# Nuclear Physics and Radioactivity

## The Nucleus

**Rutherford**, *(1911)* proposed a model for the structure of the atom that is still accepted today. He concluded that all of the positive charge and essentially all of the mass of the atom is concentrated in an infinitesimally small fraction of the total volume of the atom, which he called ***the nucleus***. We currently think of the nucleus as being composed of ***nucleons*** of two kinds called protons and neutrons.

***The proton*** is defined to be a particle that has a positive charge which is equal in magnitude to the charge on the electron. We designate the number of protons in the nucleus by Z so the charge on the nucleus is equal to *Ze*, where 'e' is the absolute value of the electric charge on the electron. *(Z is also equal to the atomic number of the element.)*

***A neutron***, the other constituent of the nucleus, is defined as a particle that has no charge. We shall designate the number of neutrons in the nucleus by *N*. The total number of nucleons in the nucleus is $N + Z = A$. The total *A* is called the ***atomic mass number***.

***Isotopes*** are nuclei with the same number of protons, same atomic number, but with a different number of neutrons, and different values of *A*. Isotopes are similar in their chemical properties because chemical changes involve only the electrons of the atom and the number of electrons is the same as the number of protons. Isotopes are symbolized by writing the atomic mass number as a superscript before the atomic symbol. For example, $^{1}H$ and $^{2}H$ represent the hydrogen isotope of mass 1 and 2 respectively. The atomic number *Z* is written as a subscript under the value of *A*. So, the complete designation for these hydrogen nuclei would be:

$$^{1}_{1}H \ and \ ^{2}_{1}H$$

*The nuclei,*

$^{10}{}_{6}C$ $^{11}{}_{6}C$ $^{12}{}_{6}C$ $^{13}{}_{6}C$ $^{14}{}_{6}C$ $^{15}{}_{6}C$

are all isotopes of carbon.

The nuclei of different elements which have the same number for *A* are called ***isobars***. This means they must have different values of *Z* and *N*. Some isobars are,

$$^{23}_{10}\mathrm{Ne} \qquad ^{23}_{11}\mathrm{Na} \qquad ^{23}_{12}\mathrm{Mg}$$

The nuclei of different elements with equal values of *N* are called ***isotones***. Some isotones are:

$$^{13}{}_{5}\mathrm{B} \qquad ^{14}{}_{6}\mathrm{C} \qquad ^{15}{}_{7}\mathrm{N} \qquad ^{16}{}_{8}\mathrm{O}$$

The two basic nucleons have approximately the same mass, the neutron mass being ***1.008665 atomic mass units (amu)*** and the proton mass being ***1.007276 amu.***

Where an atomic mass unit (amu) is defined to be one-twelfth of the mass of the carbon-12 nuclear mass or 1.660566×$10^{-27}$kg.

From the definitions and experiences, it would seem appropriate to think the mass of the nucleus should be given by the sum of mass of protons and the mass of the neutrons.

$$m = Zm_p + Nm_n$$

where $m_p$ is the mass of the proton and $m_n$ is the mass of the neutron.

The results of scattering experiments using charged particles as projectiles and the nucleus as a scatterer indicate that the radius of the nucleus is given by:

$$R = r_0 A^{\frac{1}{3}}$$

where $r_0$ = 1.2 x 10-15 m = 1.2 fermi (F).

When neutrons are scattered by the nucleus, a somewhat larger value of *R* is obtained. For this case,

$$r_0 = 1.5 \text{ x } 10\text{-}15 \text{ m} = 1.5 \text{ F}$$

The nuclear volume *V (*volume of the nucleus*)* would be given by the usual expression for the volume of a sphere,

$$V = \frac{4\pi R^3}{30} = \frac{4\pi (r_0 A^{1/3})^3}{3} = \frac{4\pi {r_0}^3 A}{3}$$

The volume is directly proportional to mass number, so the nucleus density is constant and explained by this formula:

$$\frac{A}{V} = \frac{3}{4\pi {r_0}^3} = constant$$

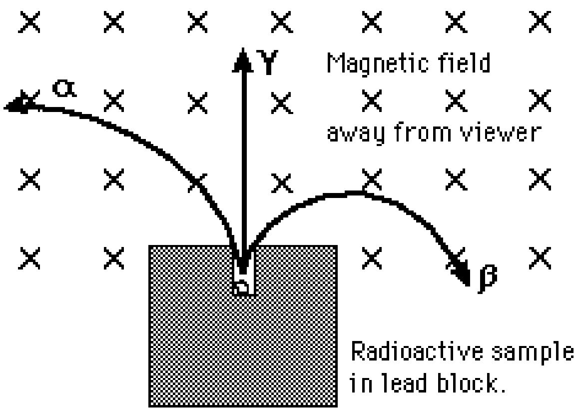
# Radioactivity

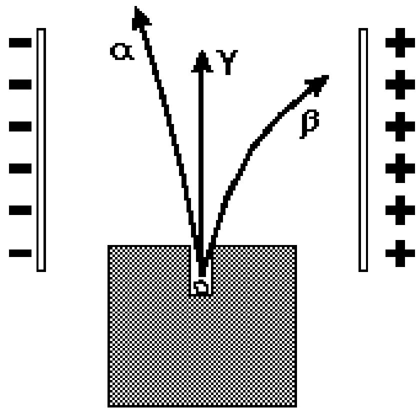
In 1896 Henri Becquerel found that certain uranium salts emitted penetrating radiations. He observed that photographic plates which were stored in a drawer with uranium salts were blackened. The results of these experiments showed that there were three types of radiation which were called ***alpha ($\alpha$-), beta ($\beta$-) and gamma ($\gamma$-) radiation***.

***$\alpha$-radiation:*** The alpha radiation was found to be positively charged particles each with a mass of the helium nucleus ( ${}_{2}^{4}He^{++}$) . They have low penetrating ability. In fact, they are stopped by a sheet of paper.

***$\beta$-radiation:*** The beta radiation carries a negative charge and has the mass of an electron; they are high- energy electrons. They were more penetrating than the $\alpha$-particle but could be stopped by thin aluminium sheets.

***$\gamma$-radiation:*** The $\gamma$-radiation was not deflected by a magnetic field; hence it carried no charge. The $\gamma$-radiation was very penetrating and behaved very much like x rays. Gamma radiation would pass through a lead plate.



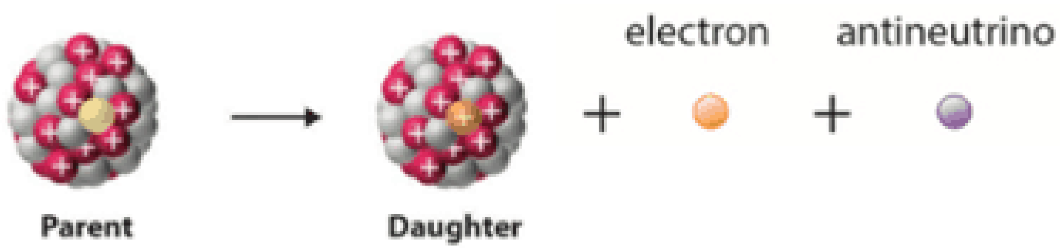

There are some principle modes of radioactive decay for natural elements. These modes are called alpha, beta and gamma decay.

1. ***Alpha decay*** involves the emission of a ${}_{2}^{4}He$ nucleus (a particle) from the radioactive nuclide. A general form for alpha decay can be written as follows:

$${}_{Z}^{A}X \rightarrow {}_{Z-2}^{A-4}Y + {}_{2}^{4}He$$

where X represents the parent nucleus, Y, the daughter nucleus.

2. ***Beta decay*** or ***β-decay*** represents the disintegration of a parent nucleus to a daughter through the emission of the beta particle. This transition ($\beta^-$ decay) can be characterized as:




$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \beta^- + \overline{\nu_e} $$

In 1934 Enrico Fermi proposed a theory that involved a new massless, chargeless particle that he called the *neutrino* ($\vartheta$). The ***neutrino*** is a particle emitted in beta decay that was unanticipated and is of fundamental importance.

If a nucleus emits a beta particle, it loses an electron (or positron). In this case, the mass number of daughter nucleus remains the same, but daughter nucleus will form different element.

- **Negative Beta Decay – Electron Decay.** In electron decay, a neutron-rich nucleus emits a high-energy electron ($\beta^-$ particle). The electrons are negatively charged almost massless particles Due to the law of conservation of electric charge, the nuclear charge must increase by one unit. In this case, the process can be represented by:

$$ {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \rightarrow {}_{\mathrm{Z+1}}{}^{\mathrm{A}}\mathrm{Y} + e^- + \tilde{\vartheta} \,; \qquad n \rightarrow p + e^- + \tilde{\vartheta} $$

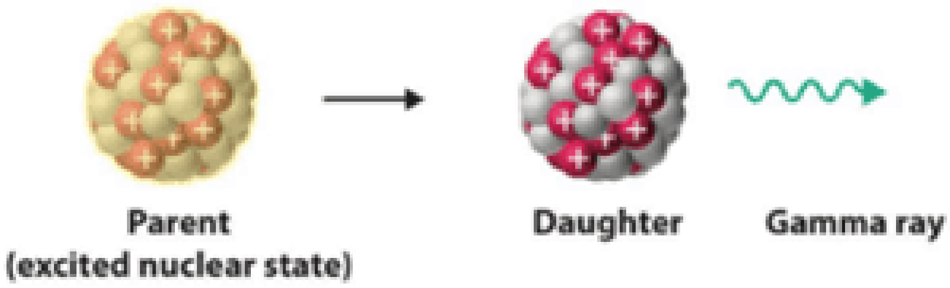
- **Positive Beta Decay – Positron Decay.** In positron decay, a proton-rich nucleus emits a positron (positrons are antiparticles of electrons, and have the same mass as electrons but positive electric charge), and thereby reduces the nuclear charge by one unit. In this case, the process can be represented by: An annihilation occurs, when a low-energy positron collides with a low-energy electron.

$$ {}^{A}_{Z}X \rightarrow {}_{Z-1}^{\ \ A}Y + e^{+} + \vartheta; \qquad p \rightarrow n + e^{+} + \vartheta $$

- **Inverse Beta Decay – Electron Capture.** In this process, a proton-rich nucleus can also reduce its nuclear charge by one unit by absorbing an atomic electron.

$$ {}^{A}_{Z}X + e^{-} \rightarrow {}_{Z-1}^{\ \ A}Y + \vartheta; \qquad p + e^{-} \rightarrow n + \vartheta $$

3. ***Gamma decay*** or ***γ-decay*** represents the disintegration of a parent nucleus to a daughter through the emission of gamma rays (high energy photons). This transition (**γ-decay**) can be characterized as:




$$ {}^{Am}_{Z}X \rightarrow {}^{A}_{Z}X + {}^{0}_{0}\gamma $$

As can be seen, if a nucleus emits a gamma ray, atomic and mass numbers of daughter nucleus remain the same, but daughter nucleus will form different energy state of the same element. Note that, nuclides with equal proton number and equal mass number (thus making them by definition the same isotope), but in a different energy state are known as nuclear isomers. We usually indicate ***isomers*** with a superscript m, thus:

$$ {}^{241m}Am \text{ or } {}^{110m}Ag. $$

# The Laws of Radioactive Decay

When a radioactive material undergoes α, β or γ-decay, the number of nuclei undergoing the decay, per unit time, is proportional to the total number of nuclei in the sample material.

So,

If N = total number of nuclei in the sample and

ΔN = number of nuclei that undergo decay in time Δt then,

$$\Delta N/\Delta t \propto N$$

$$\text{or, } \Delta N/\Delta t = \lambda N$$

where λ = radioactive decay constant or disintegration constant.

Now, the change in the number of nuclei in the sample is,

$$dN = -\Delta N \text{ in time } \Delta t.$$

Hence, the rate of change of N (in the limit Δt → 0) is,

$$dN/dt = -\lambda N$$

$$\text{or, } dN/N = -\lambda\, dt$$

Now, integrating both the sides of the above equation, we get,

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_{0}^{t} dt$$

$$\text{or, } \ln N - \ln N_0 = -\lambda (t - t_0)$$

Where, $N_0$ is the number of radioactive nuclei in the sample at some arbitrary time $t_0$ and N is the number of radioactive nuclei at any subsequent time t.

Next, we set $t_0 = 0$ and rearrange the above equation to get,

$$\ln (N/N_0) = -\lambda t$$

$$\text{or, } N(t) = N_0 e^{-\lambda t}$$

***$N(t) = N_0 e^{-\lambda t}$* is the *Law of Radioactive Decay.***

## The Decay Rate

In radioactivity calculations, we are more interested in the decay rate

$$A \, (= -\boldsymbol{dN/dt})$$

than in N itself.

This rate gives us the number of nuclei decaying per unit time.

Let's say that we consider a time interval dt and get a decay count ΔN (= –dN). The decay rate is now defined as,

$$\boldsymbol{A = -\frac{dN}{dt} = \lambda N}$$

or via rearranging the separable differential equation:

$$\boldsymbol{\frac{dN}{N} = -\lambda dt}$$

by Integrating the equation:

$$\boldsymbol{\int_{N_0}^{N} \frac{dN}{N} = -\int_0^t \lambda \, dt}$$

This give us:

$$\boldsymbol{ln \frac{N}{N_0} = -\lambda t}$$

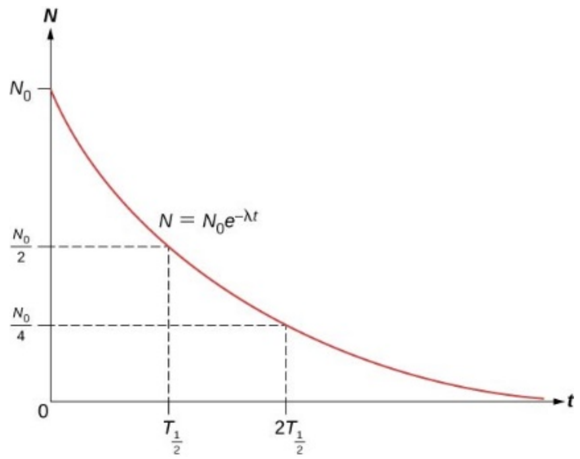
The total number N of radioactive nuclei remaining after time t is:

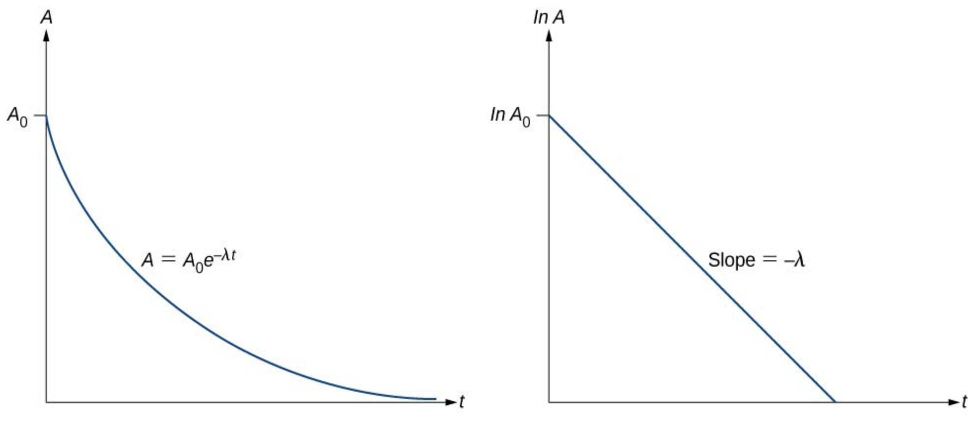
$$N = N_0 e^{-\lambda t}$$

where λ is the decay constant for the particular nucleus. And we get,

$$A = \lambda N_0 e^{-\lambda t}$$

$$\text{or, } \mathbf{A} = \mathbf{A_0 e^{-\lambda t}}$$



(a) (b)

## Radioactive decay lines

Natural radioactive materials at the end of the periodic system can be sorted into decay series. During decomposition, the mass is either unchanged (($\beta$-, $\gamma$-

decomposition) or reduced by four ($\alpha$-decomposition). Thus, there are four different types of decay series, depending on how much residue is obtained divided by four, that is should not change during either α, β or γ decay.

0 remaining (A = 4n + 0):

$$Thorium - place\ female\ member: {}^{232}Th,\ T_{\frac{1}{2}} = 1{,}41 \cdot 10^{10}év,$$

$$End\ product: {}^{208}Pb$$

1 Remnant (A = 4n + 1):

$$Neptunium - line\ parent\ element: {}^{237}Np,\ T_{\frac{1}{2}} = 2{,}14 \cdot 10^{6}év,$$

$$End\ product: {}^{209}Bi,$$

This is no longer in nature, has been degraded since the Earth was formed.

2 remaining (A = 4n + 2):

$$Uranium\ 238, mother\ element: {}^{238}U,\ T_{\frac{1}{2}} = 4{,}50 \cdot 10^{9}év,$$

$$End\ product: {}^{206}Pb$$

3 remaining (A = 4n + 3):

$$Uranium\ 235\ series, mother\ element: {}^{235}U,\ T_{\frac{1}{2}} = 7{,}1 \cdot 10^{8}év,$$

$$End\ product: {}^{207}Pb$$

Example: ${}^{238}_{92}U \xrightarrow{\alpha} {}^{234}_{90}Th \xrightarrow{\beta^-} {}^{234}_{91}Pa \rightarrow .... \xrightarrow{\alpha} {}^{226}_{88}Ra \xrightarrow{\alpha} {}^{222}_{86}Rn \xrightarrow{\alpha} .... \rightarrow {}^{206}_{82}Pb$

## Radioactivity in practice:

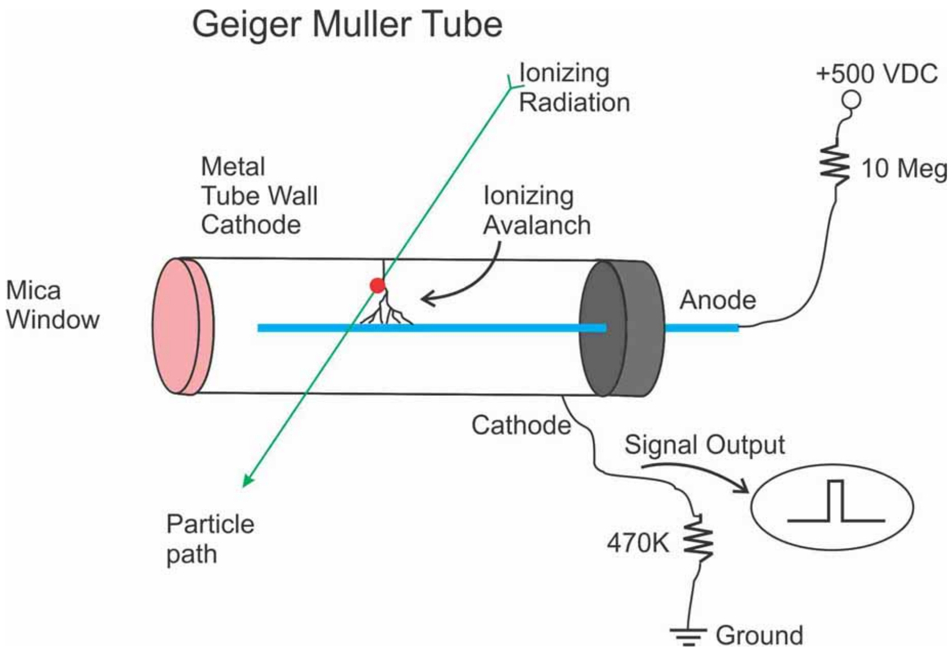
# Measurement of radioactive radiation

A ***Geiger counter (Geiger-Muller tube)*** is a device used for the detection and measurement of all types of radiation: alpha, beta and gamma radiation. Basically, it consists of a pair of electrodes surrounded by a gas. The Geiger counter, survey meter, and personal dosimeters work on the basis of the ionization chamber.

The principle of operation of an ionization chamber is that it will produce an electric current in the presence of a radioactive source. Ionization chambers consist of tubes filled with gas, such as argon. When radiation enters the tube and interacts with the gas, it removes electrons from the gas.

The gas atoms become positively charged ions, and the free electrons move through the gas to a wire in the tube, setting up a current. The current is commonly amplified and sent to a recording or counting device. This in response may produce a flash of light, ticking sounds, or an analogue readout.

Ionization chambers are capable of measuring the amount of radiation by means of measuring the amount of current produced.




*Geiger Muller Tube*

# Attenuation of gamma particles when passing through a medium

As gamma particles pass through matter, they interact with the material and get absorbed. Gamma particles are incident from the left on a slab. The slab has a thickness of *x*. After passing through the slab of material the gamma particles emerge on the right.

Let the intensity of the gammas incident from the left be denoted as $I_0$, the initial intensity, and let the intensity of gammas that emerge on the right, after passing through the slab, be denoted as *I(x),* the final intensity. As the slab get thicker, *x* gets larger and *I(x)* becomes smaller*.* As *x* increases, more radiation is absorbed in the material and less passes through and emerges on the right side.

**How *I(x)* depends on *x*:**
To a very good approximation the number of gammas that pass through the slab decrease exponentially with thickness:

$$I(x) = I_0 e^{-\alpha x}$$

This equation is referred to as ***Lambert's law*** and is applicable for linear attenuation. The geometry for linear attenuation is that the material is rectangular slab and the gammas are incident perpendicular to slab.

The units of $\alpha$ are (1/distance) since $\alpha x$ is unitless. The parameter $\alpha$ is called the ***linear attenuation coefficient***.

# Theory of radioactivity

## Nuclear interaction

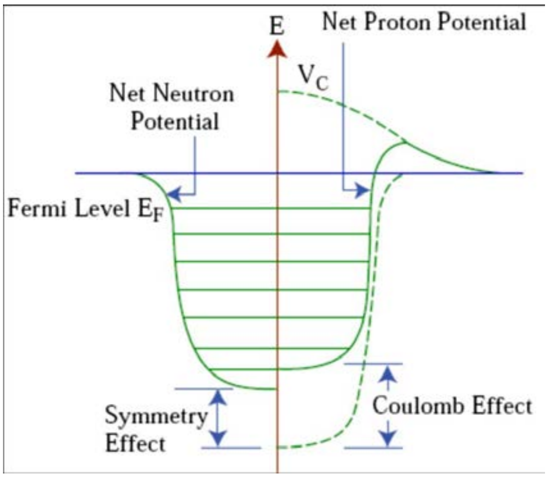
The nucleus has Z protons and neutrons, and is mostly a completely stable formation. The protons inside it repel each other, so the question is, what holds the nucleus together? Based on Heisenberg's uncertainty relation, the estimated kinetic energy of a nucleon is:

$$\Delta x \cdot \Delta p_x \geq \frac{\hbar}{2} \text{ ha } \Delta x \approx R \approx 10^{-15} m \rightarrow \Delta p_x \approx p_x \approx 10^{-20} \frac{kgm}{s}, T = \frac{p^2}{2m_p} \geq 5MeV .$$

Because nucleons are bound, their energy is negative:

$$E = T + V < 0, \text{ így } V < -T = -5MeV$$

Interaction within the nucleus is thus accompanied by a very deep potential energy associated with great forces. The interaction cannot be electric (because it would cause repulsion) or gravitational (because it is too weak). A third type of interaction between nucleons (protons and neutrons) is the so-called strong or nuclear interactions work. (We can say quite precisely that the nuclear interaction between nucleons results from the strong interaction between the 3 quarks that make up the nucleons.) Experience has shown that the nuclear interaction (the so-called core force) is charge-independent; proton-proton, proton-neutron, and neutron-neutron interaction are the same, always attractive (potential energy negative), and short-range (cease to be a few fm away), saturate (nucleons interact only with their immediate neighbours). The interaction is very strong, ~ 100 times the electrical interaction at this distance.




*The potential well in the nucleus for neutrons and protons*

In the simplest atomic nucleus model, each nucleon moves in a potential well created by other nucleons, in which, according to the quantum mechanics, protons and neutrons can only have discrete energy, and these energy levels can be loaded in pairs according to Pauli's principle. For protons, this well is always shallower because the positive Coulomb energy due to their repulsion is added to the negative energy due to nuclear attraction.

## Mass defect and Nuclear Binding Energy

Previously we assumed that,

$$m = Zm_p + Nm_n$$

Where $m_p$ is the mass of the proton and $m_n$ is the mass of the neutron.

However, measurements show that the weight of the components together is **greater** than the weight of the finished nucleus. We shall designate the difference between the computed mass in above equation and the real mass as *the mass defect.*

$$\Delta m = Zm_p + Nm_n - M$$

*Or*

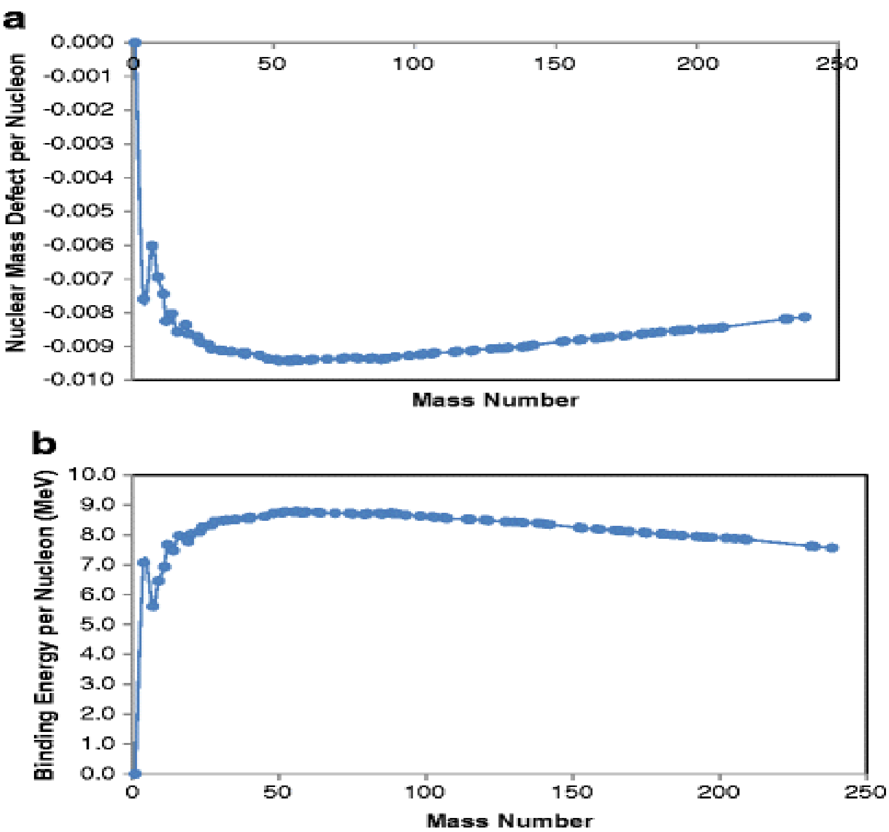
$$\Delta M(Z, A) = M(Z, A) - Zm_p - Nm_n < 0$$

Binding energy is the energy by which the combined energy of nucleon A is deeper in the equilibrium atomic nucleus than if the nucleons were spaced apart and out of range of the interaction. Where *M* is the measured mass of the nucleus (it can be measured by mass spectrometer for each element), *M(Z, A)* is the total mass of an atom, *A* is atomic mass number, *N* is the number of neutrons. We will now make use of Albert Einstein's famous mass-energy equation, mass is equivalent to energy,

$$\Delta E = \Delta mc^2 = (Zm_p + Nm_n - M)c^2 = E_{binding}$$

In absolute terms, it is necessary to invest so much energy to dismantle the nucleus into its constituent parts. Binding energies may be calculated if masses are measured accurately. One way of doing this is by using the techniques of ***mass spectroscopy***.

Since it is measurable, the binding energy can be calculated and the binding energy per nucleon can be determined. Plot this as a function of mass.




***(a)*** *Nuclear mass defect per nucleon based on the* $^{12}C$ *mass scale, and* ***(b)*** *binding energy per nucleon versus mass number for the most abundant isotopes.*

# Nuclear Fission and Applications

## Mechanism of nuclear fission

After the discovery of the neutron, a number of experiments have involved bombardment of various elements with neutrons. In such an experiment (1937) very high radioactivity was observed after irradiation of uranium with neutrons. After the reaction, medium-mass nuclei were detected.

Some typical reactions are:

$$^{235}_{92}U + n \rightarrow {}^{236}_{92}U \rightarrow {}^{94}_{36}Kr + {}^{139}_{56}Ba + 3n + energy$$

$$^{235}_{92}U + n \rightarrow {}^{236}_{92}U \rightarrow {}^{96}_{37}R_b + {}^{137}_{55}Cs + 3n + energy$$

$$^{235}_{92}U + n \rightarrow {}^{236}_{92}U \rightarrow {}^{90}_{38}Sr + {}^{144}_{54}Xe + 2n + energy$$

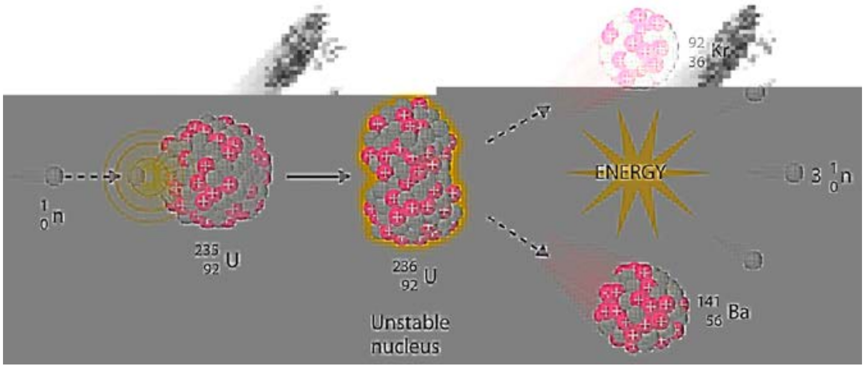
The phenomenon of a high-mass atomic nucleus splitting into two medium-mass nuclei and a few neutrons with the release of energy is called nuclear fission.

The formula of a general reaction:

$$^{235}_{92}U + n \rightarrow {}^{236}_{92}U \rightarrow {}^{96}X + {}^{137}Y + 3n + energy$$

The reaction produces two fissures of significantly different mass numbers, appearing on average per decay, and approx. 200 MeV of energy is released, which is mainly represented by the kinetic energy of the fission products:

**Mechanism of cleavage:**




*Mechanism of nuclear fission*

The incoming neutron transfers its energy to the nucleus through nuclear interaction, the nucleus vibration can be so large that the nucleus is bound and split and rapid (high kinetic energy) neutrons are generated. From the moment of the split, the nuclear interaction between the two fission nuclei ceases, only the Coulomb repulsion remains, which accelerates them to very high speeds over a very short distance. (Thus, nuclear fission ultimately releases Coulomb energy, not nuclear.)

Fissures are very radioactive because they have too much neutron excess. Stable neutron / proton ratios for medium-sized nuclei are achieved by a number of successive decays. The decay is followed by the decay, which is why fissures are very dangerous and their radioactivity is many millions of times higher than that of the initial uranium.

## Chain reaction, nuclear power plants

During neutron-induced nuclear fission, 2-3 neutrons are formed, and these neutrons can cause further fission, a process called **nuclear physical chain reaction**. However, fission generates fast neutrons, whereas $^{235}U$ slow neutrons are more likely to cleave the nucleus.

Most of the fast neutrons are absorbed by the $^{238}U$ nuclei, which inhibits the chain reaction. Natural uranium contains only 0.72% of the $^{235}U$-isotope. With so many $^{238}$U-cores, it causes such a loss of neutrons that, at any size, no chain reaction can be initiated. Therefore, natural uranium deposits have not yet been burned. The solution is associated with Leo Szilárd and Enrico Fermi. Removing neutrons from the natural uranium block, the $^{235}U$-core cannot absorb them by resonance capture. To solve this problem, a medium is used which slows down the neutrons, e.g. graphite (but water is also used for this purpose). Such a medium is called moderator (slowing down medium). Slow neutrons return to the uranium array to cleave the $^{235}U$-nuclei. In addition, uranium is often enriched, meaning that most of the nuclei are extracted. (The atom bomb also requires uranium enrichment).

The nuclear power plant reactor thus has a large nucleon fission nucleus. The energy released by fission is used to heat water, convert it into steam, drive a turbine and generate electricity through Lorentz power. The first reactor is 200W power volt.

The Paks Nuclear Power Plant has been in operation since 1982, fuel about $^{235}$U-t kb. contains 3% enriched uranium oxide. The power plant has four blocks, the reactor tanks in them are cylindrical, thick-walled and 18 m high. The capacity of the four units is 4 × 440 MW = 1760 MW, 43% of the national consumption. 1kg of $^{235}$U is approx. 23000MWh of energy can be produced, which is equivalent to burning 2400 tons of coal.

## Nuclear Fusion

Combining light nuclei also deepens the binding energy per nucleon. Transformation therefore involves the release of energy. During the hydrogen cycle in the sun, one He nucleus is created in several steps from 4 protons.

$$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu + 0,42MeV$$

$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma + 5{,}5eV$$

$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2 \cdot {}^{1}H + 12{,}8MeV$$

In these processes, the nuclei have to approach each other up to the range of the nuclear force, which requires a very high initial speed. The first reaction of the cycle, deuterium generation, is a very unlikely process, with the total hydrogen content of the sun (about 10 million Kelvin in the centre) sufficient for 10 billion years.

Of course, under ground conditions, this time cannot be expected, and the deuterium is ready to be loaded into the fusion reactor. In the case of charged particles, they can be accelerated by a particle accelerator, but at very high temperatures, the thermal motion gives the nuclei the required high speed. At ground level, much higher temperatures (at least 50 million Kelvin) are needed.

In a hydrogen bomb this is achieved by detonating an atomic bomb (based on nuclear fission). Controlled fusion is constantly being researched, the main difficulty being that the hot material cannot be stored in any container. Creating a continuously operating fusion power plant would help a lot in mankind's energy problems because there is so much hydrogen in the earth, for example. in the waters of the oceans.