

## Contents

**Preface to the Second Edition** *XI*

**Preface to the First Edition** *XIII*

<b>1</b>	<b>Aspects of Nuclear Physics and Astrophysics</b> <i>1</i>
1.1	History <i>1</i>
1.2	Nomenclature <i>2</i>
1.3	Solar System Abundances <i>4</i>
1.4	Astrophysical Aspects <i>7</i>
1.4.1	General Considerations <i>7</i>
1.4.2	Hertzprung–Russell Diagram <i>9</i>
1.4.3	Stellar Evolution of Single Stars <i>11</i>
1.4.4	Binary Stars <i>26</i>
1.5	Masses, Binding Energies, Nuclear Reactions, and Related Topics <i>33</i>
1.5.1	Nuclear Mass and Binding Energy <i>33</i>
1.5.2	Energetics of Nuclear Reactions <i>35</i>
1.5.3	Atomic Mass and Mass Excess <i>37</i>
1.5.4	Number Abundance, Mass Fraction, and Mole Fraction <i>40</i>
1.5.5	Decay Constant, Mean Lifetime, and Half-Life <i>41</i>
1.6	Nuclear Shell Model <i>42</i>
1.6.1	Closed Shells and Magic Numbers <i>43</i>
1.6.2	Nuclear Structure and Nucleon Configuration <i>46</i>
1.7	Nuclear Excited States and Electromagnetic Transitions <i>48</i>
1.7.1	Energy, Angular Momentum, and Parity <i>48</i>
1.7.2	Transition Probabilities <i>49</i>
1.7.3	Branching Ratio and Mixing Ratio <i>52</i>
1.7.4	$\gamma$ -Ray Transitions in a Stellar Plasma <i>53</i>
1.7.5	Isomeric States and the Case of $^{26}\text{Al}$ <i>54</i>
1.8	Weak Interaction <i>57</i>
1.8.1	Weak Interaction Processes <i>58</i>
1.8.2	Energetics <i>59</i>
1.8.3	$\beta$ -Decay Probabilities <i>61</i>

1.8.4	$\beta$ -Decays in a Stellar Plasma	66
	Problems	71
<b>2</b>	<b>Nuclear Reactions</b>	<b>73</b>
2.1	Cross Sections	73
2.2	Reciprocity Theorem	75
2.3	Elastic Scattering and Method of Partial Waves	77
2.3.1	General Aspects	77
2.3.2	Relationship Between Differential Cross Section and Scattering Amplitude	79
2.3.3	The Free Particle	79
2.3.4	Turning the Potential On	81
2.3.5	Scattering Amplitude and Elastic Scattering Cross Section	82
2.3.6	Reaction Cross Section	83
2.4	Scattering by Simple Potentials	86
2.4.1	Square-Well Potential	86
2.4.2	Square-Barrier Potential	93
2.4.3	Transmission Through the Coulomb Barrier	100
2.5	Theory of Resonances	103
2.5.1	General Aspects	103
2.5.2	Logarithmic Derivative, Phase Shift, and Cross Section	105
2.5.3	Breit–Wigner Formulas	108
2.5.4	Extension to Charged Particles and Arbitrary Values of Orbital Angular Momentum	112
2.5.5	<i>R</i> -Matrix Theory	117
2.5.6	Experimental Tests of the One-Level Breit–Wigner Formula	120
2.5.7	Partial and Reduced Widths	124
2.6	Continuum Theory	131
2.7	Hauser–Feshbach Theory	133
	Problems	137
<b>3</b>	<b>Thermonuclear Reactions</b>	<b>139</b>
3.1	Cross Sections and Reaction Rates	139
3.1.1	Particle-Induced Reactions	139
3.1.2	Photon-Induced Reactions	142
3.1.3	Abundance Evolution	144
3.1.4	Forward and Reverse Reactions	147
3.1.5	Reaction Rates at Elevated Temperatures	150
3.1.6	Reaction Rate Equilibria	156
3.1.7	Nuclear Energy Generation	161
3.2	Nonresonant and Resonant Thermonuclear Reaction Rates	162
3.2.1	Nonresonant Reaction Rates for Charged-Particle-Induced Reactions	163
3.2.2	Nonresonant Reaction Rates for Neutron-Induced Reactions	177

3.2.3	Nonresonant Reaction Rates for Photon-Induced Reactions	180
3.2.4	Narrow-Resonance Reaction Rates	181
3.2.5	Broad-Resonance Reaction Rates	192
3.2.6	Electron Screening	197
3.2.7	Total Reaction Rates	201
	Problems	205
<b>4</b>	<b>Nuclear Physics Experiments</b>	<b>207</b>
4.1	General Aspects	207
4.1.1	Charged-Particle Beams	208
4.1.2	Neutron Beams	210
4.2	Interaction of Radiation with Matter	212
4.2.1	Interactions of Heavy Charged Particles	213
4.2.1.1	Stopping Power	214
4.2.1.2	Compounds	220
4.2.1.3	Energy Straggling	221
4.2.2	Interactions of Photons	223
4.2.2.1	Photoelectric Effect	223
4.2.2.2	Compton Effect	225
4.2.2.3	Pair Production	227
4.2.2.4	Photon Attenuation	227
4.2.3	Interactions of Neutrons	230
4.3	Targets and Related Equipment	234
4.3.1	Backings	234
4.3.2	Target Preparation	235
4.3.2.1	Evaporated and Sputtered Targets	235
4.3.2.2	Implanted Targets	236
4.3.2.3	Gas Targets	237
4.3.2.4	Target Thickness and Stability	239
4.3.3	Contaminants	240
4.3.4	Target Chamber and Holder	241
4.4	Radiation Detectors	243
4.4.1	General Aspects	243
4.4.2	Semiconductor Detectors	246
4.4.2.1	Silicon Charged-Particle Detectors	248
4.4.2.2	Germanium Photon Detectors	249
4.4.3	Scintillation Detectors	250
4.4.3.1	Inorganic Scintillator Photon Detectors	252
4.4.3.2	Organic Scintillator Charged-Particle and Neutron Detectors	253
4.4.4	Proportional Counters	255
4.4.5	Microchannel Plate Detectors	256
4.5	Nuclear Spectroscopy	256
4.5.1	Charged-Particle Spectroscopy	257
4.5.1.1	Energy Calibrations	257

4.5.1.2	Efficiencies	258
4.5.1.3	Elastic Scattering Studies	259
4.5.1.4	Nuclear Reaction Studies	260
4.5.2	$\gamma$ -Ray Spectroscopy	262
4.5.2.1	Response Function	262
4.5.2.2	Energy Calibrations	264
4.5.2.3	Efficiency Calibrations	266
4.5.2.4	Coincidence Summing	271
4.5.2.5	Sum Peak Method	275
4.5.2.6	$\gamma$ -Ray Branching Ratios	276
4.5.2.7	$4\pi$ Detection of $\gamma$ -Rays	279
4.5.3	Neutron Spectroscopy	280
4.5.3.1	Response Function	281
4.5.3.2	Moderated Proportional Counters	282
4.5.3.3	Efficiency Calibrations	283
4.6	Miscellaneous Experimental Techniques	284
4.6.1	Radioactive Ion Beams	285
4.6.2	Activation Method	290
4.6.3	Time-of-Flight Technique	293
4.7	Background Radiation	295
4.7.1	General Aspects	296
4.7.2	Background in Charged-Particle Detector Spectra	298
4.7.3	Background in $\gamma$ -Ray Detector Spectra	301
4.7.3.1	$\gamma\gamma$ -Coincidence Techniques	304
4.7.4	Background in Neutron Detector Spectra	309
4.8	Yields and Cross Sections for Charged-Particle-Induced Reactions	311
4.8.1	Nonresonant and Resonant Yields	312
4.8.1.1	Constant $\sigma$ and $\epsilon$ Over Target Thickness	312
4.8.1.2	Moderately Varying $\sigma$ and Constant $\epsilon$ Over Target Thickness	315
4.8.1.3	Breit–Wigner Resonance $\sigma$ and Constant $\epsilon$ Over Resonance Width	316
4.8.2	General Treatment of Yield Curves	319
4.8.2.1	Target of Infinite Thickness	321
4.8.2.2	Target of Finite Thickness	321
4.8.3	Measured Yield Curves and Excitation Functions	325
4.8.4	Determination of Absolute Resonance Strengths and Cross Sections	328
4.8.4.1	Experimental Yields	329
4.8.4.2	Absolute Resonance Strengths and Cross Sections	329
4.8.4.3	Relative Resonance Strengths and Cross Sections	330
4.8.4.4	Determination of Resonance Strengths and Cross Sections Relative to Rutherford Scattering	333

4.9	Transmissions, Yields, and Cross Sections for Neutron-Induced Reactions	337
4.9.1	Resonance Transmission	338
4.9.2	Resonant and Nonresonant Yields	339
4.9.2.1	Constant $\sigma$ Over Neutron Energy Distribution	340
4.9.2.2	Narrow Resonance with $\Gamma \ll \Delta E_n$	340
4.9.3	Effective Cross Section	340
4.9.4	Measured Yields and Transmissions	341
4.9.5	Relative and Absolute Cross Sections	343
	Problems	346
<b>5</b>	<b>Nuclear Burning Stages and Processes</b>	<b>349</b>
5.1	Hydrostatic Hydrogen Burning	353
5.1.1	pp Chains	353
5.1.2	CNO Cycles	369
5.1.3	Hydrostatic Hydrogen Burning Beyond the CNO Mass Region	383
5.2	Hydrostatic Helium Burning	389
5.2.1	Helium-Burning Reactions	391
5.2.2	Nucleosynthesis During Hydrostatic He Burning	397
5.2.3	Other Helium-Burning Reactions	399
5.3	Advanced Burning Stages	400
5.3.1	Carbon Burning	400
5.3.2	Neon Burning	407
5.3.3	Oxygen Burning	412
5.3.4	Silicon Burning	420
5.3.5	Nuclear Statistical Equilibrium	432
5.4	Explosive Burning in Core-Collapse Supernovae (Type II, Ib, Ic)	438
5.4.1	Core Collapse and the Role of Neutrinos	438
5.4.2	$\nu$ - and $\nu p$ -Processes	441
5.4.3	Explosive Nucleosynthesis	443
5.4.4	Observations	451
5.5	Explosive Burning Involving Binary Stars	452
5.5.1	Explosive Burning in Thermonuclear Supernovae (Type Ia)	452
5.5.2	Explosive Hydrogen Burning and Classical Novae	460
5.5.3	Explosive Hydrogen-Helium Burning and Type I X-Ray Bursts	479
5.6	Nucleosynthesis Beyond the Iron Peak	501
5.6.1	The s-Process	505
5.6.2	The r-Process	522
5.6.3	The p-Process	542
5.7	Non-stellar Processes	553
5.7.1	Big Bang Nucleosynthesis	553
5.7.2	Cosmic-Ray Nucleosynthesis	559

5.8	Origin of the Nuclides	564
	Problems	566
<b>Appendix A</b>	<b>Solutions of the Schrödinger Equation in Three Dimensions</b>	<b>569</b>
A.1	Zero Orbital Angular Momentum and Constant Potential	571
A.2	Arbitrary Orbital Angular Momentum and Zero Potential	571
A.3	Arbitrary Orbital Angular Momentum and Coulomb Potential	572
<b>Appendix B</b>	<b>Quantum Mechanical Selection Rules</b>	<b>573</b>
<b>Appendix C</b>	<b>Kinematics</b>	<b>579</b>
C.1	Relationship of Kinematic Quantities in the Laboratory Coordinate System	579
C.2	Transformation Between Laboratory and Center-of-Mass Coordinate System	583
<b>Appendix D</b>	<b>Angular Correlations</b>	<b>587</b>
D.1	General Aspects	588
D.2	Pure Radiations in a Two-Step Process	591
D.3	Mixed Radiations in a Two-Step Process	593
D.4	Three-Step Process with Unobserved Intermediate Radiation	598
D.5	Experimental Considerations	600
D.6	Concluding Remarks	602
<b>Appendix E</b>	<b>Constants, Data, Units, and Notation</b>	<b>605</b>
E.1	Physical Constants and Data	605
E.2	Mathematical Expressions	606
E.3	Prefixes and Units	607
E.4	Physical Quantities	608
	<b>Color Plates</b>	<b>613</b>
	<b>References</b>	<b>627</b>
	<b>Index</b>	<b>639</b>