Discuss, with the use of examples, the main differences between α- and β-decay and explain how nuclear fission reactions differ from natural radioactive decay.

The differences between alpha and beta decay

	α-decay	β-decay
Emitted particle	Helium-4 nucleus, 2 protons and 2 neutrons, +2 charge, 4 amu [1]	Electron (made from a neutron dividing into an electron and a proton), -1 charge, 0.00055 amu [1]
Most common in	Heavier elements (atomic number > 83) [1]	Elements with a greater ratio of neutrons to protons (generally elements lighter than lead, atomic number < 82) [2]
Example equations [3]	$^{224}Ra \rightarrow {}^{220}Rn + {}^{4}He$ $^{231}Po \rightarrow {}^{227}Ac + {}^{4}He$ $^{238}U \rightarrow {}^{234Th} + {}^{4}He$	$^{225}Rn \rightarrow {}^{225}Ac + {}^{0}e^{-}$ $^{40}K \rightarrow {}^{40}Ca + {}^{0}e^{-}$ $^{14}C \rightarrow {}^{14}N + {}^{0}e^{-}$

Table 1 - the differences between alpha a nd beta decay
Sources [1], [2], [3]

The differences between nuclear fission and natural radioactive decay

In natural radioactive decay, an unstable isotope of an element decays into a different atom and an emission (alpha/beta particle, or energy in the case of gamma/γ radiation). This is a spontaneous natural process with a random rate.

Nuclear fission is also the splitting of a nucleus into two smaller parts, but each of these is an element in itself. Fission does not happen spontaneously; it requires a trigger. An unstable nucleus bombarded with a neutron will "elongate and divide itself like a liquid drop" [3] as its surface tension is decreased due to its charge [4].

$$^{235}U + n \rightarrow {}^{236}U^{*} \rightarrow {}^{140}Xe + {}^{94}Sr + 2n$$

Reaction 1 – a possible fission reaction of uranium
Source [5]

100 words

Explain the role of hydrogen nuclei and helium nuclei in the synthesis of elements in stars. Give a detailed explanation of the nuclear changes that happen when lithium forms in stars.

Chemical elements were originally created in stars such as the Sun, through processes collectively called **nucleogenesis** [6]. Different elements are produced under the different conditions in each star; in the Sun, the primary "building blocks" are hydrogen nuclei. These hydrogen nuclei fuse to form a helium nucleus, as shown in reaction 1.

$$4\ {}^{1}H \rightarrow {}^{4}He + \text{subatomic particles}$$

Reaction 1 – a fusion reaction of hydrogen-1 to form helium-4 [6]

The energy released by this reaction allows more fusion reactions. Once most of the hydrogen is used up, the helium nuclei start a new series of reactions.

$$2\ {}^{4}He \rightarrow {}^{8}Be$$
$${}^{4}He + {}^{8}Be \rightarrow {}^{12}C$$
$${}^{12}C + {}^{4}He \rightarrow {}^{16}O$$
$${}^{16}O + {}^{4}He \rightarrow {}^{20}Ne$$
$${}^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg$$

Reactions 2-6 – helium-4 fusion reactions [6]

As the helium is used up, the carbon produced in reaction 3 goes on to produce more elements.

$$2\ {}^{12}C \rightarrow {}^{24}Mg$$
$$2\ {}^{12}C \rightarrow {}^{23}Na + {}^{1}H$$
$$2\ {}^{12}C \rightarrow {}^{20}Ne + {}^{4}He$$

Reactions 7-9 – carbon-12 fusion reactions [6]

In reactions 8 and 9, enough hydrogen and helium nuclei are produced to allow the synthesis of more elements. Lithium has two routes by which it can be made:

Route 1: ${}^{4}He + {}^{3}H \rightarrow {}^{7}Li$

Route 2: ${}^{4}He + {}^{3}He \rightarrow {}^{7}Be$

${}^{7}Be + {}^{0}e^{-} \rightarrow {}^{7}Li$

Reactions 10-12 – synthesis of lithium through fusion reactions [6]

In the first route and the first reaction of the second route, the nuclei fuse, simply adding together the protons and the neutrons together to form a larger nucleus. However, the second reaction of the second route is more complicated. The negative electron joins with one of the positive protons in beryllium-7, forming a neutron, [7] in a way that can be thought of as the reverse of beta-decay. This decreases the atomic number by 1, so lithium is formed, but the atomic mass remains the same.

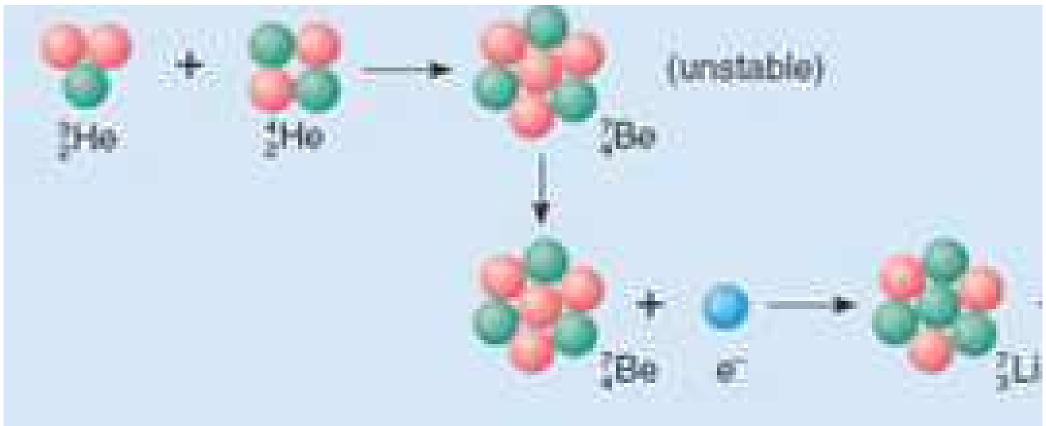

Image 1 – route 2 in the synthesis of lithium
Source [8]

190 words

Describe, with the use of examples, the main characteristics of fission and fusion reactions. Explain how each type of reaction produces energy and describe how these reactions are controlled. Outline the main advantages and disadvantages of using fission and fusion processes for generating electricity.

Fission

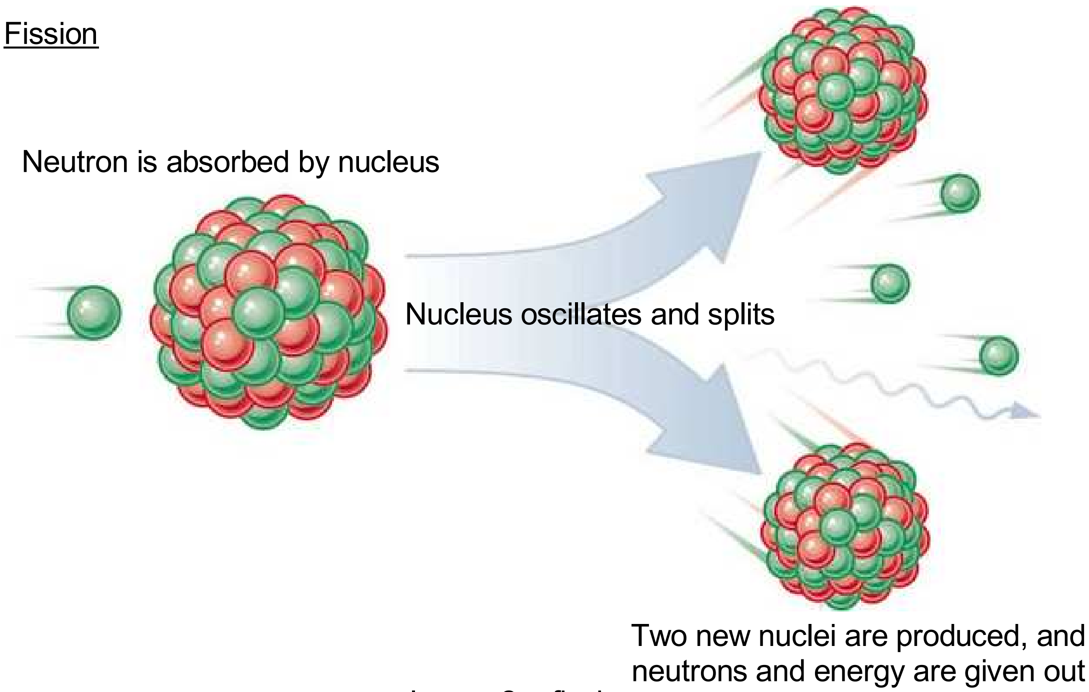

Image 2 – fission
Source [9]

Both of the new nuclei are approximately half the size of the original nucleus. The neutrons given off go on to trigger more fission reactions, in a chain reaction.

Fission reactions give off energy through conversion of some nuclear mass into energy. There is a difference in mass between the reactants and the products, as seen in reaction 13.

$${}^{1}n + {}^{235}U \rightarrow {}^{91}Kr + {}^{142}Ba + 3\,{}^{1}n$$

Reaction 13 – a possible fission reaction of uranium-235
Source [10]

The mass of the uranium + the neutron is 0.1866971 amu [10] (atomic mass unit) greater than the mass of the products combined. The rule of conservation of mass-energy, according to Einstein's $E=mc^2$ (where E is energy in Joules, m is mass in kilograms, and c is the speed of light in a vacuum, 2.99792×10^8m/s), explains that the lost mass has in fact been converted into energy – approximately 1.68×10^{10} kJ/mole [10].

If uncontrolled, fission will accelerate out of control due to more and more neutrons being given off. Nuclear reactors generate electricit y using a mixture of ^{238}U and ^{235}U. ^{238}U does not undergo fission; it absorbs neutrons, interrupting the chain reaction so helping to control it.

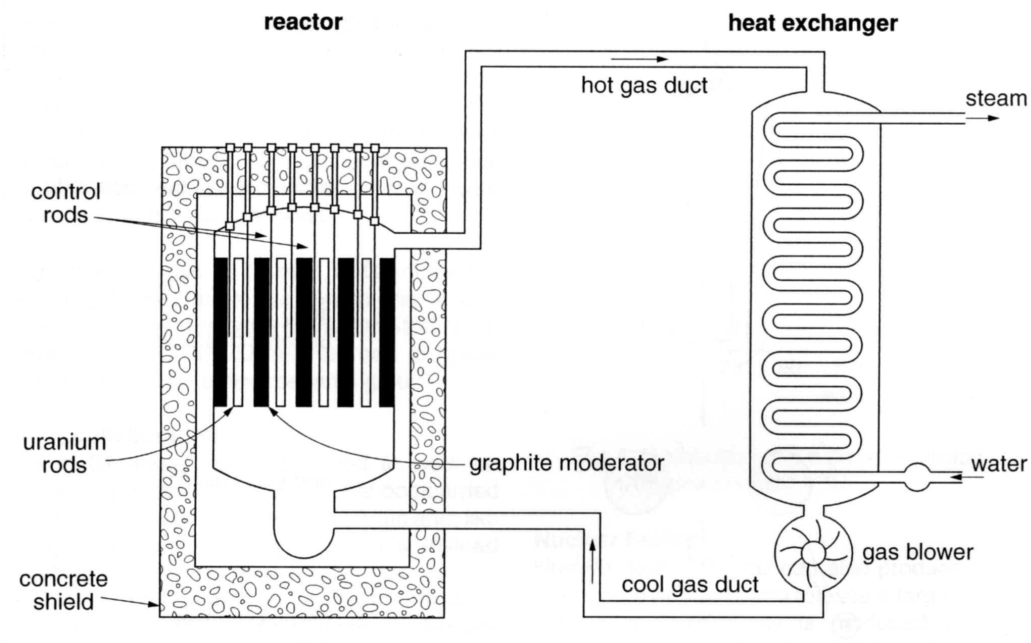

Image 3 – reactor and heat exchanger
Source [11]

The controlling features in the reactor:

- The graphite moder ator slows the neutrons from their high speeds (at which they are less likely to cause a fission reaction on collision with ^{235}U). The high energy of neutrons produced in fission led to the development of the first nuclear bombs.
- The control rods absorb ne utrons, taking them out of the chain reaction. The rods can be moved to different depths to absorb different amounts of neutrons, controlling the rate of reaction. If they are fully inserted, all of the neutrons are absorbed and the reactor shuts down.

The reactor is cooled by passing fluids (often molten sodium metal or carbon dioxide) through pipes around the reactor. This then boils water to form steam, which is used to turn turbines, generating electricity.

Advantages	Disadvantages
Relatively little fuel is needed	Possibility of nuclear meltdown from uncontrolled reaction
Relatively inexpensive once plant is built	Waste products can be used to manufacture weapons
Fuel is available around the world	High initial cost because plant requires containment safeguards
Not believed to contribute to global warming	Storage of radioactive waste with long half-life

Table 2 – advantages and disadvantages of fission as an electricity source
Source [12]

Fusion

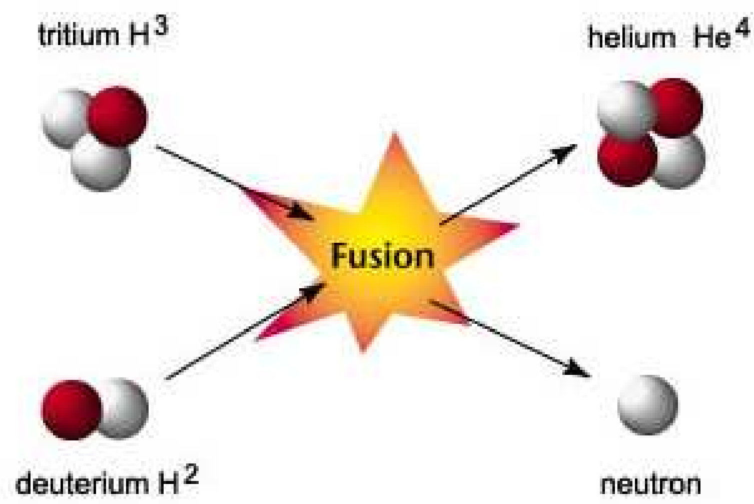

Image 4 – deuterium-tritium fusion reaction
Source [13]

Under the right conditions (see section 4), the repellent forces between the positive nuclei are overcome, and the strong nuclear forces fuse the nuclei together. For experimental electricity production on Earth, the reaction chosen by scientists is the one shown in image 4 – deuterium (hydrogen-2) and tritium (hydrogen-3) forming helium-4 and a neutron.

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

Reaction 13 – deuterium-tritium fusion reaction
Source [14]

This will release energy because the helium nuclei h ave a lower binding energy (the energy holding the neutrons and protons together in the nucleus) than those in deuterium and tritium. In a similar way to fission, the mass of the products is less than the mass of the reactants, and the apparently "missing" mass has been converted to energy [14].

Fusion reactions do not happen naturally in the conditions on Earth – they require the high temperatures found in stars. The deuterium -tritium reaction needs to occur in a 150 million °C plasma. In a plasma (ionise d gas), the electrons are delocalised, forming a "sea" around the positive nuclei. This temperature is reached using a variety of heating methods, and by keeping the plasma away from the cooler vessel walls. In a Tokamak (the structure which is most likely to be used for a fusion power station, more detail in section 4), magnetic fields are generated by large coils, which isolate the plasma from the walls, allowing it to keep its energy for a longer time.

Advantages	Disadvantages
The fuels for fusion reactions are readily available. Deuterium and Tritium are virtually inexhaustible	Scientists have not yet been able to contain a fusion reaction long enough for there to be a net energy gain
Unlike the burning of coal or other fossil fuels, fusion does not emit harmful toxins into the atmosphere, contributing to global warming	Many countries are phasing out fusion research because of the failure to reach a breakthrough
Produces only helium, a gas that is already in abundance in the atmosphere and will not contribute to global warming	The power station structure becomes radioactive due to absorption of neutrons, which may pose health risks to staff
The radioactivity of the structure has a relatively short half-life compared to fission by-products	
Cannot get out of control because only small amounts of fuel are used, and if there is a leak or malfunction, the plasma decays and the reaction stops	

Table 3 – advantages and disadvantages of fusion as an electricity source
Source [15]

490 words

Outline the main challenges that scientists face in developing fusion power stations.

The requirements for sustained fusion in a tokamak (toroidal (ring - shaped) magnetic chamber) are as follows:

- Plasma temperature of 100-200 million Kelvin
  This is needed to overcome the repellent forces between the two positive nuclei to be joined. When power in is equal to power out, it is called **Breakeven** [15]. When the power out heats the plasma so no external heating is required, it is called **Ignition** [15]. Breakeven has been achieved in the JET tokamak, but reaching Ignition would be the challenge in a commercially viable fusion power station.

- Energy confinement time of 4-6 seconds
  This is a measure of how long energy is retained in the plasma. The plasma needs to be kept away from the cooler tokamak walls to increase the energy confinement time. This can be achieved with magnetic fields, although these require a large amount of energy:

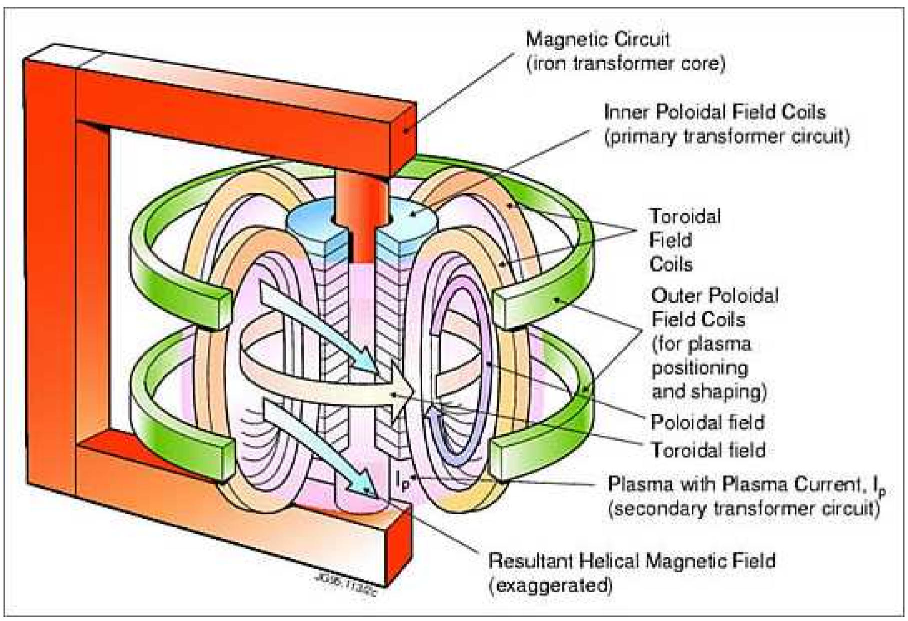

Image 3 – the magnetic fields in the JET tokamak
Source [15]

  A challenge is to find a way of keeping a high energy confinement time with a lower input of energy. This could be achieved with superconductive coils (but these have to be cooled using liquid helium) or laser-induced inertial confinement systems.

- Plasma density of 1-2 x 10^{20} particles/m^3
  The fusion power is decreased if there are impurities in the plasma, such as the helium nuclei produced from the fusion. The challenge is to remove the impurities and to replace the fuel (^2H and ^3H nuclei) without

stopping the reaction, as for Ignition to be reached, the reaction must be continuous [15].

Scientists also need to find out ways of cleaning the plasma -facing tiles of the structure of deposits (mainly hydrogen isotopes, carbon and beryllium).

One challenge is to overcome the negative public view of nuclear power. Fusion only uses a few grams of reactants at any one time, and if there is a leak or a malfunction, the plasma will immediately cool and decay, terminating the reaction.

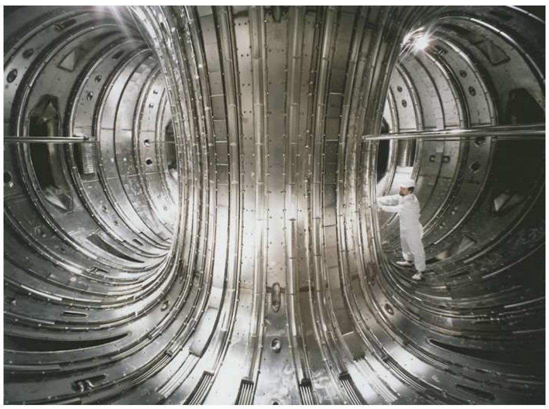

Image 4 – the JET tokamak in 1983
Source [15]

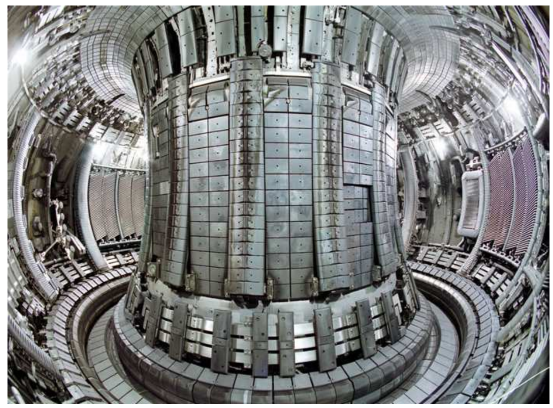

Image 5 – the JET tokamak in 2005
Source [15]

220 words

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