Open-Book Paper: Radioactive Decay, Nuclear Fission and Nuclear Fusion

Alpha and Beta Decay

Alpha and beta decay are two types of naturally occurring radioactive decay. In alpha decay, an unstable nucleus emits an **alpha particle** (α), a particle made up of two protons and two neutrons. For example:[1]

$$^{224}_{88}\mathrm{Ra} \rightarrow {}^{220}_{86}\mathrm{Rn} + {}^{4}_{2}\alpha$$

In beta decay, a neutron in the nucleus is converted into a proton and a beta particle (β), an electron. Specifically, as protons and neutrons are both made of quarks, β-decay converts an up quark into a down quark; releasing a β-particle and an antineutrino (an antineutrino has no charge or mass, so does not affect the chemistry of β-decay). This occurs by the weak nuclear force.[3] For example:[4]

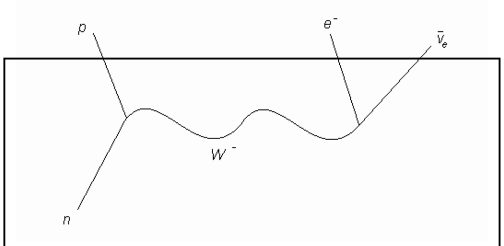


Figure 1[1]: The Feynman Diagram for beta-decay, showing a neutron (n) being converted into a proton (p), releasing an electron (e^-) and an antineutrino (ν_e). The W^- represents the exchange particle in the interaction

$$^{225}_{88}\mathrm{Ra} \rightarrow {}^{225}_{89}\mathrm{Ac} + {}^{0}_{-1}\beta^-$$

This table shows some of the differences between α-decay and β-decay emissions:[5]

	α-decay	**β-decay**
Particle emitted	helium nucleus	electron
Relative charge	+2	-1
Relative mass	4	0.00055
Range in air	< 10cm	< 10m
Stopped by	Paper	Aluminium foil
Deflection by electrical field	Low	High

The fundamental difference between radioactive decay and nuclear fission is that, whereas radioactive decay is spontaneous, nuclear fission must be induced. In nuclear fission, when an unstable nucleus absorbs a neutron, it splits, emitting more neutrons and setting off a continuous chain reaction. This leads to products with nuclear masses around half those of the initial nuclei, whereas in radioactive decay, the initial and final nuclear masses are relatively close together. The other major difference is that fission releases considerably more energy than decay. This energy comes from mass lost in fission, according to the equation $E = mc^2$, where E is energy, m is mass and c is the speed of light.

Synthesis of Elements in Stars

Stars produce their energy from nuclear fusion, in which nuclei join together to make larger nuclei. Hydrogen is used in normal-sized stars:

$$4\,{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2\mathrm{e}^{+} + 2\nu_{e}$$

(e^+ represents a positively charged electron, and v_e is a neutrino) This process requires temperatures of around 13 million K and pressures of around 300 billion atmospheres.[6] When almost all of the hydrogen has fused, the helium nuclei can collide to make nuclei such as beryllium:[7]

$$2\,{}^{4}_{2}\mathrm{He} \rightarrow {}^{8}_{4}\mathrm{Be}$$

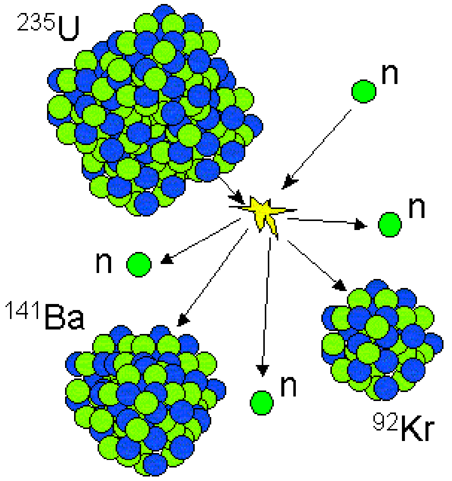
This leads to the creation of further nuclei containing four nucleons: carbon, oxygen, neon and magnesium. Once all the helium has fused, further collisions take place between the created nuclei. This leads to the production of small amounts of hydrogen and helium, producing most of the first 18 elements, such as lithium:[8]

$${}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{7}_{3}\mathrm{Li}$$

Lithium can also be produced by the collision of a Beryllium-7 nucleus and an electron. The nuclear process that takes place here is **electron capture**, in which an atom captures an electron, turning a proton into a neutron and releasing a neutrino. This happens by the weak interaction, like β-decay:[9]

$${}^{7}_{4}\mathrm{Be} + \mathrm{e}^{-} \rightarrow {}^{7}_{3}\mathrm{Li} + \nu_{e}$$

Smaller amounts of lithium can also be produced in the fission of some nuclei by cosmic rays and in supernovae, when heavy stars become unstable and explode.[10]



Producing Energy through Nuclear Fission and Fusion

In nuclear fission, an unstable nucleus absorbs a neutron, exciting the nucleus, causing it to oscillate and split into two smaller nuclei. This process releases more neutrons, causing more nuclei to split, and so on. This is shown in

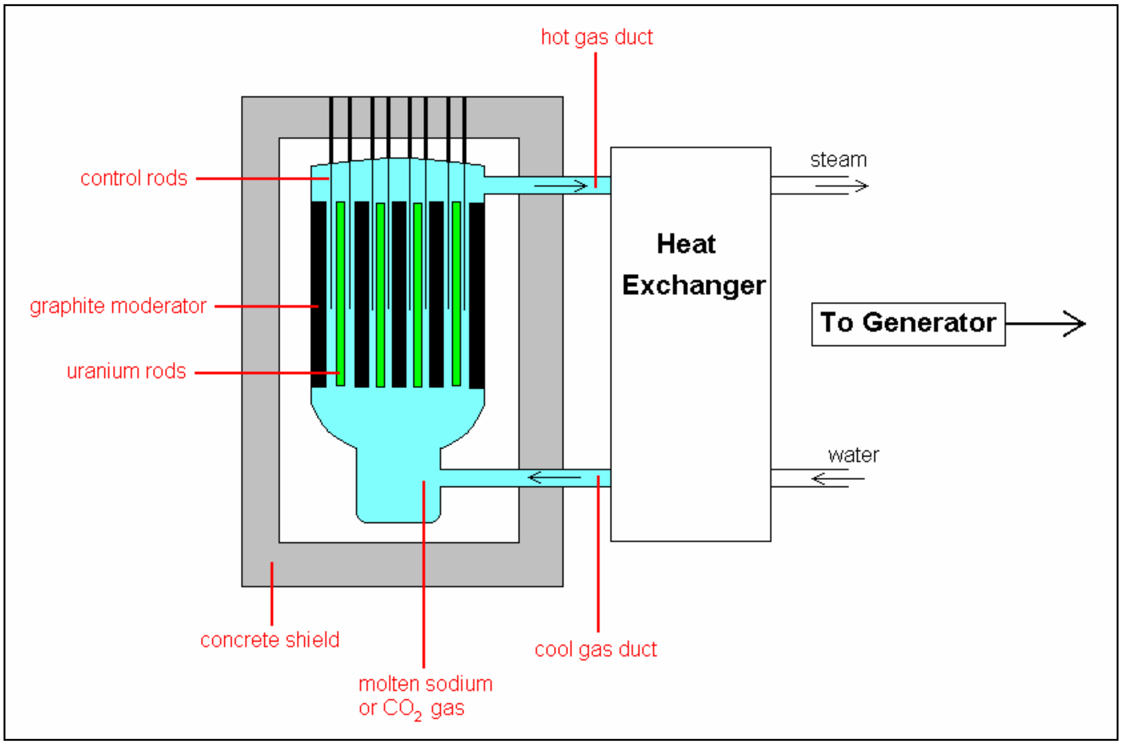


Fig. 2[11] with Uranium-235.

The energy produced by nuclear fission, by $E = mc^2$, is 3.2×10^{-11} J per fission.[12]

Figure 3[14]: Diagram of a fission reactor

Uranium-235 is used to produce energy by fission – see Fig. 3[13].

Controlling this reaction:

- Uranium-238 is mixed with uranium-235. Uranium-238 nuclei absorb neutrons but do not react by fission, breaking the chain in the reaction.
- Graphite moderators placed in between the uranium rods reduce the kinetic energy of the neutrons produced so they can induce fission.
- Boron-coated steel control rods absorb neutrons, and can be moved in and out of the reactor. If they are fully in, the reaction stops.

Nuclear fusion takes place when, under certain conditions, two nuclei fuse together. For example, with deuterium and tritium:[14]

$$^{2}_{1}\mathbf{H} + ^{3}_{1}\mathbf{H} \rightarrow \ ^{4}_{2}\mathbf{He} + ^{1}_{0}\mathbf{n}$$

The energy produced comes from the mass lost – 3.17×10^{-29} kg [15] [16]. By $E = mc^2$, this gives out 2.86×10^{-12} J per fusion. On earth, for this to happen the nuclei must be in ionised plasma at temperatures of 15×10^{8} °C. The problem with this is that it must be kept away from the walls of the container to minimise heat loss. To do this, a **tokamak** is used. This uses magnetic currents to keep the plasma from touching the walls (see Fig. 4[17]).
The walls are made of graphite, which is not harmed by the temperature.

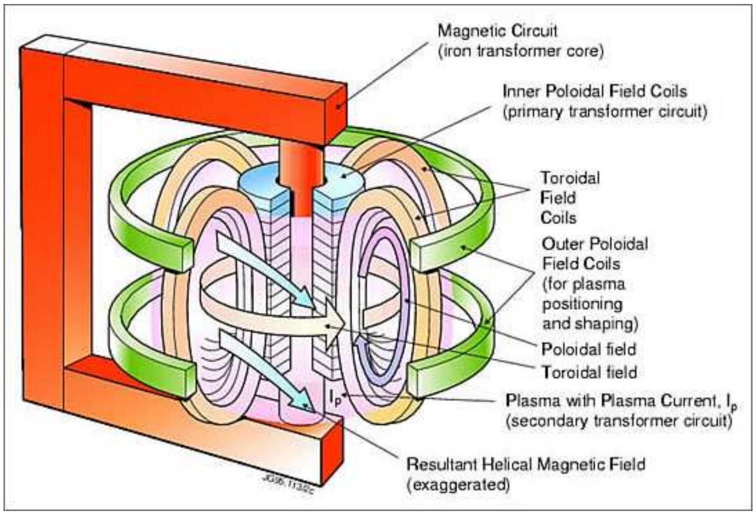


Figure 4[18]: Diagram of a tokamak

Both fission and fusion have several advantages and disadvantages for use in producing electricity:

	Advantages	**Disadvantages**
Fission	• Uranium-235 produces 3.7 million times the energy per unit mass as	• Fission produces waste radioactive actinides, which are dangerous for thousands of

	coal[18] • Uranium-235 will not run out on the same timescale as fossil fuels[19] • It produces no gases that directly cause global warming	years • Fission has led to disasters such as Chernobyl in 1986, which caused over 4000 deaths[20]
Fusion	• The fuel – hydrogen – is abundant • The radioactive waste products have half-lives hundreds of years less than those of fission • Fusion is safer than fission, as only small amounts of products are used • It produces no gases that directly cause global warming	• The conditions required for fission are hard to produce • The process used to produce energy by fusion is not yet perfect – see below

Challenges Facing the Development of Fusion Power Stations

The major problem with fusion is generating and containing the conditions required for the reaction. As detailed above, a tokamak is used, this has some problems. The plasma still touches the bottom of the chamber, and where it does this; hydrogen reacts with the walls forming hydrocarbon radicals. These can form a film, which flakes away into the plasma, affecting performance[21]. Possible solutions include removing the film with lasers[22] or using tungsten walls, which would not erode[23].

A probable source of a solution is the International Tokamak Experimental Researcher, currently being built in France. It will be used as a prototype to test the reaction on the necessary levels required. Fusion should be available to produce commercial power by 2040.

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