James E. Martin

Physics for Radiation Protection

A Handbook

Second Edition, Completely Revised and Enlarged

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To the memory of

Frank A. and Virginia E. Martin
and JoAnn Martin Burkhart.

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Preface

Physics is used to describe the production and behavior of radiation and radioactivity and interactions that determine the energy deposited in media (dose) and allow its detection and modification (shielding). These uses justify a comprehensive and applied treatise of the major physics concepts of radiation protection, an approach that was followed in the first offering and is continued here. Omissions and errors have been remedied to the extent they have been discovered, and new material has been added on internal radiation dose, the dynamics of radioactivity released into environmental media, and log-normal statistics. And, as before, numerous real world examples and problems are provided to demonstrate concepts and hone skills.

A copy of this edition has been awarded, as promised, to the health physics students at Oregon State University for discovering the wrong exponents on air attenuation coefficients for photons and improper use of the quality factor for neutron dosimetry. Other errors and omissions are almost certain to remain despite the watchful eyes of readers and best efforts of editors and preparers; therefore, readers are encouraged to continue to be watchful and to report mishaps (email: jemartin@umich.edu) for entry on the webpage: www-personal.umich.edu/~jemartin. Those who do so will, as before, be eligible to receive an edition of the book.

The book begins with a review (Chapter 1) of the basic structure of the atom as an energy system, which may be of most use for the generalist or those with minimal science background. The major discoveries in nuclear physics are revisited in Chapter 2 in an attempt to recapture the insights grasped by those who discovered the laws of nature that govern radiant energy and atomic structure. Radioactive transformation of atoms with excess energy is addressed fully in Chapter 3 because of its importance in radiation protection, and the interactions, nuclear fission, and naturally occurring sources (including radon) that yield such atoms are addressed in Chapters 4, 5, and 6, respectively.

Interactions of radiation with matter are covered in Chapter 7 along with the corollary subjects of radiation exposure and dose and the various parameters that are needed to calculate them. Shielding, which is closely allied with radiation interactions, is described in Chapter 8 and methods are provided for calculating

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exposure and dose for several common sources and geometries. Basic models and data resources are provided (Chapter 9) for determining internal radiation dose to various organs and tissues due to inhalation and ingestion of radionuclides following their dispersion in environmental media, the dynamics of which are detailed in Chapter 10. Chapter 11 describes the special situation of nuclear criticality, including aspects of reactors and critical assemblies such as nuclear weapons, and radioactive materials produced when such events happen. Chapters 12 and 13 build upon the material developed in Chapters 7 and 8 to develop principles of radiation detection, the methods and equipment used in its measurement, and statistics associated with such measurements. Neutrons and x rays represent special issues in radiation physics, and these are addressed in Chapters 14 and 15, respectively.

A course in radiation physics that is based on this book would be expected to include substantial treatment of the material in Chapters 3 – 5 and Chapters 7 and 8, with selections from the other chapters, all or in part, to develop needed background and to address specialty areas of interest to instructor and student. The book is also designed to be a resource document; thus, decay schemes and associated radiation emissions are included for about 100 of the most common radionuclides encountered in radiation protection, as are inhalation and ingestion dose factors, submersion dose factors, and atmospheric dispersion parameters. Resources are also provided on activation cross sections, fission yields, fission-product chains, photon absorption coefficients, nuclear masses, and abbreviated excerpts of the **Chart of the Nuclides**. These are developed in the detail needed for radiation physics uses and cross referenced to standard compendiums for straightforward use when these more in-depth listings need to be consulted. The data are current from the National Nuclear Data Center at Brookhaven National Laboratory (nndc@bnl.gov); the Center and its staff are truly a national resource.

The units used in radiation protection have evolved over the hundred years or so that encompass the basic discoveries and their uses in radiation physics. They continue to do so with a fairly recent emphasis on Systeme Internationale (SI) units, a trend that is not entirely accepted because U.S. standards and regulations for control of radiation and radioactivity have continued to use conventional units. To the degree possible, this book uses fundamental quantities such as electronic charge and voltage (eV), transformations, and the numbers of atoms or emitted particles and radiations to describe nuclear processes, primarily because they are basic to concepts being described but partially to avoid the need to resolve any conflict between SI units and conventional ones. Both sets of units are defined as they apply to radiation protection, but in general the more fundamental parameters are used.

This endeavor is due in large part to my students whose feedback continually shaped the teacher and to the many contributions of my research associates, Chul Lee, Arthur Ray Morton, Suellen Cook, and Ihab Kamel, who compiled and checked materials and did the expert computer work required. I am particularly indebted to Chul Lee who has for ten years running contributed expertise, skill,

and attention to detail with patience, persistence and understanding. My greatest satisfaction will occur if it helps you, the reader, understand and appreciate the basic physics of the exciting and rewarding field of radiation protection.

James E. Martin, Ph.D., CHP
Associate Professor (emeritus)
of Radiological Health
The University of Michigan

1
Atoms and Energy

"Nothing in life is to be feared.
It is only to be understood." M. Curie

Physics underpins radiation protection. It is necessary for describing the origins of radiation, the types and properties of emitted radiation(s), and the mechanisms by which radiant energy is deposited in various media. It is standard practice, which is perhaps unique for radiation protection, to optimize protection as far below established safe levels as reasonably achievable, and an understanding of the physics of the various elements is fundamental to its accomplishment.

Four basic forces of nature control the dynamics (i.e., position, energy, work, etc.) of all matter, including the constituents of atoms – protons, neutrons, and electrons. These forces, along with their magnitude relative to gravity are:

- gravity, which is an attractive force between masses = G;
- the weak force, which influences radioactive transformation $\cong 10^{24}G$;
- the electromagnetic force, which exists between electric charges $\cong 10^{37}G$;
- the nuclear force, which is strongly attractive between nucleons only $\cong 10^{39}G$.

These forces range over some 40 orders of magnitude; however, two of them largely determine the energy states of particles in the atom (gravitational forces are insignificant for the masses of atom constituents, and the weak force is a special force associated with the process of radioactive transformation of unstable atoms):

- the nuclear force between neutrons and protons which is so strong that it overcomes the electrical repulsion of the protons (which is quite strong at the small dimensions of the nucleus) and holds the nucleus and its constituent protons and neutrons together;
- the force of electrical attraction between the positively charged nucleus and the orbital electrons which not only holds the electrons within the atom, but influences where they orbit.

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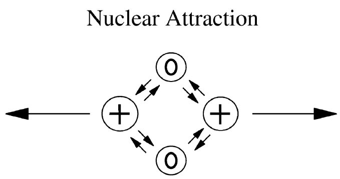
The *nuclear force*, or strong force, is amazing and a bit strange. It exists only between protons and neutrons or any combination of them; consequently it exists only in the nucleus of atoms. The nuclear force is not affected by the charge on neutrons and protons, nor the distance between them. It is strongly attractive, so much so that it overcomes the natural repulsion between protons at the very short distances in the nucleus since it is about 100 times stronger than the electromagnetic force.



The *electromagnetic force*, on the other hand, exists between charged particles no matter where they are (a nucleus can also be thought of as a large charged particle although it contains several protons, each of which has a unit positive charge). The electromagnetic force is inversely proportional to the square of the distance, r, between two particles with a charge of q_1 and q_2:

$$F_{em} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2} = k_0 \frac{q_1 q_2}{r^2}$$

where the charges on each particle are expressed in coulombs and the separation distance r is in meters. The constant k_0 is for two charges in a vacuum and has the value $k_0 = 8.9876 \times 10^9$ N m^2/C^2. This fundamental relationship is called Coulomb's law after its developer, and is referred to as the coulomb force. If q_1 and q_2 are of the same sign (i.e., positive or negative), F will be a repulsive force; if they are of opposite signs, F will be attractive.

1.1
Structure of Atoms

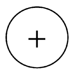
Atoms contain enormous amounts of energy distributed among the energy states of the constituent parts. Some of this energy is emitted from the atom if an overall decrease occurs in the potential energy states of one or more of the constituents, and similarly absorption of radiant energy by an atom yields an increase in the potential energy of one or more states .Atom constituents are primarily neutrons, protons, and electrons, and their number and array establish:

- what the element is and whether its atoms are stable or unstable;
- if unstable, how the atoms will emit energy (we will deal with energy later).

Modern theory has shown that protons and neutrons are made up of more fundamental particles, or quarks, but it is not necessary to go into such depth to understand the fundamental makeup of atoms and how they behave to produce radiant energy.
Atoms are bound systems – they only exist when protons and neutrons are bound together to form a nucleus and when electrons are bound in orbits around the nucleus. The particles in atoms are bound into such an array because nature forces atoms toward the lowest potential energy possible; when they attain it they are stable, and until they do they have excess energy and are thus unstable, or radioactive.

The *proton* has a reference mass of about 1.0. It also has a positive electrical charge of plus 1 (+1).

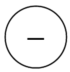
Proton



Mass = 1　　Charge = +1

The *electron* is much lighter than the proton. Its mass is about 1/1840 of that of the proton and it has an electrical charge of minus one (–1).

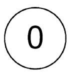
Electron



Mass = 1/1800　　Charge = –1

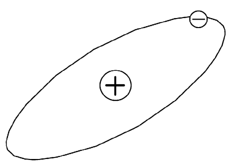
The *neutron* is almost the same size as the proton, but slightly heavier. It has no electrical charge.

Neutron

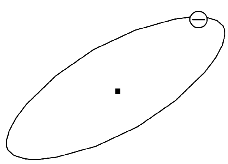


Mass = 1　　Charge = 0

When these basic building blocks are put together, which is what happened at the beginning of time, very important things become evident. First, a proton will attract a free electron to form an atom:



Schematic



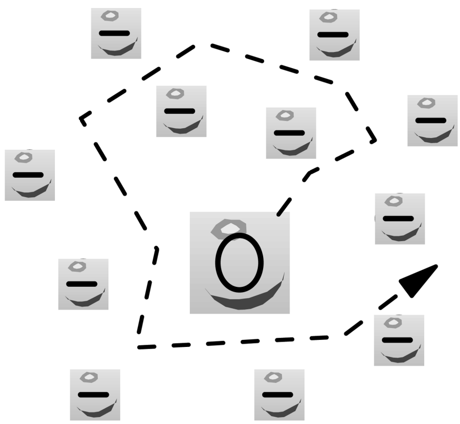
Closer to "actual"

The resulting atom is electrically neutral. That is, each –1 charge on an orbital electron is matched by a +1 positively charged proton in the nucleus. The total atom (proton plus an electron) has a diameter of about 10^{-10} m (or 10^{-8} cm) and is much bigger than the central nucleus which has a radius of about 10^{-15} m or (10^{-13} cm); thus the atom is mostly empty space. The radius of the nucleus alone is proportional to $A^{1/3}$, where A is the atomic mass number of the atom in question or

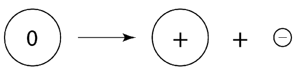
$$r = r_o A^{1/3}$$

The constant r_o varies according to the element but has an average value of about 1.3×10^{-15} m, or femtometers. The femtometer (10^{-15} m) is commonly referred to as a fermi in honor of the great Italian physicist and nuclear navigator, Enrico Fermi.

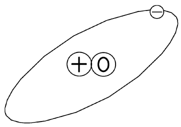
A free neutron is electrically neutral and, in contrast to a proton, an atom does not form; i.e., it is just a free neutron subject to thermal forces of motion.



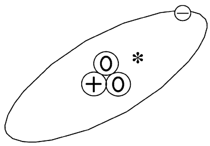
Likewise, two or more neutrons are also unaffected by any electrons present. However, if left alone for a while, a free neutron will undergo transformation (commonly referred to as decay) into a proton and an electron; therefore, in a free state, the neutron, though not an atom (no orbiting electrons), behaves like a radioactive atom by emitting a negatively charged electron.



A neutron can, however, be bound with one or more protons to form a nucleus, and in this state it does not undergo transformation but will maintain its identity as a fundamental particle. When this occurs, an electron will join with the proton–neutron nucleus to form an electrically neutral atom:



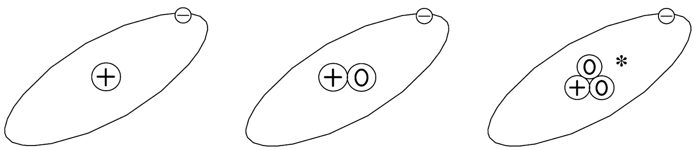
However, it now weighs about twice as much as the other one because of the added neutron mass. And, if another (a second) neutron is added, a heavier one-proton atom is formed:



* Excess energy and mass, i.e., radioactive

$^{3}_{1}H$

This atom is the same electrically neutral atom (one proton balanced by one electron) we started with, but it weighs about three times as much due to the two extra neutrons, and because of the array of the particles in the nucleus it is an atom with excess energy, i.e., it is radioactive. Each of these one-proton atoms is an atom of hydrogen because hydrogen is defined as any atom containing one proton balanced by one electron. Each atom has a different weight because of the number of neutrons it contains, and these are called isotopes (Greek: "iso" = same; "tope" = place) of hydrogen to recognize their particular features. These three isotopes of hydrogen are denoted by the following symbols:



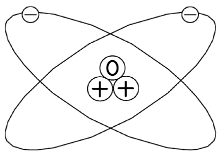
$^{1}_{1}H$ $^{2}_{1}H$ $^{3}_{1}H$

These symbols establish the nomenclature used to identify atoms: the subscript on the lower left denotes the number of protons in the atom; the superscript on the upper left refers to the mass number, an integer that is the sum of the number of protons and neutrons in the nucleus. It is common practice to leave off the subscript for the number of protons because the elemental symbol, H, defines the substance as hydrogen with only one proton. The isotopes of hydrogen are identified as protium (or hydrogen), deuterium, and tritium; the first two are stable and exist in nature, but tritium is radioactive and will be converted to an isotope of helium (He) through radioactive transformation. Almost all elements exist, or can be produced, with several different mass numbers yielding several isotopes. A particular substance is often identified by its element and the mass number of the isotope present, e.g., carbon-14 (^{14}C), hydrogen-3 (^{3}H, or tritium).

1.1.1
Two-proton Atoms

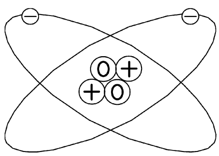
If we try to put two protons together, the repulsive coulomb force between them at the very short distance required to form a nucleus is so great that it even overcomes the strongly attractive nuclear force between the protons; thus, an atom (actually a nucleus) cannot be assembled from just these two particles.

If, however, a neutron is added, it tends to redistribute the forces, and a stable nucleus can be formed. Two electrons will then join up to balance the two positive (+) charges of the protons to create a stable, electrically neutral atom of helium.



$^{3}_{2}\mathrm{He}$

This atom is defined as helium because it has two protons. It has a mass of 3 (2 protons plus 1 neutron) and is written as helium-3 or ^{3}He. Because neutrons provide a cozy effect, yet another neutron can be added to obtain ^{4}He.



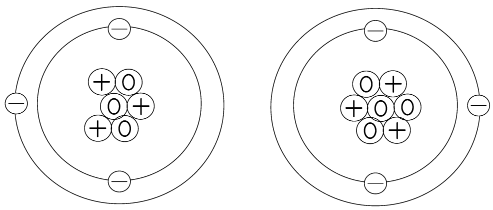
$^{4}_{2}\mathrm{He}$

Although extra mass was added in forming ^{4}He, only two electrons are needed to balance the two positive charges. This atom is the predominant form of helium (isotope if you will) on earth, and it is very stable (we will see later that this same atom, minus the two orbital electrons, is ejected from some radioactive atoms as an alpha particle, i.e., a charged helium nucleus).

If yet another neutron is stuffed into helium to form helium-5 (^{5}He), the atom now contains more mass than it can handle and it breaks apart very fast (in 10^{-21} s or so); it literally spits the neutron back out. There is just not enough room for the third neutron, and by putting it in we create a highly unstable atom. But, as we observed for hydrogen and as we will see for other atoms, adding an extra neutron (or proton) to a nucleus only destabilizes it; i.e., it will often stay for quite a while as an unstable, or radioactive, atom due to the "extra" particle mass, identified by the "isotope" of a given element.

1.1.2
Three-proton Atoms

Atoms with three protons can be assembled with three neutrons to form lithium-6 (^{6}Li) or with four neutrons, lithium-7 (^{7}Li), or



Since lithium contains three protons, it must also have three orbital electrons, but another orbit further away is required for the third electron because the first orbit can only hold two electrons (there is an important reason for this which is explained by quantum theory).

If we keep combining protons and neutrons we get heavier and heavier atoms, but they obey the same general rules. The ratio of neutrons to protons is fairly high in heavy atoms because the extra neutrons are necessary to distribute the nuclear force and moderate the repulsive electrostatic force between protons in such a way that the atoms stay together. The heaviest element in nature is ^{238}U with 92 protons and 146 neutrons; it is radioactive, but very long-lived. The heaviest stable element in nature is ^{209}Bi with 83 protons and 126 neutrons. Lead with 82 protons is much more common in nature than bismuth and for a long time was thought to be the heaviest of the stable elements; it is also the stable endpoint of the radioactive transformation of uranium and thorium, two primordial naturally occurring radioactive elements (see Chapter 6).

1.2
Nuclide Chart

This logical pattern of atom building can be plotted in terms of the number of protons and neutrons in each to create a *chart of the nuclides*, a portion of which is shown in Figure 1-1.