

Contents

1. Basic Nuclear Processes in Radioactive Sources	1
1.1 Nuclear Level Diagrams	2
1.2 Alpha Decay	3
1.3 Beta Decay	4
1.4 Electron Capture (EC)	6
1.5 Gamma Emission	6
1.5.1 Isomeric States	6
1.6 Annihilation Radiation	7
1.7 Internal Conversion	7
1.8 Auger Electrons	8
1.9 Neutron Sources	8
1.9.1 Spontaneous Fission	8
1.9.2 Nuclear Reactions	8
1.10 Source Activity Units	9
1.11 The Radioactive Decay Law	10
1.11.1 Fluctuations in Radioactive Decay	11
1.11.2 Radioactive Decay Chains	12
1.11.3 Radioisotope Production by Irradiation	14
2. Passage of Radiation Through Matter	17
2.1 Preliminary Notions and Definitions	17
2.1.1 The Cross Section	18
2.1.2 Interaction Probability in a Distance x . Mean Free Path	19
2.1.3 Surface Density Units	20
2.2 Energy Loss of Heavy Charged Particles by Atomic Collisions	21
2.2.1 Bohr's Calculation – The Classical Case	22
2.2.2 The Bethe-Bloch Formula	24
2.2.3 Energy Dependence	27
2.2.4 Scaling Laws for dE/dx	28
2.2.5 Mass Stopping Power	28
2.2.6 dE/dx for Mixtures and Compounds	29
2.2.7 Limitations of the Bethe-Bloch Formula and Other Effects	29
2.2.8 Channeling	30
2.2.9 Range	30
2.3 Cherenkov Radiation	33
2.4 Energy Loss of Electrons and Positrons	34
2.4.1 Collision Loss	35
2.4.2 Energy Loss by Radiation: Bremsstrahlung	35
2.4.3 Electron-Electron Bremsstrahlung	38
2.4.4 Critical Energy	38

2.4.5	Radiation Length	39
2.4.6	Range of Electrons	40
2.4.7	The Absorption of β Electrons	40
2.5	Multiple Coulomb Scattering	40
2.5.1	Multiple Scattering in the Gaussian Approximation	43
2.5.2	Backscattering of Low-Energy Electrons	45
2.6	Energy Straggling: The Energy Loss Distribution	46
2.6.1	Thick Absorbers: The Gaussian Limit	46
2.6.2	Very Thick Absorbers	47
2.6.3	Thin Absorbers: The Landau and Vavilov Theories	47
2.7	The Interaction of Photons	50
2.7.1	Photoelectric Effect	51
2.7.2	Compton Scattering	52
2.7.3	Pair Production	54
2.7.4	Electron-Photon Showers	56
2.7.5	The Total Absorption Coefficient and Photon Attenuation	57
2.8	The Interaction of Neutrons	58
2.8.1	Slowing Down of Neutrons. Moderation	60
3.	Radiation Protection. Biological Effects of Radiation	65
3.1	Dosimetric Units	65
3.1.1	The Roentgen	65
3.1.2	Absorbed Dose	66
3.1.3	Relative Biological Effectiveness (RBE)	67
3.1.4	Dose Equivalent	68
3.2	Typical Doses from Common Sources in the Environment	68
3.3	Biological Effects	69
3.3.1	High Doses Received in a Short Time	70
3.3.2	Low-Level Doses	70
3.4	Maximum Permissible Dose (MPD)	72
3.5	Shielding	72
3.6	Radiation Safety in the Nuclear Physics Laboratory	73
4.	Statistics and the Treatment of Experimental Data	75
4.1	Characteristics of Probability Distributions	75
4.1.1	Cumulative Distributions	76
4.1.2	Expectation Values	76
4.1.3	Distribution Moments. The Mean and Variance	76
4.1.4	The Covariance	77
4.2	Some Common Probability Distributions	78
4.2.1	The Binomial Distribution	78
4.2.2	The Poisson Distribution	79
4.2.3	The Gaussian or Normal Distribution	80
4.2.4	The Chi-Square Distribution	82
4.3	Measurement Errors and the Measurement Process	83
4.3.1	Systematic Errors	83
4.3.2	Random Errors	84
4.4	Sampling and Parameter Estimation. The Maximum Likelihood Method	85
4.4.1	Sample Moments	85

4.4.2	The Maximum Likelihood Method	86
4.4.3	Estimator for the Poisson Distribution	87
4.4.4	Estimators for the Gaussian Distribution	88
4.4.5	The Weighted Mean	90
4.5	Examples of Applications	91
4.5.1	Mean and Error from a Series of Measurements	91
4.5.2	Combining Data with Different Errors	91
4.5.3	Determination of Count Rates and Their Errors	92
4.5.4	Null Experiments. Setting Confidence Limits When No Counts Are Observed	92
4.5.5	Distribution of Time Intervals Between Counts	94
4.6	Propagation of Errors	94
4.6.1	Examples	95
4.7	Curve Fitting	96
4.7.1	The Least Squares Method	97
4.7.2	Linear Fits. The Straight Line	98
4.7.3	Linear Fits When Both Variables Have Errors	101
4.7.4	Nonlinear Fits	101
4.8	Some General Rules for Rounding-off Numbers for Final Presentation	105
5.	General Characteristics of Detectors	107
5.1	Sensitivity	107
5.2	Detector Response	108
5.3	Energy Resolution. The Fano Factor	109
5.4	The Response Function	111
5.5	Response Time	112
5.6	Detector Efficiency	113
5.7	Dead Time	114
5.7.1	Measuring Dead Time	116
6.	Ionization Detectors	119
6.1	Gaseous Ionization Detectors	119
6.2	Ionization and Transport Phenomena in Gases	122
6.2.1	Ionization Mechanisms	122
6.2.2	Mean Number of Electron-Ion Pairs Created	123
6.2.3	Recombination and Electron Attachment	124
6.3	Transport of Electrons and Ions in Gases	125
6.3.1	Diffusion	125
6.3.2	Drift and Mobility	126
6.4	Avalanche Multiplication	127
6.5	The Cylindrical Proportional Counter	129
6.5.1	Pulse Formation and Shape	129
6.5.2	Choice of Fill Gas	132
6.6	The Multiwire Proportional Chamber (MWPC)	133
6.6.1	Basic Operating Principle	133
6.6.2	Construction	135
6.6.3	Chamber Gas	136
6.6.4	Timing Resolution	136
6.6.5	Readout Methods	137

6.6.6	Track Clusters	139
6.6.7	MWPC Efficiency	139
6.7	The Drift Chamber	141
6.7.1	Drift Gases	142
6.7.2	Spatial Resolution	143
6.7.3	Operation in Magnetic Fields	143
6.8	The Time Projection Chamber (TPC)	143
6.9	Liquid Ionization Detectors	146
7.	Scintillation Detectors	149
7.1	General Characteristics	149
7.2	Organic Scintillators	151
7.2.1	Organic Crystals	154
7.2.2	Organic Liquids	155
7.2.3	Plastics	156
7.3	Inorganic Crystals	157
7.4	Gaseous Scintillators	158
7.5	Glasses	159
7.6	Light Output Response	159
7.6.1	Linearity	160
7.6.2	Temperature Dependence	163
7.6.3	Pulse Shape Discrimination (PSD)	163
7.7	Intrinsic Detection Efficiency for Various Radiations	165
7.7.1	Heavy Ions	165
7.7.2	Electrons	166
7.7.3	Gamma Rays	166
7.7.4	Neutrons	167
8.	Photomultipliers	169
8.1	Basic Construction and Operation	169
8.2	The Photocathode	170
8.3	The Electron-Optical Input System	172
8.4	The Electron-Multiplier Section	173
8.4.1	Dynode Configurations	174
8.4.2	Multiplier Response: The Single-Electron Spectrum	176
8.5	Operating Parameters	177
8.5.1	Gain and Voltage Supply	177
8.5.2	Voltage Dividers	178
8.5.3	Electrode Current. Linearity	180
8.5.4	Pulse Shape	181
8.6	Time Response and Resolution	182
8.7	Noise	184
8.7.1	Dark Current and Afterpulsing	184
8.7.2	Statistical Noise	185
8.8	Environmental Factors	186
8.8.1	Exposure to Ambient Light	186
8.8.2	Magnetic Fields	187
8.8.3	Temperature Effects	188
8.9	Gain Stability, Count Rate Shift	189

9. Scintillation Detector Mounting and Operation	191
9.1 Light Collection	191
9.1.1 Reflection	192
9.2 Coupling to the PM	193
9.3 Multiple Photomultipliers	194
9.4 Light Guides	194
9.5 Fluorescent Radiation Converters	196
9.6 Mounting a Scintillation Detector: An Example	197
9.7 Scintillation Counter Operation	200
9.7.1 Testing the Counter	200
9.7.2 Adjusting the PM Voltage	201
9.7.3 The Scintillation Counter Plateau	201
9.7.4 Maintaining PM Gain	205
10. Semiconductor Detectors	207
10.1 Basic Semiconductor Properties	207
10.1.1 Energy Band Structure	208
10.1.2 Charge Carriers in Semiconductors	209
10.1.3 Intrinsic Charge Carrier Concentration	209
10.1.4 Mobility	210
10.1.5 Recombination and Trapping	211
10.2 Doped Semiconductors	212
10.2.1 Compensation	214
10.3 The np Semiconductor Junction. Depletion Depth	215
10.3.1 The Depletion Depth	216
10.3.2 Junction Capacitance	218
10.3.3 Reversed Bias Junctions	218
10.4 Detector Characteristics of Semiconductors	219
10.4.1 Average Energy per Electron-Hole Pair	220
10.4.2 Linearity	221
10.4.3 The Fano Factor and Intrinsic Energy Resolution	221
10.4.4 Leakage Current	221
10.4.5 Sensitivity and Intrinsic Efficiency	222
10.4.6 Pulse Shape. Rise Time	223
10.5 Silicon Diode Detectors	225
10.5.1 Diffused Junction Diodes	225
10.5.2 Surface Barrier Detectors (SSB)	225
10.5.3 Ion-Implanted Diodes	226
10.5.4 Lithium-Drifted Silicon Diodes – Si(Li)	227
10.6 Position-Sensitive Detectors	227
10.6.1 Continuous and Discrete Detectors	227
10.6.2 Micro-Strip Detectors	229
10.6.3 Novel Position-Sensing Detectors	230
10.7 Germanium Detectors	231
10.7.1 Lithium-Drifted Germanium – Ge(Li)	231
10.7.2 Intrinsic Germanium	232
10.7.3 Gamma Spectroscopy with Germanium Detectors	233
10.8 Other Semiconductor Materials	234
10.9 Operation of Semiconductor Detectors	235

10.9.1	Bias Voltage	235
10.9.2	Signal Amplification	235
10.9.3	Temperature Effects	237
10.9.4	Radiation Damage	237
10.9.5	Plasma Effects	238
11.	Pulse Signals in Nuclear Electronics	241
11.1	Pulse Signal Terminology	241
11.2	Analog and Digital Signals	242
11.3	Fast and Slow Signals	244
11.4	The Frequency Domain. Bandwidth	245
12.	The NIM Standard	249
12.1	Modules	249
12.2	Power Bins	250
12.3	NIM Logic Signals	250
12.4	TTL and ECL Logic Signals	253
12.5	Analog Signals	253
13.	Signal Transmission	255
13.1	Coaxial Cables	255
13.1.1	Line Constituents	257
13.2	The General Wave Equation for a Coaxial Line	258
13.3	The Ideal Lossless Cable	259
13.3.1	Characteristic Impedance	260
13.4	Reflections	260
13.5	Cable Termination. Impedance Matching	262
13.6	Losses in Coaxial Cables. Pulse Distortion	264
13.6.1	Cable Response. Pulse Distortion	267
14.	Electronics for Pulse Signal Processing	269
14.1	Preamplifiers	269
14.1.1	Resistive vs Optical Feedback	271
14.2	Main Amplifiers	272
14.3	Pulse Shaping Networks in Amplifiers	272
14.3.1	CR-RC Pulse Shaping	273
14.3.2	Pole-Zero Cancellation and Baseline Restoration	273
14.3.3	Double Differentiation or CR-RC-CR Shaping	274
14.3.4	Semi-Gaussian Shaping	275
14.3.5	Delay Line Shaping	275
14.4	Biased Amplifiers	276
14.5	Pulse Stretchers	276
14.6	Linear Transmission Gate	276
14.7	Fan-out and Fan-in	277
14.8	Delay Lines	278
14.9	Discriminators	278
14.9.1	Shapers	279
14.10	Single-Channel Analyzer (Differential Discriminator)	279

14.11	Analog-to-Digital Converters (ADC or A/D)	281
14.11.1	ADC Linearity	283
14.12	Multichannel Analyzers	283
14.13	Digital-to-Analog Converters (DAC or D/A)	284
14.14	Time to Amplitude Converters (TAC or TPHC)	286
14.15	Scalers	286
14.16	Ratemeter	286
14.17	Coincidence Units	287
14.18	Majority Logic Units	287
14.19	Flip-Flops	288
14.20	Registers (Latches)	289
14.21	Gate and Delay Generators	289
14.22	Some Simple and Handy Circuits for Pulse Manipulation	289
14.22.1	Attenuators	290
14.22.2	Pulse Splitting	290
14.22.3	Pulse Inversion	291
14.23	Filtering and Shaping	291
14.23.1	Pulse Clipping	291
14.23.2	High-Pass Filter or CR Differentiating Circuit	292
14.23.3	RC Low-Pass Filter or Integrating Circuit	293
15.	Pulse Height Selection and Coincidence Technique	295
15.1	A Simple Counting System	295
15.2	Pulse Height Selection	296
15.2.1	SCA Calibration and Energy Spectrum Measurement	297
15.2.2	A Note on Calibration Sources	298
15.3	Pulse Height Spectroscopy with Multichannel Analyzers	299
15.4	Basic Coincidence Technique	302
15.4.1	Adjusting the Delays. The Coincidence Curve	303
15.4.2	Adjusting Delays with the Oscilloscope	304
15.4.3	Accidental Coincidences	305
15.5	Combining Pulse Height Selection and Coincidence Determination. The Fast-Slow Circuit	305
15.6	Pulse Shape Discrimination	306
16.	Electronic Logic for Experiments	309
16.1	Basic Logic Gates: Symbols	309
16.2	Boolean Laws and Identities	311
16.3	The Inhibit or Busy	313
16.4	Triggers	313
16.4.1	One-Body Scattering	314
16.4.2	Two-Body Scattering	314
16.4.3	Measurement of the Muon Lifetime	315
17.	Timing Methods and Systems	317
17.1	Walk and Jitter	317
17.2	Time-Pickoff Methods	318
17.2.1	Leading Edge Triggering (LE)	318
17.2.2	Fast Zero-Crossing Triggering	319

17.2.3	Constant Fraction Triggering (CFT)	319
17.2.4	Amplitude and Risetime Compensated Triggering (ARC)	319
17.3	Analog Timing Methods	320
17.3.1	The START-STOP Time-to-Amplitude Converter	321
17.3.2	Time Overlap TAC's	321
17.4	Digital Timing Methods	322
17.4.1	The Time-to-Digital Converter (TDC)	322
17.4.2	The Vernier TDC	323
17.4.3	Calibrating the Timing System	325
18.	Computer Controlled Electronics: CAMAC	327
18.1	CAMAC Systems	328
18.2	The CAMAC Standard	330
18.2.1	Mechanical Standards	330
18.2.2	Electrical Standards: Digital Signals	330
18.3	The CAMAC Dataway	330
18.3.1	Common Control Signals (<i>Z, C, D</i>)	333
18.3.2	Status Signals	333
18.3.3	Timing Signals	333
18.3.4	Data Signals	333
18.3.5	Address Signals	333
18.3.6	Command Signals	334
18.3.7	Pin Allocations	334
18.4	Dataway Operations	335
18.4.1	Dataway Timing	336
18.4.2	Block Transfers	338
18.5	Multi-Crate Systems – The Branch Highway	340
18.6	CAMAC Software	341
Appendix	345
A.	A Review of Oscilloscope Functions	345
A.1	Basic Structure	345
A.1.1	Bandwidth and Risetime	345
A.2	Controls and Operating Modes	346
A.2.1	Input Coupling	346
A.2.2	Vertical and Horizontal Sensitivity	346
A.2.3	Triggering (Synchronization)	347
A.2.4	Display Modes	347
A.3	Applications and Examples	348
A.3.1	Signal Viewing	348
A.3.2	Comparison of Signals	348
B.	Physical and Numerical Constants	349
C.	Resistor Color Code	350
References	351
Subject Index	361