Group I : β$^-$-Conversion

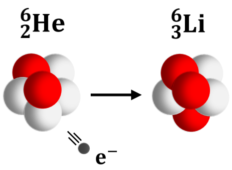
Profile: β$^-$-Conversion

The β$^-$-Conversion is a nuclear conversion which occurs when the atomic nucleus has a low number of protons and a higher number of neutrons. In order to achieve a **stable state** (stable nuclear configuration) from this **neutron excess**, a neutron is converted into a proton in the nucleus. This conversion also produces an **Electron e^-** and a **Neutrino ν**, which are released as radiation. The neutrino can be neglected for our considerations, but the electron makes up the so-called **Beta-Minus Radiation**. Although this has a low penetration power, it is harmful to the human body in high doses.
In summary, the following reaction takes place in the core :

$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e^- + {}^{0}_{0}\nu$$

Neutron is converted into Proton, giving off an Electron and Neutrino

For the entire nucleus, this means that a new chemical element is created (since the daughter nuclide has one more proton). The mass number remains the same during the reaction.



A stable lithium nucleus can be created from a helium nucleus with neutron excess with the help of beta-minus conversion

In a Nutshell

- ✓ The overall reaction is generally $^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + {}^{0}_{0}\nu$
- ✓ Occurs at: **Neutron excess**
- ✓ Radiation released: **Electrons**

Expert Task | Nuclear Medicine

In medicine, radioactive nuclides are often used for radionuclide therapy. For example, beta-minus emitters are introduced into the organism, where they decay and release radiation. A typical example **is I-131** (iodine), which accumulates in the thyroid gland and undergoes beta-minus decay there.

a) Set up the reaction equation of I-131 and find out which element is produced. Use the nuclide table and the general formula from the Nutshell box.

b) It may actually be medically useful to introduce a radioactive material such as I-131 into the human body. Make assumptions to answer the following question:

What medical purpose could radioactive iodine 131 have?

Home Group Task

What to explain:
- Pick any radioactive beta-minus nuclide from the nuclide chart and write down the reaction equation. Using the equation, briefly summarize the beta-minus conversion and its properties.
- Briefly describe the principle of radionuclide therapy. Discuss your assumptions about b) with your group members and, if necessary, check your ideas with an Internet search on radionuclide therapy.

What you have to find out:
- With the help of group 2, compare the beta-minus conversion with beta-plus and electron capture. Consider the three reaction equations and describe the relationship between the three reactions.

Group II : β⁺- Conversion

Profile : β⁺-Conversion

The β^+-Conversion is a nuclear decay which always occurs when the atomic nucleus has a high number of protons and a too low number of neutrons. To achieve a stable state (stable nuclear configuration) from this **neutron deficiency**, a **Proton** is converted to a **Neutron** in the nucleus. This conversion also produces a **Positron e^+** and a **Neutrino ν**, which are released as radiation. The neutrino can be neglected for our considerations, but the positron makes up the so-called **Beta-Plus Radiation**.

Although this has a low penetration power, it is harmful to the human body in high doses. In summary, the following reaction takes place in the core :

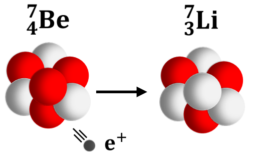
$$^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{1}\mathrm{e}^{+} + {}^{0}_{0}\nu$$

Proton is converted into Neutron, giving off an Positron and Neutrino

For the entire nucleus, this means that a new chemical element is created (since the daughter nuclide has one less proton). The mass number remains the same during the reaction. Besides the β^+-Conversion, **Electron Capture** (ϵ) is also possible in case of neutron deficiency. Here, the same daughter nucleus is formed as in the β^+-Conversion. The only difference is that no positron is emitted, but an electron is absorbed. Electron capture is, so to speak, the alternative conversion channel of the β^+-Conversion.

$$^{1}_{1}\mathrm{p} + {}^{0}_{1}\mathrm{e}^{-} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{0}\nu$$

Proton is converted into Neutron, with absorption of an electron



A stable lithium nucleus can be created from a beryllium nuclide with a neutron deficiency with beta-plus conversion

In a Nutshell

- ✓ The overall reaction is
  β^+: $^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + {}^{0}_{1}e + {}^{0}_{0}\nu$
  ϵ: $^{A}_{Z}X + {}_{-1}^{0}e \rightarrow {}_{Z-1}^{A}Y + {}^{0}_{0}\nu$
- ✓ Occurs at:
  Neutron Deficiency
- ✓ Radiation released:
  Positrons

Expert Task | Stay Positive

a) Set up the reaction equation of **F-18 (Fluorine)** and find out which element is produced. Use the nuclide table and the general formula from the Nutshell box.

b) The Isotope **Potassium-40** ($^{40}_{19}\mathrm{K}$) can transform by both electron capture and beta-plus conversion. Write the two reaction equations of K-40.

Home Group Task

What to explain:

- Pick any radioactive nuclide that undergoes beta-plus conversion or electron capture from the nuclide table and write down the two reaction equations. Using the equation, briefly summarize beta-plus conversion and electron capture and their properties.

What you have to find out:

- The Potassium-40 from task b) can undergo one more nuclear conversion. Check it in the nuclide table and note this additional nuclear transformation. Discuss the following question together:

How can it be that a nuclide can pass into several different daughter nuclei?

Group Puzzle | Nuclear Reactions

Group III : Nuclear Fusion

Profile : Nuclear Fusion

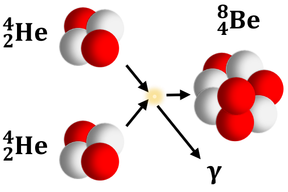
Nuclear fusion refers to nuclear reactions in which two atomic nuclei "**fuse**" to form one or more new nuclides. As we know, nuclear fusion does not take place under natural conditions on Earth (unlike radioactive nuclear conversions such as beta conversion). This is because a physical force "prevents" nuclei from fusing: The two atomic nuclei have positive charges (Protons) and actually **repel each other** due to the **Coulomb force**. However, if the ambient temperature and pressure are high enough - that is, if the distance between the nuclides is low and the energy of the nuclides is high enough - the Coulomb barrier can be overcome and fusion can occur. A natural environment in which this is possible is stars. For example, in our Sun, hydrogen nuclei fuse to form helium (The so-called **Hydrogen Burning**). Examples of possible reactions are

$$^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \gamma$$

Or another example:

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

In fusion reactions, there are always **two atomic nuclei** on the left side of the equation. On the right side there is at least one daughter nucleus. A wide variety of other particles can be released, such as here a gamma quantum (**Photon**, denoted by γ). Often the daughter nucleus is also radioactive can undergo further nuclear conversions.



An important nuclear fusion in stars is the fusion of two helium-4 nuclei. Here a beryllium nucleus is formed and gamma radiation is released.

In A Nutshell

- ✓ The overall reaction is generally $^{A_1}_{Z_1}X_1 + {}^{A_2}_{Z_2}X_2 \rightarrow {}^{A_3}_{Z_3}Y + \ldots$
- ✓ Occurs at: **High Temperatures & Pressure**
- ✓ Radiation released: ***different***

Expert Task | Fusion in the Laboratory

In 1917, Ernest Rutherford succeeded in performing a fusion reaction in the laboratory. He irradiated a gas of **Nitrogen** $^{12}_{7}\mathrm{N}$ mit accelerated **Helium Nuclei** $^{4}_{2}\mathrm{He}$. The reaction produced a **daughter nucleus** and a **single proton** $^{1}_{1}\mathrm{p}$.

a) Write the reaction equation. Use the conservation of mass number and proton number and the nuclide table to find the daughter nucleus (the formula in the Nutshell box can help you).

b) Make conjectures to answer the following question:

Although this fusion reaction was observed as early as 1917 and today a wide variety of nuclear fusions can be carried out with the help of particle accelerators, it is not yet possible to use nuclear fusion as an effective energy source. How can this be?

Home Group Task

What to explain:

- Write down the reaction equation of the fusion of two helium-4 nuclei (there is only one daughter nuclide and a photon released). Using the equation, briefly summarize nuclear fusion and its properties.

What you have to find out:

- The resulting isotope of the Rutherford reaction from task a) is radioactive. Use the nuclide map to set up the subsequent Conversion equation with the help of Group 1.

Group IV: Neutron Capture

Profile : Neutron Capture

Nuclear reactions are physical processes in which **two nuclides** (atomic nuclei) react or fuse with each other. One nuclear reaction of particular importance in nuclear astrophysics is neutron capture. Here, one of the two reactants is a **Neutron**. An example of neutron capture is the following reaction with natural gold (Au-197):

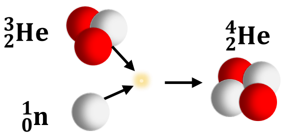
$$^{197}_{79}\mathrm{Au} + ^{1}_{0}\mathrm{n} \rightarrow ^{198}_{79}\mathrm{Au} + \gamma$$

The nuclide Au-197 absorbs a neutron, creating a new isotope. This isotope Au-198 is in a highly excited state, and emits its excess energy in the form of a gamma quantum (= **photon**, γ). Nuclear reactions usually require energy to be added to make the reaction possible. However, unlike other nuclear reactions, neutron capture is possible at very low kinetic energies of the neutron. One can also calculate the released energy ΔE in a nuclear fusion like neutron capture:

$$\begin{aligned}&\text{Rest Energy Parent Nuclide} + \text{Energy Neutron}\\ &= \text{Rest Energy Daughter Nuclide} + \text{released Energy}\end{aligned}$$

Or as formula:

$$\mathrm{E}_0(\mathrm{X}) + \mathrm{E}(\mathrm{n}) = \mathrm{E}_0(\mathrm{Y}) + \Delta\mathrm{E}$$



Helium-3 is stable, but can react with a free neutron to produce Helium-4, which has a higher binding energy.

In a Nutshell

- ✓ The overall reaction is generally $^{A}_{Z}\mathbf{X} + ^{1}_{0}\mathbf{n} \rightarrow ^{A+1}_{Z}\mathbf{Y} + \boldsymbol{\gamma}$
- ✓ Occurs at: **Free Neutrons**
- ✓ Radiation released: **Photons**

Expert Task | Nuclear Waste

A significant proportion of nuclear waste from nuclear reactors is produced by neutron capture in nuclear reactors. In this process, the original nuclear fuel (usually Uranium) reacts with free neutrons to produce radioactive isotopes with even higher mass numbers. An example of this is neutron capture with **U-238** (Uranium isotope, which even occurs naturally in small quantities).

a) Set up the reaction equation and use conservation of mass number and proton number and the nuclide table to determine the daughter nucleus (The formula in the Nutshell box can help you).

b) Calculate the energy released ΔE. Use the following values:
$\mathrm{E}_0(\text{U-238}) = 221{,}70\ \mathrm{GeV}$ $\mathrm{E}_0(\text{U-239}) = 222{,}63\ \mathrm{GeV}$ $\mathrm{E}(\mathrm{n}) = 1{,}16\ \mathrm{GeV}$

Home Group Task

What to explain:
- Choose any stable nuclide and write down the reaction equation for neutron capture. Using the equation, briefly summarize neutron capture and its properties.
- Explain how to calculate the energy released in a fusion reaction.

What you have to find out:
- Why can neutron capture occur at particularly low kinetic energies? Ask group 3 and find out what the "Problem" is in nuclear fusion and what the Coulomb barrier is.