Interaction of the ionizing radiation with the atomic nuclei

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The first condition for the successful start of this reaction is an **effective collision of the particle with the target nucleus**. The target nucleus is usually represented by a stable nuclide. In cases when it is a long-term radionuclide and the element doesn't in fact have a stable nuclide, the target nucleus can be a radionuclide. The product of such reaction is then a transmuted nucleus and another emitted particle.

The charge and size of the target nucleus play an important role during the execution of various types of nuclear reactions. The nuclei can be roughly classified as light (A < 25), medium weight (A = 25 to 80) and heavy (A > 80).

Activation particles represent the most common second condition required to start a nuclear reaction. This is a certain kind of "nuclear missiles" with high enough energy. These "missiles" can be:

1. *a-particles* in the form of rays emitted by natural emitters or accelerated in the form of helium ions.
2. *Protons* and deuterons in the form of accelerated ions of light and heavy hydrogen.
3. *Gamma radiation photons* in the form of rays emitted by natural radionuclides.
4. *Hard X-radiation* artificially obtained, for example in a betatron.
5. *Neutrons*.

Neutrons are the only particles that can react with the target nucleus **without any energy restrictions**. Because of their wide energy spectrum, neutrons have the ability to induce very different reactions. That is why they are usually divided into several individual groups:

- The group of **slow neutrons** can be represented by **thermal neutrons** (energy 0,002 up to 0,5 eV; speed $2{,}2.10^3$ $m.s^{-1}$ at 0,025 eV).
- The group with **medium energy** can reach the energy levels of up to 500 keV.
- The **fast neutrons** fall into the energy range of 0,5 up to 10 MeV (the speed of neutron with the energy of 1 MeV is about $1{,}4.10^7$ $m.s^{-1}$).
- The neutrons with **high energy** reach values up to 50 MeV.

The result of the ionizing radiation interaction with the atomic nuclei is a newly produced (transmuted) nucleus. The transmuted nucleus can be either stable or radioactive, and it can emit a particle (such as α, p, d, n) or gamma radiation quantum.

Neutrons and their interactions with the nucleus

Almost all stable nuclides, with the exception of ${}^{4}{}_{2}He$, are able to react with neutrons. This interaction represents to **most common nuclear reaction**. As neutrons are not electrically charged they do not have to overcome the nuclear potential barrier of the target nucleus. They penetrate the nucleus quite easily, and give origin to a **compound nucleus**. Neutrons are not able to ionize directly, but can **indirectly ionize**, especially in an environment containing lightweight elements such as hydrogen. The hydrogen nuclei are set to motion through elastic collisions and ionize the atoms in their vicinity. This indirect ionization effect of neutrons also has its significance in biological tissues and liquids.

Sources generating neutrons usually produce poly-energetic particles. When the target nucleus is irradiated with poly-energetic neutrons, there are several different types of resultant products obtained from irradiating both light and heavy target nuclei. It is possible for the neutron to be deviated from its original course due to nuclear forces. Then the neutron is forced to continue along a new trajectory. This way of interaction is called **potential scattering**.

When a neutron is **absorbed** by target nucleus it gives origin to a compound nucleus. This nucleus then for a very short period of time remains in an excited state (10-16 up to 10^{-12} s). The easiest way of returning back to a ground state is a **neutron emission**. In this case, if the sum of the kinetic energies characterising the neutron and the nucleus before the reaction equals the sum of their kinetic energies afterwards, the reaction is called elastic scattering (n,n). If the nucleus remains in the excited state even after the emission of a neutron, the reaction is called inelastic scattering (n, n,). The remainder of the kinetic energy is then emitted from the nucleus in the form of electromagnetic radiation.

A compound nucleus can also reach the ground state via the emission of one or more particles (n, x). The products of these reactions are nuclides, and differ from the target nuclide by their mass number, their proton number or both. This process is less common for the heavy elements, as these reactions are usually "energetically negative". Therefore they require neutrons with significantly high energy, reaching up to several tens of MeV. Upon entering the nucleus, the neutron supplies the binding energy E_1. In order to emit particles the nucleus needs to supply those particles with binding energy E_2. If the difference $E_1 – E_2 > 0$, the reaction is considered to be **exoergic** and it can continue without any additional energy needed. If the difference $E_1 – E_2 < 0$, the reaction is considered to be **endoergic**. The endoergic reactions can continue only if the entering neutron has sufficient kinetic energy to overcome the negative energy of this reaction.

The reactions with the highest yield are nuclear exoergic reactions of the type (n, γ), which are also called **radiation capture**. During this nuclear reaction the neutron remains in the compound nucleus. The nucleus is trying to dispose of the energy supplied by the neutron via an emission of gamma radiation. This type of reaction shows the highest yield with the use of thermal neutrons. Such reactions are also the most important nuclear reactions, which can be used to produce most of the radionuclides.

A compound nucleus can also split and produce two new nuclei. This process is called **nuclear fission** (n, f). However the number of elements, whose nuclei can be split with the use of neutrons, is limited.

There is different probability for different types of neutron interactions with the nucleus. The measure of probability that a certain reaction will occur is called the **cross-section**. The amount of reactions X_i, which will occur over the time of 1 second when irradiating a medium with the amount of target nuclei N, is directly proportional to the amount of nuclei (N). It is also directly proportional to the density of the electrons ray Φ, and can be described by the following relationship:

$$X_i = \sigma_i N\Phi$$

where the proportionality constant σ_i is the cross-section of a given reaction.

The interactions of positively charged particles with the nucleus

The reactions between **α-particles** and target nucleus are most often of the type (α, p), (α, n), (α, 2n). These are mostly reactions of synthetic nature, as the resultant nucleus possesses 2-3 nucleons more than the target nucleus. The charge of the nucleus increases by 1 or 2 units. For energetic reasons, the reactions involving α-particles with low energy (such as α particles produced by artificial emitters) are limited to the nuclei of light elements. Only with the use of heavy a-particles with higher energy, a transmutation of heavy elements is made possible.

The reactions of **deuterons** and target nucleus are most often of the type (d, p), (d, n), (d, α). The processes caused by these "nuclear missiles" are very common, and can be explained by their very strong exoergic nature. The most common reaction is the reaction (d, p), in which the final nucleus is an isotope of the target nuclei.

The reactions of **protons** and target nucleus are most commonly of the type (p, α), (p, γ), (p, n), (p, d). These reactions generally produce a significantly lower yield than the ones using deuterons.

Nuclear reactions of the gamma radiation

The process of the gamma radiation interaction with the target nucleus is usually described as a **photonuclear reaction**. During this reaction, one or more nucleons are ejected from the target nucleus. These can be (γ, n), (γ, p), (γ, α), and (γ, 2n). This is why the gamma radiation photon needs to have higher energy than the binding energy of the resulting particles, and means that these reactions are predominantly endoergic. The yield of this reaction type is usually a lot lower (by one or two orders) than the one of the reactions involving corporeal particles of the same energy.

The reaction type (γ, n) is the most often found type of photonuclear reaction. It can be found in the light elements as well, starting with the deuteron splitting: 21D + 00 γ → 11p + 10n. The reaction type (γ, p) is less frequent due to the potential barrier of the emitted proton, while the reaction type (γ, α) is even less frequent due to even higher potential barrier of the emitted α particle. The reaction type (γ, 2n) has been observed in lightweight, medium weight, and heavy nuclei. The interaction of gamma radiation with the target nucleus can also fall under the reaction type (γ, γ,) category. This type of reaction leads to the origin of isomers.

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