Radioactivity and Radiation Detection

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Introduction

THE PURPOSE of this text is to provide a summary of the practical and theoretical information needed for the intelligent application of radiation detectors. Emphasis is placed on the information that the author has found to be essential to an understanding of the applications and limitations of radiation detectors in the radiochemical laboratory and the nuclear technologies. The many topics to be discussed are presented in summary form in order to offer the reader an opportunity to become rapidly conversant with the vocabulary and basic concepts involved in understanding radioactivity and radiation detection. Each topic covered in this text can certainly be expanded and appropriate experimental problems can be devised within the capability of the equipment available to individual readers. It has been the author's experience that merely the exposure of a student to the concepts presented here provides an invaluable background for the subsequent understanding of the practical application of radiation detection techniques.

The material presented here has provided the basis for a very successful course in radiochemical instrumentation presented to technicians, scientists, and engineers who had widely different technical backgrounds.

No attempt is made to discuss each of the large number of different types of radiation detectors but only to discuss the systems most commonly used for the detection of alpha and beta particles and x-ray or gamma photons. It is intended that this discussion of these fundamental detection systems will provide a basis of understanding for the utilization of any other more specialized system.

Although this text assumes that the reader has only a first year college level background in physics and chemistry, it is intended that it will provide a useful reference for all workers in any area involving the use of radioactive materials or the detection of radiation.

Rather than the usual practice of merely referencing various specific pieces of literature in the body of the text, a complete chapter is devoted to the technical literature of radiation detection and radioactivity. Since this text is written primarily for the beginning student of radiation detection, it was felt that the importance of knowledge concerning available technical literature warranted separate treatment of this subject.

72-84

Contents

Introduction v

Chapter 1 Radioactive Decay 1

Radiations emitted 1

Alpha particle 1
Beta particle 3
Gamma photon 5
Conversion electron 5
X-ray photon 5
Positron 6
Annihilation radiation 6
Electron capture 7
Fission products 7
Delayed neutron 7

Decay schemes 7
Decay rate 13
Half-life 14
Specific activity 16
The curie 19
Dose rate 20
Inverse square law 22
Decay heat 22
Problems 23

Chapter 2 Interaction of Radiation with Matter 25

Alpha particles 25

Ion pair formation 26
Range vs energy 27

Beta particles 28

Ion pair formation 29
Secondary ionization 29
Bremsstrahlung 30
Half-thickness 31

Gamma photons 31
Photoelectric effect 31
Compton scattering 31
Pair production 32
Exponential absorption 33
Mass absorption coefficient 33
Linear absorption coefficient 33
Neutrons 37
Thermal neutrons 37
Epithermal neutrons 37
Fast neutrons 37
Nuclear interaction 38
Scattering 38
Capture 38
Cross section 39
Exponential absorption 39
Problems 40

Chapter 3 Detection of Radiation 41
Gas filled detectors 41
Gas ionization 42
Electric field gradient 45
Gas amplification 46
Voltage pulse 46
Ionization chamber 47
Proportional counter 47
Geiger-Muller counter 47
Pulse spectrum 49
Voltage plateau 53
Resolving time 54
Counting efficiency 57
Physical geometry 58
Backscattering 59
Intrinsic efficiency 59
Gamma spectrometry using sodium iodide crystals . 61
Differential pulse height spectrum 62
Single channel analyzer 62
Multichannel analyzer 63
Photopeak resolution 65
Representative spectra 68
Counting efficiency 72
Gamma spectrometry using germanium crystals . 74
Resolution 74
Counting efficiency 74

Homogeneous detectors 75
Junction detectors 75
Statistical limitation on resolution 80
Neutron detectors 82
Boron interaction 83
Proton scattering 83
Fission 83
Helium-3 84
Scintillation techniques 84
Activation of foils 85

Problems 86

Chapter 4 Quantitative Measurement of Radiation . . . 88

Counting efficiency 88
Precision 89
Standard deviation 89
Variance 89
Poisson distribution 90
Normal distribution 91
Confidence level 93
Confidence limits 93
Control chart 94
Precision of net count 96
Chi square test 97
Precision vs accuracy 98

Chapter 5 The Literature of Radiation Detection . . . 101

Appendix 105

Index 109

CHAPTER 1

Radioactive Decay

A LARGE NUMBER of the natural and artificially produced isotopes of the elements are unstable and decay to stable states by the emission of sub-atomic particles and gamma or x-ray photons. The process of emission of these particles is called radioactive decay and the isotopes undergoing such decay are called radioisotopes or radionuclides. The identity and concentration of the decaying nuclide or mixture of nuclides can be determined by detection and quantitative measurement of the associated radiation. It is this detection and measurement that is the subject of this text.

RADIATIONS EMITTED

The principal radiations emitted during the decay of the most commonly encountered radionuclides are: alpha particles, beta particles, positrons, gamma photons, x-ray photons, conversion electrons, and annihilation photons. The nature of each of these radiations will be described in turn:

Alpha particle (α)

The alpha particle is a helium nucleus and is associated with the decay of the heavy elements such as polonium, radon, radium, uranium, and plutonium. Since the alpha particle is the nucleus of a helium atom it is very large with respect to the other "sub-atomic" particles (electrons, protons, neutrons). This large mass of the alpha particle plays an important role in its interaction with matter—to be discussed in a later section of the text.

An example of a radioisotope that decays by alpha emission is U-238, the most abundant of the isotopes in naturally occuring uranium. This decay can be written:

$$_{92}U^{238} \rightarrow {}_{90}Th^{234} + {}_{2}\alpha^{4}$$

This equation shows U-238 decaying to Th-234 by alpha particle emission. The subscripts associated with the symbols for the uranium atom, thorium atom, and alpha particle indicate the atomic number of the element, i.e., the atomic number of U = 92, Th = 90, and He = 2. The superscripts indicate the atomic weight of the isotope, i.e., U = 238, Th = 234, and He = 4. This is the accepted convention for designating any isotope of the elements. The general form is:

$$_{Z}M^{A}$$

where Z = atomic number and A = atomic weight of an element whose chemical symbol is M. The atomic number (Z) of an isotope is equal to the number of protons in the nucleus and, therefore, to the number of electrons in the electron shells surrounding the nucleus. The atomic weight (A) is equal to the sum of the proton and neutron masses in the nucleus. It follows, therefore, that the number of neutrons in any isotope is equal to A–Z. Note the numerical balance of protons (Z) and protons-plus-neutrons (A) in the U-238 decay: 238 = 234 + 4, and 92 = 90 + 2. The loss of an alpha particle reduces the atomic number of the parent isotope by 2 units and the atomic weight by 4 units.

If the alpha emissions from the decay of U-238 are detected by an instrument capable of measuring the kinetic energy of these particles, it is found that two discreet alpha particle energies are observed. Alpha particles from U-238 are observed with energies of either 4.18 Mev or 4.13 Mev. The 4.13 Mev particles are emitted during 23% of the disintegrations while the 4.18 Mev particles are emitted during the other 77%. No other alpha energies are observed. This discreet energy phenomenon of alpha particle emission is characteristic of all alpha emitters. Although an alpha emitter may decay by the emission of alpha particles of either one, two, or several different energies, each alpha particle is emitted at a discreet energy rather than over a continuous distribution of energies.

Observation of the energy of the particles associated with the decay of any alpha emitter can, therefore, be employed to identify the isotope involved.

The alpha particles (helium nuclei) released during the radioactive decay of an alpha emitter will pick up two electrons and become an electrically neutral helium atom. It is quite obvious, therefore, that alpha emission can be detected by collecting and measuring the amount of gaseous helium formed. This has been done but is not a common technique because of the extremely small gas volume produced in the decay of reasonable quantities of the alpha emitters.

Beta particle (β)

A beta particle is an electron. The effect of removing an electron from the nucleus of an atom is to convert a neutron to a proton within the nucleus:

$$n \rightarrow p^+ + e^-$$

Since the number of protons in the nucleus is equal to the atomic number (Z) of the isotope, the overall effect of beta particle emission is to increase Z by one unit. The emission of a beta particle is the preferred mode of decay for isotopes that are unstable because of large values of the ratio of neutrons to protons (n/p) in the nucleus. The conversion of a neutron to a proton in such a nucleus effectively lowers this ratio. The ratio of neutrons to protons in the nuclei of the stable isotopes fall within the narrow band shown in Figure 1. As shown on this figure, an isotope with a high neutron to proton ratio decays by beta emission to move into the stable region.

An example of a radionuclide that decays by beta particle emission is Cs-137:

$$_{55}Cs^{137} \rightarrow {}_{56}Ba^{137m} + \beta^-$$

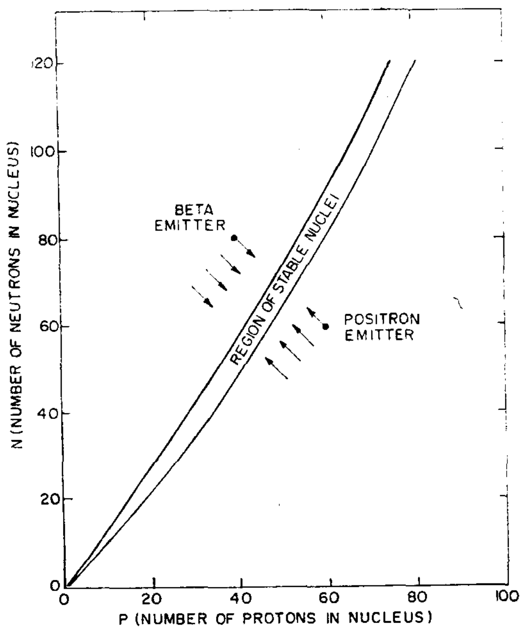

Figure 1 Neutron to proton ratio of stable nuclei

This equation shows the decay of the parent Cs-137 atom to Ba-137m, the daughter atom, by the release of a beta particle. The small letter, m, following the atomic weight of the barium atom merely indicates that this daughter atom is formed in a metastable state. The significance of this metastable state will become evident under the discussion of gamma photon emission. Note that the atomic weight of the parent decaying by beta emission and its daughter are the same because the *total* number of protons plus neutrons in the nucleus remains the same. The atomic number increases by one unit due to the formation of one additional proton in the nucleus.

In contrast to the orderly, discreet energies exhibited by alpha particles, beta particles from a given nucleus are emitted over a continuous energy distribution from a maximum value characteristic of each beta emitter down to zero. Two examples of this distribution of beta particle energies are shown in Figure 2.

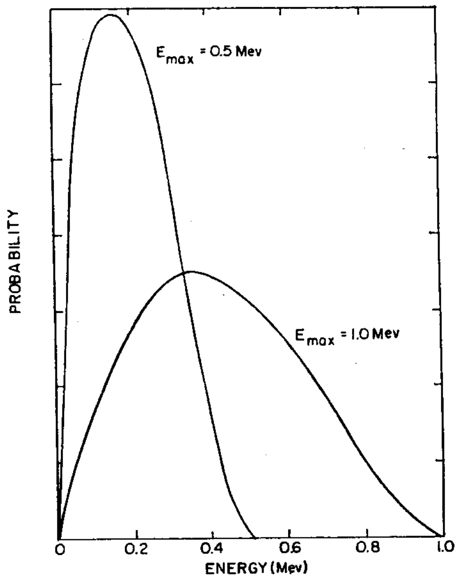

Figure 2 Distribution of energy in beta decay

Since the initial and final states associated with a particular beta emitter are always the same, e.g., Cs-137 always produces Ba-137m, the total energy change must always be the same. But how can this be true if the beta energy varies in the continuous distribution shown in Figure 2? This question lead to the discovery of the neutrino. The neutrino is an extremely small (rest mass near zero), neutral particle. It is difficult to detect because of the extremely small probability that it will interact with any detection device. It was found that the energy discrepancy between the maximum beta energy and any particular beta particle in the continuous distribution is carried off by a neutrino emitted along with each beta particle.

Gamma photon (γ)

A gamma photon is a quantum of electromagnetic radiation like visible light, ultraviolet light, x-rays, radiowaves, etc. In most instances, the daughter nucleus resulting from the alpha or beta particle emission is left in an excited state, i.e., it possesses energy above its normal or ground state. This excess energy is released as gamma photons immediately following the alpha or beta decay. This gamma emission produces no change in the atomic number or atomic weight of the nucleus and is called an isomeric transition. Gamma photons all possess discreet energies, like alpha particles, rather than displaying a continuous spectrum of energies like beta particles.

An example of gamma photon emission is the isomeric transition:

$$_{56}Ba^{137m} \rightarrow {}_{56}Ba^{137} + \gamma$$

After the parent Cs-137 atom beta decays, the daughter atom, Ba-137m, is a metastable state of stable Ba-137. The Ba-137m decays to the stable state of Ba-137 by emitting a gamma photon with an energy of 661 kev.

Conversion electron (e^-)

When a gamma photon is emitted by a nucleus it may interact with one of the orbital electrons surrounding that nucleus. When this interaction occurs, an orbital electron (usually a K shell electron) is ejected from the atom instead of the gamma photon. This process is called "internal conversion" and the electron is called a conversion electron. The energy of the conversion electron is equal to the original gamma photon energy minus the binding energy of the electron. The energy of the conversion electron is, then, a discreet value like that of gamma photons rather than a continuous distribution of energies like that observed for beta particles.

X-ray photons ($h\nu$)

When electrons are ejected from the electron shells of an atom by the internal conversion process (or by any other process), other electrons eventually fall into the vacated orbitals with the simultaneous emission of x-ray photons.

X-ray photons have discreet energies characteristic of the changes in energy level of the orbital electrons. Since the electron structure of every element is different than that of every other element, the x-rays emitted by the excitation of an atom can be used to characterize the element involved.

The difference between x-ray and gamma-ray photons is, then, that x-rays originate in the electron shells surrounding an atom while gamma-rays originate in the nucleus of the atom. X-ray energies are generally less than about 100 kev while gamma-ray energies are generally greater than about 100 kev—with some exceptions in both cases.

Positron (β^+)

A positron is a particle of the same mass as that of an electron. The positron possesses a single, positive charge relative to the single, negative charge of the electron or beta particle. Positron emission from the nucleus of an atom is often called "beta-plus" emission.

The emission of a positron from the nucleus is the equivalent of converting a proton to a neutron:

$$p^+ \rightarrow n + \beta^+$$

Positron emission is the preferred mode of decay of atoms that are unstable because of a small ratio of neutrons to protons (n/p) since the conversion of a proton to a neutron is an effective method of increasing this ratio. It should be noted that positron emission and beta emission have the opposite effect on the ratio n/p, i.e., positron emission increases while beta emission decreases the ratio of neutrons to protons in the nucleus. This effect is shown in Figure 1.

Positrons are emitted over the same continuous energy distribution as observed for beta emission and are, likewise, accompanied by neutrinos.

Annihilation radiation ($h\nu$)

When positrons interact with their surroundings they eventually capture an electron and the resulting positron-electron pair is annihilated to form two photons each with an energy of 511 kev. The two 511 kev photons are called annihilation radiation and they travel in exactly opposite directions from the site of the annihilation. The latter point is important to remember when measuring positron emitters by detection of their associated annihilation radiation. The two annihilation quanta always possess an energy of exactly 511 kev since that energy corresponds to the rest mass of both the positron and the electron (a direct mass-energy equivalence).

Electron capture

Electron capture competes with positron emission in neutron deficient nuclei for the conversion of a nuclear proton to a neutron. In the electron capture process, an orbital electron (usually a K shell electron) is captured by the nucleus to convert a proton to a neutron:

$$p^+ + e^- \rightarrow n$$

This process is an effective method for neutron deficient nuclei to increase their n/p ratio (see Figure 1). As mentioned above, electron capture and positron emission are competing modes of decay for neutron deficient nuclei. Electron capture predominates for the high Z elements while positron decay predominates for the low Z elements.

Fission products

Some of the very high Z elements are extremely unstable and decay by spontaneous fission. As the term indicates, spontaneous fission is nuclear decay by the breaking up of the unstable isotope to form two lighter nuclei. Spontaneous fission is always accompanied by neutron emission. An example of spontaneous fission is:

$${}_{96}Cm^{242} \begin{matrix} \nearrow FP_1 \\ \searrow FP_2 \end{matrix} + {}_0n^1$$

Delayed neutron (${}_0n^1$)

Certain fission products possess metastable states with respect to neutron emission. These nuclei decay to stable states by ejection of a neutron. An example of delayed neutron decay is:

$${}_{36}Kr^{87m} \rightarrow {}_{36}Kr^{86} + {}_0n^1$$

A neutron is a small, neutral particle with a mass of one atomic mass unit. The realtionship of neutrons to protons, electrons, and positrons was shown in the previous discussion of decay by positron emission and electron capture.

DECAY SCHEMES

A decay scheme is a graphical presentation describing the mode of decay, energy transitions, and abundance of the various decay routes when a nuclide emits particles or photons at more than one energy. Often the half-lives of the parent nuclide and any metastable states of the daughter nuclide are also shown on the decay scheme. The "half-life" of a radionuclide is that time required for the number of atoms present to decrease by a factor of two. The half-life concept will be discussed in more detail later in the text.

A decay scheme for a typical beta emitter is shown in Figure 3. This decay scheme shows that Cs-137 decays with a half-life of 30 years by the emission of beta particles of two different energies. In 92% of the beta decays the metastable Ba-137m is formed. This metastable nucleus contains excess energy of 0.662 Mev. The energy of the beta emission that lead to this metastable nucleus was, then, the difference between the total decay energy, Q, for the Cs-137 decay (1.18 Mev) and this metastable energy level (0.66 Mev), i.e., $E = 1.18 - 0.66 = 0.52$ Mev. In 8% of the disintegrations of Cs-137, the daughter nucleus is formed directly in its ground state and the energy of the beta emission leading to this state must have corresponded to the total Q of Cs-137 or 1.18 Mev. Remember that when a beta particle energy is specified it is always the maximum beta energy associated with a given transition and that the distribution of energies below that maximum is as shown in Figure 2 and discussed previously. It should be noted that the decay scheme is constructed as a qualitative plot of energy on the vertical axis vs atomic number on the horizontal axis.

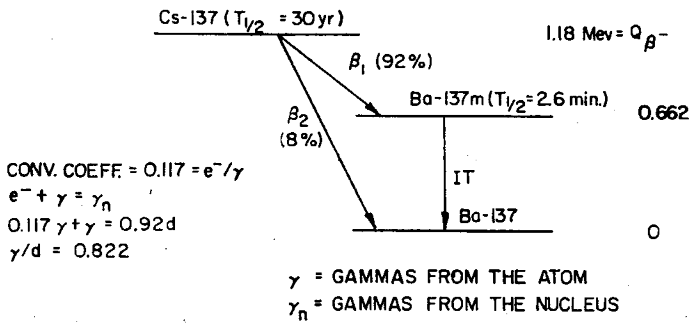

Figure 3 Decay scheme of Cs-137

A decay scheme for an alpha emitter, U-238, is shown in Figure 4. This decay scheme shows that U-238 decays with a half-life of 4.5×10^9 years by the emission of alpha particles of two different energies. In 23% of the alpha decays of U-238, the daughter nucleus (thorium) is left in an excited or metastable state. This metastable state is 48 kev above the ground state of Th-234. The Th-234m decays to stable Th-234 by emitting a gamma photon with an energy of 48 kev. In 77% of the alpha disintegrations of U-238, the daughter nucleus is formed at its ground state. The value Q_α shown at the energy level of U-238 in the decay scheme is the total alpha decay energy of this isotope, i.e., the total energy released in the decay of a U-238 atom to a Th-234 atom is 4.27 Mev.

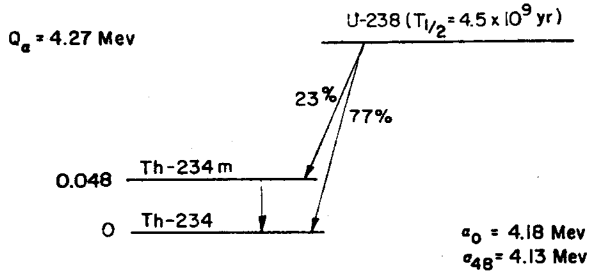

Figure 4 Decay scheme of U-238

In the case of the beta emitter (Cs-137) it was possible to deduce the energy of the beta transitions by merely taking the difference between the total decay energy (Q_β) and the energy state of the daughter nucleus. This is not exactly true in the case of the alpha emitter. Since the alpha particle is rather massive, its ejection from the nucleus causes the daughter nucleus to recoil so that the total decay energy is divided between the kinetic energy of the alpha particle and the kinetic energy of the recoiling daughter nucleus (Th-234). This energy is divided between the alpha particle and the Th-234 nucleus as a function of their respective masses, i.e., the alpha particle carries 234/238 of the total energy while the Th-234 atom carries 4/238 (conservation of momentum).

The law of Conservation of Momentum is applicable to nuclear reactions just as it is applicable to the firing of a projectile from a gun or the operation of a jet engine. This very widely applicable law states that the total momentum of an isolated system is constant. All internal forces are equal and opposite and act for equal times and produce, therefore, equal and opposite changes in momentum which cancel each other. In the case for the recoiling gun and the ejected bullet or the recoiling nucleus and the ejected alpha particle, conservation of momentum demands that:

$$m_1v_1 = m_2v_2$$

where m_1 and v_1 are the mass and velocity of the recoiling object and m_2 and v_2 are the mass and velocity of the projectile. In the case of the alpha disintegration of U-238, conservation of momentum demands, therefore, that:

$$m_{234}v_{234} = m_4v_4$$