Introduction to Nuclear Reactor Physics

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

J. Frýbort, L. Heraltová

Department of Nuclear Reactors

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References

- The recommended source of fundamental information about nuclear physics applicable to nuclear reactors are DOE Fundamentals Handbooks:
  - Nuclear Physics and Reactor Theory, Vol. 1 and 2
  - These references are freely available from the DOE website
- There are numerous books dealing with fundamentals of reactor and neutron physics, recommended are:
  - John R. Lamarsh – Introduction to Nuclear engineering
  - Paul Reuss – Neutron Physics
- Multimedia CD available from IAEA
  - Multimedia on Nuclear Reactor Physics

Elementary Particles

- There are more than 100 elementary particles, most of them with anti-particles
- The name *elementary particles* has more historical meaning
- Many particles believed to be elementary were found to be composed of *quarks*
- Particles without inner structure:
  - fermions – quarks, leptons (electron)
  - bosons
- Composite particles
  - hadrons – baryons (proton, neutron), mezon
- Reactor physics operates mostly with subatomic particles

Atom

- Atom is the smallest amount of matter that retains the properties of an element
- Atoms are composed of smaller particles that no longer have the properties of the overall element
- One element of the other is distinguished by the kind of atom of which it consists
- Since the atom nature proof in 1803 it was believed that atoms are the elementary particles
- Discovery of radiation indicated that there are subatomic particles

Subatomic Particles

Proton was discovered in 1886

- proton is a positively charged particle with mass 1.673×10^{-27} kg
- charge of a proton is the same in magnitude but opposite in sign to an electron

Electron was discovered in 1897

- electrons are negatively charged particles
- mass of an electron is 9.110×10^{-31} kg

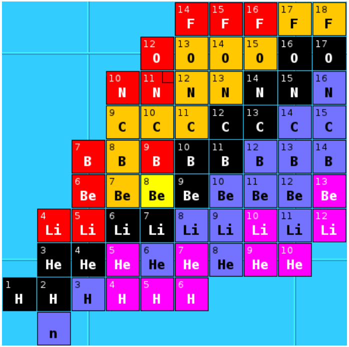
Neutron was discovered in 1932

- neutron is a neutral particle with mass 1.675×10^{-27} kg
- free neutron is unstable with half-life about 10.4 min.

Elements and Isotopes

- Atoms of a particular element must have the same number of protons
- Isotopes are variants of an atom with different number of neutrons
- The following notation is used:

$$^{A}_{Z}X^{N}$$



Z – Atomic number, number of protons
N – Neutron number, number of neutrons
A – Mass number, A = N + Z, number of nucleons

Example for Carbon

- Carbon-12, carbon-13 and carbon-14 are three isotopes of the element carbon
- All of them have 6 protons in the nucleus and 6 electrons in orbitals
- They differ in a mass number – 12, 13, and 14, respectively
- There are 6, 7 or 8 neutrons in the nucleus
- These isotopes are designated as ^{12}C, ^{13}C, and ^{14}C

Atom and Atom Nucleus Dimensions

- Dimensions of electron orbitals are not fixed
- Common definition gives an average distance between the last electron and the nucleus. Typical value is (except for the lightest elements) 2×10^{-10} m
- Density of the electron orbitals is increasing for heavier elements
- Also the dimensions of an atom nucleus are not fixed
- It was determined by measurement of neutrons scattered by a nucleus that radius can be very roughly approximated by the following equation (not valid for light elements):

$$R = 1.25\,A^{1/3} \times 10^{-15}\text{ m}\,,\text{ where A is atom mass number}$$

- Density of a nucleus remains the same with increasing mass number – fundamental requirement for *liquid drop model of atom nucleus*

Basic Units and Constants

- Nuclear physics required for nuclear reactors operates mostly with atoms and neutrons
- Energy of individual reactions is small, therefore it is convenient to use a special energy unit *eV*

$$1\ \mathrm{eV} = 1.602 \times 10^{-19}\ \mathrm{J}$$

- Mass on atomic scale is expressed by *unified atomic mass unit – u*
  - it is by definition 1/12 of the rest mass of an unbound atom of ^{12}C

$$1\ \mathrm{u} = 1.661 \times 10^{-27}\ \mathrm{kg}$$

- Avogadro number expresses the number of elementary entities per 1 mole of a substance
  - equals to number of atoms in 0.012 kg of ^{12}C

$$N_A = 6.022 \times 10^{23}\ \mathrm{mol}^{-1}$$

Atomic Mass and Atomic Weight

Atomic Mass is mass of a specific isotope. Can be expressed relatively in unified atomic mass units (m_a)

Atomic Weight is average mass of atoms of an element expressed in u (A_r)

Molar Mass is mass of one mole of a substance (M)

- These quantities are often confused
- Relative atomic weight is given in periodic table of elements
- Molar mass is calculated from atomic weight as:

$$M = A_r \times 1\ \mathrm{g/mol}$$

Quantities Describing Material Properties

- Properties of a material depend on its composition
- Individual components of the material can be expressed in mass fractions (w_i) or atomic fractions (a_i)

$$w_i = \frac{m_i}{m}$$
$$a_i = \frac{N_i}{N}$$

- Number of atoms in 1 cm^3 of matter is expressed by *number density*

$$N = \frac{\rho N_A}{M}$$

Isotopic Mixtures

- Elements in the nature are occurring in isotopic mixtures
  - For example natural oxygen is a mixture of three isotopes, ^{16}O, ^{17}O and ^{18}O, atom percent abundance of ^{16}O is 99.76 %, for ^{17}O it is 0.04 % and 0.20 % for ^{18}O
- Molar mass (atomic weight) is weighted mean of the molar masses (atomic weights) weighted by isotopic abundance

$$M = \sum_i a_i M_i \tag{1-1}$$

- Example for lithium
  - lithium has isotopes ^{6}Li with atom percent abundance 7.5 % and atomic mass 6.015122 u and ^{7}Li, 92.5 %, 7.016003 u
  - atomic mass of natural lithium (M_{Li}) can be calculated as: 0.075×6.015122 u + 0.925×7.016003 u = 6.9409 u

Conversion of Mass and Atomic Fractions

- Composition of mixtures is usually given in mass or atomic fractions
- Atomic fraction can be calculated from mass fraction as:

$$a_i = w_i \times \frac{M}{M_i} \tag{1-2}$$

- Given the above equation, molar mass of an isotopic mixture can be calculated using mass fractions as:

$$\frac{1}{M} = \sum_i \frac{w_i}{M_i} \tag{1-3}$$

Mass and Energy

- Equivalence between mass and energy is one of results of Einstein theory of relativity
- Rest energy of a particle corresponds to its rest mass

$$E_0 = m_0 c^2$$

- From the point of view of the theory of relativity, total energy is a sum of rest energy and kinetic energy

$$E = mc^2 = E_0 + E_{kin} = m_0 c^2 + E_{kin}$$

- Relativistic effect are important for particles velocities higher than 0.2c:

$$E \geqslant 0.02 E_0$$

- Given the typical neutron energies in nuclear reactors it is usually not necessary to take into account the relativistic effects for neutrons

Equivalence of Mass and Energy

- On the nuclear level it is possible to convert between mass and energy
- Sum of energy and mass must be conserved
- Careful measurements have shown that the mass of a particular atom is always slightly less than the sum of the masses of the individual neutrons, protons, and electrons of which the atom consists
- Difference between the mass of the atom and the sum of the masses of its parts is called *mass defect* – Δm

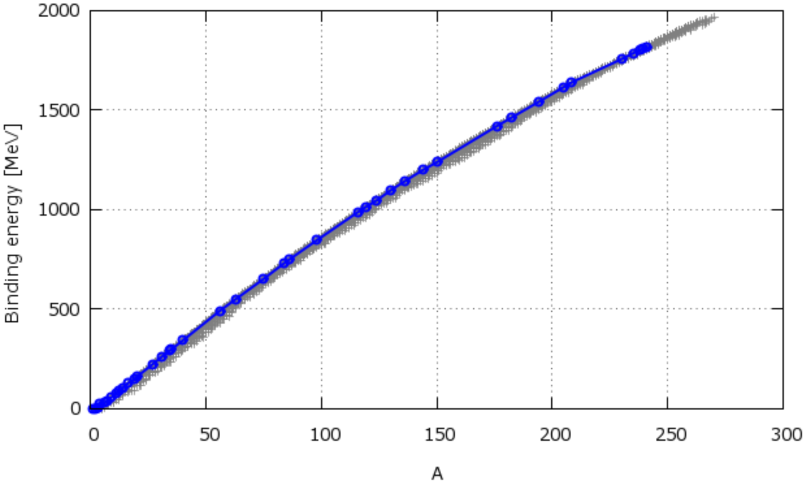
$$\Delta \mathrm{m} = [\mathrm{Z}(\mathrm{m_p} + \mathrm{m_e}) + (\mathrm{A} - \mathrm{Z})\mathrm{m_n}] - \mathrm{m_{atom}} \tag{1-4}$$

where m_p, m_e and m_n are masses of proton, electron and neutron, respectively

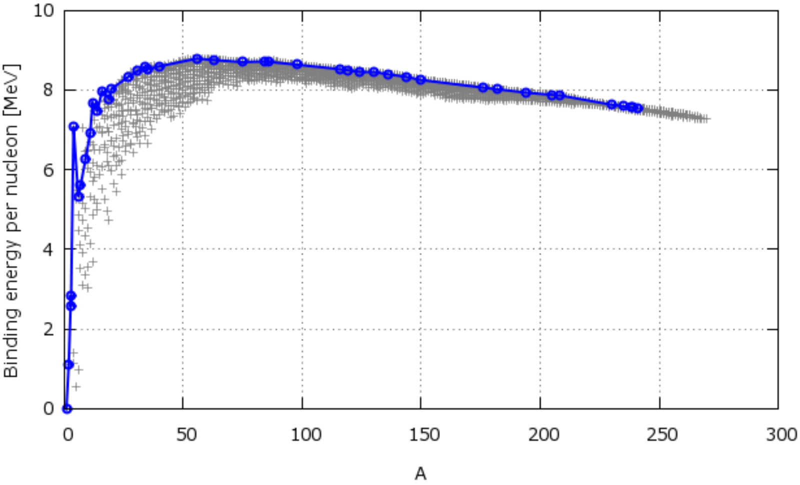
Binding Energy

- Mass defect by an atom formation is a result of mass transformation to binding energy
- *Binding energy* is defined as an energy, which must be given to the nucleus to fully disintegrate
- The same binding energy is released by formation of a nucleus from individual components
- The binding energy is usually expressed per one nucleon

Plot of Binding Energy



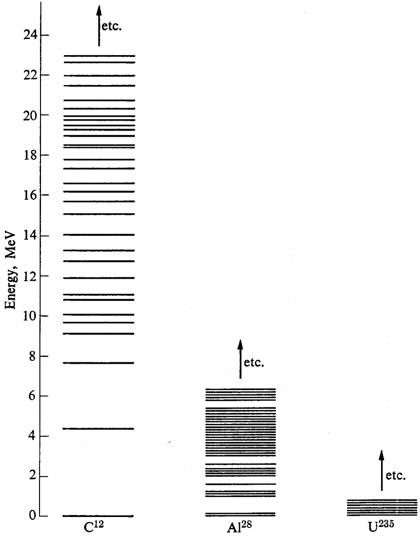
Plot of Binding Energy per Nucleon



Excitation States of a Nucleus

- Similar to electrons in atom orbitals, even atom nucleus can be in various energy states
- Energies of excitation states of nuclei are considerably higher
- Energy quantum is released during transition between individual energy levels
- This radiation is called *gamma radiation*
- The excitation energy is distributed among the nucleons in the nucleus. This is opposite to electron orbitals, where first only one particle is excited
- Also inner conversion is possible. In this process, the excitation energy is transferred to the innermost electron, which is in turn released with excitation energy decreased by ionization energy

Plot of Excitation States of a Nucleus



Radioactivity

- Atoms found in the nature are either stable or emit particles in order to reach more stable configuration
- Non-stable nuclides have excess or deficiency of neutrons and can undergo beta (β) decay, or emit alpha (α) particles, or neutrons.
- Radioactivity is natural or it can be induced
- During radioactive decay holds four conservation principles:
    - conservation of electric charge (possible neutralisation of positive and negative charge)
    - conservation of mass number (conversion between neutrons and protons is allowed)
    - conservation of mass and energy (sum of mass and energy must be constant)
    - conservation of momentum (distribution of available kinetic energy)

Radioactive Decay Rates

- Radioactivity is the property of certain nuclides to spontaneously emit particles or gamma radiation
- Radioactive decay occurs at random manner, only average behaviour can be expressed
- There is a certain probability that in a given time a certain fraction of the nuclei within a sample will decay – *radioactive decay constant* (λ)
- The unit of radioactive decay constant is usually s^{-1} (minute^{-1}, hour^{-1}, etc.)
- *Activity* (A) of a sample is the rate of decay of the sample measured in the number of disintegrations that occur per second

$$A = \lambda N \text{ , where N is number of atoms in the sample} \tag{1-5}$$

Units for Measurement of Radioactivity

- There are two common units for measurement of activity – *curie* (Ci) and *becquerel* (Bq)
- 1 Ci = 3.7×10^{10} Bq
- Radioactivity decreases exponentially according to the following equation:

$$A = A_0 e^{-\lambda t} \text{, where } A_0 \text{ is initial activity} \tag{1-6}$$

- According to the same equation decreases also the number of radioactive nuclides

$$N = N_0 e^{-\lambda t} \text{, where } N_0 \text{ is initial number of nuclides} \tag{1-7}$$

Radioactive Half-Life

- Radioactive half-life ($T_{1/2}$) is useful for quick estimation of decay of radioactive nuclides
- It is defined as time required for radioactivity to decrease to one-half of its original value
- It is calculated from decay constant as follows:

$$T_{1/2} = \frac{\ln 2}{\lambda} \tag{1-8}$$

- After seven half-lifes only 0.78 % of the original number of atoms remains
- It is generally assumed that after 10 half-lifes, the number of existing atoms is negligible

Alpha Decay

- Emission of an alpha particle (helium nucleus)
- During decay atomic number is reduced by 2 and mass number is reduced by 4

$$^{234}_{92}\text{U} \rightarrow {}^{230}_{90}\text{Th} + {}^{4}_{2}\alpha + \gamma + \text{kinetic energy}$$

- This decay leads to $^{230}_{90}$Th formation and emission of 0.068 MeV gamma radiation
- The kinetic energy corresponds to thorium and α particle
- The sum of kinetic energy and energy of γ radiation must be equal to mass difference between original uranium nucleus and final particles
- Resulting α particles carry off 98 % of the kinetic energy

Beta Decay

- Emission of an electron or a positron of nuclear rather than orbital origin
- Negative electron emission effectively converts a neutron to a proton and an electron

$$ {}^{1}_{0}\mathrm{n} \rightarrow {}^{1}_{1}\mathrm{p} + {}^{0}_{-1}\mathrm{e} + {}^{0}_{0}\bar{\nu} $$
$$ {}^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu} $$

- This example of beta decay is typical for isotopes with excess neutrons
- Typical positron beta decay for nuclei with lack of neutrons follows

$$ {}^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{1}\mathrm{e} + {}^{0}_{0}\nu $$
$$ {}^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{+1}\beta + {}^{0}_{0}\nu $$

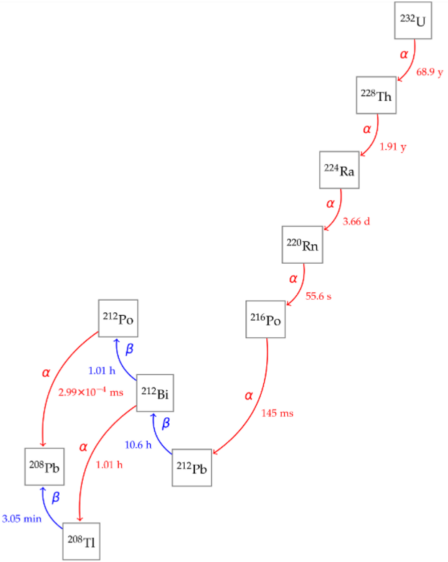
- Neutrino has a little practical importance but must be considered for conservation rules

Gamma Emission

- Gamma radiation is a high-energy electromagnetic radiation that originates in the nucleus
- It is emitted in the form of photons, discrete bundles of energy that have both wave and particle properties
- Daughter nuclides are often left in an excited state after a radioactive decay
- They will drop to the ground state by the emission of gamma radiation

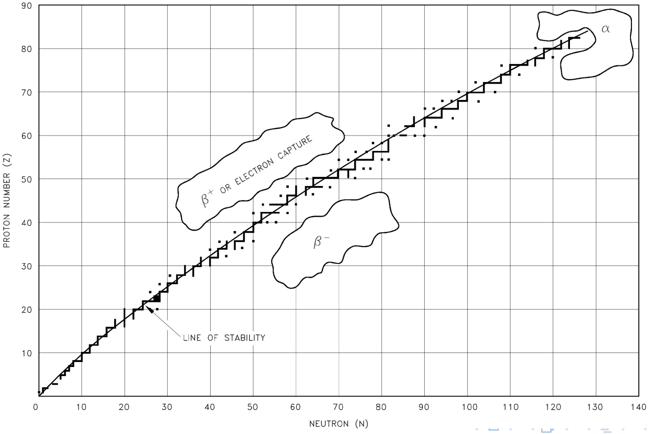
Decay Chains

- Daughter nucleus resulting from a decay must not necessarily be stable
- It is often unstable and can undergo further decay
- This is usually true for heavier isotopes
- There is an example for decay chain of ^{232}U leading to formation of a stable nuclide of ^{208}Pb

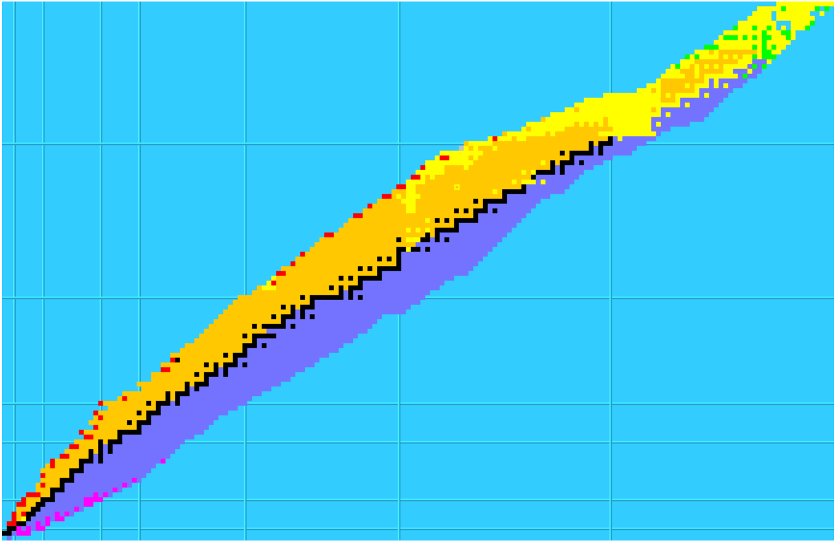


Predicting Types of Radioactive Decay

- There is a *line of stability* with certain ratio of number of neutrons to number of protons in the nucleus
- Radioactive nuclides tend to decay in a way to get closer to this line



Line of Stability



Nuclear Reactions

- Two nuclear particles can interact together
- As a result two or more nuclear particles or γ-rays are produced
- Nuclear particle can mean nucleus or nucleon

$$\mathrm{a} + \mathrm{b} \rightarrow \mathrm{c} + \mathrm{d}$$

$$\mathrm{a}(\mathrm{b}, \mathrm{d})\mathrm{c}$$

where *a* is the target in the rest before reaction and *b* is projectile

- For example oxygen bombardment by energetic neutrons:

$$^{16}_{8}\mathrm{O} + ^{1}_{0}\mathrm{n} \rightarrow ^{16}_{7}\mathrm{N} + ^{1}_{1}\mathrm{H}$$

$$^{16}\mathrm{O}(\mathrm{n}, \mathrm{p})^{16}\mathrm{N}$$

- All conservation laws valid for radioactive decay have to be preserved also during nuclear reactions