Nuclear Physics

In nuclear physics and nuclear chemistry, a nuclear reaction is a process in which two nuclei, or a nucleus and an external subatomic particle, collide to produce one or more new nuclides. Thus, a nuclear reaction must cause a transformation of at least one nuclide to another. If a nucleus interacts with another nucleus or particle and they then separate without changing the nature of any nuclide, the process is simply referred to as a type of nuclear scattering, rather than a nuclear reaction.

In principle, a reaction can involve more than two particles colliding, but because the probability of three or more nuclei to meet at the same time at the same place is much less than for two nuclei, such an event is exceptionally rare (see triple alpha process for an example very close to a three-body nuclear reaction). The term "nuclear reaction" may refer either to a change in a nuclide induced by collision with another particle or to a spontaneous change of a nuclide without collision.

Natural nuclear reactions occur in the interaction between cosmic rays and matter, and nuclear reactions can be employed artificially to obtain nuclear energy, at an adjustable rate, on-demand. Nuclear chain reactions in fissionable materials produce induced nuclear fission. Various nuclear fusion reactions of light elements power the energy production of the Sun and stars.

In 1919, Ernest Rutherford was able to accomplish transmutation of nitrogen into oxygen at the University of Manchester, using alpha particles directed at nitrogen $^{14}N + \alpha \rightarrow {}^{17}O + p$. This was the first observation of an induced nuclear reaction, that is, a reaction in which particles from one decay are used to transform another atomic nucleus. Eventually, in 1932 at Cambridge University, a fully artificial nuclear reaction and nuclear transmutation was achieved by Rutherford's colleagues John Cockcroft and Ernest Walton, who used artificially accelerated protons against lithium-7, to split the nucleus into two alpha particles. The feat was popularly known as "splitting the atom", although it was not the modern nuclear fission reaction later (in 1938) discovered in heavy elements by the German scientists Otto Hahn, Lise Meitner, and Fritz Strassmann.

Nuclear reaction equations

Nuclear reactions may be shown in a form similar to chemical equations, for which invariant mass must balance for each side of the equation, and in which transformations of particles must follow certain conservation laws, such as conservation of charge and baryon number (total atomic mass number). An example of this notation follows:

$$^{6}_{3}Li + {}^{2}_{1}H \rightarrow {}^{4}_{2}He + ?.$$

To balance the equation above for mass, charge and mass number, the second nucleus to the right must have atomic number 2 and mass number 4; it is therefore also helium-4. The complete equation therefore reads:

$$^{6}_{3}\mathrm{Li} + ^{2}_{1}\mathrm{H} \rightarrow ^{4}_{2}\mathrm{He} + ^{4}_{2}\mathrm{He}.$$

or more simply:

$$^{6}_{3}\mathrm{Li} + ^{2}_{1}\mathrm{H} \rightarrow 2\,^{4}_{2}\mathrm{He}.$$

Instead of using the full equations in the style above, in many situations a compact notation is used to describe nuclear reactions. This style of the form A(b,c)D is equivalent to A + b producing c + D. Common light particles are often abbreviated in this shorthand, typically p for proton, n for neutron, d for deuteron, α representing an alpha particle or helium-4, β for beta particle or electron, γ for gamma photon, etc. The reaction above would be written as 6Li(d,α)α.

Different Types of Nuclear Reaction

Although the number of possible nuclear reactions is enormous, nuclear reactions can be sorted by types. Most nuclear reactions are accompanied by gamma emissions. Some examples are:

Elastic scattering: Occurs when no energy is transferred between the target nucleus and the incident particle.

$$^{4}\mathrm{He} + ^{197}\mathrm{Au} \rightarrow ^{4}\mathrm{He} + ^{197}\mathrm{Au}$$

Inelastic scattering: Occurs when energy is transferred. The difference of kinetic energies is saved in an excited nuclide.

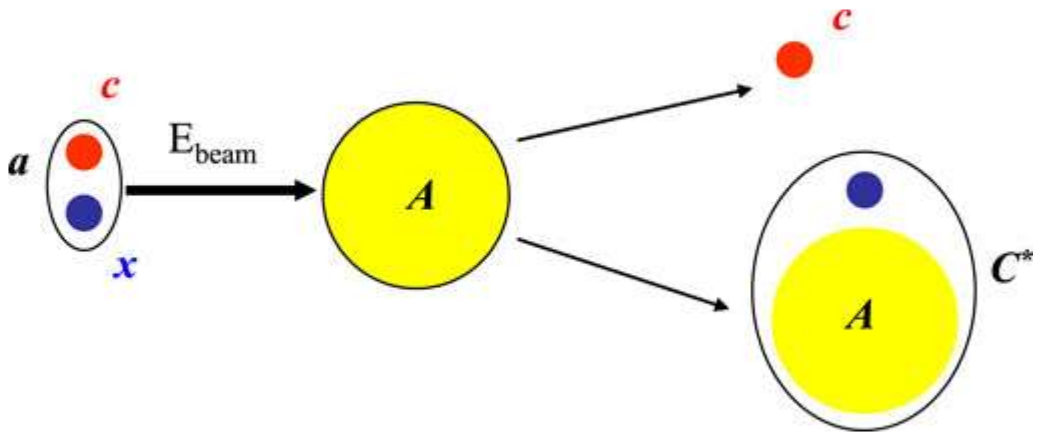
$$^{7}\mathrm{Li} + ^{1}\mathrm{H} \rightarrow ^{7*}\mathrm{Li} + ^{1}\mathrm{H}$$

Capture reactions: Both charged and neutral particles can be captured by nuclei. This is accompanied by the emission of γ-rays. Neutron capture reaction produces radioactive nuclides (induced radioactivity).

$$^{14}\mathrm{N} + ^{1}\mathrm{H} \rightarrow [^{15*}\mathrm{O}] \rightarrow ^{15}\mathrm{O} + \gamma$$

Transfer Reactions: The absorption of a particle accompanied by the emission of one or more particles is called the transfer reaction.

The transfer reaction will then be A(*a*,c)C, where *a* is a composite system made of *x* and *c*. The valence states of the final nucleus C will be populated, and the reaction mechanism will be considered as *a* one step direct reaction if the reaction occurs without perturbation of the target (core) nucleus A or the projectile *a*



Sketch of a transfer reaction where the particle *x* is transferred from the projectile *a* to the target nucleus *A* forming the final state C*.

Fission reactions: Nuclear fission is a nuclear reaction in which the nucleus of an atom splits into smaller parts (lighter nuclei). The fission process often produces free neutrons and photons (in the form of gamma rays) and releases a large amount of energy.

The process of fission occurs when a nucleus splits into smaller pieces. Fission can be induced by a nucleus capturing slow moving neutrons, which results in the nucleus becoming very unstable.

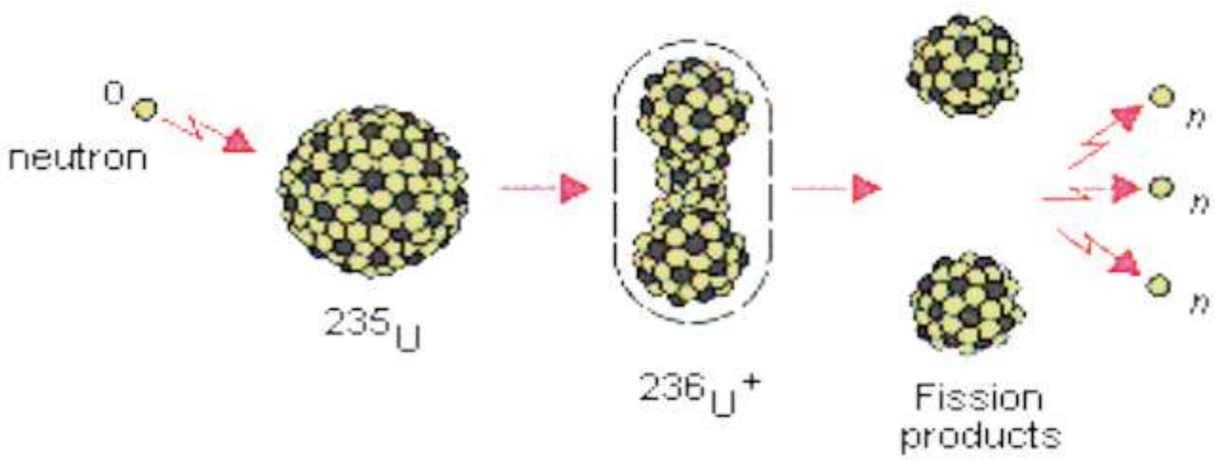


Figure-1: Fission Reactions Process

The following equations represent fission reactions, where n is neutron. All these fission reactions also release a large amount of energy.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\ ^{1}_{0}n + Energy$$

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{131}_{50}Sn + ^{103}_{42}Mo + 2\ ^{1}_{0}n + Energy$$

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{137}_{52}Te + ^{97}_{40}Zr + 2\ ^{1}_{0}n + Energy$$

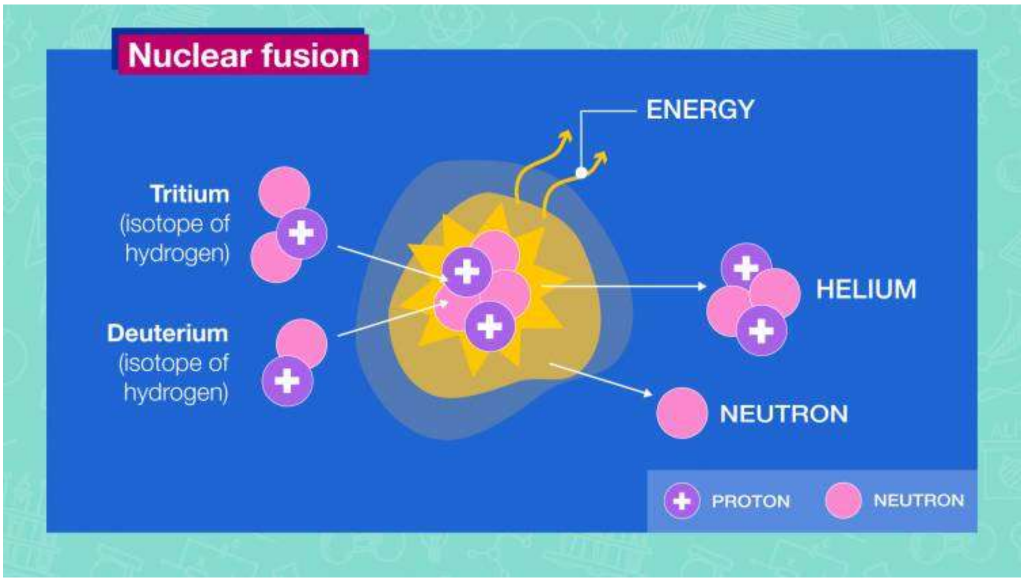
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{138}_{54}Xe + ^{95}_{38}Sr + 3\ ^{1}_{0}n + Energy$$

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{152}_{60}Nd + ^{81}_{32}Ge + 3\ ^{1}_{0}n + Energy$$

Fusion reactions: Occur when two or more atomic nuclei collide at a very high speed and join to form a new type of atomic nucleus. The fusion reaction of deuterium and tritium is particularly interesting because of its potential of providing energy for the future.

An important fusion reaction for practical energy generation is that between deuterium and tritium (the D-T fusion reaction). It produces helium (He) and a neutron (n) and is written

$$D + T \rightarrow He + n.$$



Spallation reactions: Occur when a particle hits a nucleus with sufficient energy and momentum to knock out several small fragments or smash them into many fragments.

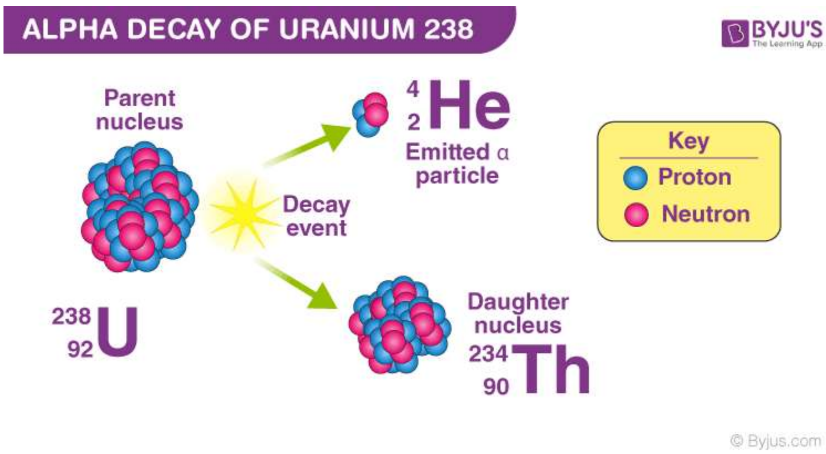
$$p + {}^{7}_{3}\mathrm{Li} \rightarrow {}^{7}_{4}\mathrm{Be} + n$$
$$p + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{9}_{5}\mathrm{B} + n$$

Nuclear decay (Radioactive decay): Occurs when an unstable atom loses energy by emitting ionizing radiation. Radioactive decay is a random process at the level of single atoms, in that, according to quantum theory, it is impossible to predict when a particular atom will decay. There are many types of radioactive decay:

$$^{93}\mathrm{Rb} \xrightarrow{6\ \mathrm{s}} {}^{93}\mathrm{Sr} \xrightarrow{7\ \mathrm{min}} {}^{93}\mathrm{Y} \xrightarrow{10\ \mathrm{h}} {}^{93}\mathrm{Zr} \xrightarrow{10^{6}\ \mathrm{y}} {}^{93}\mathrm{Nb}$$

$$^{141}\mathrm{Cs} \xrightarrow{25\ \mathrm{s}} {}^{141}\mathrm{Ba} \xrightarrow{18\ \mathrm{min}} {}^{141}\mathrm{La} \xrightarrow{4\ \mathrm{h}} {}^{141}\mathrm{Ce} \xrightarrow{33\ \mathrm{d}} {}^{141}\mathrm{Pr}$$

Alpha radioactivity. Alpha particles consist of two protons and two neutrons bound together into a particle identical to a helium nucleus. Because of its very large mass (more than 7000 times the mass of the beta particle) and its charge, it heavily ionizes material and has a very short range.



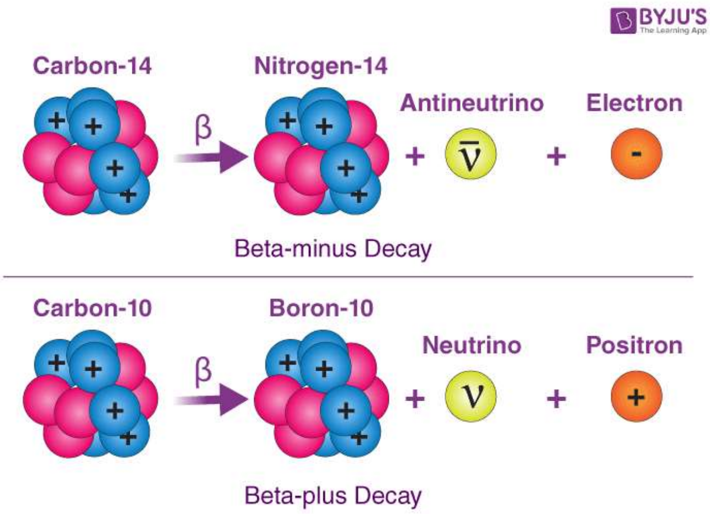
Beta radioactivity: Beta particles are high-energy, high-speed electrons or positrons emitted by certain radioactive nuclei such as potassium-40. The beta particles have a greater range of penetration than alpha particles but still much less than gamma rays. The beta particles emitted are a form of ionizing radiation, also known as beta rays. The production of beta particles is termed beta decay.

One of the examples of beta decay is the β– decay of the carbon atom. Here, a neutron of carbon is converted into a proton, and the emitted beta particle is an electron. Similarly, the β+ decay of carbon-10 can be represented by an equation as follows:

$$^{10}_{6}\mathrm{C} \rightarrow {}^{10}_{5}\mathrm{B} + {}^{0}_{1}\mathrm{e}^{+}$$

Here, the proton of the carbon atom is converted into a neutron, and the emitted beta particle is a positron.

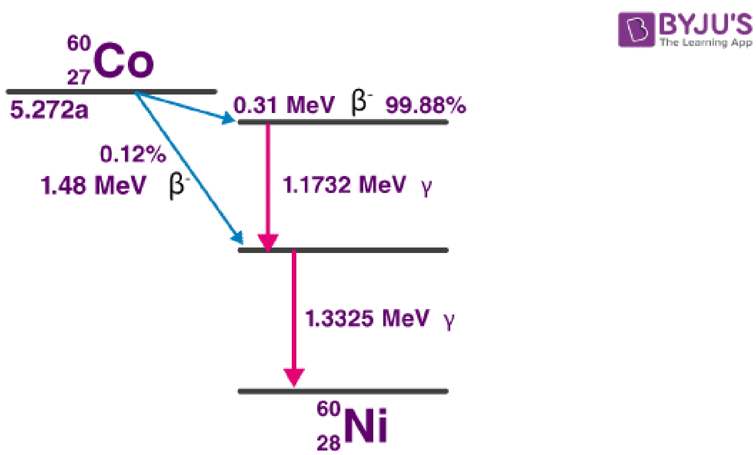
The below image depicts the example of beta minus (β–) decay and beta plus (β+) decay.



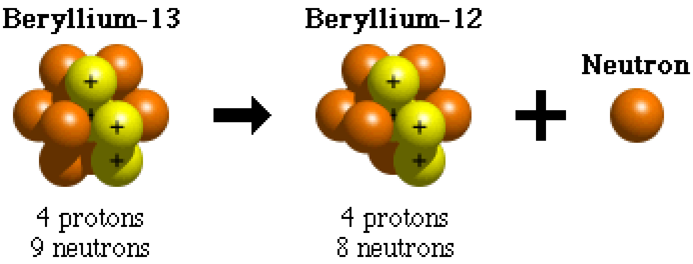
Gamma radioactivity: Gamma rays are electromagnetic radiation of a very high frequency and are therefore high-energy photons. Nuclei decay produces them as they transition from a high-energy state to a lower state known as gamma decay. Gamma emissions accompany most nuclear reactions.

$$^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + e^- + \nu + \gamma + 1.17\ MeV$$

$$^{60}_{28}Ni^* \rightarrow {}^{60}_{28}Ni + \gamma + 1.33\ MeV$$

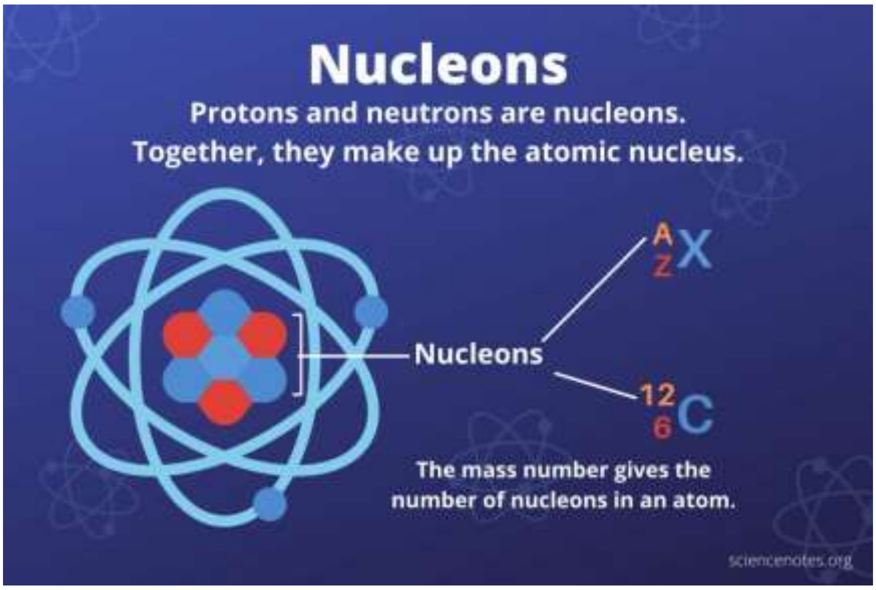


Neutron emission: Neutron emission is a type of radioactive decay of nuclei containing excess neutrons (especially fission products), in which a neutron is ejected from the nucleus. This type of radiation plays a key role in nuclear reactor control because these neutrons are delayed neutrons.



Conservation Laws in Nuclear Reactions

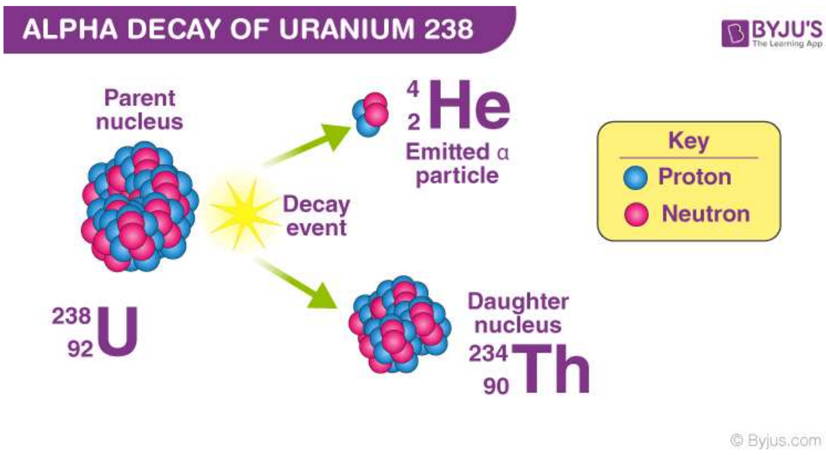
1. Conservation of nucleons: The total number of nucleons before and after a reaction are the same. This is an important law which is readily observed during any decay is the law of conservation of nucleon number. This means that the reactants and the products of any radioactive decay always have the same number of nucleons (protons plus neutrons).



2. **Conservation of charge:** The sum of the charges on all the particles before and after a reaction are the same.

Uranium-238 decays into thorium-234. The numbers after the element's symbol are the mass numbers, and notice that 238 and 234 are not equal. 4 AMU are missing. We can account for this mass because U-238 undergoes alpha decay, and a nuclear equation shows how the mass and electrical charge is conserved.

$$^{238}_{92}\mathrm{U} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{234}_{90}\mathrm{Th}$$

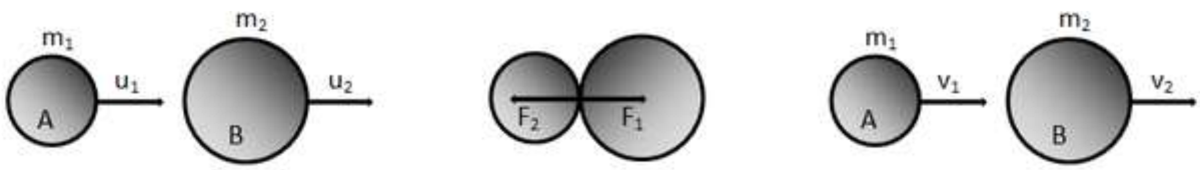


3. **Conservation of momentum:** The total momentum of the interacting particles before and after a reaction is the same.

The law of conservation of linear momentum states that if no external forces act on the system of two colliding objects, then the vector sum of the linear momentum of each body remains constant and is not affected by their mutual interaction.

Let us consider an isolated system of n particles having initial momentum p1, p2 ... pn. Due to the collision, let the momentum of the particles after collision be p1', p2' ... pn' respectively. Then according to the principle of conservation of linear momentum, in the absence of external force,

$$p1 + p2 + ... + pn = p1' + p2' + ... + pn'$$



To prove this principle, we consider a collision between two spheres A and B having masses of m1 and m2 respectively. Let u1 and u2 be the velocities of the spheres before collision such that u1 > u2 and moving on the same straight line as shown in the figure. After collision, let their velocities be v1 and v2 on the same line. If they collide with each other for a short time interval t, each sphere exerts a force on the other sphere and so, the force experienced by A is given as

$$F_2 = \frac{\text{change in momentum}}{\text{time}} = \frac{m_1 v_1 - m_1 u_1}{t}$$

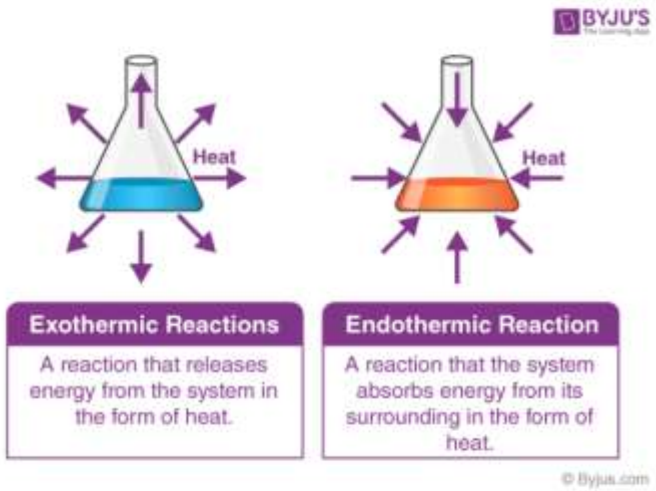
Similarly, force experienced by B is

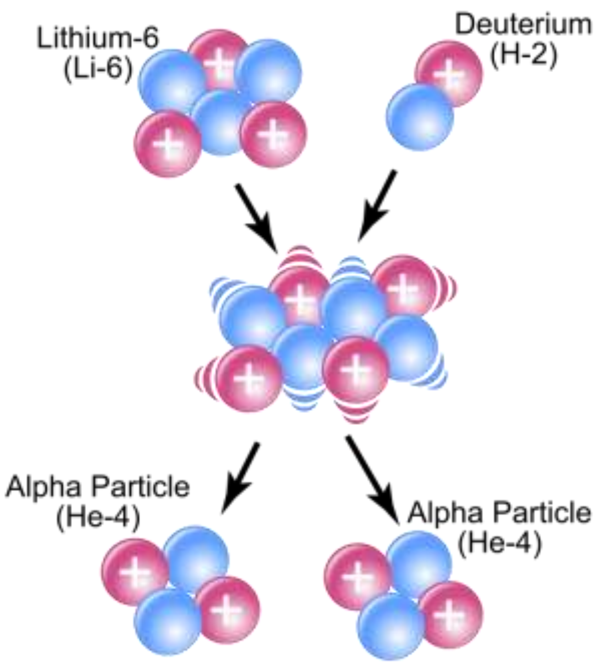
$$F_1 = \frac{\text{change in momentum}}{\text{time}} = \frac{m_2 v_2 - m_2 u_2}{t}$$

According to Newton's third law of motion, the force experienced by A and B are equal and opposite, or, That is, total momentum before collision is equal to total momentum after collision if no external forces act on them which proves the principle of conservation of linear momentum.

4. **Conservation of energy:** Energy, including rest mass energy, is conserved in nuclear reactions.

Note that kinetic energy may be released during the course of a reaction (exothermic reaction) or kinetic energy may have to be supplied for the reaction to take place (endothermic reaction).





Lithium-6 – Deuterium Reaction

This can be calculated by reference to a table of very accurate particle rest masses, the ${}^{6}_{3}Li$ nucleus has a standard atomic weight of 6.015 atomic mass units (abbreviated u), the deuterium has 2.014 u, and the helium-4 nucleus has 4.0026 u. Thus:

- the sum of the rest mass of the individual nuclei = 6.015 + 2.014 = 8.029 u;
- the total rest mass on the two helium-nuclei = 2 × 4.0026 = 8.0052 u;
- missing rest mass = 8.029 – 8.0052 = 0.0238 atomic mass units.

In a nuclear reaction, the total (relativistic) energy is conserved. The "missing" rest mass must therefore reappear as kinetic energy released in the reaction; its source is the nuclear binding energy. Using Einstein's mass-energy equivalence formula $E = mc^2$, the amount of energy released can be determined. We first need the energy equivalent of one atomic mass unit:

$1 \text{ u } c^2 = (1.66054 \times 10^{-27} \text{ kg}) \times (2.99792 \times 10^{8} \text{ m/s})^2$

$= 1.49242 \times 10^{-10} \text{ kg (m/s)}^2 = 1.49242 \times 10^{-10} \text{ J (joule)} \times (1 \text{ MeV} / 1.60218 \times 10^{-13} \text{ J})$

$= 931.49 \text{ MeV}$,

so $1 \text{ u } c^2 = 931.49 \text{ MeV}$.

Hence, the energy released is 0.0238 × 931 MeV = 22.2 MeV.

Expressed differently: the mass is reduced by 0.3%, corresponding to 0.3% of 90 petajoule(PJ)/kg is 270 terajoule(TJ)/kg.

This is a large amount of energy for a nuclear reaction; the amount is so high because the binding energy per nucleon of the helium-4 nucleus is unusually high because the He-4 nucleus is "doubly magic". (The He-4 nucleus is unusually stable and tightly bound for the same reason that the helium atom is inert: each pair of protons and neutrons in He-4 occupies a filled **1s** nuclear orbital in the same way that the pair of electrons in the helium atom occupy a filled **1s** electron orbital). Consequently, alpha particles appear frequently on the right-hand side of nuclear reactions.

The energy released in a nuclear reaction can appear mainly in one of three ways:

- kinetic energy of the product particles (fraction of the kinetic energy of the charged nuclear reaction products can be directly converted into electrostatic energy);
- emission of very high energy photons, called gamma rays;
- some energy may remain in the nucleus, as a metastable energy level.

When the product nucleus is metastable, this is indicated by placing an asterisk ("*") next to its atomic number. This energy is eventually released through nuclear decay. A small amount of energy may also emerge in the form of X-rays. Generally, the product nucleus has a different atomic number, and thus the configuration of its electron shells is wrong. As the electrons rearrange themselves and drop to lower energy levels, internal transition X-rays (X-rays with precisely defined emission lines) may be emitted.

Q-value of nuclear reaction

In nuclear and particle physics, the energetics of nuclear reactions are determined by the reaction's Q-value. The Q-value of the reaction is defined as the difference between the sum of the masses of the initial reactants and the sum of the masses of the final products in energy units (usually in MeV).

Consider a typical reaction in which the projectile a and target A place to two products, B and b. This can also be expressed in the notation we have used so far, a + A → B + b, or even in a more compact notation, A(a,b)B.

The Q-value of this reaction is given by:

$$Q = [m_a + m_A - (m_b + m_B)]c^2$$

which is the same as the excess kinetic energy of the final products:

$$Q = T_{final} - T_{initial}$$
$$= T_b + T_B - (T_a + T_A)$$

For reactions in which there is an increase in the kinetic energy of the products, Q is positive. The positive Q reactions are said to be exothermic (or exergic). There is a net release of energy since the kinetic energy of the final state is greater than the kinetic energy of the initial state.

For reactions in which there is a decrease in the kinetic energy of the product, Q is negative. The negative Q reactions are endothermic (or endoergic), and they require net energy input.

The energy released in a nuclear reaction can appear mainly in one of three ways:

- The kinetic energy of the products.
- Emission of gamma rays. Gamma rays are emitted by unstable nuclei in their transition from a high-energy state to a lower state known as gamma decay.
- Metastable state. Some energy may remain in the nucleus as a metastable energy level.

A small amount of energy may also emerge in the form of X-rays. Generally, products of nuclear reactions may have different atomic numbers, and thus the configuration of their electron shells is different in comparison with reactants. As the electrons rearrange themselves and drop to lower energy levels, internal transition X-rays (X-rays with precisely defined emission lines) may be emitted.

Atomic Mass Unit

An atomic mass unit is defined as accurately 1/12 the mass of a carbon-12 atom. The carbon-12 atom has six neutrons and six protons in its nucleus. It is represented as a.m.u or u (unified). It is a unit of mass used to express atomic masses. 1 a.m.u is the average of the proton rest mass and the neutron rest mass.

$$m_u = \frac{m(^{12}\mathrm{C})}{12} = 1\ \mathrm{Da}.$$

The formula used for conversion is:

$$1\ \mathrm{Da} = m_u = \frac{M_u}{N_A} = \frac{M(^{12}C)}{12\ N_A} = 1.660\ 539\ 066\ 60(50) \times 10^{-27}\ \mathrm{kg},$$

where M_u is the molar mass constant, N_A is the Avogadro constant,[4] and $M(^{12}\mathrm{C})$ is the experimentally determined molar mass of carbon-12.[5]

Cross-section

- What is cross section?

In general, the cross-section is an effective area that quantifies the likelihood of certain interactions between an incident object and a target object. The cross-section of a particle is the same as the cross-section of a hard object if the probabilities of hitting them with a ray are the same.

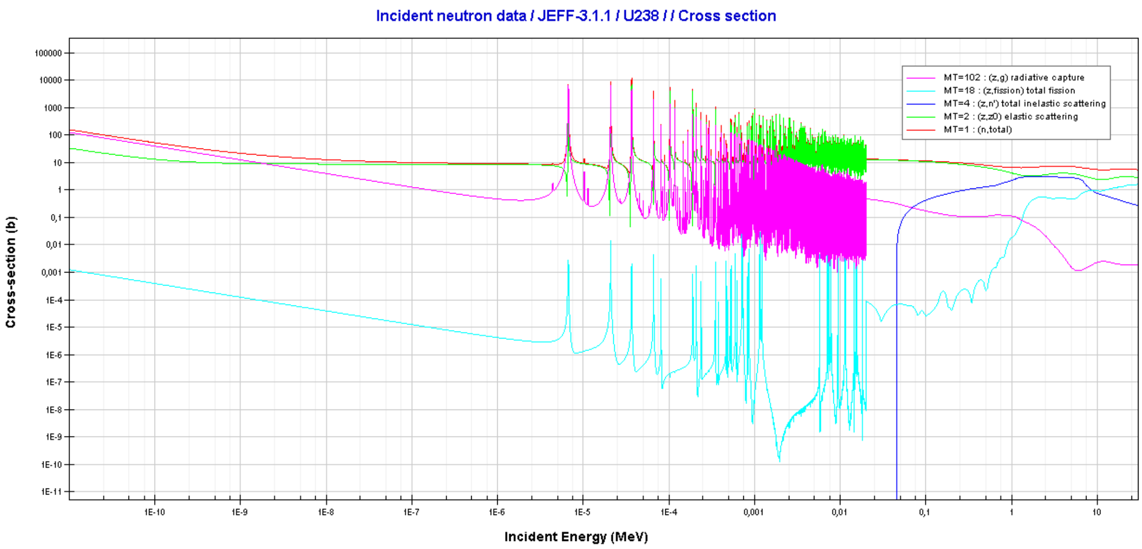
For a given event, the cross-section **σ** is given by

$$\boldsymbol{\sigma = \mu / n}$$

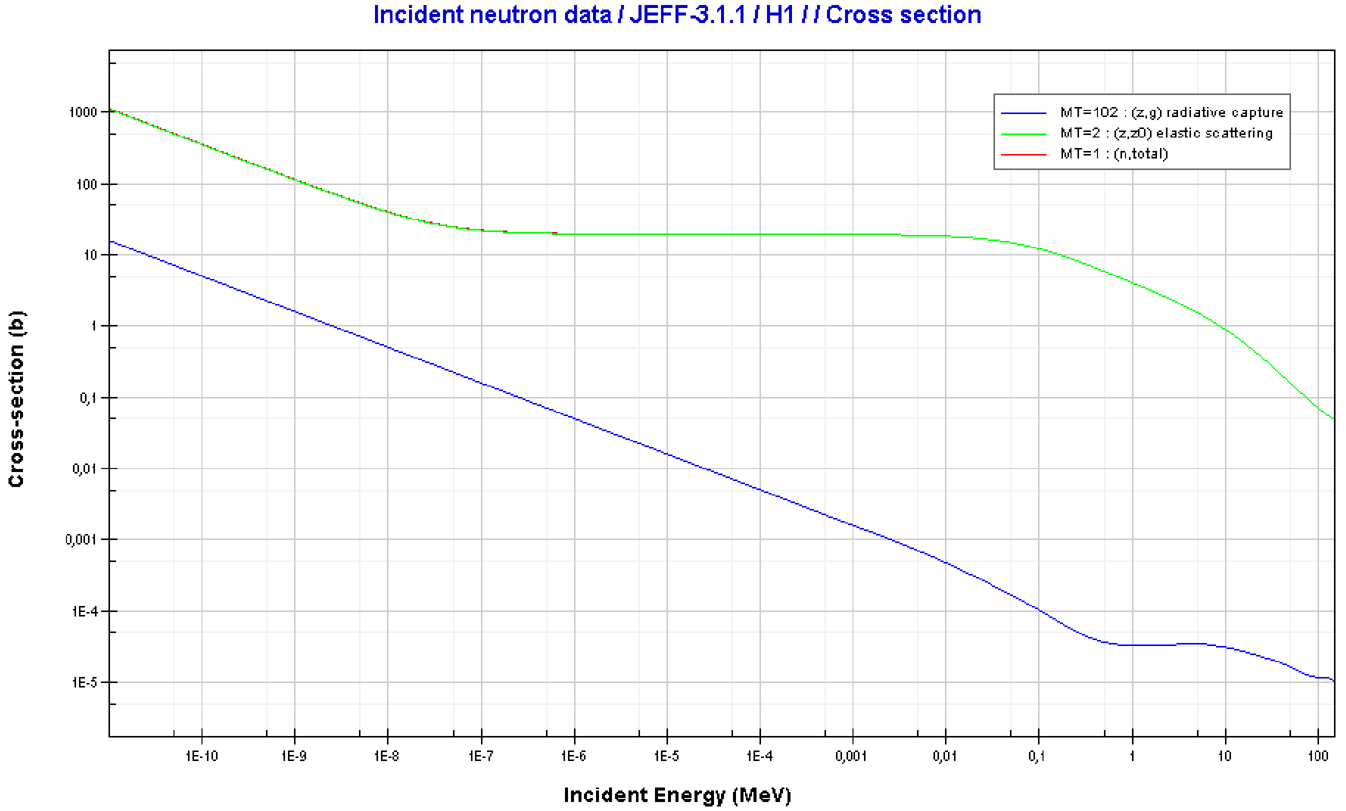
where

- **σ** is the cross-section of this event [m²],
- **μ** is the attenuation coefficient due to the occurrence of this event [m⁻¹],
- **n** is the density of the target particles [m⁻³].

In nuclear physics, the nuclear cross section of a nucleus is commonly used to characterize the **probability** that a nuclear reaction will occur. The cross-section is typically denoted **σ** and measured in units of area [m²]. The standard unit for measuring a nuclear cross section is the **barn**, which is equal to **10^{-28} m² or 10^{-24} cm²**. It can be seen the concept of a nuclear cross section can be quantified physically in terms of **"characteristic target area"** where a larger area means a larger probability of interaction.



Uranium 238. Comparison of cross-sections.



Hydrogen. Neutron absorption and scattering. Comparison of cross-sections.

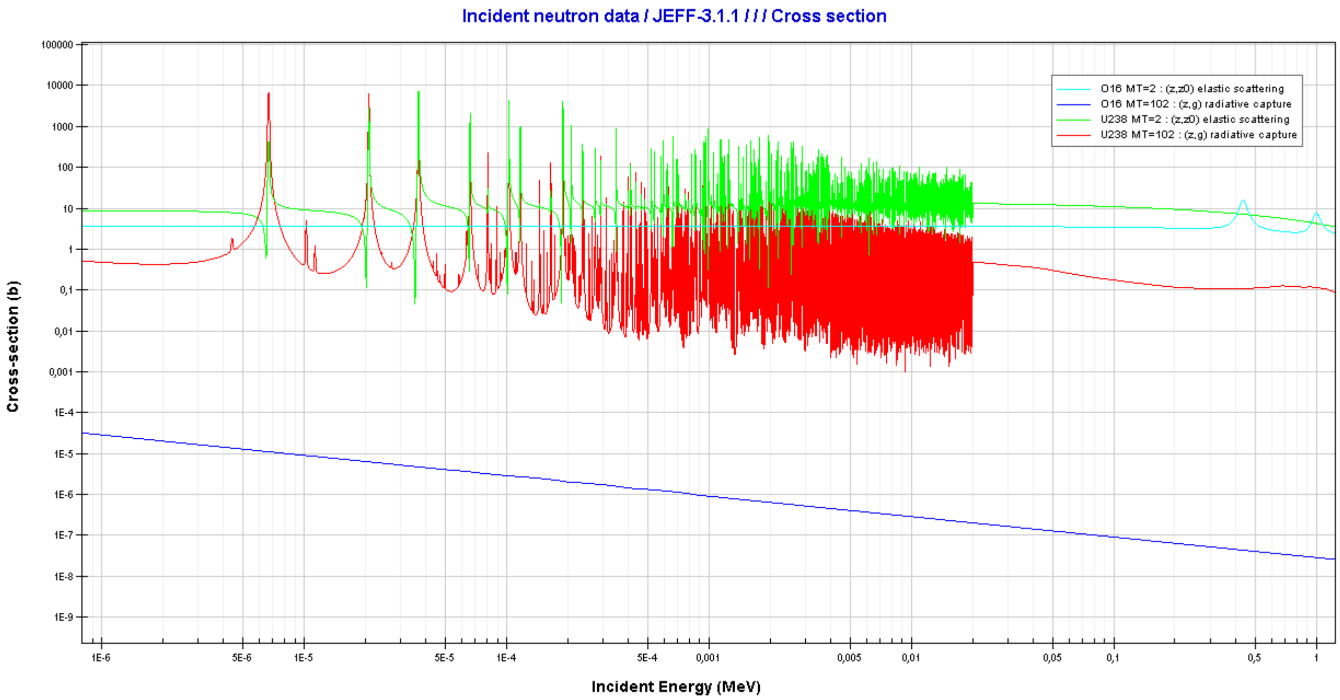
		Thermal neutron			Fast neutron		
		Scattering	Capture	Fission	Scattering	Capture	Fission
Moderator	H-1	20	0.2	-	4	0.00004	-
	H-2	4	0.0003	-	3	0.000007	-
	C-12	5	0.002	-	2	0.00001	-
Structural materials, others	Zr-90	5	0.006	-	5	0.006	-
	Fe-56	10	2	-	20	0.003	-
	Cr-52	3	0.5	-	3	0.002	-
	Ni-58	20	3	-	3	0.008	-
	O-16	4	0.0001	-	3	0.00000003	-
Absorber	B-10	2	200	-	2	0.4	-
	Cd-113	100	30	-	4	0.05	-
	Xe-135	400	2,000,000	-	5	0.0008	-
	In-115	2	100	-	4	0.02	-
Fuel	U-235	10	99	583	4	0.09	1
	U-238	9	2	0.00002	5	0.07	0.3
	Pu-239	8	269	748	5	0.05	2

Table of cross-sections

Neutron Capture Cross-section

The radiative capture cross-section represents the likelihood of a neutron radiative capture as σ_γ. As usual, the cross-section can be divided into three regions according to the incident neutron energy.

- **1/v Region**
- **Resonance Region**
- **Fast Neutrons Region**



Radiative capture and elastic scattering cross-sections in ^{16}O and ^{238}U

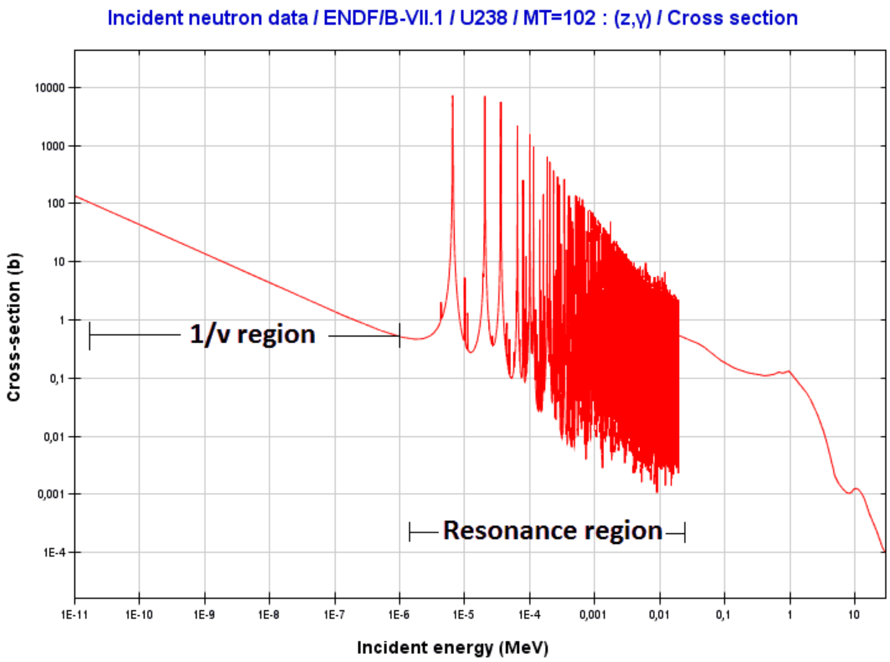
1/v Region

In the common case, the cross-section is usually **much larger at low energies** than at high energies. For thermal neutrons (in 1/v region), radiative capture cross-sections also increase as the neutron's velocity (kinetic energy) decreases. Therefore the 1/v Law can be used to determine a shift in capture cross-section if the neutron is in equilibrium with a surrounding medium. This phenomenon is because the nuclear force between the target nucleus and the neutron has a longer time to interact.

Resonance Region

The largest cross-sections are usually at neutron energies that lead to long-lived states of the compound nucleus. The compound nuclei of these certain energies are called **nuclear resonances,** and their formation is typical **in the resonance region**. The widths of the resonances increase in general with increasing energies. At higher energies, the widths may reach the order of the distances between resonances, and then no resonances can be observed. The narrowest resonances are usually compound states of heavy nuclei (such as fissionable nuclei).

Since the **mode of decay** of the compound nucleus **does not depend on the way the compound nucleus was formed**, the nucleus sometimes emits a gamma-ray (radiative capture) or sometimes emits a neutron (scattering). To understand how a nucleus will stabilize itself, we have to understand the behavior of the compound nucleus.



Radiative Capture Cross-section – region of resonances of 238U nuclei.

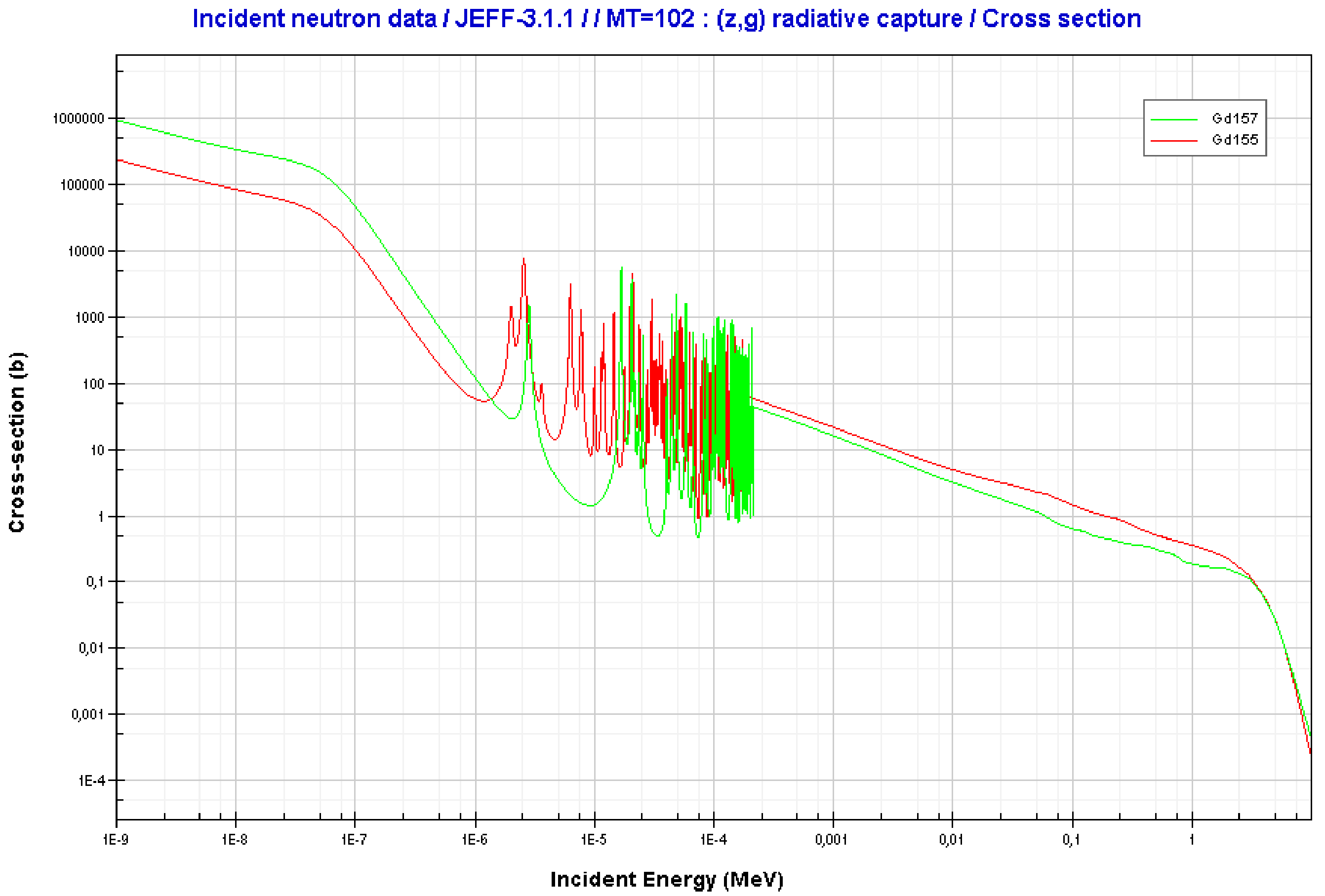
The compound nucleus emits a neutron only after one neutron obtains energy in collision with another nucleon greater than its binding energy in the nucleus. It has some delay because the excitation energy of the compound nucleus **is divided** among several nucleons. The average time that elapses before a neutron can be emitted is much longer for nuclei **with many nucleons** than when only a few nucleons are involved. It is a consequence of sharing the excitation energy among a large number of nucleons.

This is why the **radiative capture** is comparatively **unimportant in light nuclei** but becomes increasingly **important in heavier nuclei**.

The lifetime of a compound nucleus is inversely proportional to its total width. **Narrow resonances,** therefore, correspond to capture, while the wider resonances are due to scattering.

Fast Neutrons Region

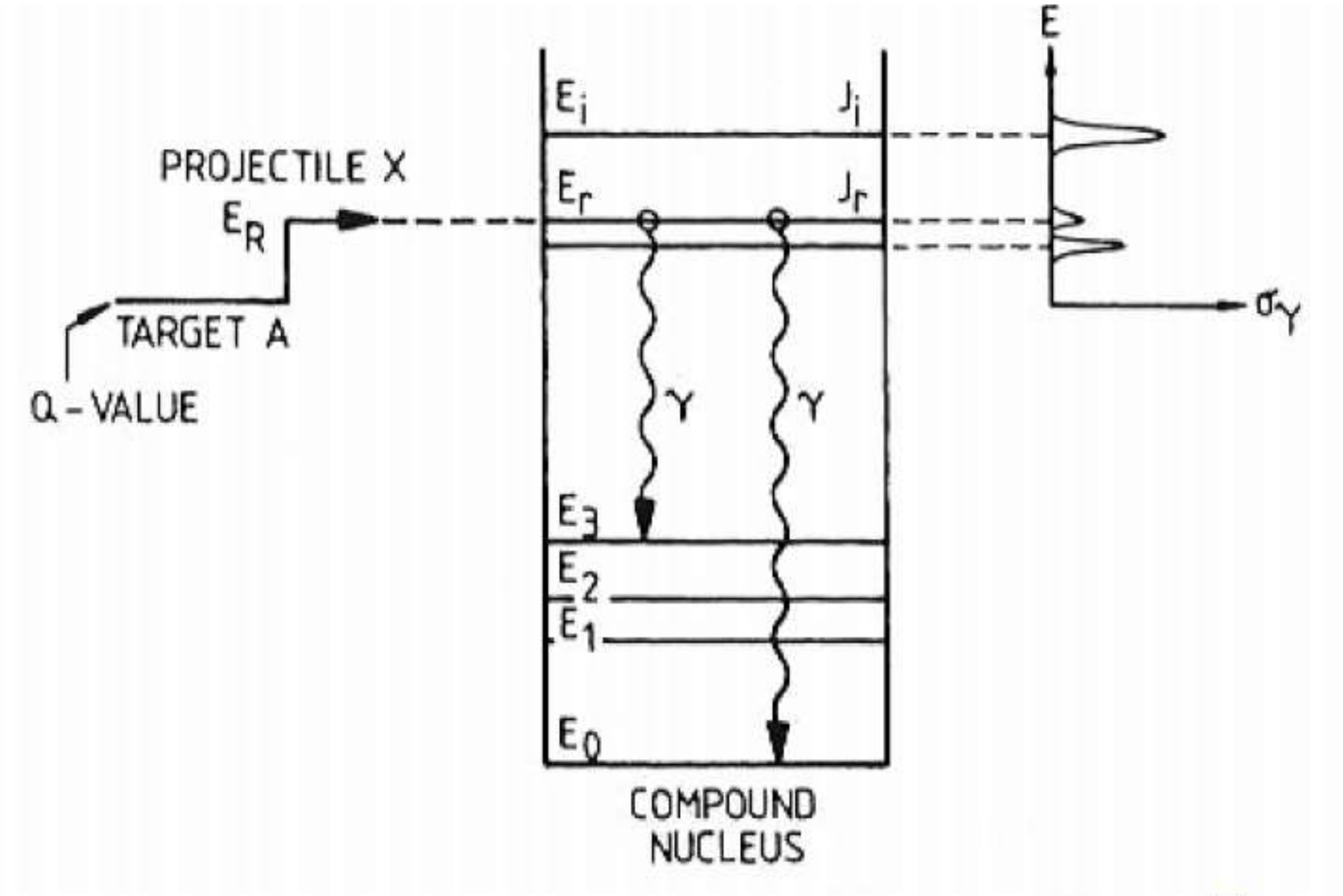
The radiative capture cross-section at energies above the resonance region **drops rapidly** to very small values. This rapid drop is caused by the compound nucleus, which is formed in more highly excited states. In these **highly excited states,** it is more likely that one neutron obtains **energy** in collision with another nucleon **greater than its binding energy** in the nucleus. **The neutron emission becomes dominant,** and gamma decay becomes less important. Moreover, at high energies, the inelastic scattering and **(n,2n) reaction** are highly probable at the expense of both elastic scattering and radiative capture.



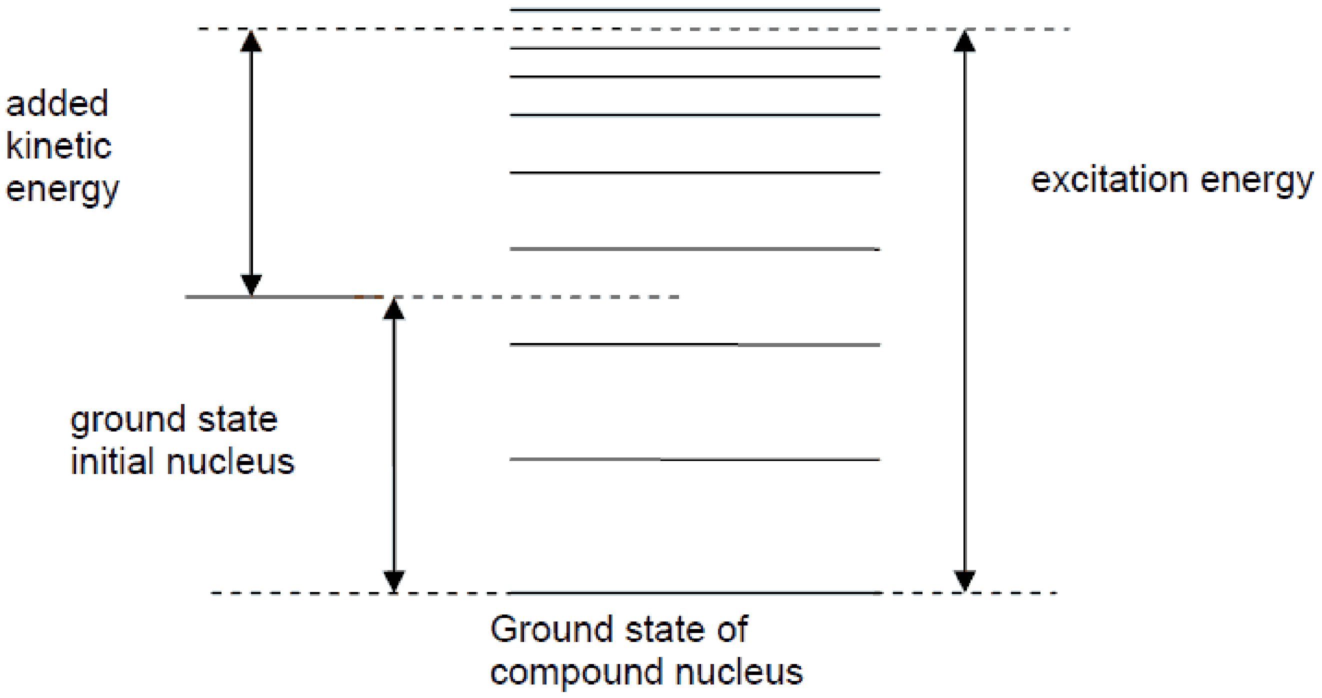
Gadolinium 155 and 157. Comparison of radiative capture cross-sections.

Example

The first resonance in ^{238}U **at 6.67 eV**, which corresponds to the first **virtual level in ^{239}U**, has a total width of only 0.027 eV, and the mean life of this state is 2.4×10^{-14} s. By contrast, the resonance observed at **443 keV in ^{16}O**, which corresponds to the first virtual state in ^{17}O, has a total width of 41 keV, giving a mean lifetime of 1.5×10^{-21} s. Thus it is highly likely that **the compound state in ^{239}U** decays at least to some extent **by gamma-ray emission**, while **the compound state in ^{17}O** must decay primarily **by nucleon emission**. The 443-keV resonance in ^{16}O is clearly a scattering resonance, whereas the 6.67-eV resonance in ^{238}U is in part a capture resonance.



Energy levels of the compound state. For neutron absorption reaction on 238U, the first resonance E1 corresponds to the excitation energy of 6.67eV. E0 is a base state of 239U.



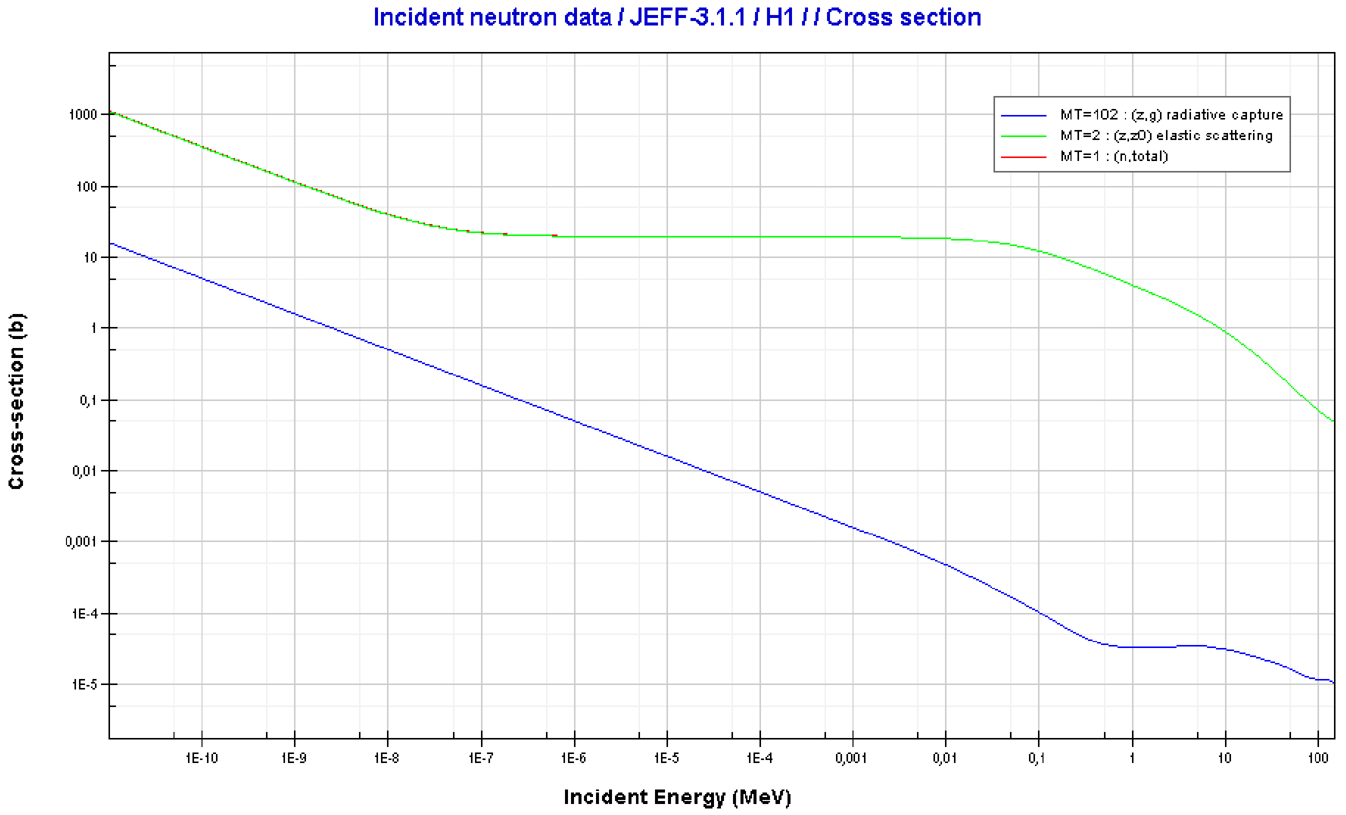
Energy levels of compound state. For neutron absorption reaction on 238U the first resonance E1 corresponds to the excitation energy of 6.67eV. E0 is a base state of 239U.

Neutron Absorption Cross-section

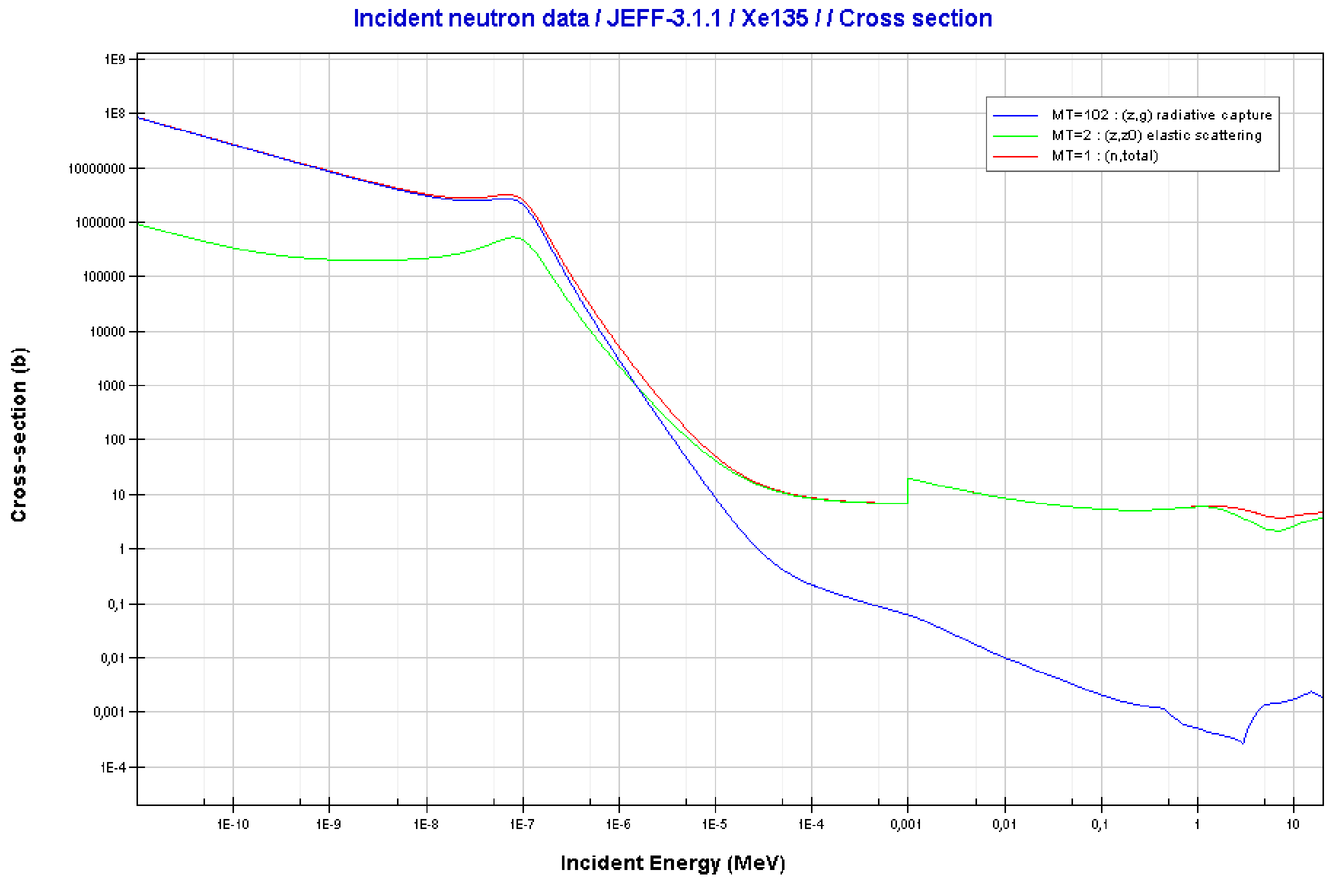
The **absorption cross-section** represents the likelihood of a neutron absorption as $\boldsymbol{\sigma_a}$. The relative likelihoods of an absorption reaction or a neutron scattering are represented by dividing the total cross-section into scattering and absorption cross-sections:

$$\boldsymbol{\sigma_t = \sigma_s + \sigma_a}$$

Given a collision, $\boldsymbol{\sigma_a / \sigma_t}$ is the probability that the neutron will be absorbed and $\boldsymbol{\sigma_s} / \boldsymbol{\sigma_t}$ is the probability that the neutron will be scattered.



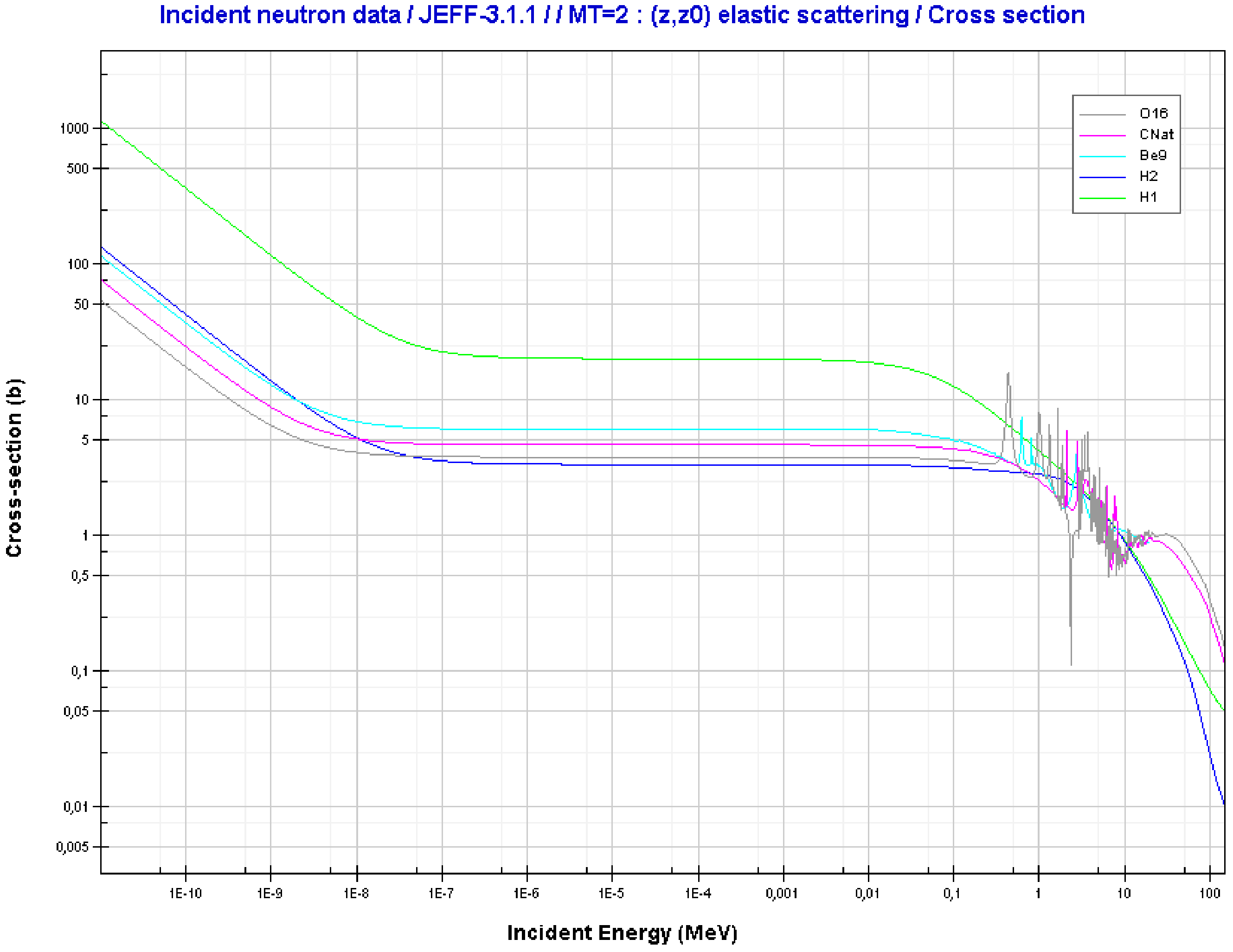
Hydrogen. Neutron absorption and scattering. Comparison of cross-sections.



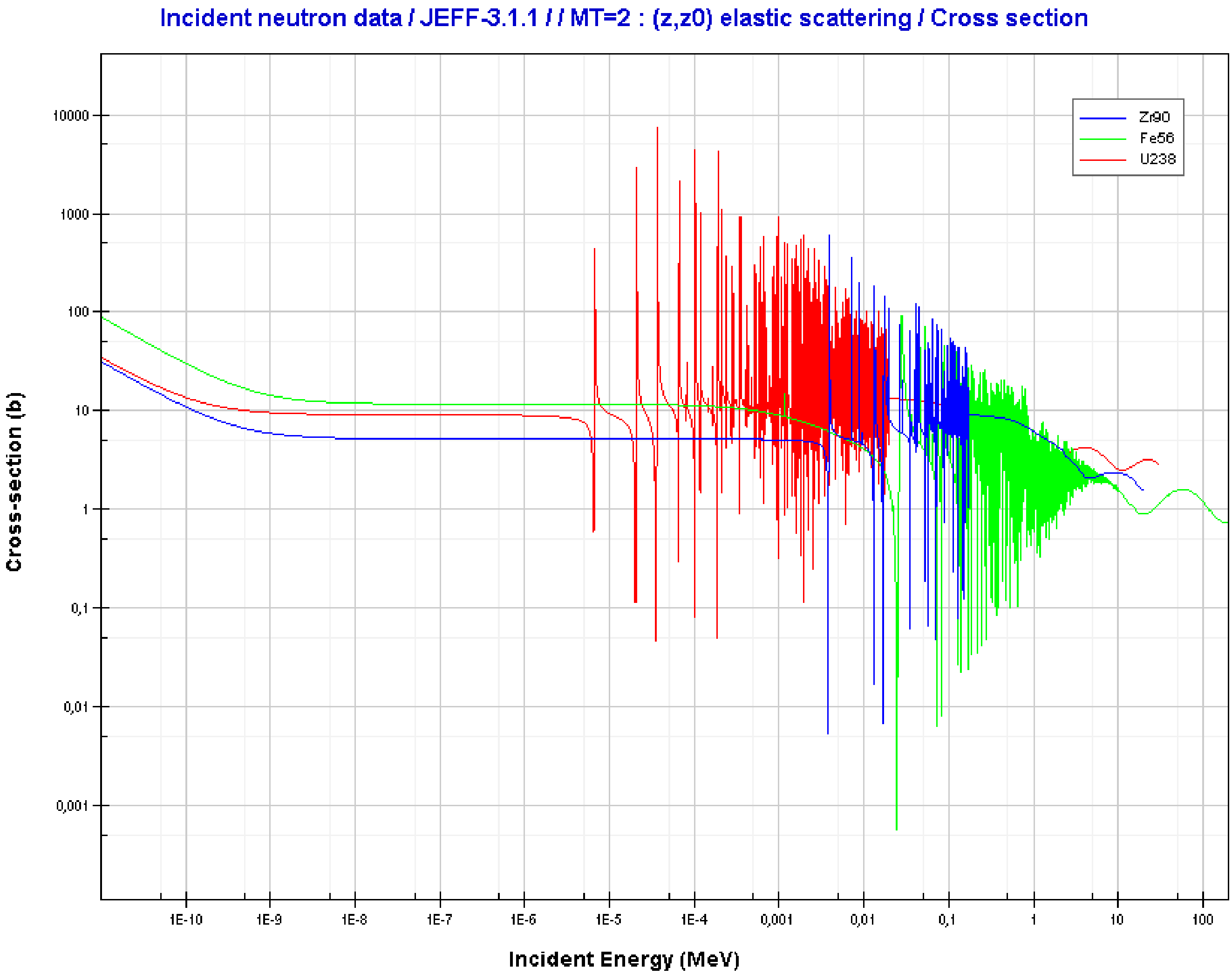
Xenon – 135. Neutron absorption and scattering. Comparison of cross-sections.

Elastic Scattering Cross-section

To be **an effective moderator**, the probability of elastic reaction between neutron and the nucleus must be high. In terms of cross-sections, the elastic scattering cross section (σs) of a moderator's nucleus must be high.



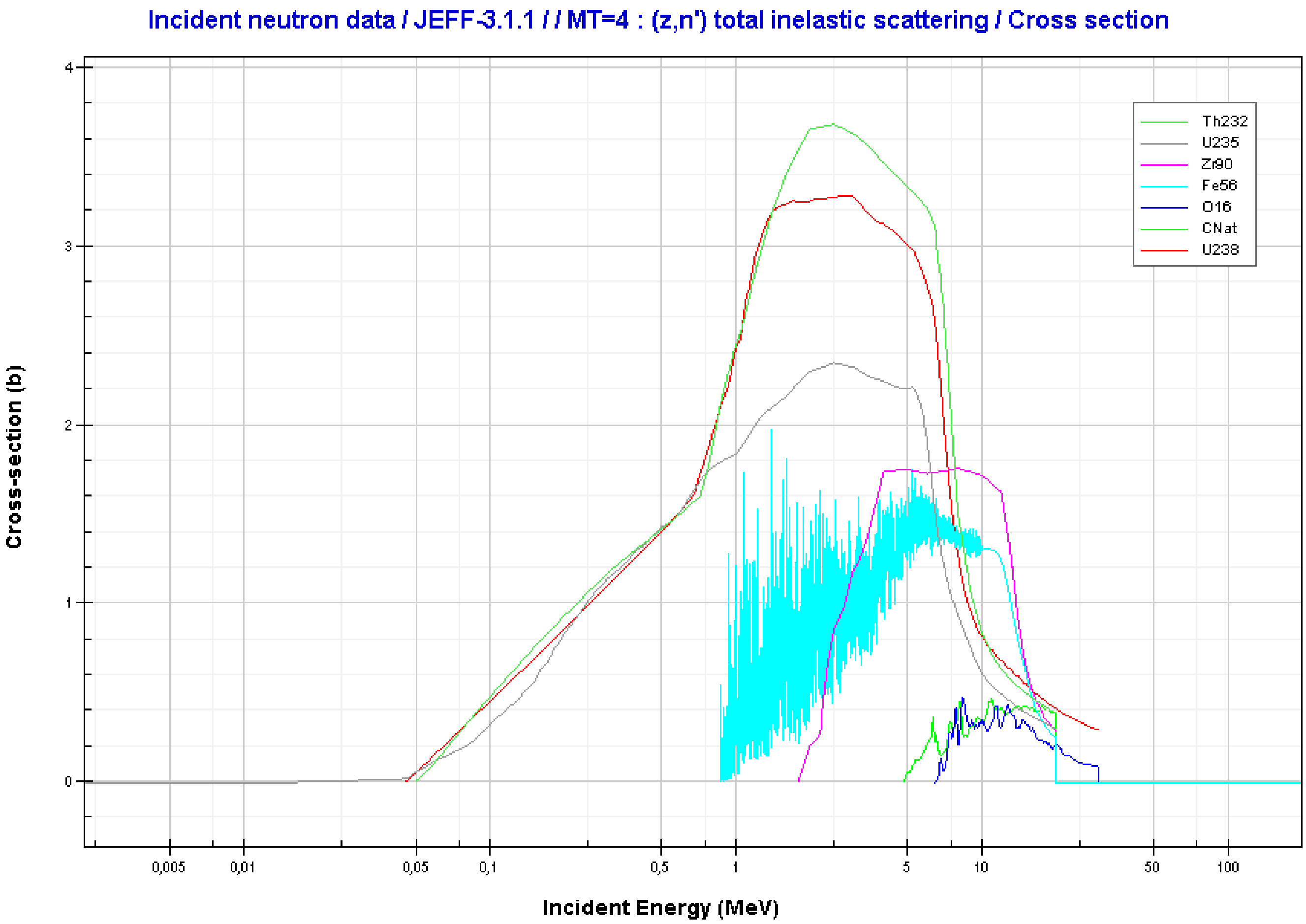
Elastic scattering cross-sections for light elements are more or less independent of neutron energy up to 1 MeV.



For intermediate and heavy elements, the elastic cross-section is constant at low energy with some specifics at higher energy.

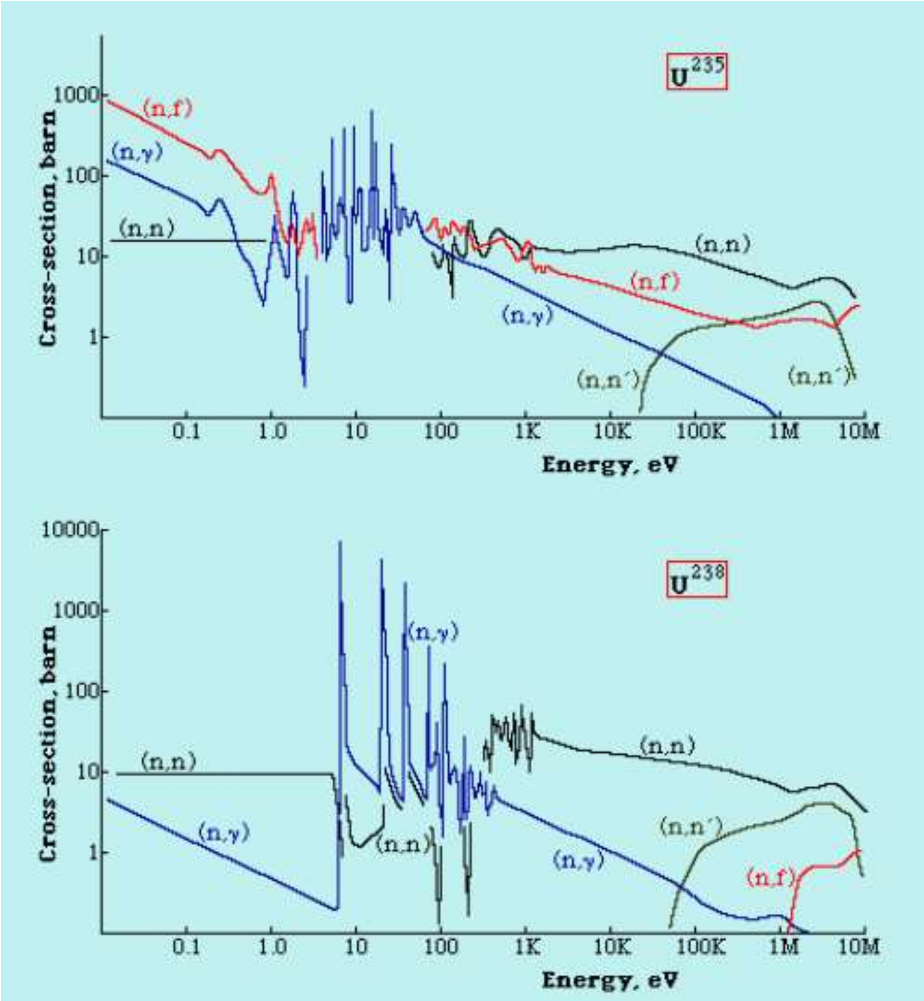
Inelastic Scattering Cross-section

Inelastic scattering plays an important role in slowing down neutrons, especially at high energies and heavy nuclei.



Fission Cross-section

^{235}U will fission (n, f) at all energies of the absorbed neutron. It is a Fissile Material. Note the 1/v behavior of fission cross section at low velocities, typical of exothermal processes. ^{235}U fission cross section can grow Very large, to 500 barns sat thermal energies. ^{238}U has a threshold for fission (n, f) at a neutron energy of 1 MeV. This effectively prevents fission from occurring in ^{238}U. There is very strong resonant capture of neutrons (n, γ) for energies in the range 10-100 eV - particularly in the case of ^{238}U where the cross-section reaches very high values.



Total Cross-section

In general, **nuclear cross-sections** can be measured for all possible interaction processes together. In this case they are called **total cross-sections (σ_t)**. The total cross-section is the sum of all the partial cross-sections such as:

- elastic scattering cross-section (σ_s)
- inelastic scattering cross-section (σ_i)
- absorption cross-section (σ_a)
- radiative capture cross-section (σ_γ)
- fission cross-section (σ_f)

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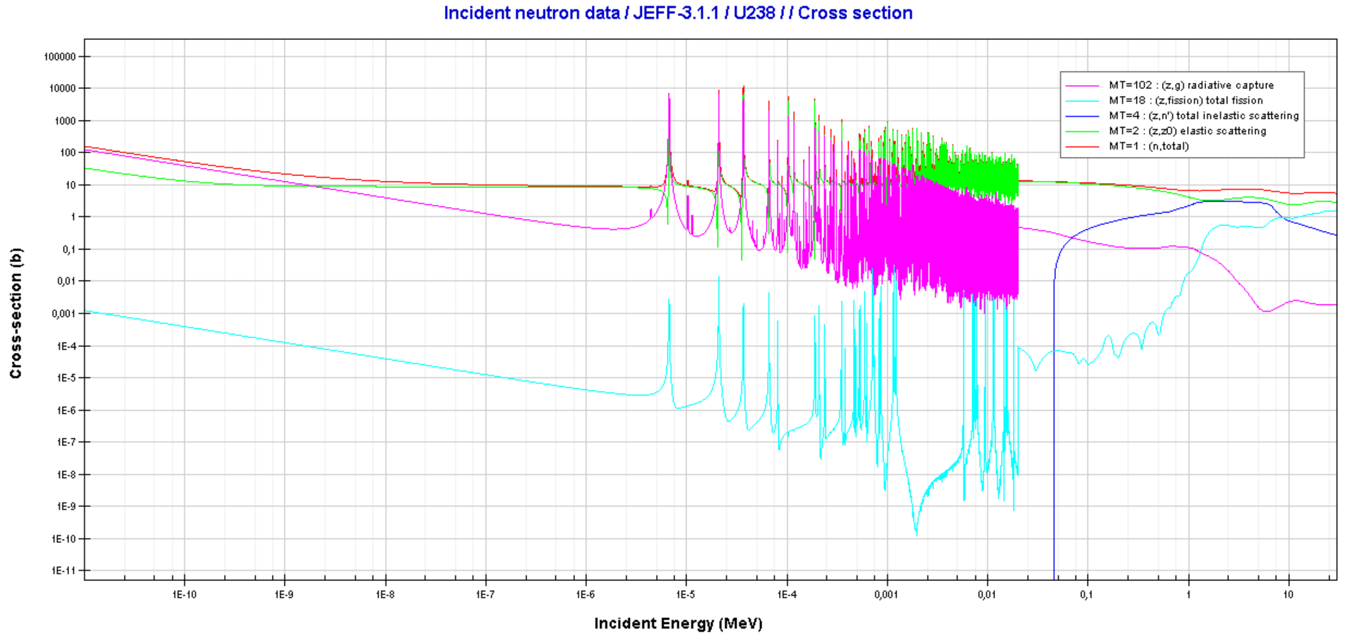
$$\boldsymbol{\sigma_t = \sigma_s + \sigma_i + \sigma_\gamma + \sigma_f + \ldots\ldots}$$

The total cross-section measures the probability that an interaction of any type will occur when neutron interacts with a target.



Uranium 238. Comparison of cross-sections

Cross-sections of Uranium

Naturally-occurring Isotopes of Uranium

The main **naturally-occurring isotopes**, which have to be considered in the fuel cycle of all commercial light water reactors, are:

- **^{238}U**. ^{238}U belongs to the group of fertile isotopes.
- **^{235}U**. ^{235}U belongs to the group of fissile isotopes. ^{235}U is the only existing fissile nucleus from naturally occurring isotopes, and therefore it is a highly strategic material.
- **^{234}U**. ^{234}U belongs to the group of fertile isotopes.

Artificial Isotopes of Uranium

The main **artificial isotopes**, which have to be considered in the fuel cycle of all commercial light water reactors, are:

- **^{233}U**. ^{233}U belongs to the group of fissile isotopes. It is produced by radiative neutron capture in nuclear reactors containing thorium fuel. [2]
- **^{236}U**. ^{236}U is neither a fissile isotope nor a fertile isotope. ^{236}U is fissionable only by fast neutrons. Isotope ^{236}U is formed in a nuclear reactor from fissile isotope ^{235}U.
- **^{232}U**. ^{232}U belongs to the group of fertile isotopes. ^{232}U is a side product in the thorium fuel cycle, and also this isotope is a decay product of ^{236}Pu in the uranium fuel.

Fertile material

Fertile material is a material that, although not fissile itself, can be converted into a fissile material by neutron absorption.

Naturally occurring fertile materials that can be converted into a fissile material by irradiation in a reactor include:

- thorium-232 which converts into uranium-233
- uranium-234 which converts into uranium-235
- uranium-238 which converts into plutonium-239

Artificial isotopes formed in the reactor which can be converted into fissile material by one neutron capture include:

- plutonium-238 which converts into plutonium-239
- plutonium-240 which converts into plutonium-241

Fissile material

In nuclear engineering, **fissile material** is material capable of sustaining a nuclear fission chain reaction. By definition, fissile material can sustain a chain reaction with neutrons of therma energy. The predominant neutron energy may be typified by either slow neutrons (i.e., a thermal system) or fast neutrons. Fissile material can be used to fuel thermal-neutron reactors, fast-neutron reactors and nuclear explosives.

Fissile nuclides in nuclear fuels include:

- Uranium-233 bred from thorium-232 by neutron capture with intermediate decays steps omitted.
- Uranium-235 which occurs in natural uranium and enriched uranium
- Plutonium-239 bred from uranium-238 by neutron capture with intermediate decays steps omitted.
- Plutonium-241 bred from plutonium-240 directly by neutron capture.

Compound Nucleus Reactions

The compound nucleus is the intermediate state formed in a compound nucleus reaction. It is normally one of the excited states of the nucleus formed by the combination of the incident particle and target nucleus. The compound nucleus is excited by both the kinetic energy of the projectile and by the binding nuclear energy.

To understand the nature of nuclear reactions, the classification according to the time scale of these reactions has to be introduced. Interaction time is critical for defining the reaction mechanism.

There are two extreme scenarios for nuclear reactions (not only neutron nuclear reactions):

- A projectile and a target nucleus are within the range of nuclear forces for a very short time allowing for an interaction of a single nucleon only. These types of reactions are called direct nuclear reactions.
- A projectile and a target nucleus are within the range of nuclear forces, allowing for a large number of interactions between nucleons. These types of reactions are called the compound nucleus reactions.

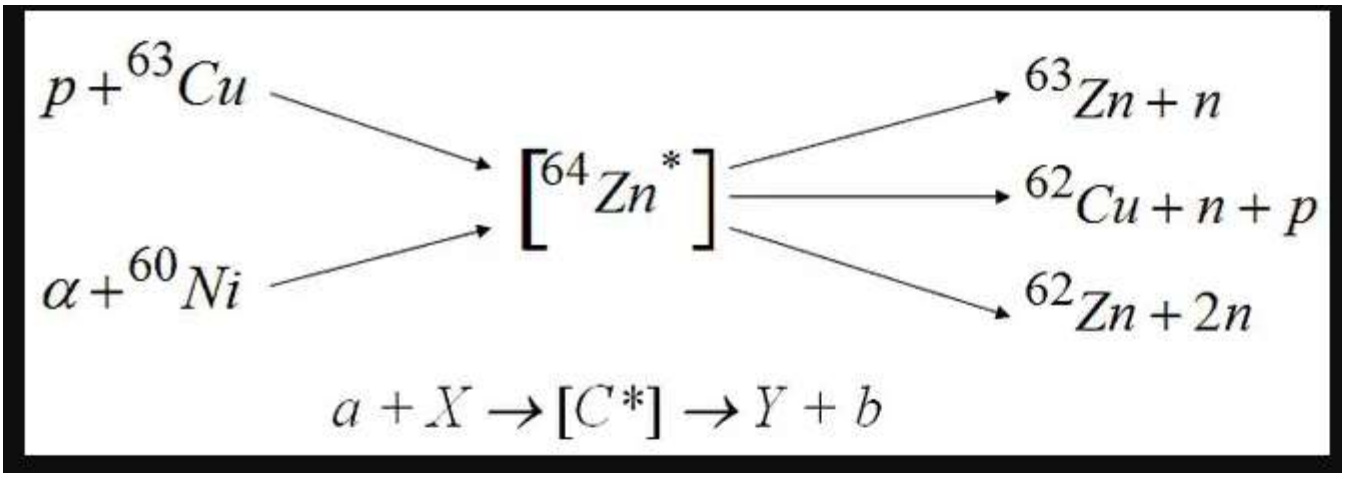
There is always some **non-direct** (multiple internuclear interactions) component in all reactions, but the direct reactions have this component limited.

What is the Compound Nucleus and the Nuclear Resonance?

There is no difference between the compound nucleus and the nuclear resonance.

The compound nucleus is the intermediate state formed in a compound nucleus reaction. It is normally one of the excited states of the nucleus formed by the combination of the incident particle and target nucleus. Suppose a target nucleus X is bombarded with particles a. In that case, it is sometimes observed that the ensuing nuclear reaction occurs with appreciable probability only if the particle’s energy is in the neighborhood of certain definite energy values. These energy values are referred to as resonance energies. The compound nuclei of these certain energies are referred to as nuclear resonances. Resonances are usually found only at relatively low energies of the projectile. The widths of the resonances increase in general with increasing energies. At higher energies, the widths may reach the order of the distances between resonances, and then no resonances can be observed. The narrowest resonances are usually the compound states of heavy nuclei (such as fissionable nuclei) and thermal neutrons (usually in (n,γ) capture reactions). The observation of resonances is by no means restricted to neutron nuclear reactions.
Danish physicist Niels Bohr introduced the compound nucleus model (the idea of compound nucleus formation) in 1936. This model assumes that the incident particle and the target nucleus become indistinguishable after the collision and constitute the nucleus’s particular excited state – the compound nucleus. The projectile has to suffer collisions with constituent nucleons of the target nucleus until it has lost its incident energy to become indistinguishable. Many so these collisions lead to a complete thermal equilibrium inside the compound nucleus. The compound nucleus is excited by both the kinetic energy of the projectile and by the binding nuclear energy.
This compound system is a relatively long-lived intermediate state of the particle-target composite system. From the definition, the compound nucleus must live for at least several times longer than is the time of transit of an incident particle across the nucleus (~10^{-22} s). The time scale of compound nucleus reactions is 10^{-18} s – 10^{-16} s, but lifetimes as long as 10^{-14} s have also been observed.

A very important feature and a direct consequence of the thermal equilibrium inside a compound nucleus is that the mode of decay of the compound nucleus does not depend on how the compound nucleus is formed. Many collisions between nucleons lead to the loss of information on the entrance channel from the system. The decay mechanism (exit channel) that dominates the decay of C* is determined by the excitation energy in C* and by the law of probability.



These reactions can be considered as two-stage processes.

- The first stage is the formation of a compound nucleus expressed by $\boldsymbol{\sigma_{a+X\rightarrow C^*}}$
- The second stage is the decay of a compound nucleus expressed by $\mathbf{P_{C^*\rightarrow b+Y}}$

The result cross-section of certain reaction a+X→[C*]→b+Y is given by $\boldsymbol{\sigma_{(a,b)} = \sigma_{a+X\rightarrow C^*} \cdot P_{C^*\rightarrow b+Y}}$

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow [{}^{236}_{92}U] \xrightarrow{85\%} fission\ (e.g.\ {}^{139}_{56}Ba + {}^{94}_{36}Kr + 3\ {}^{1}_{0}n) $$

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow [{}^{236}_{92}U] \xrightarrow{15\%} {}^{236}_{92}U + \gamma $$

Absorption reaction of fissile ^{235}U. The uncertainty of the exit channel is caused by “loss of memory” of resonance [^{236}U].

Direct Nuclear Reactions

Nuclear reactions that occur in a time comparable to the time of transit of an incident particle across the nucleus (~10^{-22} s) are called direct nuclear reactions. Interaction time is critical for defining the reaction mechanism. The very short interaction time allows for an interaction of a single nucleon only (in extreme cases). There is always some non-direct (multiple internuclear interactions) component in all reactions, but the direct reactions have this component limited. The reaction has to occur at high energy to limit the time available for multiple internuclear interactions.

Direct reactions have another very important property. Products of a direct reaction are not distributed isotropically in angle, but they are forward-focused. This reflects that the projectiles make only one, or very few, collisions with nucleons in the target nucleus, and its forward momentum is not transferred to an entire compound state.

The cross-sections for direct reactions vary smoothly and slowly with energy in contrast to the compound nucleus reactions. These cross-sections are comparable to the geometrical cross-sections of target nuclei.

Types of direct reactions:

- **Elastic scattering** in which a passing particle and target stay in their ground states.
- **Inelastic scattering** in which a passing particle changes its energy state. For example, the (p, p') reaction.
- **Transfer reactions** in which one or more nucleons are transferred to the other nucleus. These reactions are further classified as:
  - **Stripping reaction** in which one or more nucleons are transferred to a target nucleus from passing particles. For example, the neutron stripping in the (d, p) reaction.
  - **Pick-up reaction** in which one or more nucleons are transferred from a target nucleus to a passing particle. For example, the neutron pick-up in the (p, d) reaction.
- **Break-up reaction** in which a breakup of a projectile into two or more fragments occurs.
- **Knock-out reaction** in which a single nucleon or a light cluster is removed from the projectile by a collision with the target.

$$ {}^{1}_{0}n + {}^{10}_{5}B \xrightarrow{(E_k > 1.2MeV)} {}^{3}_{1}H + {}^{4}_{2}He + {}^{4}_{2}He $$

Example: This threshold reaction of a fast neutron with an isotope ^{10}B is one of the ways how radioactive tritium in the primary circuit of all PWRs is generated.

Direct Reactions vs. Compound Nucleus Reactions

Direct Reactions

- The direct reactions are fast and involve a **single-nucleon interaction**.
- The interaction time must be very short **(~10^{-22} s)**.

- The direct reactions require incident particle energy **larger than ~ 5 MeV/Ap**. (Ap is the atomic mass number of a projectile)
- Incident particles interact **on the surface** of a target nucleus rather than in the volume of a target nucleus.
- Products of the direct reactions **are not distributed isotropically in angle**, but they are forward-focused.
- Direct reactions are of importance in measurements of nuclear structure.

Compound Nucleus Reactions

- The compound nucleus is a **relatively long-lived** intermediate state of the particle-target composite system.
- The compound nucleus reactions involve **many nucleon-nucleon interactions**.
- A large number of collisions between the nucleons leads to a **thermal equilibrium** inside the compound nucleus.
- The time scale of compound nucleus reactions is **10^{-18} s – 10^{-16} s**.
- The compound nucleus reactions are usually created if the projectile has **low energy**.
- Incident particles interact in the volume of a target nucleus.
- Products of the compound nucleus reactions are distributed **near isotropically in angle** (the nucleus loses memory of how it was created – **Bohr's hypothesis of independence**).
- **The decay mode** of the compound nucleus **does not depend on how the compound nucleus is formed**.
- Resonances in the cross-section are typical for the compound nucleus reaction.

Neutron Sources

A neutron source is any device that **emits neutrons**. Neutron sources have many applications, and they can be used in research, engineering, medicine, petroleum exploration, biology, chemistry, and **nuclear power**. A number of factors characterize a neutron source:

- **Significance of the source**
- **Intensity.** The rate of neutrons emitted by the source.
- **Energy distribution** of emitted neutrons.
- **Angular distribution** of emitted neutrons.
- **Mode of emission.** Continuous or pulsed operation.

Classification by significance of the source

- **Large (Significant) neutron sources**
  - **Nuclear Reactors.** There are nuclei that can undergo fission on their own spontaneously, but only certain nuclei, like uranium-235, uranium-233, and plutonium-239, can sustain a fission chain reaction. This is because these nuclei release neutrons when they break apart, which can induce the fission of other nuclei. Uranium-235, which exists as 0.7% of naturally occurring uranium, undergoes nuclear fission with thermal neutrons with the production of, on average, 2.4 fast neutrons and the release of ~ 180 MeV of energy per fission. Free neutrons released by each fission play a very important role as a trigger of the reaction, but they can also be used for another purpose. For example, one neutron is required to trigger further fission. Part of free neutrons (let say 0.5 neutrons/fission) is absorbed in other material, but an excess of neutrons (0.9 neutrons/fission) can leave the surface of the reactor core and can be used as a neutron source.

  - **Fusion Systems.** Nuclear fusion is a nuclear reaction in which two or more atomic nuclei (e.g. D+T) collide at very high energy and fuse together. They byproduct of DT fusion is a free neutron (see picture). Therefore, nuclear fusion reactions can produce large quantities of neutrons.
  - **Spallation Sources.** A spallation source is a high-flux neutron source in which protons that have been accelerated to high energies hit a heavy target material, causing the emission of neutrons. The reaction occurs above a certain energy threshold for the incident particle, which is typically 5 – 15 MeV.

- **Medium neutron sources**

  - **Bremssstrahlung from Electron Accelerators / Photofission.** When slowed down rapidly in a heavy target, energetic electrons emit intense gamma radiation during the deceleration process. This is known as **Bremsstrahlung** or braking radiation. The interaction of the gamma radiation with the target produces neutrons via the (γ,n) reaction, or the (γ, fission) reaction when a fissile target is used. e-→Pb → γ→ Pb →(γ,n) and (γ,fission). The Bremsstrahlung γ energy exceeds the binding energy of the "last" neutron in the target. A source strength of 10^{13} neutrons/second produced in short (i.e., < 5 μs) pulses can be readily realized.
  - **Dense plasma focus.** The dense plasma focus (DPF) is a device known as an efficient source of neutrons from **fusion reactions**. The dense plasma focus (DPF) mechanism is based on nuclear fusion of **short-lived plasma** of deuterium and/or tritium. This device produces a short-lived plasma by electromagnetic compression and acceleration that is called **a pinch**. This

plasma is during the pinch hot and dense enough to cause nuclear fusion and the emission of neutrons.

- **Light ion accelerators.** Neutrons can also be produced by **particle accelerators** using targets of deuterium, tritium, lithium, beryllium, and other low-Z materials. In this case, the target must be bombarded with accelerated hydrogen (H), deuterium (D), or tritium (T) nuclei.

- **Small neutron sources**
  - **Neutron Generators.** Neutrons are produced in the fusion of deuterium and tritium in the following exothermic reaction. $\mathbf{^{2}D + ^{3}T \rightarrow ^{4}He + n + 17.6\ MeV}$. The neutron is produced with a kinetic energy of 14.1 MeV. This can be achieved on a small scale in the laboratory with a modest 100 kV accelerator for deuterium atoms bombarding a tritium target. Continuous neutron sources of $\sim 10^{11}$ neutrons/second can be achieved relatively simply.
  - **Radioisotope source – (α,n) reactions.** In certain light isotopes, the 'last' neutron in the nucleus is weakly bound and is released when the compound nucleus formed following α-particle bombardment decays. The bombardment of beryllium by α-particles leads to the production of neutrons by the following exothermic reaction: $\mathbf{^{4}He + ^{9}Be \rightarrow ^{12}C + n + 5.7\ MeV}$. This reaction yields a weak source of neutrons with an energy spectrum resembling that from a fission source and is used nowadays in **portable neutron sources.** Radium, plutonium, or americium can be used as an α-emitter.
  - **Radioisotope source – (γ,n) reactions.** (γ,n) reactions can also be used for the same purpose. In this type of source, because of the greater range of the γ-ray, the two physical components of the source can be separated, making it possible to 'switch off' the reaction if so required by removing the radioactive source from the beryllium. (γ,n) sources produce monoenergetic neutrons, unlike (α,n) sources. The (γ,n) source uses antimony-124 as the gamma emitter in the following endothermic reaction.

$$\mathbf{^{124}Sb \rightarrow ^{124}Te + \beta^{-} + \gamma}$$
$$\mathbf{\gamma + ^{9}Be \rightarrow ^{8}Be + n - 1.66\ MeV}$$

  - **Radioisotope source – spontaneous fission**. Certain isotopes undergo spontaneous fission with the emission of neutrons. The most commonly used spontaneous fission source is the radioactive isotope **californium-252**. Cf-252 and other spontaneous fission neutron sources are produced by irradiating uranium or another transuranic element in a nuclear reactor, where neutrons are absorbed in the starting material and its subsequent reaction products, transmuting the starting material into the SF isotope.

Properties of the Neutron

A neutron is one of the subatomic particles that make up matter. The neutron has **no electric charge** and a rest mass equal to 1.67493×10^{-27} kg - marginally greater than that of the proton but nearly 1839 times greater than that of the electron. The neutron has a mean square radius of about 0.8×10^{-15} m or 0.8 fm, and it is a spin-½ fermion.

Key properties of neutrons are summarized below:

- **Mean square radius** of a neutron is ~ 0.8 x 10^{-15}m (0.8 fermi)
- **The mass** of the neutron is 939.565 MeV/c^2.
- Neutrons are **½ spin** particles – fermionic statistics.
- Neutrons are **neutral particles** – no net electric charge.
- Neutrons have a **non-zero magnetic moment**.
- **Free neutrons** (outside a nucleus) are unstable and decay via beta decay. The decay of the neutron involves the weak interaction and is associated with a quark transformation (a down quark is converted to an up quark).
- The mean lifetime of a free neutron is 882 seconds (i.e., the **half-life** is 611 seconds).
- A **natural neutron background** of free neutrons exists everywhere on Earth. It is caused by muons produced in the atmosphere, where high-energy cosmic rays collide with particles of Earth's atmosphere.
- Neutrons **cannot directly cause ionization**. Neutrons ionize matter only indirectly.
- Neutrons can travel hundreds of feet in the air without any interaction. Neutron radiation is **highly penetrating**.
- Neutrons **trigger nuclear fission**.
- The fission process produces **free neutrons** (2 or 3).
- Thermal or cold neutrons have wavelengths similar to atomic spacings. They can be used in **neutron diffraction** experiments to determine the atomic and/or magnetic structure of a material.