

Nuclear Electronics

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Preface

Electronic techniques have always been closely associated with nuclear radiation measurements and in recent years such techniques have become extensively used in many disciplines. At the same time the scope and complexity of the techniques has greatly increased. This has been occasioned partly by the need to exploit the characteristics of semiconductor detectors, but also by the ready availability of circuit elements such as field effect transistors, tunnel diodes and integrated circuits. The user is now faced with a formidable array of techniques; in this book I have attempted to provide the basis for a systematic appraisal of electronic techniques associated with nuclear particle detection.

In writing the book it has proved impossible to cite all of the vast number of original publications relevant to the subject. The approach therefore has been necessarily selective. For each topic precedence has generally been given to any theoretical analyses, where such exist. I have then attempted to isolate the major trends in experimental techniques and these have been illustrated with what appeared to be the best examples of circuits published in recent years.

By adopting this scheme the treatment should appeal to a spectrum of readership. Commercial electronic equipment is readily available, but users will need to know the scope of the techniques available in order to assemble equipment appropriate to any given application. Such users require a knowledge of the possibilities and limitations of the techniques: this often involves the familiar exchange of performance in one respect with performance in other respects. For the more specialist applications the reader should find that the topics are dealt with in sufficient depth to enable him to design new circuits.

This book arose out of a course of lectures given for a number of years to M.Sc. students. Some of the fundamentals of the subject nominally fall within the fields of electronic engineering and statistics and, for that reason,

may be unfamiliar or inaccessible to many readers. In order to provide a reasonably self-contained treatment I have therefore included introductory outlines of several of the relevant topics.

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Contents

1	An Outline of Detection Methods	1
1.1	Interaction of nuclear radiation with matter	1
1.1.1	Introduction	1
1.1.2	Heavy charged particles	1
1.1.3	Electrons and positrons	3
1.1.4	X- and γ -rays	4
1.1.5	Neutrons	8
1.2	Statistics of the production of ionization	11
1.3	Gas filled detectors	13
1.3.1	Ionization chambers	13
1.3.2	Proportional counters	17
1.3.3	Geiger counters	19
1.4	Semiconductor detectors	20
1.4.1	Introduction	20
1.4.2	Homogeneous (bulk) detectors	23
1.4.3	PN junction detectors	24
1.4.4	Surface junction detectors	24
1.4.5	Lithium drifted detectors	25
1.4.6	Thin, totally depleted dE/dx detectors	26
1.5	Scintillation counters	27
1.5.1	Introduction	27
1.5.2	Organic scintillators	28
1.5.3	Inorganic scintillators	30
1.5.4	Photomultiplier tubes	31
1.5.5	Response to different particle energies and types	33
1.6	Other detection methods	35
1.6.1	Cerenkov detectors	35
1.6.2	Spark chambers	36

2 Basic Pulse Circuits	39
2.1 Linear (analogue) circuits	39
2.1.1 RC low pass filter	39
2.1.2 CR high pass filter	41
2.1.3 Transmission of pulses in various systems	44
2.2 Transient response of linear circuits	48
2.2.1 Transform methods	48
2.2.2 The impulse response and the time convolution method	53
2.3 Digital circuits	55
2.3.1 Digital logic	55
2.3.2 Logic gates	58
2.3.3 Regenerative trigger circuits	61
2.3.4 Bistable (flip-flop) circuits	64
2.3.5 Monostable circuits	68
2.3.6 Tunnel diode circuits	70
2.4 Counting and storage circuits	73
2.4.1 Counters and scalars	73
2.4.2 Registers and memories	79
2.4.3 Count rate meters	84
3 Pulse Shaping Methods for Spectroscopy	88
3.1 Factors affecting the energy resolution	88
3.1.1 Pulse height spectra	88
3.1.2 Pulse pile up	90
3.1.3 Noise	91
3.1.4 Detector pulse shape and ballistic deficit	92
3.1.5 Unipolar and bipolar pulse shaping	95
3.2 Linear pulse shaping methods	97
3.2.1 Conditions at the detector	97
3.2.2 CR-RC shaping	100
3.2.3 $(CR)^2$ -RC shaping	102
3.2.4 Delay line pulse shaping	103
3.2.5 Single delay line (DL) shaping	104
3.2.6 Double delay line $(DL)^2$ shaping	107
3.2.7 Delay line plus integration (triangular) shaping	108
3.2.8 Semi-Gaussian shaping	108
3.2.9 Pole-zero cancellation	109
3.3 Baseline restorers	113
3.3.1 Purpose of baseline restoration	113
3.3.2 Simple diode restorer	113
3.3.3 The Robinson restorer	115

3.3.4	Gere-Miller restorer	118
3.3.5	Other methods	120
4	Resolution in Spectroscopy Systems	122
4.1	Noise	122
4.1.1	Statistical nature of noise	122
4.1.2	Johnson or thermal noise	126
4.1.3	Current shot noise	127
4.1.4	Flicker or excess noise	128
4.2	Signal to noise ratio, fwhm and the equivalent noise charge (ENC)	128
4.3	Optimization of signal to noise ratio	130
4.3.1	General case	130
4.3.2	Radiation detector systems	133
4.3.3	Optimization under additional constraints	136
4.4	Signal to noise ratio for practical systems	139
4.4.1	CR-RC shaping	139
4.4.2	Various systems	141
4.5	Effects of pile up	149
4.5.1	Overloading	149
4.5.2	Estimation of loss of resolution	150
4.5.3	Effect of AC coupling and finite detector load	154
4.6	Effect of baseline restoration on signal to noise ratio	156
4.7	Sampling methods, time variant and non-linear pulse shaping	158
5	Amplifiers	166
5.1	Introduction	166
5.2	The field effect transistor	166
5.2.1	Properties of the FET	166
5.2.2	Noise in the FET	168
5.2.3	Equivalent circuit for detector and preamplifier	170
5.3	Preamplifier configurations	172
5.3.1	Conditions at the input	172
5.3.2	Charge sensitive configuration	173
5.3.3	Current sensitive configuration	175
5.4	Semiconductor detector preamplifiers	175
5.4.1	General considerations	175
5.4.2	Preamplifier circuits	179
5.4.3	Circuits not using FETs	190
5.5	Requirements on main amplifiers for spectroscopy	190
5.5.1	Summary of requirements	190
5.5.2	Bandwidth requirements	191

5.5.3	Gain stability	192
5.5.4	Stability to oscillation	196
5.6	Practical examples of high stability amplifiers	200
5.7	Fast amplifiers	205
6	Pulse Height and Shape Discriminators	210
6.1	Types of pulse height discriminator or analyser	210
6.2	Preservation of timing information	212
6.3	General requirements of pulse height discriminators	216
6.4	Practical circuits	218
6.4.1	Schmitt trigger circuits	218
6.4.2	Diode type discriminators	218
6.4.3	Tunnel diode discriminators	226
6.5	Pulse shape discrimination (PSD)	233
6.5.1	Introduction	233
6.5.2	Zero crossing method	237
6.5.3	Double integration method	241
6.5.4	Other techniques	243
7	Timing Circuits	248
7.1	Characteristics of timing circuits	248
7.1.1	Introduction	248
7.1.2	Coincidence detection and time jitter	248
7.1.3	Other aspects of time jitter	253
7.2	Time pick-offs	255
7.2.1	Limiter type	255
7.2.2	Leading edge trigger	257
7.2.3	Zero crossing type	259
7.2.4	Constant fraction of pulse height pick-off	259
7.3	Timing for scintillation counters	261
7.4	Timing for semiconductor detectors	265
7.5	Fast coincidence circuits	274
7.5.1	Additive type	274
7.5.2	Diode AND gate	275
7.5.3	Differential coincidence circuits	278
7.5.4	Other types	280
7.6	Multichannel time analysers	281
7.6.1	Introduction	281
7.6.2	Multiple coincidence circuit type	282
7.6.3	Time to digital converters	283
7.6.4	Vernier chronotrons	284
7.6.5	Time to amplitude converters (TACs)	286

<i>Contents</i>	<i>xiii</i>
7.7 Time to amplitude converters (TACs)	287
7.7.1 Pulse overlap type	287
7.7.2 Start-stop type	288
7.7.3 Compensation of amplitude time walk in TACs	291
7.8 Linear gates	292
7.9 Pile up rejector circuits	296
8 Multichannel Pulse Height Analysers	303
8.1 Components of multichannel analysers (MCAs)	303
8.1.1 Analogue to digital converter (ADC)	303
8.1.2 Storage of digital data	304
8.1.3 Ancillary circuits	305
8.2 ADCs	307
8.2.1 Stacked discriminator type	307
8.2.2 Wilkinson type	309
8.2.3 Successive approximation type	310
8.2.4 Hybrid types	312
8.3 Speed and precision of ADCs	313
8.3.1 Relative speed and precision of the different types	313
8.3.2 Sliding scale method of channel smoothing	315
8.4 Design examples of ADCs	317
8.4.1 Wilkinson type	317
8.4.2 Successive approximation type	321
8.4.3 Dual ramp Wilkinson	325
8.5 Spectral stabilization	328
8.6 Additional facilities on MCAs	332
9 Multiparameter and Computer Analysis	337
9.1 Multiparameter analysis	337
9.1.1 Introduction	337
9.1.2 Optical display	341
9.2 Partial storage of selected descriptors	342
9.2.1 Associative storage	342
9.2.2 Associative zone storage	345
9.2.3 Transformation method	347
9.2.4 Use of contents-addressable memory	347
9.3 Large computer systems	349
9.4 Data highways	354
Appendix A Transform Methods in Transient Analysis	358
A.1 The general differential equation	358

A.2	Excitation by an eternal exponential	360
A.3	The Fourier transform	363
A.4	The Laplace transform	366
A.5	Rules for finding transforms and inverse transforms	367
Appendix B	Statistics of Counting	369
B.1	General considerations	369
B.2	Radioactive decay—the binomial distribution	370
B.3	The Poisson distribution	371
B.4	Optimum apportioning of time with source and background	371
B.5	Counting losses due to dead time	374
B.6	Accidental coincidence rates	376
Index	379

An Outline of Detection Methods

1.1 Interaction of nuclear radiation with matter

1.1.1 Introduction

Nearly all detection methods, the Cerenkov detector being a notable exception, make use of the ionization or excitation produced in a detection medium as a result of the absorption of all or part of the energy of the nuclear particle. In the case of charged particles, ionization and excitation is produced directly by the interaction of the electromagnetic field of the particle with the electrons of the detection medium and the resultant ionization and excitation is distributed as a track centred on the track of the particle. In the case of uncharged particles such as X- and γ -ray photons, the particle must first undergo some process, such as a photoelectric or Compton interaction, which transfers all or part of its energy to an electron which in turn produces the track of ionization or excitation. Similarly neutrons must undergo an interaction, such as a collision with a nucleus, the charged product of which then produces the ionization or excitation. In consideration of their interaction with the detection medium the commoner nuclear particles may be divided into four groups:

- (i) heavy charged particles (protons, alpha particles, heavy ions, mesons)
- (ii) electrons and positrons
- (iii) X-rays and γ -rays
- (iv) neutrons

1.1.2 Heavy charged particles

A heavy charged particle entering the detection medium loses its energy by a succession of interactions, mainly between its electromagnetic field and that of electrons in the medium, resulting in electronic excitation and ionization. According to classical mechanics the maximum energy E_{\max} that

an electron of mass m_0 can acquire in a collision with a particle of mass M and energy E is given by

$$E_{\text{max}} = \frac{4m_0ME}{(m_0 + M)^2} \simeq 4E \frac{m_0}{M} \quad (1.1)$$

The quantum mechanical treatment shows that there is a small probability of the electron acquiring an energy slightly higher than the classical maximum E_{max} . The more energetic of the electrons, often termed 'delta' rays, can

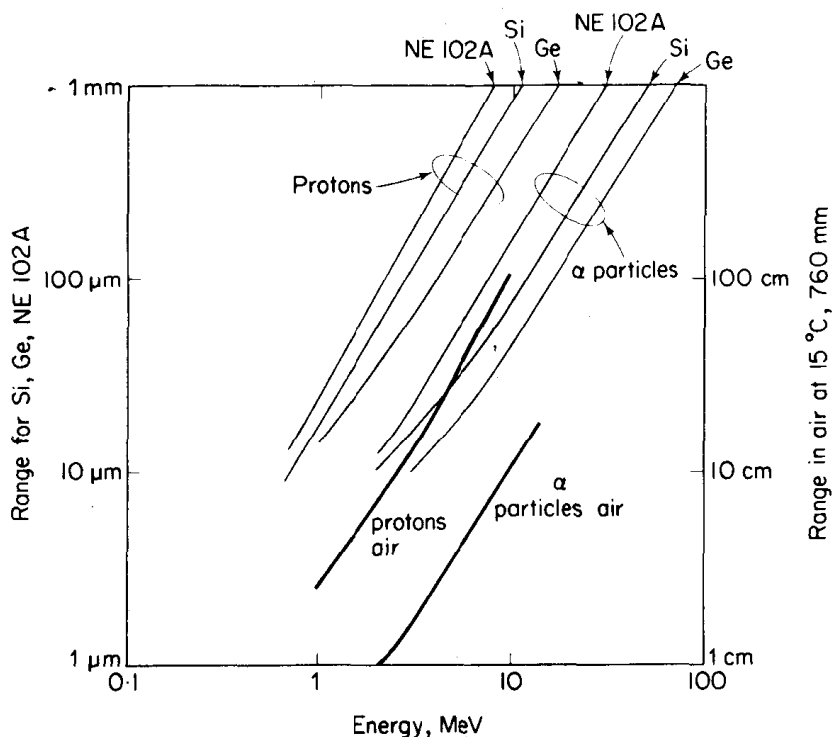


Figure 1.1 Range of α particles and protons in various detector media. Data taken from Goulding⁴ for Si and Ge, Evans² for air, and Nuclear Enterprises Ltd³ for plastic scintillator type NE 102A

themselves produce further ionization; it is this factor that governs the width of the track of ionization. Since the fraction of energy lost per collision of the particle, given by (1.1), is small, the resulting deflections of the particle path are small and the track is comparatively straight. Owing to the large number of collisions necessary to bring the particle to rest, the range is comparatively well defined (typically with a standard deviation of 1–5%).

For a given particle type and energy, if the range R_1 is known for a medium of density ρ_1 and atomic weight A_1 , then the range R_2 in a medium

of density ρ_2 and atomic weight A_2 may be estimated by a simple empirical relation known as the Bragg-Kleeman rule:

$$\frac{R_1}{R_2} = \frac{\rho_2 \sqrt{A_1}}{\rho_1 \sqrt{A_2}} \quad (1.2)$$

For mixtures and compounds the same rule can be used if an effective atomic weight A is used where

$$\sqrt{A} = \frac{n_1 A_1 + n_2 A_2 + \dots}{n_1 \sqrt{A_1} + n_2 \sqrt{A_2} + \dots} \quad (1.3)$$

where n_1, n_2, \dots are the atomic fractions of the constituent elements of atomic weights A_1, A_2, \dots . Figure 1.1 shows the ranges of protons and alpha particles calculated for various detection media.

1.1.3 Electrons and positrons

For energies up to 10 MeV, electrons lose their energy to the detection medium mainly by excitation and ionization of the electrons of the medium, as in the case of heavy charged particles. For higher energy electrons the loss of energy as bremsstrahlung becomes increasingly important and the intensity of this varies as Z^2 where Z is the atomic number of the medium. Thus, for example, 9 MeV electrons in lead lose as much energy due to bremsstrahlung as due to ionization.

In absorption due to ionization, owing to the lower mass of the electron compared to that of a heavy charged particle, a much greater fraction of the particle energy is transferred to the absorber electron in each collision so that the delta rays are correspondingly more energetic and are capable of causing considerable secondary ionization at a greater distance from the original particle track. For a 0.1 MeV electron in air about two-thirds of the total ionization is due to secondary ionization.

Owing to the large energy loss per collision, the path of the particle shows considerable deflections and the range is not well defined. Since an electron travels at a much higher velocity than a heavy charged particle of the same energy, it spends less time in the vicinity of the absorber atoms and so the rate of energy loss and the density of ionization are correspondingly less. For this reason the range of electrons is much greater than that of heavy particles of the same energy. Figure 1.2 shows the range (essentially an approximate figure) for several detector media. For various medium atomic weight absorbers the range, for a given energy, expressed in terms of mass per unit area of the absorber, is approximately constant provided bremsstrahlung does not account for significant energy loss. Finally for beta rays having a maximum energy of E_{\max} , the nomogram in Figure 1.3 gives the approximate percentage transmission for absorbers having different mass

per unit area when the absorber is interposed between source and detector (external absorber), or where the source itself is thick and causing self-absorption.

Positrons have ranges differing only slightly from those of electrons of the same energy. When brought to rest a positron will annihilate with a neighbouring electron and emits the characteristic annihilation radiation of two γ -rays, each of energy m_0c^2 (511 keV), in mutually opposite directions.

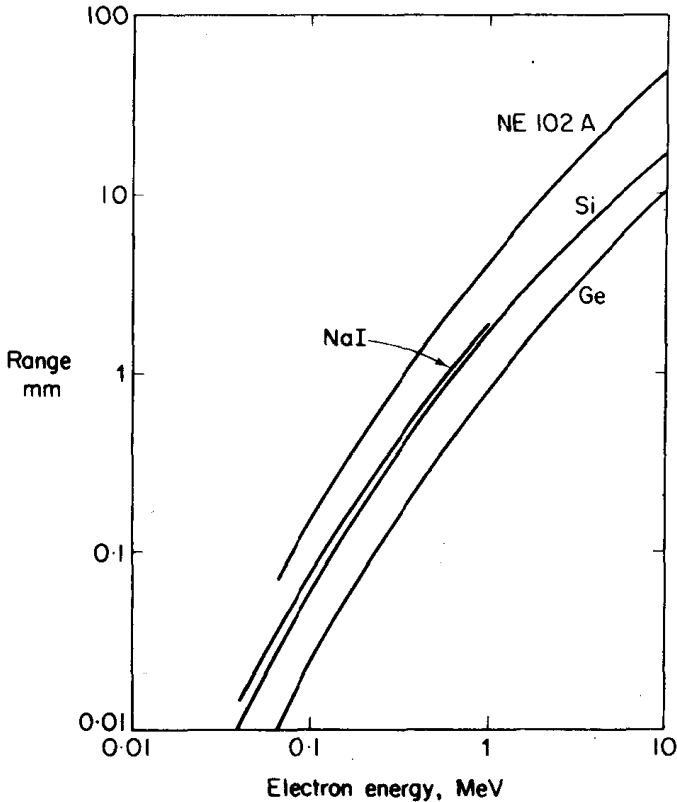


Figure 1.2 Range of electrons in various detector media. Data taken from Goulding⁴ for Ge and Si, Nelms⁵ for NaI, and Nuclear Enterprises Ltd³ for NE 102A plastic scintillator

1.1.4 X- and γ -rays

X- and γ -rays lose energy in matter by three main processes:

- (i) photoelectric effect
- (ii) Compton effect
- (iii) pair production

In the photoelectric effect, all the energy of the photon is transferred to an electron, the original photon disappearing in the process. The process is