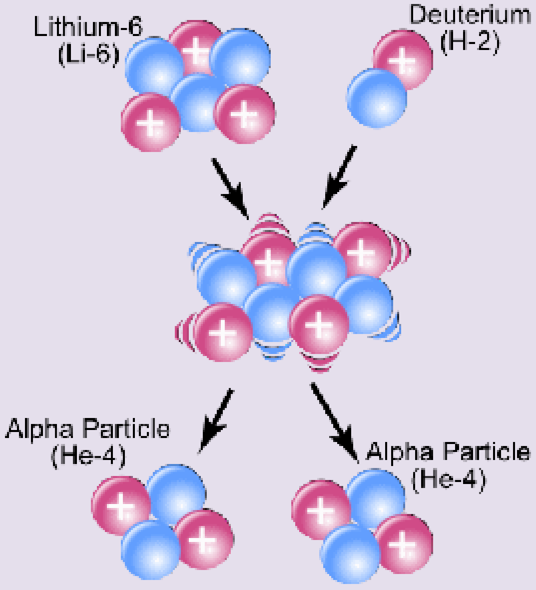
NUCLEAR REACTIONS

In nuclear physics, a **nuclear reaction** is a process in which two nuclei or nuclear particles collide to produce products different from the initial particles. 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. While the transformation is spontaneous in the case of radioactive decay, it is initiated by a particle in the case of a nuclear reaction. If the particles collide and separate without changing, the process is called an elastic collision rather than a reaction.

In the symbolic figure shown below, ^{6}Li and deuterium react to form the highly excited intermediate nucleus ^{8}Be which then decays immediately into two alpha particles. Protons are symbolically represented by red spheres, and neutrons by blue spheres.



Lithium-6 – Deuterium Reaction

The reaction equation

A nuclear reaction can be written in terms of a formula just like a chemical reaction. Nuclear decays can be written in a similar way, but with only one nucleus on the left side.

Every particle partaking in the reaction is written with its chemical symbol, with the mass number at the upper left and the atomic number at the lower left. The neutron is written "n"; the proton can be written "^{1}H" or "p".

The equation is correct only if the sums of the mass numbers on both sides are identical (as required by the conservation law for baryon number), and if the sums of the atomic numbers on both sides are identical (as required by the conservation law for electric charge). In the example shown above, this leads to (assuming we would know only one particle to the right):

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

To make the sums correct, 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:

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

Energy conservation

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). This can be calculated by reference to a table of very accurate particle rest masses (see [1] as follows. According to the reference tables, the ${}^{6}_{3}$Li nucleus has a relative atomic mass of 6.015 atomic mass units (abbreviated u), the deuteron has 2.014 u, and the helium-4 nucleus has 4.0026 u Thus:

- Total rest mass on left side = 6.015 + 2.014 = 8.029 u
- Total rest mass on right side = 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:

$1 \text{ u } c^2 = (1.66054 \text{ x} 10^{-27} \text{ kg}) \text{ x } (2.99792 \text{ x } 10^8 \text{ m/s})^2$
$= 1.49242 \text{ x } 10^{-10} \text{ kg } (\text{m/s})^2 = 1.49242 \text{ x } 10^{-10} \text{ J}$
$(\text{Joule})\text{x } (1 \text{ MeV} / 1.60218 \text{ x } 10^{-13} \text{ J})$
$= 931.49 \text{ MeV}$,

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

Hence, the energy released is 0.0238 × 931 MeV = 22.4 MeV. Expressed differently: the mass is reduced by 0.3 %, corresponding to 0.3 % of 90 PJ/kg is 300 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
- 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 and energy balance

In writing down the reaction equation, in a way analogous to a chemical equation, one may in addition give the reaction energy on the right side:

$$\text{Target nucleus + projectile} \dashrightarrow \text{Final nucleus + ejectile} + Q.$$

For the particular case discussed above, the reaction energy has already been calculated as Q = 22.4 MeV. Hence:

$$^{6}\mathrm{Li}_{3} + {}^{2}\mathrm{H}_{1} \rightarrow {}^{4}\mathrm{He}_{2} + {}^{4}\mathrm{He}_{2} + 22.4\ \mathrm{MeV}$$

The reaction energy (the "Q-value") is positive for exothermal reactions and negative for endothermal reactions. On the one hand, it is the difference between the sums of kinetic energies on the final side and on the initial side. But on the other hand, it is also the difference between the nuclear rest masses on the initial side and on the final side (in this way, we have calculated the Q-value above).

Reaction rates

If the reaction equation is balanced, that does not mean that the reaction really occurs. The rate at which reactions occur depends on the particle energy, the particle flux and the reaction cross section.

Notable types of reactions:

While the number of possible nuclear reactions is immense, there are several types which are more common, or otherwise notable. Some examples include:

- Fusion reactions - two light nuclei join to form a heavier one, with additional particles (usually protons or neutrons) thrown off to conserve momentum.
- Fission reactions - a very heavy nucleus, spontaneously or after absorbing additional light particles (usually neutrons), splits into two or sometimes three pieces. (α decay is not usually called fission.)
- Spallation - a nucleus is hit by a particle with sufficient energy and momentum to knock out several small fragments or, smash it into many fragments.
- Induced gamma emission belongs to a class in which only photons were involved in creating and destroying states of nuclear excitation.

Direct reactions

An intermediate energy projectile transfers energy or picks up or loses nucleons to the nucleus in a single quick (10^{-21} second) event. Energy and momentum transfer are relatively small. These are particularly useful in experimental nuclear physics, because the reaction mechanisms are often simple enough to calculate with sufficient accuracy to probe the structure of the target nucleus.

Ex: Pick-up and Stripping reactions

Inelastic scattering

Only energy and momentum are transferred.

- (p,p') tests differenced between nuclear states
- (α,α') measures nuclear surface shapes and sized. Since α particles that hit the nucleus react more violently, elastic and shallow inelastic α scattering are sensitive to the shapes and sizes of the targets, like light scattered from a small black object.
- (e,e') is useful for probing the interior structure. Since electrons interact less strongly than do protons and neutrons, they reach to the centers of the targets and their wave functions are less distorted by passing through the nucleus.

Transfer reactions

Usually at moderately low energy, one or more nucleons are transferred between the projectile and target. These are useful in studying outer shell structure of nuclei.

- (α,n) and (α,p) reactions. Some of the earliest nuclear reactions studied involved an alpha particle produced by alpha decay, knocking a nucleon from a target nucleus.
- (d,n) and (d,p) reactions. A deuteron beam impinges on a target; the target nuclei absorb either the neutron or proton from the deuteron. The deuteron is so loosely bound that this is almost the same as proton or neutron capture. A compound nucleus may be formed, leading to additional neutrons being emitted more slowly. (d,n) reactions are used to generate energetic neutrons.
- The strangeness exchange reaction (K,π) has been used to study hypernuclei.

Compound nuclear reactions

Either a low energy projectile is absorbed or a higher energy particle transfers energy to the nucleus, leaving it with too much energy to be fully bound together. On a time scale of about 10^{-19} seconds, particles, usually neutrons, are "boiled" off. That is, it remains together until enough energy happens to be concentrated in one neutron to escape the mutual attraction. Charged particles rarely boil off because of the coulomb barrier. The excited quasi-bound nucleus is called a compound nucleus.

Proton induced nuclear reactions:

$^{6}Li(p,\alpha)^{3}He$ and $^{7}Li(p,\alpha)^{4}He$

$^{7}Li(p,\_)^{4}He$, $^{6}Li(p,\_)^{3}He$ and $^{7}Li(p,p)^{7}Li$

$^{124}Te(p,n)^{124}I$ and $^{125}Te(p,2n)^{124}I$

$^{11}B(p,n)^{11}C$.

Deuteron induced nuclear reactions:

$^{78}Kr(d,\alpha)\ ^{76}Br$, $^{78}Kr(d,n)\ ^{79}Rb$ and $^{78}Kr(d,x)\ ^{79}Kr$

$^{27}Al\ (d,\ \_\ )^{22,24}Na$

$^{89}Y\ (d,\ \_\ )^{88,89}Zr$

Alpha induced nuclear reactions:

$^{197}Au(alpha,n)$, $^{197}Au(alpha\ ,2n)$,

$^{40}Ca(\alpha,p)^{43}Sc$ $^{44}Ti(\alpha,p)^{47}Sc$

Photodisintegration is a physical process in which extremely high energy gamma rays interact with an atomic nucleus and cause it to enter an excited state, which immediately decays into two or more daughter nuclei.

i) $^{2}D_{1} + \gamma \rightarrow {}^{1}H_{1} + n$

ii) Photo-disintegration of Oxygen into Two ^{8}Be Nuclei ;

iii) $^{4}He(\gamma,\ P)^{3}H$