NCRP REPORT No. 58

A HANDBOOK OF RADIOACTIVITY MEASUREMENTS PROCEDURES

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With Nuclear Data for Some Biologically Important Radionuclides

Recommendations of the NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS

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Preface

In 1961 the NCRP issued NCRP Report No. 28, *A Manual of Radioactivity Procedures,* which was published as the National Bureau of Standards Handbook 80. The report came to be one of the definitive works in the area of radioactivity measurements. As the development of new techniques, procedures, and equipment made parts of the Report obsolescent, the NCRP recognized the need to update and extend the document. The report consisted essentially of three parts: Part One being "Radioactivity Standardization Procedures"; Part Two, "Measurement of Radioactivity for Clinical and Biological Purposes"; and Part Three, "Disposal of Radioactive Material". Since the disposal of radioactive material constitutes a subject in itself, the NCRP, in preparing the revision of Report No. 28, decided to concentrate on the first two parts of the Report.

Because of the projected bulk of the revised report, it was decided to divide the task of preparation into two parts. NCRP Scientific Committee 18A was given the task of drafting the material on general measurement and standardization procedures; and Scientific Committee 18B was charged with drafting the material on those measurement procedures specifically concerned with medical and biological applications. This report is the result of Committee 18A's work. As such, it follows, to a high degree, the general format of the original report. Thus, the physics of detectors is discussed in Section 2.0 and then the uses to which these detectors may be put are discussed in those sections dealing with direct and indirect measurements. At the same time, each of the sections has been developed in much more detail than previously and it is therefore inevitable that some duplication occurs. In fact, some duplication has been deliberately included so that individuals may utilize given sections of the Report without having to refer back to earlier sections where similar material may have been covered. In almost every case, it is believed that the repetition will not only emphasize the suitability of a detector for a particular application, but will also add detail to the information already given.

In a report of this length it is inevitable that the supply of unique symbols would be exhausted. Where, however, there may have been

some duplications in the use of symbols, every effort has been made to keep them consistent within the short section in which they appear.

Acknowledgments are made to Dr. Ayres who acted as secretary to the Committee, and to Dr. Hoppes who, while making no specific written contribution, served invaluably by spending many hours in valuable discussion with the Chairman of the Scientific Committee during the course of editing and clarifying the original text. The assistance of Miss P. A. Mullen in the work of coordinating the references is also gratefully acknowledged.

The Council has noted the action taken by the General Conference of Weights and Measures to make available special names for some of the units of the International System (SI) used in connection with ionizing radiation. Gray (Gy) has been adopted as a special name for the SI unit, joule per kilogram, for absorbed dose, absorbed dose index, kerma, and specific energy imparted. Becquerel (Bq) has been adopted as a special name for the SI unit of activity (of a radionuclide). Since the transition from the special units currently employed—rad and curie—to the new special names is expected to take some time, the Council has determined to continue, for the time being, the use of rad and curie. To convert from one set of units to the other, the following relationships pertain:

$$1 \text{ rad} = 0.01 \text{ J kg}^{-1} = 0.01 \text{ Gy}$$
$$1 \text{ curie} = 3.7 \times 10^{10} \text{ s}^{-1} = 3.7 \times 10^{10} \text{ Bq (exactly)}.$$

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The Council wishes to express its appreciation to the members and consultants for the time and effort they devoted to the preparation of this report.

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Bethesda, Maryland
February 15, 1978

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1. Introduction

1.1 General

Radioactivity is the term used to describe those spontaneous, energy-emitting, atomic transitions that involve changes in state of the nuclei of atoms. The energy released in such exoergic transformations is emitted in the form of electromagnetic or corpuscular radiations. The radiations interact, in varying degrees, with matter as they traverse it.

Radioactivity was discovered in 1896 by A. H. Becquerel, who was investigating the fluorescence of a double sulphate of uranium and potassium, using a photographic plate. He found that the plate was affected by certain *radiations actives*, irrespective of whether or not the salt was caused to fluoresce. Marie Curie, who coined the word *radioactivité*, investigated this property in a number of minerals containing uranium, which she found to be more active, atom for atom, than uranium itself. Postulating an element that was unknown except for its radioactivity, she and Pierre Curie set about the isolation of this hypothetical element, thereby applying, for the first time, techniques that now comprise the field of radiochemistry. In 1898 they discovered polonium and, in collaboration with G. Bemont, radium. E. Rutherford showed that two types of radiation were emitted by uranium, namely the alpha rays, that were completely stopped by a thin sheet of paper, and the beta rays, that were much more penetrating. In 1900, even more highly penetrating radiations, the gamma rays, were discovered by P. Villard. Subsequently, the alpha and beta rays were shown to be ionized helium-4 atoms and electrons, respectively, and the gamma rays to be photons.

In due course, three separate generic families of naturally occurring radioactive materials were discovered, namely the uranium, thorium, and actinium series. In each of these, one radionuclide—uranium-238, thorium-232, and uranium-235 (known originally as actinium)—in undergoing radioactive change, gives rise to a series of between twelve and eighteen radioactive progeny, usually referred to as *daughters*. The atomic mass number of each member of each series is obtained by substituting $n = 51, 52 \ldots 59$ in $(4n + 2)$ (uranium), $n = 52, 53 \ldots 58$ in $4n$ (thorium), and $n = 51, 52 \ldots 58$ in $(4n + 3)$ (actinium). Following

the discovery of the transuranic elements, a fourth such family of radioactive elements was discovered, namely the neptunium series of which the atomic weights are given by substituting n = 52, 53 . . . 60 in (4n + 1). The common step of 4n in each series represents, of course, the loss of an alpha particle, the loss of a beta particle from the nucleus leaving the atomic mass number unchanged.

The early history of radioactivity, and the underlying principles of its detection and measurements, are treated in such textbooks as *Radiations from Radioactive Substances* by E. Rutherford, J. Chadwick, and C. D. Ellis (1930); *The Atomic Nucleus* by R. D. Evans (1955); *Nuclear and Radiochemistry* by G. Friedlander, J. W. Kennedy, and J. M. Miller (1964); and *Alpha-, Beta-, and Gamma-ray Spectroscopy*, edited by K. Siegbahn (1965). A brief and more elementary treatise, that may be useful for those involved as technicians in nuclear-medicine measurements, is *Radioactivity and Its Measurement* by W. B. Mann, R. L. Ayres, and S. B. Garfinkel (1979).

The present state of the art in radioactive metrology was the subject of an International Summer School on Radionuclide Metrology held at Herceg Novi, Yugoslavia in 1972. The proceedings, published a year later, (Herceg Novi, 1973) are a very valuable contribution to the literature of the subject.

In 1932 the neutron was discovered by James Chadwick and, in 1933, artificial radioactivity by Frederic and Irene Joliot-Curie. Thereafter, in the late 1930's and in the 1940's many artificially produced radioactive elements were discovered by many investigators using nuclear reactions produced in the cyclotron of Ernest Lawrence and the nuclear reactor developed by Enrico Fermi and his colleagues. In discussing such nuclear reactions we use the designations: n for neutron, p for proton, d for deuteron, α for alpha particle, and γ for gamma radiation; and the further convention of, for example, (n,γ), meaning capture of a neutron by a nucleus and emission of a prompt gamma ray. The reactions giving rise to artificial radioactivity in cyclotrons and other particle accelerators are many, including (p,n), (p,γ), (d,n), (d,p), (α,p), and so on. In many cases accelerated ions of higher atomic-number elements have also been used to produce nuclear reactions that result in radioactive elements. Among these, delayed proton emitters have also been observed. In reactors, in addition to the many radioactive fission products produced in the nuclear fission process, a vast quantity of radioactive materials has been produced by (n,γ), (n,2n), (n,p), (n,α), and other reactions. With high-energy accelerators producing photons of many millions of electron volts of energy, prolific photonuclear reactions occur, corresponding to ($h\nu$,xn) and ($h\nu$,xp) where $h\nu$ (the product of Planck's constant and photon frequency)