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

I

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

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

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

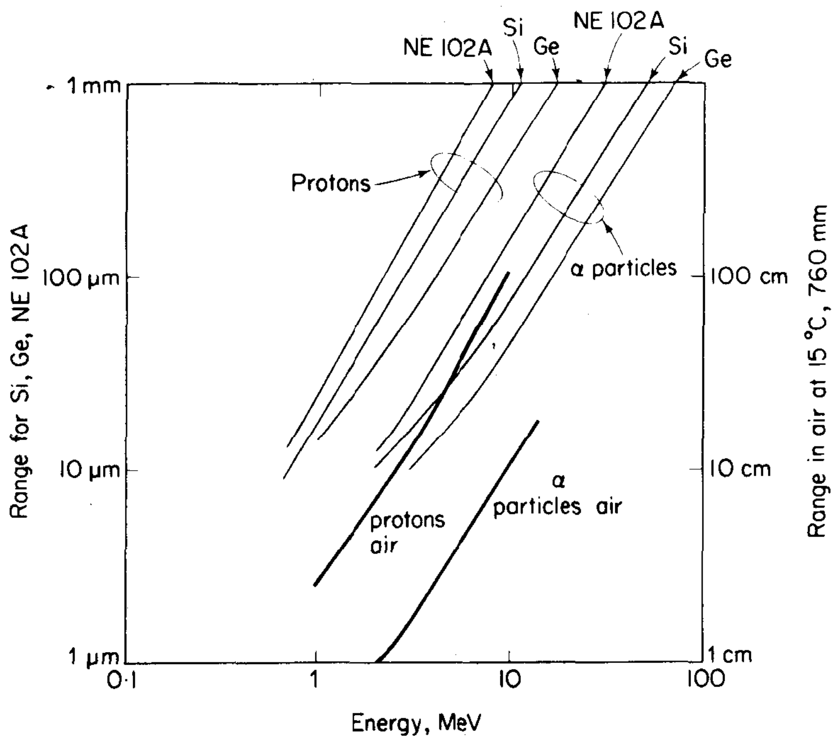

Figure 1.1 Range of α particles and protons in various detector media. Data taken from Goulding[4] for Si and Ge, Evans[2] for air, and Nuclear Enterprises Ltd[3] for plastic scintillator type NE 102A

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**:

$$\frac{R_1}{R_2} = \frac{\rho_2\sqrt{A_1}}{\rho_1\sqrt{A_2}} \tag{1.2}$$

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

$$\sqrt{A} = \frac{n_1A_1 + n_2A_2 + \dots}{n_1\sqrt{A_1} + n_2\sqrt{A_2} + \dots} \tag{1.3}$$

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 accout 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.

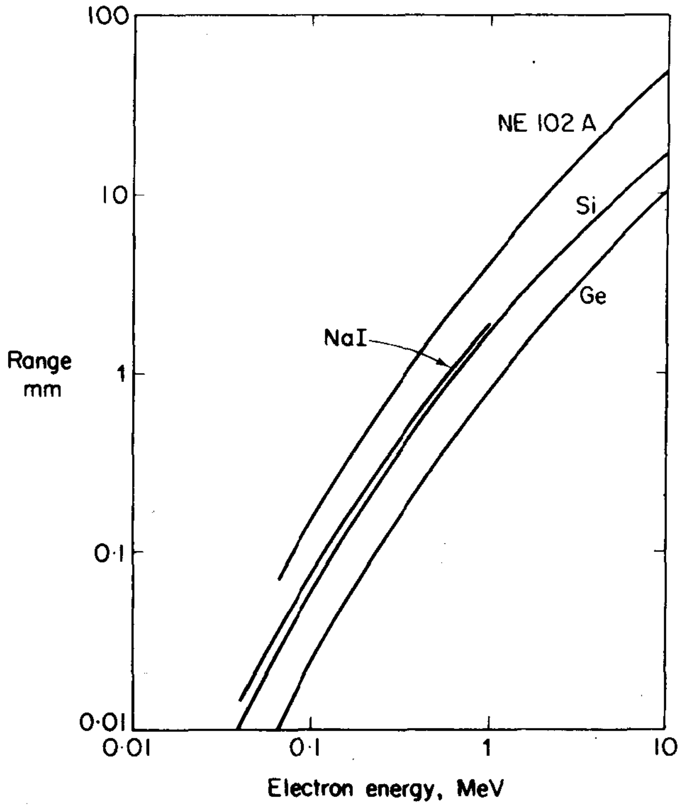

Figure 1.2 Range of electrons in various detector media. Data taken from Goulding[4] for Ge and Si, Nelms[5] for NaI, and Nuclear Enterprises Ltd[3] for NE 102A plastic scintillator

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