

Several other important terms are listed in Table II.1.

**TABLE II.1. Useful terms and their definitions**

Term	Definition	Example
Nuclide	An atom or nucleus identified by its proton and neutron number. A nuclide may be stable or unstable.	${}^A_Z X_N$ , ${}^{235}_{92}U$
Radionuclide	An unstable nuclide which spontaneously transforms into another nuclide.	See Section II.1.2
Isotopes	Nuclides with the same Z but with different N	${}^1_1H$ - hydrogen, H ${}^2_1H$ - deuterium, D ${}^3_1H$ - tritium, T
Radioisotope	A radioactive isotope	${}^3_1H$ , ${}^{235}_{92}U$
Isobars	Nuclides with the same A but with different Z	${}^3_1H$ and ${}^3_2He$
Isotones	Nuclides with the same N but with different Z	${}^3_1H$ and ${}^4_2He$
Isomers	Nuclides having the same mass number and atomic number but occupying different energy states	${}^{144}_{59}Pr$ and ${}^{144m}_{59}Pr$
Isomeric state	An excited nuclear state having a mean life long enough to be observed	
Radioactive decay	The spontaneous decay of unstable nuclei, with emission of particles or radiation	$X \rightarrow Y + y_1 + y_2 + \dots$
Nuclear reaction	An event in which, because of interaction with a particle or radiation (a projectile), a nucleus (target) is changed in mass, charge or energy state, and particles or radiation is emitted.	$x + X \rightarrow Y + y$

Nuclear transformations are usually classified into two basic types: spontaneous transformations (*radioactive decay* - Section II.1.2) and induced transformations (*nuclear reactions* - Section II.1.3). Unstable nuclides decay spontaneously in order to reduce their total internal energy. The excess of internal energy is released as radiation, kinetic energy of the final products of the decay, and/or in the form of “new” particles created in the decay process. In nuclear reactions there are two or more particles involved (projectiles and targets), and again interaction among them tend to lead to the products with the reduced total internal energy.

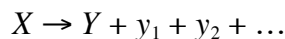
There are several quantities that must be conserved during nuclear transformations. The most important are: mass/energy, linear (and angular) momentum (if no external forces are present), charge and number of nucleons. The list of basic conservation laws for nuclear transformations and their definitions are given in Table II.2.

**TABLE II.2. Basic conservation laws for nuclear transformations**

Conservation Law	Definition
Conservation of Mass/Energy	The total energy of the system before nuclear transformation must be equal to the total energy of the system after the transformation
Conservation of Linear Momentum	Total linear momentum of the system (a vector) before nuclear transformation must be equal to the total linear momentum of the system (a vector) after the transformation
Conservation of Charge	Total charge of the system before nuclear transformation must be equal to the total charge of the system after the transformation
Conservation of Nucleons	Total number of nucleons (protons and neutrons) of the system before nuclear transformation must be equal to the total number of nucleons (protons and neutrons) of the system after the transformation

### II.1.2 Radioactive Decay Modes

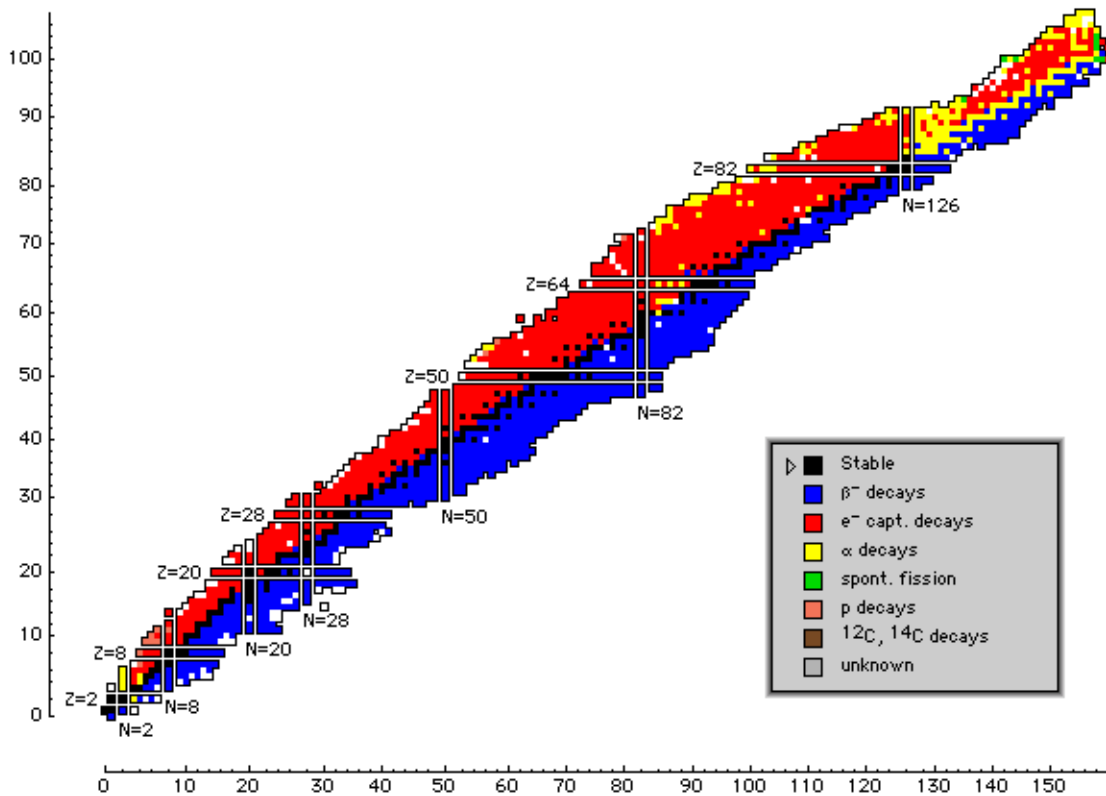
Only certain combinations of protons and neutrons form a stable nucleus. Figure II.2 shows a plot of nuclides as a function of their atomic and neutron numbers. For the atomic numbers greater than 20 there are more neutrons than protons in nuclei in order to compensate the repulsive Coulomb forces between the positively charged protons. Nuclei containing 2, 6, 8, 14, 20, 28, 50, 82, or 126 neutrons or protons are especially stable (“magic” nuclei). Unstable nuclei undergo spontaneous nuclear transformations, with a formation of new elements and emission of charged and/or neutral particles. Symbolically, the decay of a nuclide X into nuclide Y can be written as



where  $y_1, y_2, \dots$  represent particles or radiation emitted during the decay.

These unstable nuclides are called **radioactive nuclides**, and the spontaneous nuclear transformation is called **radioactivity**. The type of radioactive decay or the decay mode depends on the particular type of nuclear instability (whether the neutron to proton ratio is either too high or too low) and on the mass-energy relationship among the parent nucleus, daughter nucleus, and emitted particle. There are many decay modes: alpha decay, beta decay, gamma decay, electron capture,

internal conversion, isomeric transformations, delayed neutron (proton, alpha), spontaneous fission, but we will cover in details only those that are the most important.



**FIGURE II.2.** The chart of nuclides showing stable and unstable nuclei, decay modes, and “magic” nuclei (MacNuclide V2.1)

The simplest way to find the selected properties of the various nuclides in electronic form is the Table of Nuclides maintained by the Korea Atomic Energy Research Institute (KAERI - <http://atom.kaeri.re.kr/>), and the various other nuclear data can be found on the Web pages of the National Nuclear Data Center (NNDC - <http://www.nndc.bnl.gov/>) of the Brookhaven National Laboratory (BNL).

The energy released in the radioactive decay,  $Q$ , comes from the conversion of mass into energy. If the mass loss is  $\Delta M$ , then the energy released is given by  $Q = \Delta M c^2$ , where  $c$  is the speed of light. (The decay  $Q$ -values can be determined on-line: <http://www.nndc.bnl.gov/nndc/qcalc/>)

Alpha Decay An alpha particle is a highly energetic and highly stable nucleus of helium ( ${}^4\text{He}$ ), consisting of two protons and two neutrons. Heavy nuclides with mass numbers higher than 150 can disintegrate by alpha-emission. In this decay, the atomic number of the parent nuclide is reduced by two, and the mass number by four. For example:



Emitted alpha particles are monoenergetic, and their energy spectrum can be essentially represented by lines, as illustrated in Figure II.3.

**EXAMPLE II.1** As an example, we will determine the energy  $Q$  released in the decay of  ${}^{226}\text{Ra}$  given in Eq. II.7, and the kinetic energy of the emitted alpha particle and the recoil radon nucleus. From the Table of Nuclides we can obtain the following data for  ${}^{226}\text{Ra}$  (<http://atom.kaeri.re.kr/cgi-bin/nuclide?nuc=Ra-226/>): a half-life of 1600 year; it decays by alpha emission into either the ground state or one of the excited states of  ${}^{222}\text{Rn}$ ; the energies of emitted alpha particles and branch intensities (probabilities) are 4.784 MeV (94.45%), 4.601 MeV (5.55%), 4.340 MeV (0.0065%), 4.191 MeV (0.0010%), and 4.160 MeV (0.00027%);  ${}^{222}\text{Rn}$  deexcites by emission of one or more gamma rays.

Figure II.3 shows: (a) the decay scheme of  ${}^{226}\text{Ra}$  with possible branches and branch intensities, and (b) the simplified decay scheme with the two most probable branches, and corresponding energies of alpha particles and gamma rays. The mass difference corresponding to Eq. II.7 is given by

$$\Delta M = M(\text{Ra}) - M(\text{Rn}) - M(\text{He}). \quad (\text{II. 8})$$

Instead of nuclear mass difference we can use the atomic mass difference (they are nearly equal - the binding energy of electrons in an atom is neglected). The energy  $Q$  is then determined from

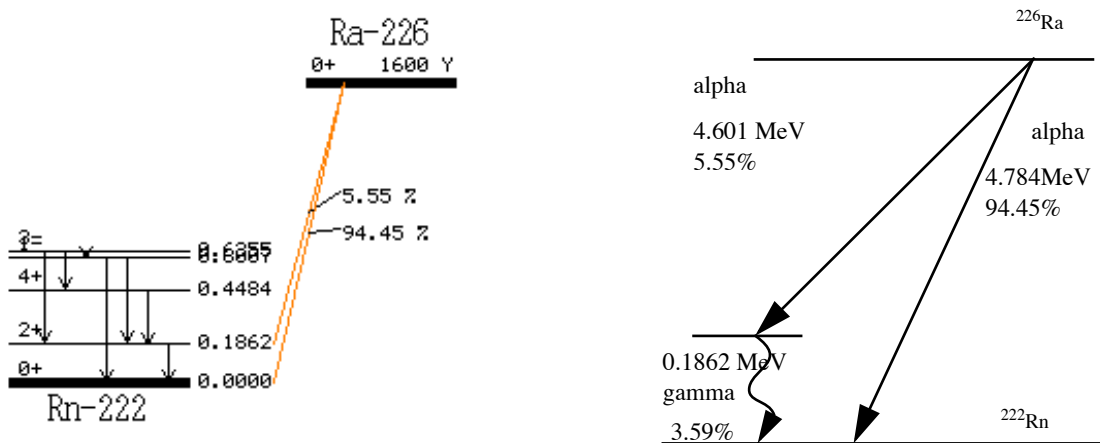


FIGURE II.3. Decay Scheme of Radium-226 (<http://atom.kaeri.re.kr/cgi-bin/decay?Ra-226+A>)