Radiation Science for Physicians and Public Health Workers

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Springer Science+Business Media, LLC

Library of Congress Cataloging-in-Publication Data

Zaider, M.
Radiation science for physicians and public health workers Marco Zaider and Harald H. Rossi
p. cm.
Includes bibliographical references and index.
ISBN 978-1-4613-5486-4 ISBN 978-1-4615-1301-8 (eBook)
DOI 10.1007/978-1-4615-1301-8
1. Radiology, Medical. 2. Medical physics. 3. Radiology, Medical—Safety measures. I.
Rossi, Harald H., 1979- II. Title.
R895 .Z35 3000
616.07'57—dc21
00-034895

ISBN 978-1-4613-5486-4

Originally published by Kluwer Academic Plenum Publishers, New York in 2001
Softcover reprint of the hardcover 1st edition 2001

http: www.wkap.nl

10 9 8 7 6 5 4 3 2 1

A C.I.P. record for this book is available from the Library of Congress

Preface

We have considered it to be a demanding assignment to provide a complete exposition dealing with the nature of radiation, its effects, and protection against it to workers in health-related activities. "Radiation" (and more precisely "ionizing radiation") is emitted by X-ray machines, nuclear reactors, and nuclear weapons, but also comes from natural sources to which we are all exposed. It would have been easier to deal with this subject area with the terminology and mathematics employed by specialists. However, although most of the potential readers probably have obtained further pertinent knowledge, we assume no more than a high school education in science and mathematics and the challenge was to provide maximum information within this constraint.

This book contains five sections: (A) Radiation Physics, (B) Radiological Physics, (C) Radiation Biology, (D) Radiation Effects on Human Populations, and (E) Radiation Protection.

Each section is preceded by a synopsis covering its essential features. It provides sufficient information to enable readers to obtain a general understanding of the subject of the section and an adequate background for comprehension of other sections. The more detailed presentation in the bulk of each section is followed by appendixes that generally contain more advanced topics.

This scheme necessarily involves some repetition but permits a more flexible approach for readers who are especially interested in the contents of particular sections.

In view of our continuing concern—and much disinformation—about radiation, we consider it important that health-care professionals have an adequate knowledge of this subject. This can also enable them to answer questions by patients or others.

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Section A

Radiation Physics

Synopsis

In its interaction with matter, radiation—or more specifically **ionizing radiation**—should be considered to consist of particles. X- and γ-rays exhibit the wavelike characteristics of visible light, which is the same kind of (electromagnetic) radiation, but of much longer wavelength. However, their action is better understood if they are considered to be particles, termed **photons**, moving with the speed of light.

All other forms of ionizing radiation are components of atoms that can move with speeds comparable to, but never attaining, the speed of light.

Atoms consist of **nuclei** that are combinations of positively charged **protons** and electrically neutral **neutrons**. The nuclei are surrounded by **electrons** that carry negative charges in a region with a diameter that is about 100,000 times larger than that of the nucleus. This makes for atomic diameters in the neighborhood of 10^{-8} cm (one hundred millionth of a centimeter). The mass of an electron is roughly 2000 times lower than that of either the proton or the neutron, both of which have nearly equal masses. Most of the mass of the atom therefore is found in the nucleus. One gram of water contains some 10^{23} (1 followed by 23 zeros) atoms that are chemically combined in **molecules** of H_2O (two atoms of hydrogen and one atom of oxygen). Molecules are formed by sharing of electrons by atoms. The chemical characteristics of atoms of an element are determined by the orbital electrons.

Atoms are electrically neutral because the number of orbital electrons is equal to that of the protons in the nucleus. Each of these particles carries the same (negative or positive) unit of elementary electrical charge. The electrons can be visualized as existing in "shells" around the nucleus, with the larger (higher) shells subject to a weaker force of attraction to the nucleus.

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Absorption of photons of light raises electrons into higher shells from which they can return by emission of photons. X- and γ ray photons impart sufficient energy to atomic electrons to eject them in the process termed **ionization**. The liberated electrons usually have sufficient energy to cause further ionization by ejecting electrons from other atoms in turn. Ionization generally causes the disruption of molecules, leading to the physical, chemical, and biological effect of ionizing radiation.

Different types of ionizing radiation involve nuclear phenomena and components. **Isotopes** are forms of a given element that contain varying numbers of neutrons in their nuclei. Only certain combinations of protons and neutrons constitute stable nuclei. Others may exist for various times but eventually disintegrate in a process known as **radioactivity** (or **radioactive decay**). If the number of neutrons is too large, a high-energy electron, termed a **β (beta) particle**, is emitted. If the number of protons is too large, the particle emitted by most radionuclides is the **positron**, which is an evanescent positively charged electron. In heavy elements the excess positive charge is removed by **α (alpha) particles** which are the nuclei of helium. In most instances there is also emission of γ photons.

Certain heavy elements and their decay products have existed for many millions of years; they are termed the **natural radioactive elements**. Together with **cosmic radiation** incident on earth (in a combination termed **background radiation**) they account for most of the radiation to which populations are exposed. Because of the wide distribution of radioactive elements, virtually all objects are radioactive. Some examples are **radium** (commonly occurring in drinking water), **radon** (a radioactive gas that can seep into homes from the ground), and an isotope of potassium that causes the radioactivity of the human body.

Several stable isotopes exist for nearly every element, and there are a total of several hundred radioisotopes. The latter decay with **half-lives** (times required for 50% of the atoms to decay) ranging from a small fraction of a second to many years. β-ray emitters, other than those occurring in natural radioactivity, are generally produced by neutron bombardment of stable nuclei.

Cosmic radiation contains neutrons; much higher numbers are produced in accelerators ("atom smashers"), and there is a still higher yield of neutrons in nuclear reactors. Positron emitters are made by bombarding stable isotopes with protons and other positive high-energy nuclei in particle accelerators. A variety of interactions are involved in these processes which are termed **nuclear reactions**. A very important one is **fission**, in which absorption of a neutron by certain heavy nuclei results in their separation into two highly radioactive nuclei with the emission of a few neutrons, a process that can lead to a **chain reaction**.

The energies involved in atomic or nuclear processes are measured in **electron-volts** (eV) and often in terms of a million electron-volts (MeV). In the macroscopic world, this is a very small energy. One gram of matter falling a distance of 1 cm acquires an energy of some 6×10^8 (600 million) MeV, reaching a velocity of less than half a meter per second. However, because of its small mass an electron having energy of only 1 MeV has a velocity nearly equal to the velocity of light.

After photons, neutrons are the most important ionizing radiation. Over a wide range of energies their principal interaction with matter is collision with atomic nuclei that recoil with comparable energies. Biologically, the most important modality is the production of high-energy protons (hydrogen nuclei) that can acquire the entire energy of neutrons. A lesser energy transfer is in the collisions with other atoms, especially oxygen and carbon.

Commonly encountered radiations have energies of no more than a few million electron-volts. At such energies the range of charged particles is small. A 5 MeV electron traverses some 2.5 cm of tissue or water and a proton of the same energy has a range of less than 0.5 mm.

The usual mechanism of human radiation exposure thus involves a two-step process in which primary uncharged particles (photons or neutrons), which are far more penetrating, produce short-range charged particles in the body. Exceptions to this pattern are extremely highly (10 MeV or more) charged particles employed in cancer treatments, and a component of the cosmic radiation consisting of very penetrating charged (and unstable) particles called **muons**.

Radiation quantities provide information on the number and energy of particles and their interaction with matter, as well as numerical characterization of radiation levels and their energy transfer to matter.

Introduction

Matter generally consists of molecules, which in turn consist of atoms. Broadly speaking, chemistry is concerned with the ways in which atoms form molecules and with interactions between molecules, while **atomic physics** is concerned with the structure of atoms and the interaction between atoms in the form of radiation.

Atomic physics can also be said to deal with elementary particles and their combinations. Here, the term "particles" refers not only to electrons and atomic nuclei but also to all radiations. Both visible light and X- or γ-rays are electromagnetic radiation that propagates with the speed of light and exhibits the wave properties of interference and diffraction. However, the transfer of radiation energy to matter must be understood to occur as a result of interactions between particles termed **photons** and atoms. The issue of whether X-rays are waves or particles may cause confusion but it can be likened to the question of whether water exists as waves or as drops.

There is an even more disparate aspect in the converse case of the wave nature of particles. In the popular pictures of atoms, the nucleus is surrounded by elliptical orbits of electrons. However, atomic electrons cannot be said to be located in orbits or even precisely located at all. They can only be considered to be distributed in the atom at positions that are determined by a probability that depends on their energy. Moving electrons and other particles can produce diffraction patterns. The major difference between radiation and particles is that the latter have finite mass when at rest and cannot move with the speed of light, and that they can have electrical charge.

These complexities are the subject of quantum mechanics, which is briefly reviewed in an appendix (A.2) to this chapter. It is important to remember that although this science deals with uncertainties that are expressed as probabilities it can also produce quite precise information. While quantum mechanics thus can provide what may be considered to be an explanation of the rules that govern the behavior of radiation and matter, knowledge of the subject is not required once these rules are accepted.

The Radiation Field

In accord with the preceding remarks, all radiations are considered to be swiftly moving particles (in the case of photons with the speed of light), and the first step in radiation physics is to provide quantitative information on the **radiation field**, that is, the region traversed by radiation.

This chapter contains an elementary description of the quantities characterizing the radiation field and of the applicable units, which is adequate for an understanding of the presentation that follows. A more precise accounting is given in Appendix A.1.

Units

The **International System of Units (SI)** is the group of units widely accepted in science. It differs from other systems such as the so-called English system. Thus the SI unit of **mass**, the kilogram (kg), is equal to about 2.2 pounds (lb.) and the meter (m) is a **length** of about 39.4 inches (in.). Other so-called base units of the SI include the second (s) for **time** and the coulomb (C) for **electric charge**. The base units are employed in the definition of subsidiary quantities such as ampere (A) for electric current and the joule (J) for energy (equal to about 0.74 foot-pounds).

The description of atomic phenomena employs vastly smaller special units. The **electron-volt** (eV) is an energy of 1.6×10^{-19} J and the **atomic mass unit** (amu) is 1.7×10^{-27} kg.[1]

Quantities

Most of the quantities employed in radiation physics are defined when they are first mentioned. The following gives only some examples of those in two categories.

Radiometric Quantities

A description of the radiation field requires reference to the **number of particles**, N, and their distribution in space or time. Thus the **fluence**, Φ, is the number of particles per unit area and the **fluence rate**, $\dot{\Phi}$, is the number of particles per unit area and per unit time.

Interaction Quantities

The degree of interaction between particles and matter can be specified in various ways. The fundamental interaction quantity is the **cross section**, σ, which may be visualized as the effective target area of an entity (atom, nucleus, etc.) for interaction with a particle. Its special unit, the **barn**, is 10^{-28} m^2 (square meters).

A third category, **dosimetric quantities**, is considered in Section B.

Atomic Physics

Atoms consist of nuclei surrounded by electrons. As detailed under the heading, Nuclear Physics, the nucleus consists of two kinds of particles (**nucleons**): protons, which carry the elementary (smallest) positive electrical charge, and neutrons, which do not carry charge. The dimensions of these particles are of the order of 10^{-15} m, and their mass differs little from the **atomic mass unit** (amu), which is 1.7×10^{-27} kg. The mass of the nucleus constitutes nearly the entire mass of the atom, although the atomic diameter determined by the electrons is generally 100,000 times larger than the nuclear diameter. The mass of the electrons is only about 0.0016 amu and about 1/1800 of the proton mass. It carries a negative elementary charge.

The electrical neutrality of atoms is due to the fact that the number of electrons is equal to that of protons. They are arranged in what are termed **shells** in numbers that are in accord with rules established by quantum mechanics. The chemical property of an atom is largely determined by the number of electrons in its outermost shell because this governs the type and degree in which bonds can form between the atoms of molecules.

The simplest atom, **hydrogen**, H, consists of a nucleus of one proton and a shell containing one electron. All other nuclei contain neutrons. Thus the next possibility is **deuterium**, ^{2}H, with a nucleus of one proton and one neutron but still only one electron, which results in essentially equal chemical properties. The superscript denotes the number of nucleons. Nuclei containing equal numbers of protons but different numbers of neutrons are termed **isotopes**. The following discussion deals only with stable, rather than radioactive, atoms.

Addition of a proton results in ^{3}He, a rather rare isotope of **helium**, which is primarily ^{4}He with a nucleus of two protons and two neutrons. This nucleus is the doubly charged **α (alpha) particle**, which is important in radioactivity.

The maximum number in the innermost electron shell, known as the **K shell**, is 2. Hence helium has a **closed shell** which greatly resists chemical binding and it is the lightest of the **inert gases**. Beginning with lithium (Li), successive additions of one proton and one electron (and some neutrons) form beryllium, Be; boron, B; carbon, C; nitrogen, N; oxygen, O; fluorine, F; and neon, Ne. This closes the L shell and Ne is again an inert gas.

The (next), **M shell**, can contain up to 10 electrons. There is a complication in that electrons may be in the N shell before the M shell is filled. There is no element in which the K, L, and M shells are filled without electrons in the higher shells. This is due to the existence of overlapping **subshells**.

The number of protons (or electrons) in an atom is its **atomic number** (Z); the number of nucleons (protons plus neutrons) is its **mass number**

(*A*). The symbol for an isotope, X, may be written as $^{A}_{Z}X$. For instance, in $^{35}_{17}Cl$ the subscript is the atomic number and indicates that the nucleus contains 17 protons (it is commonly omitted because this is implied by the chemical symbol for the element chlorine) and the superscript is the mass number indicating that the nucleus contains 35 nucleons (17 protons and 18 neutrons).

Because of the electrostatic (Coulomb) forces between the positive nucleus and the atomic electrons these latter are said to be "bound" to the nucleus; correspondingly, the term **binding energy** (of a particular electron) refers to the minimum amount of energy that must be given to the electron to free it from the atom. This process is called **ionization** of the atom; the ionized atom left behind is now a positive **ion**. More generally, the term "ion" refers to a positively or negatively charged atom, this latter being the case when, for instance, an additional electron attaches to the atom. The ion and the electron form an **ion pair**. Typical binding energies (BEs) range from 10 eV to 100 keV; for instance, liberating a K-shell electron requires less than 300 eV in the case of carbon but 115,000 eV in the case of uranium. The reason for this is the increasing attraction between the positive nucleus and electrons as the atomic number increases; it also leads to a "shrinkage" of the shells, particularly the K shell.

When the energy imparted is less than the binding energy the atom may still absorb this energy with the result that the electron—while remaining bound—is raised to a higher energy level. This process is termed **atomic excitation**. Frequently, but not always,[2] the excited atom or molecule deexcites within a very short time (~10^{-9} s) by emitting a photon (a quantum of the electromagnetic field; see later) and thus returning to its original state.

Electromagnetic radiation is the transmission of energy in oscillating electric and magnetic fields that propagate in vacuum at what is termed the **velocity of light**, c (~3×10^{8} m/s). The **frequency** of the oscillation, ν, is related to the **wavelength**, λ, by the equation:

$$c = \lambda\nu$$

The unit of ν is s^{-1} with the special name **hertz** (Hz). **Figure 1** shows the electromagnetic spectrum; in addition to showing λ (in m) and ν (in Hz), this figure also contains a third scale of energy, E (in eV). This is related to the fact that in transfer of energy the electromagnetic radiation appears as **photons** that are quanta (packages of energy) according to:

$$E = h\nu$$

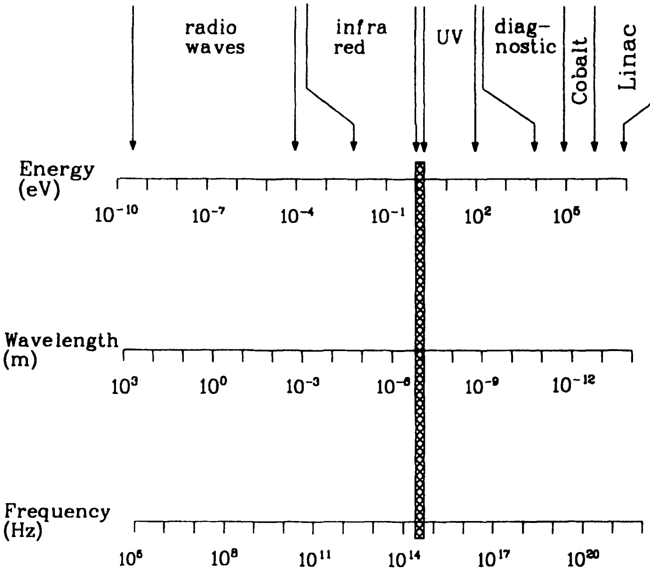

Figure 1. The electromagnetic spectrum. Visible light (cross-hatched shading) is only a small portion of the spectrum.

where h, **Planck's constant**, is equal to 6.626×10^{-34} J s. These equations are equivalent to[3]:

$$E/\text{eV} = \frac{1.24\ 10^{-6}}{\lambda/\text{m}}$$

The absence of the electron from its shell (termed a **vacancy**) leads to its replacement by an electron from a higher shell. Thus ionization in (or excitation from) the K shell can result in the "dropping" of an electron from the L shell with emission of a **fluorescent**, K photon with a wavelength that corresponds to the difference of energy between the K and the L shell which generally identifies the atom of origin. Further, such transitions (e.g., the transition of an electron from the M to the L shell) result in photons of lower energy.

An alternative to such cascading of electrons is the **Auger process**. The K photon may, for instance, eject an electron from the M shell with an energy that is equal to $\omega_K - \omega_L - \omega_M$ (with $\omega_K - \omega_L$ being the photon energy and ω_M the binding energy of the M shell electron). The importance of the Auger process is that it creates multiply ionized atoms.

Only some of the transitions between the various energy states are possible, with the others said to be "forbidden." This is also the case when atoms are arranged in solids, and as shown in Section B, it is of importance in what is termed thermoluminescent dosimetry.

Nuclear Physics

Nuclear Structure and Stability

The attractive force (termed the **strong force**) that constrains the **nucleons** (protons and neutrons) to form atomic nuclei is of such short range that it may be visualized to exist only within distance of the order of nucleon dimensions. This explains—among other things—why stable nuclei generally have more neutrons than protons (see **Figure 2**): The strong force must balance the electrostatic repulsion among protons due to their positive charges. The magnitude of the Coulomb repulsion energy, E_c, is proportional to the number of distinct proton pairs in the nucleus, which is approximately proportional[4] to Z^2, because the range of the Coulomb force is infinite. In contrast, the short range of the strong force makes the total energy associated with it, E_s, roughly proportional to the number of nucleons (rather than $\sim Z^2$). As the atomic mass number A becomes higher, E_c increases faster than E_s and thus more neutrons are needed to compensate it. Ultimately, addition of neither a proton nor a neutron results in a stable nucleus. The heaviest stable nucleus is that of ^{209}Bi, in which the number of neutrons (126) is more than 50% larger than the number of protons (83).[5] In addition to these general features the stability of nuclei is subject to complexities due to the existence of substructures. This results in a seemingly erratic pattern in which nuclei of the elements exist with varying stability. There are 11 stable isotopes of tin (Sn) with atomic number 50 but there are no stable isotopes of technetium (Tc) with $A = 43$.

In analogy to the Coulomb force that binds together the atomic nucleus and its electrons, the existence of the strong force means that to separate a nucleus into its individual nucleons,[6] energy must be deposited in the nucleus. This energy is the **total binding energy** of the nucleus and its magnitude is a measure of the stability of the nucleus. Equivalently, binding energy may be defined as the energy released in the formation of a nucleus (more generally, a system) from its components. Also, one may consider the binding energy of individual nucleons in the nucleus. The nuclear binding energy is generally comparable to the masses involved, according to[7]:

$$E = mc^2 \tag{1}$$

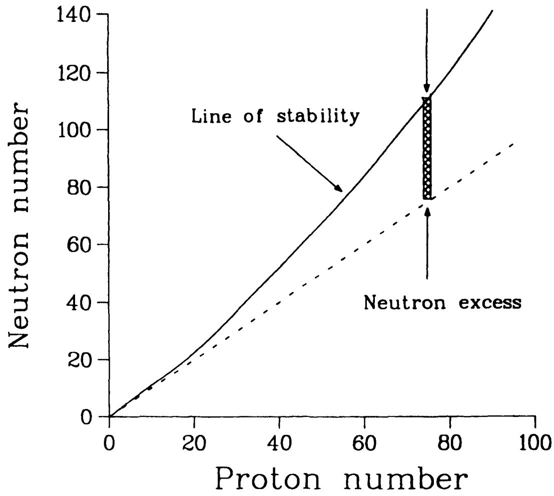

Figure 2. Stable isotopes are distributed around the solid line labeled line of stability. The dashed line represents the locus of elements with an equal number of protons and neutrons.

which is a basic relation of the theory of special relativity that governs the conversion of energy into mass and vice versa,[8] where c is the velocity of light (3×10^8 m s^{-1}). For instance, measurements show that the mass of deuteron ($^2H_1$) is 1875.61340 MeV, which is less than the sum of the masses of its individual components (m_{proton} = 938.27231 MeV; $m_{neutron}$ = 939.56563 MeV). The difference is the binding energy:

$$BE = (m_p + m_n) - m_d = 2.224 \text{ MeV} \quad (2)$$

The difference is known also as the **mass defect** of the nucleus and it is a measure of nuclear cohesion. Another measure of nuclear stability is the **binding energy per nucleon**, defined as:

$$\frac{BE}{\text{nucleon}} = \frac{BE}{A - 1} \quad (3)$$

The binding energy per nucleon depends on the atomic mass number of the element. For the deuteron this quantity is 2.224 MeV, and for ^{12}C $BE/(A - 1)$ = 7.6 MeV/nucleon. **Figure 3** shows a graph of experimental values of $BE/(A - 1)$ as a function of A. Assume that one creates a helium nucleus ($^4He_2$) by fusing together two deuterium nuclei. Because the sum of

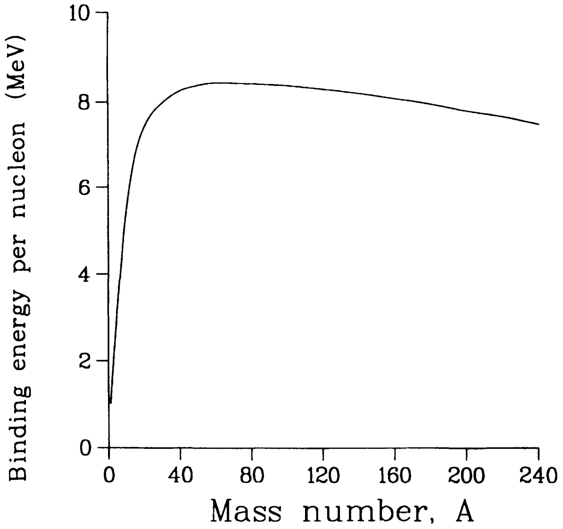

Figure 3. Binding energy per nucleon as a function of mass number *A*. The peak of this curve is at ^{56}Fe.

their binding energies is lower than that of the helium nucleus this reaction will be accompanied by a release of energy. By the same token, if a uranium atom will be split (fissioned) into two lighter nuclei (each of larger binding energy per nucleon), again energy will be released. As explained in more detail under the heading "Reactors" these properties are used to produce **nuclear energy**.

A consequence of mass defects, and of the mass difference between the proton and the neutron, is that nuclear masses are not precisely proportional to the mass number, *A*, which is the number of nucleons. This is in contrast to the **atomic number**, *Z*, which is equal to the number of protons in the nucleus (or of electrons in the shells). A unit of energy often used in nuclear energy is the **atomic mass unit** (amu), which is defined as 1/12 of the mass of $^{12}C_6$ and equals 931.9432 MeV.

Addition of a neutron to a deuteron results in the nucleus of tritium, ^3H, containing two neutrons and one proton. ^1H, ^2H, and ^3H (having as nuclei the proton, the deuteron, and the triton) are **isotopes**, that is, nuclei containing the same number of protons (in this case only one). Isotopes have equal numbers of electrons in their shell(s) and therefore essentially identical chemical characteristics.

^3H is an **isobar** (i.e., a nucleus with the same mass number) of ^3He that contains two protons and one neutron. The mass defect of ^3He is larger and

^3H is unstable and decays to ^3He. The ^4He nucleus consists of two neutron–proton pairs and it is the most stable of nuclei other than the proton. With a mass deficit of about 28 MeV or 7 MeV per nucleon, it can be visualized to be a nuclear substructure and it is emitted by heavy nuclei having excess positive charge as α radiation (see the heading "Radioactive Decay").

Like the electrons that surround the nucleus at various energy levels, the nucleons (and combinations of nucleons such as the α particle) exist at various energy levels as well. The rearrangements of the electronic shells, with emission of photons of energy as high as that of X-rays, is paralleled in the production of, generally still more energetic photons, termed γ-gamma rays, which arise from nuclear transitions.[9]

In certain cases the internal transitions of nuclei may require hours or days, which has led to the designation of **isomers** to nuclei of equal composition but different energy levels.

Nuclear Reactions

Nuclear reactions are encounters between nuclei involving changes of mass and/or charge. Formally, one represents a nuclear reaction as:

$$x + X \rightarrow y + Y + \ldots \tag{4}$$

where x and X are the reacting particles and y, Y, etc. are the reaction products. In any reaction several quantities are conserved; this means that the total amount of that quantity on the left-hand side of Eq. (4) is the same in the right-hand side, irrespective of the nature of the reaction products. Among these quantities are: the total energy, the total momentum, the total mass number (A), and the total charge (sum of atomic numbers, Z).

Consider the reaction between a deuteron, d, and a triton, t, resulting in an alpha particle, α, and a neutron, n:

$$d + t \rightarrow \alpha + n \tag{5}$$

where α is the helium nucleus, ^4He. The conservation of the total energy requires that:

$$(m_d + T_d) + (m_t + T_t) = (m_\alpha + T_\alpha) + (m_n + T_n) \tag{6}$$

where T is the kinetic energy. The difference between the total mass of the reacting particles and the total mass of the outgoing particles: