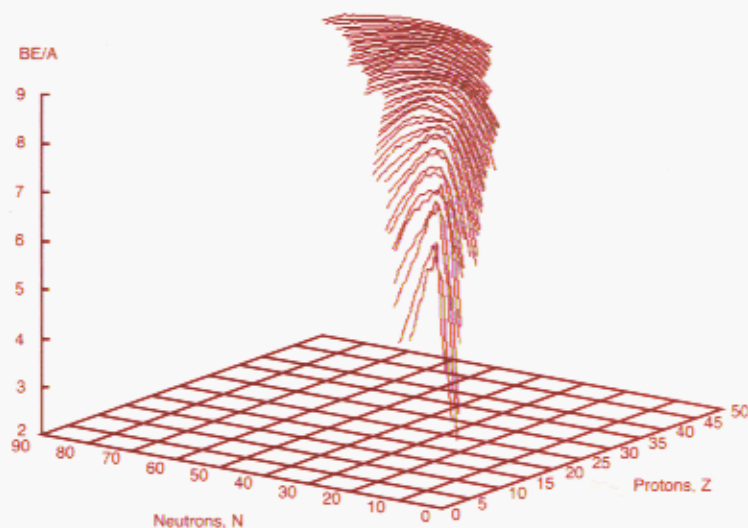


FUNDAMENTALS OF NUCLEAR SCIENCE AND ENGINEERING



J. KENNETH SHULTIS
RICHARD E. FAW

Contents

1	Fundamental Concepts	1
1.1	Modern Units	1
1.1.1	Special Nuclear Units	4
1.1.2	Physical Constants	5
1.2	The Atom	5
1.2.1	Atomic and Nuclear Nomenclature	6
1.2.2	Atomic and Molecular Weights	8
1.2.3	Avogadro's Number	9
1.2.4	Mass of an Atom	10
1.2.5	Atomic Number Density	10
1.2.6	Size of an Atom	11
1.2.7	Atomic and Isotopic Abundances	12
1.2.8	Nuclear Dimensions	12
1.3	Chart of the Nuclides	13
1.3.1	Other Sources of Atomic/Nuclear Information	13
2	Modern Physics Concepts	16
2.1	The Special Theory of Relativity	16
2.1.1	Principle of Relativity	18
2.1.2	Results of the Special Theory of Relativity	19
2.2	Radiation as Waves and Particles	22
2.2.1	The Photoelectric Effect	23
2.2.2	Compton Scattering	25
2.2.3	Electromagnetic Radiation: Wave-Particle Duality	27
2.2.4	Electron Scattering	28
2.2.5	Wave-Particle Duality	29
2.3	Quantum Mechanics	30
2.3.1	Schrödinger's Wave Equation	30
2.3.2	The Wave Function	32
2.3.3	The Uncertainty Principle	33
2.3.4	Success of Quantum Mechanics	34
2.4	Addendum 1: Derivation of Some Special Relativity Results	34
2.4.1	Time Dilation	34

2.4.2	Length Contraction	35
2.4.3	Mass Increase	36
2.5	Addendum 2: Solutions to Schrödinger's Wave Equation	37
2.5.1	The Particle in a Box	37
2.5.2	The Hydrogen Atom	39
2.5.3	Energy Levels for Multielectron Atoms	43
3	Atomic/Nuclear Models	48
3.1	Development of the Modern Atom Model	48
3.1.1	Discovery of Radioactivity	48
3.1.2	Thomson's Atomic Model: The Plum Pudding Model	50
3.1.3	The Rutherford Atomic Model	51
3.1.4	The Bohr Atomic Model	52
3.1.5	Extension of the Bohr Theory: Elliptic Orbits	55
3.1.6	The Quantum Mechanical Model of the Atom	56
3.2	Models of the Nucleus	57
3.2.1	Fundamental Properties of the Nucleus	57
3.2.2	The Proton-Electron Model	59
3.2.3	The Proton-Neutron Model	60
3.2.4	Stability of Nuclei	62
3.2.5	The Liquid Drop Model of the Nucleus	64
3.2.6	The Nuclear Shell Model	68
3.2.7	Other Nuclear Models	68
4	Nuclear Energetics	71
4.1	Binding Energy	72
4.1.1	Nuclear and Atomic Masses	72
4.1.2	Binding Energy of the Nucleus	73
4.1.3	Average Nuclear Binding Energies	74
4.2	Nucleon Separation Energy	76
4.3	Nuclear Reactions	78
4.4	Examples of Binary Nuclear Reactions	78
4.4.1	Multiple Reaction Outcomes	79
4.5	Q-Value for a Reaction	80
4.5.1	Binary Reactions	81
4.5.2	Radioactive Decay Reactions	81
4.6	Conservation of Charge and the Calculation of Q-Values	81
4.6.1	Special Case for Changes in the Proton Number	82
4.7	Q-Value for Reactions Producing Excited Nuclei	83
5	Radioactivity	86
5.1	Overview	86
5.2	Types of Radioactive Decay	88
5.3	Energetics of Radioactive Decay	88
5.3.1	Gamma Decay	88
5.3.2	Alpha-Particle Decay	89
5.3.3	Beta-Particle Decay	92

5.3.4	Positron Decay	93
5.3.5	Electron Capture	95
5.3.6	Neutron Decay	96
5.3.7	Proton Decay	96
5.3.8	Internal Conversion	97
5.3.9	Examples of Energy-Level Diagrams	98
5.4	Characteristics of Radioactive Decay	98
5.4.1	The Decay Constant	98
5.4.2	Exponential Decay	100
5.4.3	The Half-Life	101
5.4.4	Decay Probability for a Finite Time Interval	101
5.4.5	Mean Lifetime	102
5.4.6	Activity	102
5.4.7	Half-Life Measurement	103
5.4.8	Decay by Competing Processes	104
5.5	Decay Dynamics	105
5.5.1	Decay with Production	105
5.5.2	Three Component Decay Chains	106
5.5.3	General Decay Chain	110
5.6	Naturally Occurring Radionuclides	111
5.6.1	Cosmogenic Radionuclides	111
5.6.2	Singly Occurring Primordial Radionuclides	111
5.6.3	Decay Series of Primordial Origin	112
5.6.4	Secular Equilibrium	112
5.7	Radiodating	115
5.7.1	Measuring the Decay of a Parent	116
5.7.2	Measuring the Buildup of a Stable Daughter	117
6	Binary Nuclear Reactions	122
6.1	Types of Binary Reactions	123
6.1.1	The Compound Nucleus	123
6.2	Kinematics of Binary Two-Product Nuclear Reactions	124
6.2.1	Energy/Mass Conservation	125
6.2.2	Conservation of Energy and Linear Momentum	125
6.3	Reaction Threshold Energy	128
6.3.1	Kinematic Threshold	128
6.3.2	Coulomb Barrier Threshold	129
6.3.3	Overall Threshold Energy	130
6.4	Applications of Binary Kinematics	131
6.4.1	A Neutron Detection Reaction	131
6.4.2	A Neutron Production Reaction	131
6.4.3	Heavy Particle Scattering from an Electron	132
6.5	Reactions Involving Neutrons	133
6.5.1	Neutron Scattering	133
6.5.2	Neutron Capture Reactions	136
6.5.3	Fission Reactions	136
6.6	Characteristics of the Fission Reaction	138

6.6.1	Fission Products	140
6.6.2	Neutron Emission in Fission	142
6.6.3	Energy Released in Fission	146
6.7	Fusion Reactions	149
6.7.1	Thermonuclear Fusion	149
6.7.2	Energy Production in Stars	152
6.7.3	Nucleogenesis	156
7	Radiation Interactions with Matter	161
7.1	Attenuation of Neutral Particle Beams	162
7.1.1	The Linear Interaction Coefficient	163
7.1.2	Attenuation of Uncollided Radiation	164
7.1.3	Average Travel Distance Before an Interaction	164
7.1.4	Half-Thickness	165
7.1.5	Scattered Radiation	166
7.1.6	Microscopic Cross Sections	166
7.2	Calculation of Radiation Interaction Rates	168
7.2.1	Flux Density	168
7.2.2	Reaction-Rate Density	169
7.2.3	Generalization to Energy- and Time-Dependent Situations	169
7.2.4	Radiation Fluence	170
7.2.5	Uncollided Flux Density from an Isotropic Point Source	171
7.3	Photon Interactions	174
7.3.1	Photoelectric Effect	174
7.3.2	Compton Scattering	175
7.3.3	Pair Production	177
7.3.4	Photon Attenuation Coefficients	178
7.4	Neutron Interactions	178
7.4.1	Classification of Types of Interactions	181
7.4.2	Fission Cross Sections	187
7.5	Attenuation of Charged Particles	188
7.5.1	Interaction Mechanisms	188
7.5.2	Particle Range	190
7.5.3	Stopping Power	192
7.5.4	Estimating Charged-Particle Ranges	194
8	Detection and Measurement of Radiation	202
8.1	Gas-Filled Radiation Detectors	203
8.1.1	Ionization Chambers	205
8.1.2	Proportional Counters	206
8.1.3	Geiger-Mueller Counters	207
8.2	Scintillation Detectors	211
8.3	Semiconductor Ionizing-Radiation Detectors	214
8.4	Personal Dosimeters	218
8.4.1	The Pocket Ion Chamber	218
8.4.2	The Film Badge	218
8.4.3	The Thermoluminescent Dosimeter	218

8.5	Measurement Theory	219
8.5.1	Types of Measurement Uncertainties	219
8.5.2	Uncertainty Assignment Based Upon Counting Statistics	219
8.5.3	Dead Time	220
8.5.4	Energy Resolution	221
9	Radiation Doses and Hazard Assessment	223
9.1	Historical Roots	223
9.2	Dosimetric Quantities	225
9.2.1	Energy Imparted to the Medium	226
9.2.2	Absorbed Dose	227
9.2.3	Kerma	227
9.2.4	Calculating Kerma and Absorbed Doses	227
9.2.5	Exposure	230
9.2.6	Relative Biological Effectiveness	231
9.2.7	Dose Equivalent	232
9.2.8	Quality Factor	232
9.2.9	Effective Dose Equivalent	233
9.2.10	Effective Dose	234
9.3	Natural Exposures for Humans	235
9.4	Health Effects from Large Acute Doses	237
9.4.1	Effects on Individual Cells	237
9.4.2	Deterministic Effects in Organs and Tissues	237
9.4.3	Potentially Lethal Exposure to Low-LET Radiation	240
9.5	Hereditary Effects	242
9.5.1	Classification of Genetic Effects	243
9.5.2	Summary of Risk Estimates	244
9.5.3	Estimating Gonad Doses and Genetic Risks	246
9.6	Cancer Risks from Radiation Exposures	246
9.6.1	Dose-Response Models for Cancer	247
9.6.2	Average Cancer Risks for Exposed Populations	248
9.7	Radon and Lung Cancer Risks	250
9.7.1	Radon Activity Concentrations	252
9.7.2	Lung Cancer Risks	253
9.8	Radiation Protection Standards	255
9.8.1	Risk-Related Dose Limits	255
9.8.2	The 1987 NCRP Exposure Limits	256
10	Principles of Nuclear Reactors	263
10.1	Neutron Moderation	264
10.2	Thermal-Neutron Properties of Fuels	264
10.3	The Neutron Life Cycle in a Thermal Reactor	265
10.3.1	Quantification of the Neutron Cycle	266
10.3.2	Effective Multiplication Factor	270
10.4	Homogeneous and Heterogeneous Cores	273
10.5	Reflectors	275
10.6	Reactor Kinetics	276

10.6.1	A Simple Reactor Kinetics Model	276
10.6.2	Delayed Neutrons	277
10.6.3	Reactivity and Delta-k	278
10.6.4	Revised Simplified Reactor Kinetics Models	279
10.6.5	Power Transients Following a Reactivity Insertion	281
10.7	Reactivity Feedback	285
10.7.1	Feedback Caused by Isotopic Changes	285
10.7.2	Feedback Caused by Temperature Changes	286
10.8	Fission Product Poisons	288
10.8.1	Xenon Poisoning	288
10.8.2	Samarium Poisoning	292
10.9	Addendum 1: The Diffusion Equation	293
10.9.1	An Example Fixed-Source Problem	296
10.9.2	An Example Criticality Problem	297
10.9.3	More Detailed Neutron-Field Descriptions	298
10.10	Addendum 2: Kinetic Model with Delayed Neutrons	299
10.11	Addendum 3: Solution for a Step Reactivity Insertion	301
11	Nuclear Power	306
11.1	Nuclear Electric Power	306
11.1.1	Electricity from Thermal Energy	306
11.1.2	Conversion Efficiency	308
11.1.3	Some Typical Power Reactors	308
11.1.4	Coolant Limitations	311
11.2	Pressurized Water Reactors	312
11.2.1	The Steam Cycle of a PWR	312
11.2.2	Major Components of a PWR	314
11.3	Boiling Water Reactors	322
11.3.1	The Steam Cycle of a BWR	322
11.3.2	Major Components of a BWR	322
11.4	New Designs for Central-Station Power	327
11.4.1	Certified Evolutionary Designs	328
11.4.2	Certified Passive Design	328
11.4.3	Other Evolutionary LWR Designs	328
11.4.4	Gas Reactor Technology	329
11.5	The Nuclear Fuel Cycle	329
11.5.1	Uranium Requirements and Availability	331
11.5.2	Enrichment Techniques	332
11.5.3	Radioactive Waste	334
11.5.4	Spent Fuel	335
11.6	Nuclear Propulsion	339
11.6.1	Naval Applications	339
11.6.2	Other Marine Applications	340
11.6.3	Nuclear Propulsion in Space	341
12	Other Methods for Converting Nuclear Energy to Electricity	347
12.1	Thermoelectric Generators	347
12.1.1	Radionuclide Thermoelectric Generators	349

12.2	Thermionic Electrical Generators	352
12.2.1	Conversion Efficiency	355
12.2.2	In-Pile Thermionic Generator	357
12.3	AMTEC Conversion	358
12.4	Stirling Converters	360
12.5	Direct Conversion of Nuclear Radiation	360
12.5.1	Types of Nuclear Radiation Conversion Devices	362
12.5.2	Betavoltaic Batteries	363
12.6	Radioisotopes for Thermal Power Sources	364
12.7	Space Reactors	366
12.7.1	The U.S. Space Reactor Program	366
12.7.2	The Russian Space Reactor Program	368
13	Nuclear Technology in Industry and Research	373
13.1	Production of Radioisotopes	373
13.2	Industrial and Research Uses of Radioisotopes and Radiation	374
13.3	Tracer Applications	376
13.3.1	Leak Detection	376
13.3.2	Pipeline Interfaces	377
13.3.3	Flow Patterns	377
13.3.4	Flow Rate Measurements	377
13.3.5	Labeled Reagents	378
13.3.6	Tracer Dilution	378
13.3.7	Wear Analyses	378
13.3.8	Mixing Times	378
13.3.9	Residence Times	379
13.3.10	Frequency Response	379
13.3.11	Surface Temperature Measurements	379
13.3.12	Radiodating	379
13.4	Materials Affect Radiation	379
13.4.1	Radiography	379
13.4.2	Thickness Gauging	382
13.4.3	Density Gauges	383
13.4.4	Level Gauges	384
13.4.5	Radiation Absorptiometry	384
13.4.6	Oil-Well Logging	385
13.4.7	Neutron Activation Analysis	385
13.4.8	Neutron Capture-Gamma Ray Analysis	386
13.4.9	Molecular Structure Determination	386
13.4.10	Smoke Detectors	387
13.5	Radiation Affects Materials	387
13.5.1	Food Preservation	387
13.5.2	Sterilization	388
13.5.3	Insect Control	388
13.5.4	Polymer Modification	388
13.5.5	Biological Mutation Studies	388
13.5.6	Chemonuclear Processing	389

14 Medical Applications of Nuclear Technology	392
14.1 Diagnostic Imaging	394
14.1.1 X-Ray Projection Imaging	394
14.1.2 Fluoroscopy	398
14.1.3 Mammography	399
14.1.4 Bone Densitometry	399
14.1.5 X-Ray Computed Tomography (CT)	400
14.1.6 Single Photon Emission Computed Tomography (SPECT)	404
14.1.7 Positron Emission Tomography (PET)	407
14.1.8 Magnetic Resonance Imaging (MRI)	411
14.2 Radioimmunoassay	414
14.3 Diagnostic Radiotracers	416
14.4 Radioimmunoscinigraphy	417
14.5 Radiation Therapy	417
14.5.1 Early Applications	418
14.5.2 Teletherapy	418
14.5.3 Radionuclide Therapy	420
14.5.4 Clinical Brachytherapy	420
14.5.5 Boron Neutron Capture Therapy	421
 Appendix A: Fundamental Atomic Data	 425
 Appendix B: Atomic Mass Table	 440
 Appendix C: Cross Sections and Related Data	 458
 Appendix D: Decay Characteristics of Selected Radionuclides	 466
 Index	 495