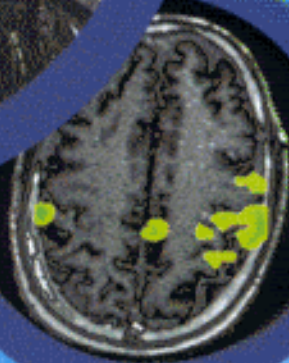


Nuclear Physics

Principles
and Applications

John Lilley



Contents

Flow diagram	Inside front cover
Editors' preface to the Manchester Physics Series	xiii
Author's preface	xv
PART I PRINCIPLES	1
1 INTRODUCTION AND BASIC CONCEPTS	3
1.1 Introduction	3
1.2 Early Discoveries	4
1.3 Basic Facts and Definitions	6
1.3.1 The nucleus and its constituents	6
1.3.2 Isotopes, isotones and isobars	7
1.3.3 Nuclear mass and energy	7
1.4 Nuclear Potential and Energy Levels	9
1.4.1 Nucleon states in a nucleus	9
1.4.2 Energy levels of nuclei	12
1.4.3 Occurrence and stability of nuclei	13
1.5 Radioactivity and Radioactive Decay	14
1.5.1 Alpha emission	14
1.5.2 Beta emission and electron capture	15
1.5.3 Gamma emission and internal conversion	17
1.5.4 Rate of radioactive decay	18
1.5.5 Radioactive decay chains	19
1.5.6 Radioactivity in the environment	21
1.5.7 Radioactive dating	22
1.6 Nuclear Collisions	22
1.6.1 Nomenclature	23
1.6.2 Probes	23
1.6.3 Cross section, differential cross section and reaction rate	24
1.6.4 Isotope production	25
1.6.5 Examples of nuclear reactions	27
PROBLEMS 1	32

2	NUCLEAR STRUCTURE	35
2.1	Introduction	35
2.2	Nuclear Mass	36
2.2.1	The nuclear force	36
2.2.2	Semi-empirical mass formula	38
2.2.3	Nuclear stability	41
2.3	Nuclear Shell Model	45
2.3.1	Evidence for shell structure	45
2.3.2	Independent particle motion and the shell model	46
2.3.3	The spin-orbit potential	48
2.4	Single-Particle Features	50
2.4.1	Parity	50
2.4.2	Spectra of single-particle or single-hole nuclei	51
2.5	Collective States	54
2.5.1	Vibrational states	55
2.5.2	Deformed nuclei	58
2.5.3	Rotational states	59
2.5.4	Superdeformation	61
	PROBLEMS 2	63
3	NUCLEAR INSTABILITY	65
3.1	Introduction	65
3.2	Gamma Emission	65
3.2.1	General features and selection rules	66
3.2.2	Transition rate	67
3.2.3	Internal conversion	73
3.3	Beta Decay	74
3.3.1	Beta-particle energy spectrum	75
3.3.2	Allowed transitions	77
3.3.3	Forbidden transitions	80
3.3.4	Comparison of β -decay rates	82
3.3.5	Electron capture	83
3.4	Alpha Decay	84
3.4.1	Semi-classical theory of α decay	84
3.4.2	Alpha-particle energies and selection rules	88
3.4.3	Transuranic nuclei	89
	PROBLEMS 3	90
4	NUCLEAR REACTIONS	93
4.1	Introduction	93
4.2	General Features of Nuclear Reactions	94
4.2.1	Energy spectra	94
4.2.2	Angular distributions	96
4.2.3	Cross sections	97

4.3	Elastic Scattering and Nuclear Size	104
4.3.1	Electron scattering	104
4.3.2	Optical model for nuclear scattering	106
4.4	Direct Reactions	108
4.4.1	Angular momentum transfer in direct reactions	108
4.4.2	Selectivity in direct reactions	110
4.5	Compound Nucleus Reactions	113
4.5.1	Resonance in a compound nuclear reaction	114
4.5.2	Low-energy, neutron-induced fission	116
4.6	Heavy-Ion Reactions	117
4.6.1	Elastic scattering and direct reactions	118
4.6.2	Fusion	120
4.6.3	Deep inelastic reactions and limits to fusion	122
	PROBLEMS 4	124
PART II INSTRUMENTATION AND APPLICATIONS		127
5	INTERACTION OF RADIATION WITH MATTER	129
5.1	Introduction	129
5.2	Heavy Charged Particles	129
5.2.1	Bethe-Bloch formula	130
5.2.2	Energy dependence	131
5.2.3	Bragg curve	132
5.2.4	Projectile dependence	133
5.2.5	Stopping medium dependence	134
5.3	Electrons	134
5.4	Gamma Rays	136
5.4.1	Photoelectric effect	138
5.4.2	Compton scattering	139
5.4.3	Pair production	140
5.4.4	Attenuation	141
5.5	Neutrons	142
5.5.1	Attenuation	143
5.5.2	Neutron moderation	144
	PROBLEMS 5	148
6	DETECTORS AND INSTRUMENTATION	151
6.1	Introduction	151
6.2	Gas Detectors	152
6.2.1	Ionization chamber	152
6.2.2	Proportional counter	153
6.2.3	Geiger-Mueller counter	155
6.3	Scintillation Detectors	156
6.4	Semiconductor Detectors	158
6.4.1	The p-n junction detector	160

6.4.2	The intrinsic detector	162
6.5	Detector Performance for Gamma Rays	162
6.5.1	Response to monoenergetic photons	162
6.5.2	Energy resolution	164
6.5.3	Peak-to-total ratio	165
6.6	Neutron Detectors	166
6.6.1	Slow-neutron detection	166
6.6.2	Fast-neutron detection	167
6.7	Particle Identification	168
6.7.1	$E - \Delta E$ counter telescope	168
6.7.2	Time of flight	168
6.7.3	Magnetic analysis	169
6.8	Accelerators	171
6.8.1	DC machines	171
6.8.2	AC machines	173
	PROBLEMS 6	178
7	BIOLOGICAL EFFECTS OF RADIATION	181
7.1	Introduction	181
7.2	Initial Interactions	182
7.2.1	Direct and indirect physical damage	182
7.2.2	Indirect chemical damage	183
7.3	Dose, Dose Rate and Dose Distribution	185
7.3.1	Absorbed dose	185
7.3.2	Dose rate	185
7.3.3	Dose distribution and relative biological effectiveness	186
7.3.4	Equivalent dose	187
7.3.5	Effective dose	188
7.4	Damage to Critical Tissue	189
7.4.1	Complex molecules	189
7.4.2	Nucleic acids and damage repair	190
7.4.3	Modifying factors	192
7.5	Human Exposure to Radiation	195
7.5.1	Radiation in the environment	195
7.5.2	Evaluating the dose	198
7.6	Risk Assessment	200
7.6.1	Risk to occupationally exposed workers	201
	PROBLEMS 7	202
8	INDUSTRIAL AND ANALYTICAL APPLICATIONS	205
8.1	Introduction	205
8.2	Industrial Uses	205
8.2.1	Tracing	205
8.2.2	Gauging	207
8.2.3	Material modification	208

8.2.4	Sterilization	209
8.2.5	Food preservation	210
8.2.6	Other applications	211
8.3	Neutron Activation Analysis	212
8.4	Rutherford Backscattering	215
8.5	Particle-Induced X-Ray Emission	219
8.6	Accelerator Mass Spectrometry	223
8.7	Significance of Low-Level Counting	226
8.7.1	Null measurements with zero background	226
8.7.2	Low-level counting with finite background	227
	PROBLEMS 8	229
9	NUCLEAR MEDICINE	233
9.1	Introduction	233
9.2	Projection Imaging: X-Radiography and the Gamma Camera	234
9.2.1	Imaging with external radiation	234
9.2.2	Imaging with internal radiation	235
9.3	Computed Tomography	238
9.4	Positron Emission Tomography	242
9.5	Magnetic Resonance Imaging	245
9.5.1	Principles of MRI	246
9.5.2	Excitation of a selected region	248
9.5.3	Readout and MRI image formation	248
9.5.4	Time variations of the signal	249
9.5.5	Functional MRI	251
9.6	Radiation Therapy	253
9.6.1	Photons and electrons	253
9.6.2	Radionuclides	256
9.6.3	Neutron therapy	256
9.6.4	Heavy charged particles	257
	PROBLEMS 9	259
10	POWER FROM FISSION	263
10.1	Introduction	263
10.2	Characteristics of Fission	264
10.2.1	Fission and fission products	264
10.2.2	Fission energy budget	265
10.2.3	Delayed neutrons	267
10.2.4	Neutron interactions	267
10.2.5	Breeder reactions	268
10.3	The Chain Reaction in a Thermal Fission Reactor	269
10.3.1	A nuclear power plant	269
10.3.2	The neutron cycle in a thermal reactor	271
10.3.3	Moderator	274
10.3.4	Optimizing the design	275

10.4	The Finite Reactor	276
10.4.1	Diffusion	276
10.4.2	The continuity equation	277
10.4.3	Diffusion length	278
10.4.4	Reactor equation	279
10.4.5	Solving the reactor equation	281
10.5	Reactor Operation	283
10.5.1	Reactor power and fuel consumption	283
10.5.2	Reactor kinetics	284
10.5.3	Reactor poisoning	285
10.6	Commercial Thermal Reactors	287
10.6.1	Early gas-cooled reactors	287
10.6.2	Advanced gas-cooled reactor (AGR)	288
10.6.3	Pressurized-water reactor	288
10.6.4	Boiling-water reactor	289
10.6.5	Heavy-water reactors	290
10.7	Future of Nuclear Fission Power	291
10.7.1	The breeder reactor	292
10.7.2	Accelerator-driven systems	294
	PROBLEMS 10	295
11	THERMONUCLEAR FUSION	299
11.1	Introduction	299
11.2	Thermonuclear Reactions and Energy Production	300
11.2.1	Basic reactions and Q values	300
11.2.2	Cross sections	301
11.3	Fusion in a Hot Medium	302
11.3.1	Reaction rate	302
11.3.2	Performance criteria	304
11.4	Progress Towards Fusion Power	305
11.4.1	Magnetic confinement	306
11.4.2	Inertial confinement fusion	311
11.5	Fusion in the Early Universe	313
11.6	Stellar Burning	315
11.6.1	Hydrogen burning	315
11.6.2	Helium burning	318
11.6.3	Beyond helium burning	319
11.7	Nucleosynthesis Beyond $A \approx 60$	320
	PROBLEMS 11	323
	APPENDIX A: Useful Information	325
A.1	Physical Constants and Derived Quantities	325
A.2	Masses and Energies	325
A.3	Conversion Factors	326
A.4	Useful Formulae	326

APPENDIX B: Particle in a Square Well	329
APPENDIX C: Density of States and the Fermi Energy	333
C.1 Density of States	333
C.2 Fermi Energy	335
APPENDIX D: Spherical Harmonics	337
APPENDIX E: Coulomb Scattering	341
APPENDIX F: Mass Excesses and Decay Properties of Nuclei	343
APPENDIX G: Answers and Hints to Problems	355
References	379
Bibliography	381
Index	385