PRINCIPLES OF NUCLEAR RADIATION DETECTION

LABORATORY MANUAL

by

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PREFACE

It has been about 15 years since the last general textbooks on nuclear radiation detection were written. In that time some fundamental changes have occurred, both with respect to the complexity and sophistication of counting equipment and to the more widespread use of radiation technology in medicine and industry. Many of the changes reflect the replacement of vacuum tubes by semiconductor devices and the consequent increase in speed and variety of data handling capability; many others arise from the development and maturing of detector systems that were only in their infancy then. For these reasons it seems appropriate to bring out a new book that represents more clearly the present status of the field.

This book is intended for senior undergraduate and beginning graduate students in physics, nuclear engineering, health physics and nuclear medicine, and for specialized training courses for radiation protection personnel and environmental safety engineers. To keep the size of the book manageable, material has been selected to stress those detectors that are in widespread use. Attempts have also been made to emphasize alternatives available in approaching various measurement problems and to present the criteria by which a choice among these alternatives may be made. Limited bibliographies are provided to encourage further reading and numerical problems to develop a feeling for the orders of magnitude of various system parameters. The SI system of units has been adopted as far as practical, though the curie and the roentgen have been retained where it seemed appropriate to reflect current usage.

The contents represent the outcome of courses presented at the Georgia Institute of Technology over many years, and we are grateful to out colleagues, B. Kahn, M. T. Ryan and M. D. Matheny, for their helpful comments.

A companion volume is provided to serve as a laboratory manual for radiation detection courses. The manual is cross-referenced to the present book, but either can be used separately as desired. Additional questions and problem sets will be found in the laboratory manual.

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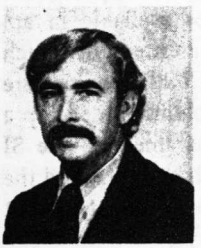
Dr. Eichholz headed the Physics and Radiotracer Subdivision of the Canadian Bureau of Mines for twelve years, where he focused on problems of uranium ore analysis, industrial instrumentation, radiation protection and industrial uses of radioisotope tracers. In 1963 he joined the faculty of Georgia Tech where his research and teaching focus on radiation detection problems, radiation effects on materials, environmental applications of radiotracers and radiation safety. Professor Eichholz is author of *Environmental Aspects of Nuclear Power*, published by Ann Arbor Science, and editor of the book *Radioisotope Engineering*.



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Dr. Poston was employed as an Experimental Reactor Physicist by the Babcock and Wilcox Company for six years and was a staff member in the Health Physics Division at the Oak Ridge National Laboratory for thirteen years. During this latter period he was involved in various aspects of external and internal dosimetry and was head of the Medical Physics and Internal Dosimetry Section. His research at ORNL concentrated on programs related to the activities of the Atomic Bomb Casualty Commission and the International Commission on Radiological Protection. He joined the faculty of Georgia Tech in 1977 where his teaching and research interests include radiation detection and applied radiation protection at nuclear facilities.

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CHAPTER 1

INTRODUCTION

Nuclear and atomic radiations find many applications in our society, from chest X-ray radiography to the control of the thickness of aluminum foil, from tracer measurements of stream flow or natural gas reservoirs to measurements of cardiac output from the heart, from determination of cosmic ray intensities on mountain tops to the monitoring of radiation levels around nuclear power reactors or supervoltage particle accelerators. In each case the measurement of radiation intensity or radiation exposure requires a thorough understanding of the characteristics of alternative detection systems available, an appreciation of the physical problem to be solved, and an informed selection of the detector type that is most suited to the particular application. Since nuclear radiations are not sensed by the common human senses, a detector is required to provide a conversion to a readily measurable phenomenon. The properties of these detectors and any refinements that can be supplied to improve their performance must form the core of any discussion of radiation detection systems. The performance of a detector system depends on the characteristics of all of its components, that is, the detector proper which responds to the incident radiation and converts it into a more tractable form, usually electric charges or voltages, the amplifier system, and the data display or evaluation system.

Nuclear radiations comprise several forms of energy transmission that are characterized by their ability to excite, ionize or otherwise interact with most atoms or molecules that they encounter. They derive their name from the fact that they are emitted as the result of the de-excitation processes that a nucleus undergoes following bombardment or capture reactions; the type and energy spectrum of the emitted radiation reflect the characteristic energies associated with these processes. The radiations of particular importance are called alpha (α), beta (β) and gamma (γ) radiations and neutrons, though a whole host of other charged and uncharged particles fit the same general

description and may be encountered in specific research situations. X-Rays, whose characteristics are closely allied to gamma radiation, are usually included in considerations of nuclear radiation detectors as a matter of convenience, though strictly they are not of nuclear origin but arise from transitions between orbital electron energy levels.

Radiation detection may consist of different types of operations; these are variously referred to as *detection, monitoring, analysis or dosimetry* with each type requiring slightly different equipment and emphasizing a different aspect of the measurement process. In detection one tends to concentrate on verifying the presence or absence of a given kind of radiation above a certain level of intensity. In monitoring operations this process is typically related to a time-dependent observation or to established safety standards of exposure. Analysis of radiation requires further identification of various radiation sources, if present, and a determination of energy distributions or spectra, and, in some cases, discrimination in time sequence of events. Finally, dosimetry relates the type and energy distribution of the radiation field to the absorption of this energy in body tissue and to any related health effects that may arise from this exposure.

Consequently, one may divide detector systems into those that are intended and most suited for the measurement of radiation intensity, those dedicated to the measurement of radiation dose, and those capable of determining energy distributions or spectra. In general, each detector system will be capable of responding principally to only one type of radiation, though high levels of other radiation types may cause interference; hence, a wide variety of detector types and detector systems have been developed for different purposes.

All radiations represent a transfer of energy from the emitting source to the surrounding media where they may interact to an extent determined by the characteristics of the radiation and the nature and structure of the intervening medium. If the interaction between the radiation and the target medium is strong, energy is transferred at a rapid rate and the radiation is strongly attenuated. If radiation attenuation is weak, the radiation may have an appreciable range and may be detected at great distances from the source. Since all detection methods depend on finding an efficient interaction mechanism to transfer some of this energy so that it can be converted into readable form, these interaction processes are central to any discussion of radiation detection.

The energy of radiations emitted by nuclei is of the order of nuclear excitation energies or binding energies; these are of the order of kiloelectron-volts (keV) and megaelectron-volts (MeV), where 1 MeV = 0.16 picojoule (pJ).

The radiations will interact with materials, that is, they will lose kinetic energy to any solid, liquid or gas through which they pass by a variety of interaction mechanisms that depend on the energy of the incident radiation, the density and atomic number of the absorbing medium, and the relative

probability for one or another process to take place. These probabilities are called cross sections and are usually expressed in barns (1 barn = 10^{-24} cm^2 = 10^{-28} m^2). The result of these interaction processes is a gradual slowing down of any incident particle until it is brought to rest or "stopped" at the end of its range. Although the terminology varies among the nuclear physicist, the health physicist, the radiobiologist and the radiation chemist, they all are interested in the rate of energy loss or transfer ("dE/dx, LET") as the incident particle is slowed down, the total energy lost or transferred by various secondary processes and the consequent effect per unit mass or unit volume on the target material.

Since charged particles lose energy at a fairly steady rate when transversing material substances, it is possible to relate their initial energy to the distance traveled in that medium. This is called the *range* of the particle and represents the average distance traversed in a given medium by a particle of specified energy.

The emission of radiation from nuclear processes occurs randomly in time; consequently all radiation detection processes deal with statistically random events and the data evaluation and interpretation of detector response must take into account the statistical nature of all events. This has considerable bearing on the sensitivity and accuracy of radiation detection systems and this aspect will be treated in some detail in Chapter 3.

RADIATION INTENSITY

The intensity of a radiation field can be described in several ways. The simplest is to describe it in terms of a particle flux or flux density, *i.e.*, the number of particles passing unit area per unit time, with all particle paths projected normally onto the reference plane. This is a convenient way of expressing field intensities for parallel beams of particles or for fields created by a point source. It is the customary way of describing neutron fields around a reactor where one also needs to distinguish between neutrons in different energy ranges. Flux density is usually expressed in number of particles/cm^2-sec.

For X-rays and gamma-rays, a more experimentally oriented approach is customary in which the field intensity is expressed in terms of the number of ions produced in a known mass or volume of detector. Such a measure of the ionization produced in air by X- or gamma radiation is called the *exposure*. The unit of exposure is the Roentgen (R). It has been defined as that quantity of X- or gamma radiation that would, through associated corpuscular radiation, produce one statcoulomb of charge of either sign in one cubic centimeter of dry air at STP.

$$1\ R = 2.58 \times 10^{-4}\ \text{coulomb/kg of air}$$

The energy *absorbed* by that 1 cm^3 air volume represents an equivalent of 87.7 ergs per gram of air or 8.77×10^{-9} joule/kg; this quantity is useful in comparing exposure values and dose values, but it is important to maintain the distinction.

SOURCE STRENGTH

Radiation will originate from natural or artificial sources, which may be steadily decaying radioactive materials, nuclear reactors, astronomic sources or high-voltage accelerators of various types. The *source strength* is a measure of the rate of emission of radiation. More than one kind of radiation and more than one energy group of a given radiation type may be emitted; this fact needs to be considered in describing the source characteristics. Consequently there are several ways in which a radiation source can be described.

Emergent Flux

For machine sources and reactor cores it may often be easiest to describe source strength in terms of total number of particles or photons emitted per unit time into the total solid angle (4π). This procedure is not appropriate if the emission is not isotropic or if there is significant conversion of the radiation within the source volume. In reactors or machines any measurement of this quantity must allow for reflection or backscattering effects and, in the case of neutrons, for spectral shift. The result is usually a description of the *particle or photon flux* at a given external point near the source, which is assumed to be concentrated to a small volume.

In reactors the equivalent source strength of the core region may involve both prompt fission effects and delayed fission product activity; hence it is rarely practical to describe ambient radiation fields in terms of an equivalent source strength.

Radioactive Sources

For radioactive materials it is customary to describe the source strength in terms of the *source activity*, which is defined as the number of disintegrations per unit time occurring in a given quantity of this material. For any pure radioactive substance, the rate of decay is usually described by its half-life τ, *i.e.*, the time it takes for a specified source material to decay to half its initial activity. The activity A can be written as

$$A = \lambda N = \frac{\log_e 2}{\tau} N = \frac{0.693\, N}{\tau} \qquad (1\text{-}1)$$

where λ = decay constant (sec^{-1}) and N = total number of atoms of the radioactive species.

The SI unit of activity is the *becquerel* (Bq), equivalent to a source activity of one disintegration per second. More widely used is the traditional unit of activity, the *curie*, which is defined as:

$$1 \text{ curie (Ci)} = 3.70 \times 10^{10} \text{ disintegrations/sec} = 3.70 \times 10^{10} \text{ Bq}$$

Since activity is proportional to the number of atoms of the radioactive material, the quantity of any radioactive material is usually expressed in curies, regardless of its purity or concentration. The usual metric multiples apply to the curie. Since many nuclides have complex decay schemes, the activity does not in itself indicate the emergent flux from any source.

To calculate the radiation field for a given radioactive source it is necessary to know the decay scheme of the material, any branching ratios and the composition of the emitted radiation. Also note that the activity of a given source is a function of time since the number of radioactive atoms decreases exponentially:

$$N = N_0 e^{-\lambda t} = N_0 e^{\frac{-0.693t}{T}} \tag{1-2}$$

where N_0 = number of atoms at time t = 0. Hence,

$$A = A_0 e^{\frac{-0.693t}{T}} \tag{1-3}$$

In the case of radioactive materials contained in living tissue an additional allowance has to be made for the reduction in observed activity due to regular processes of elimination of the respective chemical or biochemical substance from the organism. This introduces a rate constant called the biological half-life, which is approximately the same for both stable and radioactive isotopes of a given element.

Under such conditions the time required for a radioactive element in any living organism to be halved as a result of the combined action of radioactive decay and biological elimination is the effective half-life:

$$T_{eff} = \frac{T_{biol} \times T_{RA}}{T_{biol} + T_{RA}} \tag{1-4}$$

To identify a radioactive material, four types of measurement may have to be conducted:

1. determination of the mass number, or atomic number,
2. determination of the source strength or activity,
3. determination of the half life,and
4. determination of the energy or energy spectrum, types of radiation and decay schemes.

To establish the effect of the radiation field on a given target material, a different type of measurement is required:

1. measurement of the radiation intensity (or flux),
2. measurement of the energy loss,
3. measurement of absorbed energy (dose), and
4. measurement of the dose effect on a given target material.

ABSORBED DOSE

Since different types of radiation interact differently with any material through which they pass, any attempt to assess their effect on the human body or on plants and animals should take into account these differences. The quantity of interest is the absorbed dose, D, which is defined as the energy imparted by the incident radiation to unit mass of the target material or

$$D = \frac{\Delta E_D}{\Delta m} \tag{1-5}$$

The conventional unit of absorbed dose is the *rad*; 1 rad = 100 erg/gram = 0.01 J/kg. The SI unit of absorbed dose is the *gray*. 1 gray (Gy) = 1 J/kg. The rate of energy absorption is called the absorbed dose rate $\Delta D/\Delta t$ and is expressed in rad/hr, rad/min, Gy/sec, as appropriate.

The physical meaning of dose has concerned health physicists for many years and has led to many attempts at clarification. The problem arises from two sources: one, to measure internally the amount of energy actually transferred to an organic material and to correlate any observed effects with this energy deposition, and two, to account for and predict any secondary processes, such as collision effects or biologically triggered effects, that are an indirect consequence of the primary interaction event. Measuring instruments designed specifically to indicate absorbed dose are referred to as *dosimeters.*

CHARACTERISTICS OF NUCLEAR RADIATIONS

Although the term "radiation" is applied to all forms of energy emission from nuclear events, there are in fact significant and characteristic differences between the various types of radiation that are emitted or can be emitted under various circumstances of nuclear excitation. Basically one can distinguish between emission of electromagnetic radiation ("photons"), resulting from

transitions between excited states of a given nuclide, and particulate radiations representing transformations or ejection of one or more nucleons from an atomic nucleus. The particles consist of charged and uncharged particles and are differentiated on the basis of mass, charge and spin, and among the more exotic particles by additional characteristics such as "charm," "strangeness" and "color." Most of the latter particles are produced only under very-high-energy excitation conditions and require particularly sophisticated methods of data evaluation for their detection. However, the methods available for their detection in principle are not significantly different from methods employed at lower energies and little specific reference will be made in this book to the high-energy region and its radiations.

Table 1.1 lists the characteristics of the radiations commonly encountered in nuclear engineering and in medical and industrial radiation applications. The names reflect a historical order of discovery for alpha, beta and gamma radiation. Because of their varied characteristics, methods of detection appropriate to each type have to be selected in every case. In general, no one detector method or system will be equally applicable to more than one radiation type or even to more than a limited energy range of that radiation. Thus, different detector systems may be called for in the case of "thermal" (low-energy) and "fast" (high-energy) neutrons or for "soft" or "hard" beta-rays or X-rays.

In general terms one distinguishes three radiation types for purposes of selecting interaction mechanisms and detector types:

1. Electromagnetic radiations, γ- or X-rays, that interact primarily through spin coupling with the orbital electrons of irradiated targets, causing ionization, excitation or Compton scattering events.
2. Charged particles, including heavy particles such as protons, deuterons, tritons and alpha particles as well as heavier charged ions, and the lighter particles such as electrons (β- and β+) and mesons, which have rest masses substantially below atomic masses. Charged particles can interact both with orbital electrons and the central nucleus.
3. Uncharged particles, principally neutrons, which have masses comparable to protons, and neutrinos, which have vanishingly small rest masses. Neutrons interact almost entirely with the central nucleus, since they are not screened off by the electrons, and may undergo capture or a scattering event, leading to transfer of some kinetic energy to the nucleus and deflection of the incident neutron.

DETECTOR SYSTEMS

The detector systems developed for each of these radiations attempt to utilize these interaction characteristics by interposing a medium of appropriate properties in which, by a process of excitation, ionization or momentum transfer, a more readily detectable signal is produced which can be counted, accumulated or sorted to provide the desired information about the radiation field being studied.