
19.10	Exercises	340
	References	341
20	Other Important Applications of Nuclear-Reaction Techniques	345
20.1	Archaeology, Geology, and Art	345
20.1.1	Archaeology and Age Determination	345
20.2	Materials Analysis and Modification	346
20.2.1	RBS	347
20.2.2	PIXE	347
20.2.3	Neutron Radiography	348
20.2.4	Materials Modifications	349
20.3	Exercises	349
	References	350
21	Trends and Future Developments of Nuclear Reactions	351
21.1	Exotic Nuclei	351
21.2	Low-Cross Section Reactions	352
21.3	Accelerator Developments	352
21.4	Theoretical Progress	353
	References	353
22	Appendices	355
22.1	Appendix A—Tables of Useful Numbers and Relations	355
22.2	Appendix B—Practical Units	356

Contents	xxv
22.3 Appendix C—Angular-Momentum Recoupling Coefficients . . .	357
22.3.1 Coupling of Two Angular Momenta	357
22.3.2 Coupling of Three Angular Momenta	357
22.3.3 Coupling of Four Angular Momenta	358
22.3.4 Spherical Harmonics	358
22.4 Appendix D—General Resources	359
References	359
Index	361

Nuclear Reactions

An Introduction

Paetz gen. Schieck, H.

2014, XXV, 365 p. 184 illus., 87 illus. in color., Softcover

ISBN: 978-3-642-53985-5