Fission and Fusion

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Nuclear fission

Nuclear fission is the splitting up of a large atomic nucleus into smaller parts (lighter nuclei). It releases lots of energy, which can be used to heat water and turn it into steam. The steam drives a turbine, which is connected to a generator and generates electricity.

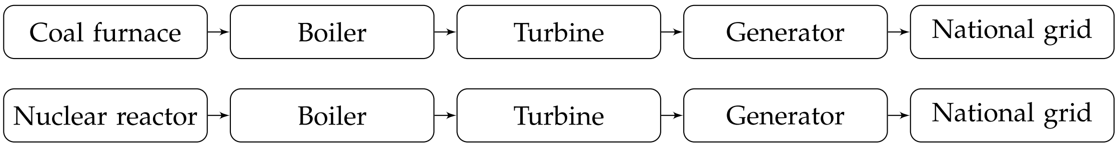

Figure 1: A comparison of a coal-fired power station and a nuclear power station. You should note that these are identical, besides the source of heat used to boil water.

Most nuclear reactors use uranium-235. For fission to occur, the uranium-235 nucleus must first absorb a neutron. An isotope which will undergo fission when it absorbs a neutron in this way is termed *fissionable*. There are two fissionable substances in common use in nuclear reactors: uranium-235 and plutonium-239. When fission occurs the nucleus undergoing fission splits into two smaller nuclei and two or three neutrons, and energy is released.

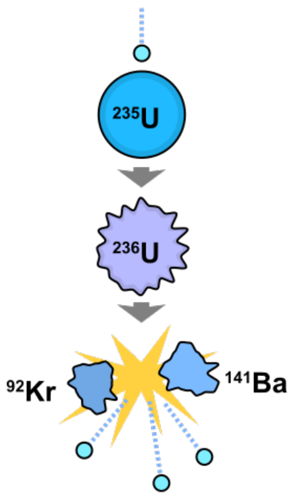

Figure 2: An induced fission reaction. A neutron is absorbed by U-235 nucleus, turning it briefly into an excited U-236 nucleus. This splits and releases three free neutrons.

The extra neutrons released may go on to cause further nuclei to split up, and this can start a chain reaction, in which the neutrons released in one step cause fission in the next.

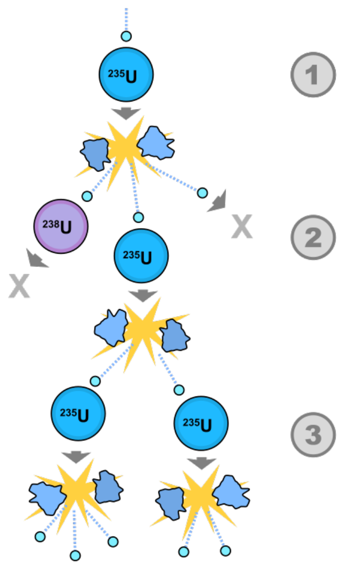

Figure 3: A fission chain reaction. At each stage, at least one neutron released by each fission must go on to cause a further fission on average, or the chain reaction will fizzle out. In stage 2, one neutron is absorbed by an atom of U-238 and another is lost without colliding with anything.

Nuclear fusion

Nuclear fusion is the joining of two small atomic nuclei (like hydrogen) to form a larger one.

This is the process by which energy is released in stars: during a star's lifetime, nuclei of lighter elements join to produce heavier

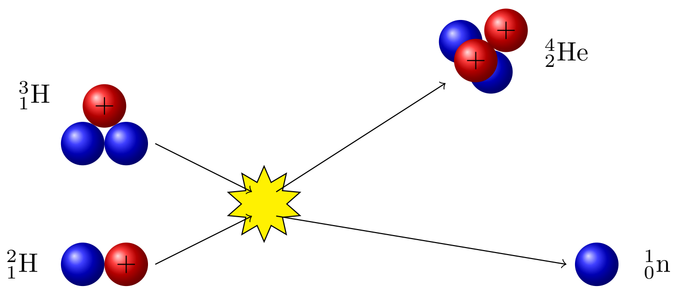

Figure 4: Fusion of deuterium and tritium (two isotopes of hydrogen) to make helium-4. A free neutron and lots of energy are also produced in this process.

elements. These reactions release the energy which is then radiated by stars.

Stellar evolution

Stars form when enough dust and gas from space is pulled together by the attractive force of gravity. At this stage smaller masses may also form and be attracted by a larger mass to form planets, which end up orbiting the star. As the dust and gas is pulled together, the gravitational potential energy lost causes the temperature to rise, and providing enough matter is present, it may become hot enough for nuclear fusion to occur.

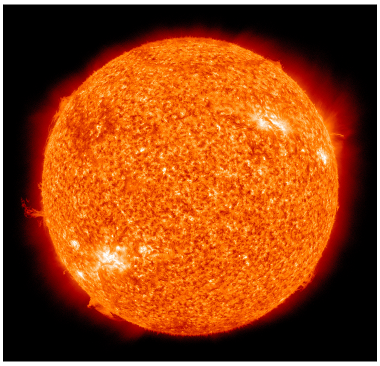

Figure 5: Our star, the Sun, is one of around 100 billion stars in the Milky Way galaxy, which in turn is one of over 100 billion galaxies which make up the universe as a whole. A small fraction (<0.5%) of the Sun's mass comprises the heaviest elements and these are also present in the inner planets; since the Sun is not able to make these elements, this suggests that the Solar System is made up of material produced when earlier stars exploded. The Sun is now about 4.6 billion years old and is around half way through the main sequence. It is producing energy at a rate of 3.8×10^{26} W, fusing 620 million tonnes of hydrogen per second in the process. At the end of the main sequence, our Sun will become a red giant, and it will subsequently collapse into a white dwarf and cool to become a black dwarf.

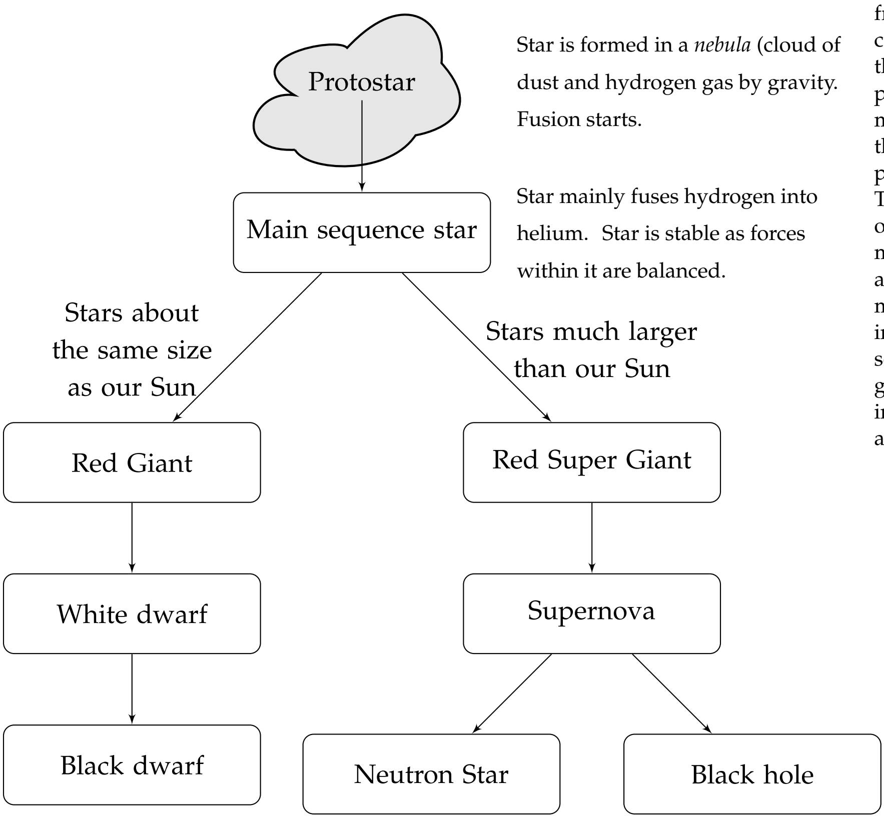

Figure 6: The life cycle of a star is only determined by its mass.

As these processes take place, a star goes through a life cycle. This life cycle is determined by the size of the star, but all stars start by fusing hydrogen to make helium. This process releases huge amounts of energy, meaning that they can maintain their energy output for millions of years. During this 'main sequence' period of its life cycle a star is stable because the forces within it are balanced.

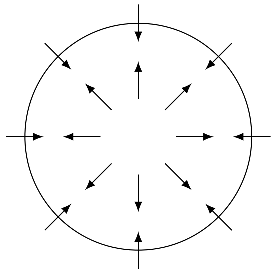

Figure 7: Although the very high temperatures in the centre of stars (close to 15.7 million kelvin for the Sun) create an internal pressure—called the 'radiation pressure'—which tends to make them expand, this is balanced by the force of gravity which attracts all of the matter in the star and tends to bind it together into a ball.

As the star exhausts its supply of hydrogen (this happens in a shorter time for more massive stars, as they have a higher pressure inside meaning that the rate of fusion is greater) the outward pressure needed to counteract the force of gravity is reduced, leading to the core of the star contracting. What happens next depends on the mass of the star.

For mid-sized stars, having a similar mass to our Sun, as the core contracts, it increases in temperature, which heats the outer layers of the star, causing them to expand and cool to a red colour. The star is then called a *red giant*. Eventually, the red giant will contract under its own gravity (or the outer layers may be blown away by radiation pressure from the core, forming a 'planetary nebula') to form a *white dwarf* star. The matter from which it is made may then be millions of times denser than any matter on Earth. It will start out quite hot, but it will gradually lose energy over the next billion years or so to form a *black dwarf*.[1]

[1] The Universe is not old enough for any black dwarfs to exist yet.

Massive stars—which have many times the mass of our Sun—expand much more to become a *red super giant*, although they do not survive in this state. Instead, at some point their core collapses and rebounds in a huge stellar explosion known as a *supernova*. This blows off almost all of the mass of the star in a violent event which releases a huge amount of energy. Indeed, it is common for supernovæ to outshine their entire galaxy for a short time. Such great energy—only found in a supernova—is needed to make elements heavier than iron by nuclear fusion. The matter which is left behind forms a small (usually only 10 km across) dense object is known as a *neutron star*.[2] If enough mass remains, its gravitational field will be so strong that nothing can escape from it, not even light. This kind of object is called a *black hole*.

[2] The pressure is so great at the centre that electrons and protons react together to create neutrons. Although neutron stars are usually only about 10 km across, they are incredibly massive objects.

The early Universe contained only hydrogen but now contains a large variety of different elements, which have been produced by fusion processes within stars. Elements up to iron are made in the stable period of the star, and elements heavier than iron are made in a supernova. All of these naturally occuring elements are distributed thoughout the Universe by the supernova explosions of massive stars at the end of their lives.

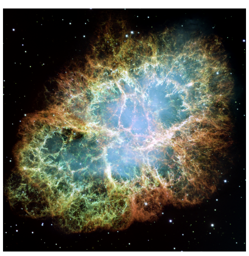

Figure 8: The Crab Nebula, the shattered remnants of a star which exploded as a supernova, the light of which reached Earth in AD 1054