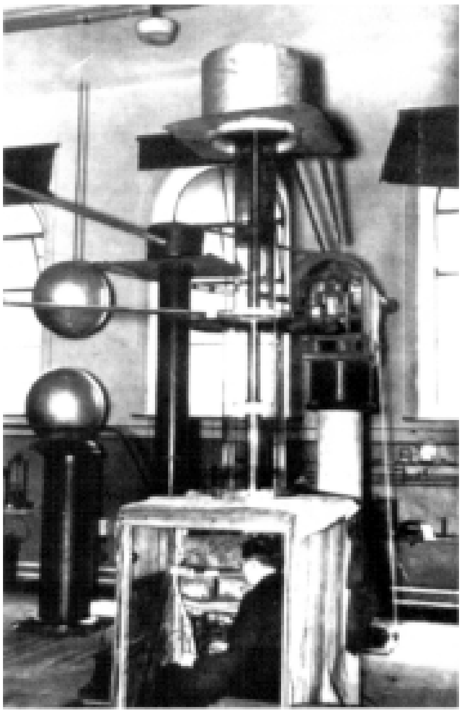
After the Discovery of the Nucleus

All the early work was done using natural radioactivity, mainly alpha particles from radium.

This was a limitation because of the limited energies available, (the maximum was 8MeV) and there was a need to accelerate atoms (as charged particles) to higher energies in a controlled manner.

Walton and Cockcroft were employed by Rutherford to build such a machine, called an accelerator, in a disused room Cambridge. Building a "string and sealing wax" machine with a voltage multiplier system delivering several hundred kilovolts and a zinc sulphide (ZnS) detector, they were able to observe scintillations (flashes of light) characteristic of alpha particles when lithium was bombarded with hydrogen atoms (protons).

These experiments were confirmed by observation in a cloud chamber.



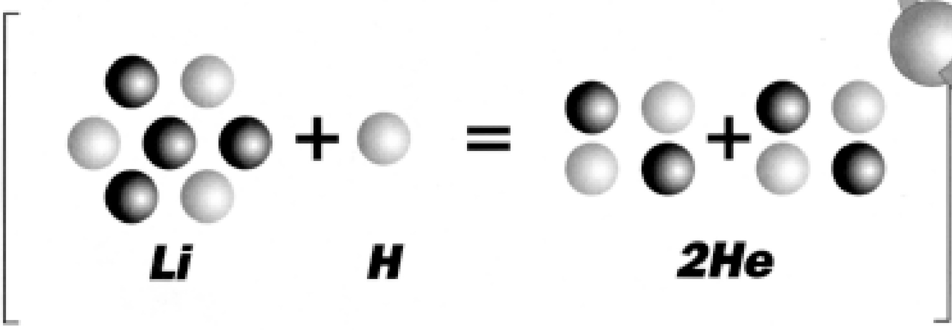
Cockroft/Walton Accelerator

Discovery of the Neutron

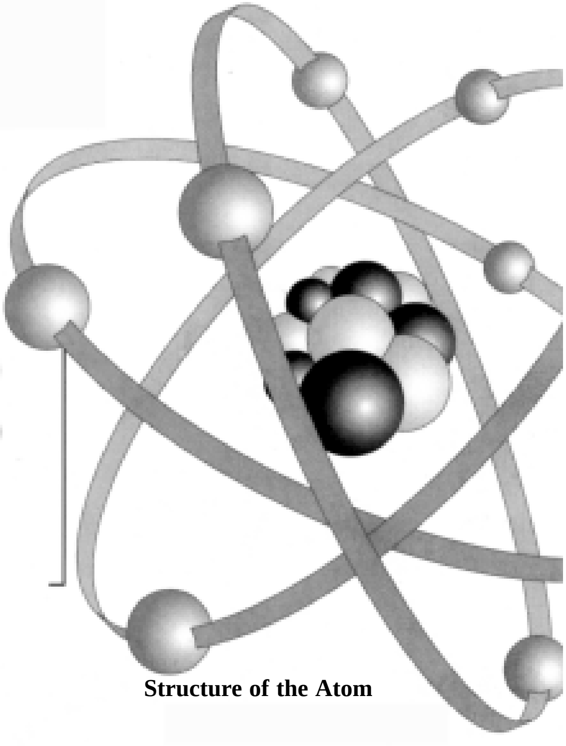
Further parts of the jigsaw puzzle of the structure of the atom came from the discovery of the neutron by Chadwick in 1932. This again was the result of bombardment experiments. Alpha particles on Li or Be produced a particle which caused light atoms to recoil and produced the following nuclear at the Cavendish Laboratory in reaction which was identified in cloud chamber.

$$^{14}_{7}N + ^{1}_{0}n = ^{4}_{2}He + ^{11}_{5}B$$

the alpha particle and the B recoil being identified, but the neutron "appeared out of the blue" because it did not cause ionization being uncharged.



lithium/hydrogen equation



Structure of the Atom

Structure of the Atom

Rutherford thought that the neutron consisted of a proton and an electron as this would explain the absence of charge and give approximately the correct mass. The proton is now thought to consist of a neutron and a positron (a positively charged electron).

The discovery of the relationship between x-ray spectra (emission of light in the form of x-rays from excited atoms) and atomic number (the number of protons in an atom) by H.G.J. Moseley and the proposal of quantum numbers by Neils Bohr gave further explanation as to how the atomic structure worked.

So the discovery and subsequent investigation of radioactivity provided the basis of the modern theory of atomic structure.

In 1935 O. Hahn and F. Strassman working at the Kaiser Wilhelm Institute, Dahlem, bombarded uranium with neutrons and demonstrated that the products had a much lower mass than uranium.

By 1939 they had identified at least ten different radioactive species. They had, for the first time, caused the atomic nucleus to split into fragments, which is fission. Subsequent work showed that beside producing fission products, 2 or 3 neutrons were produced.

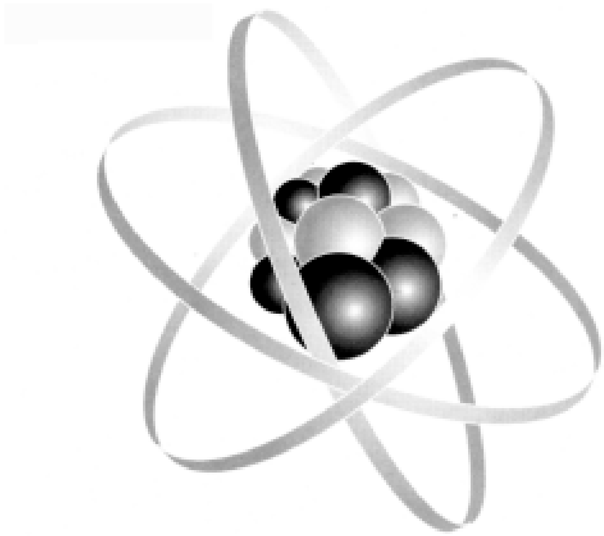
The fission of uranium-235 does not produce the same products each time but can occur in a variety of different ways.

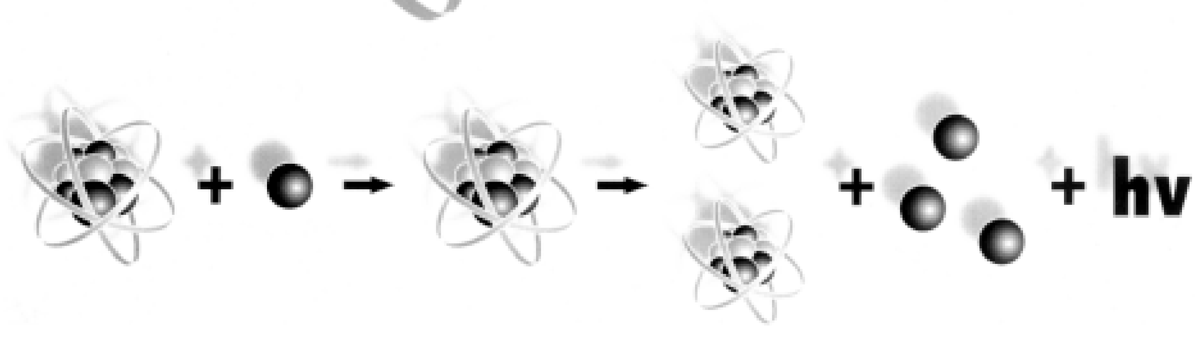
O. Hahn and E Strassman

Fission Yield from Uranium-235

Clearly for each fission taking place the sum of the masses of the two fission fragments plus the number of neutrons must equal 236, 235 + 1 neutron.

The fission of uranium-235 is initiated by slow neutrons, that is with low energy, whilst the neutrons which are produced by the fission process have a high energy and are called fast neutrons. If the energy of these neutrons could be reduced then they would create fissions in further uranium-235 atoms thus creating a chain process.





235U neutron 236U fission neutrons energy

The fission process

Atomic Pile at the University of Chicago

The first nuclear reactor demonstrating a controlled chain reaction was erected by Enrico Fermi in 1942. It was constructed on the squash court of Stagg Field at the University of Chicago under conditions of great secrecy. Even the President of the University was not informed!!!

The fuel for the reactor was natural uranium and graphite acted as a moderator. The moderator reduces the energy of the fast neutrons. Thus on December 2nd 1942 the operation of a controlled self-sustained nuclear reactor was demonstrated and the reactor was said to have "gone critical". The reactor was shut down the same day by inserting boron rods to absorb the neutrons.

Manhattan Project Team

Nuclear fission is accompanied by the production of energy which is released as heat, hence nuclear reactors using uranium could be used for the the second World War the Manhattan Project at Los Alamos, USA was set up to use this newly discovered process of fission for the purpose of mass destruction.

Isotopic Composition of Natural Uranium

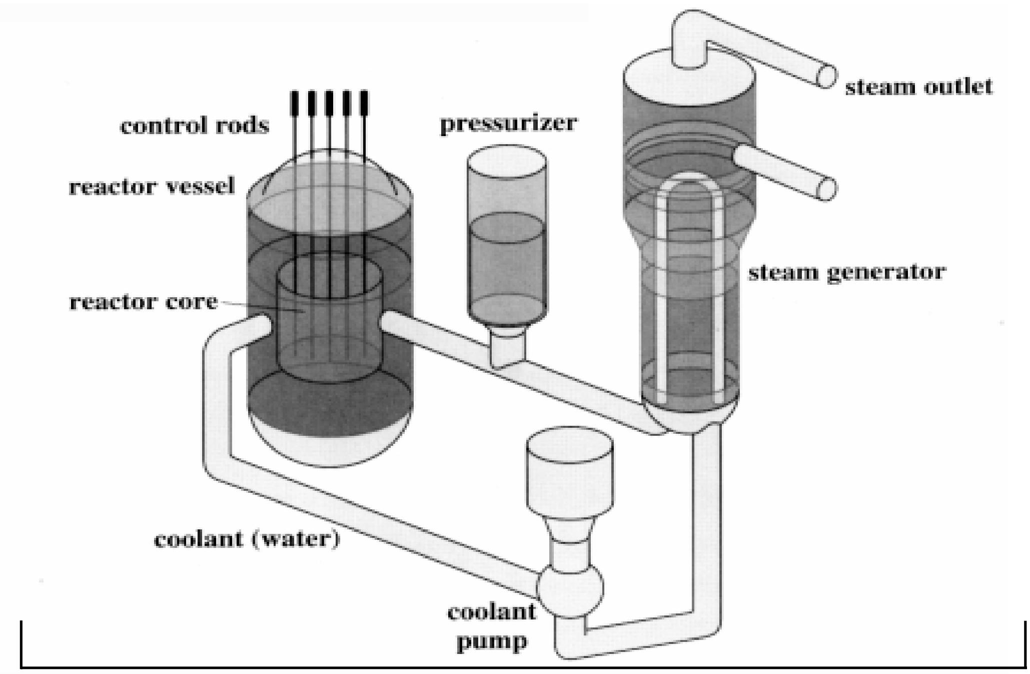
Uranium-238 is the most abundant isotope of uranium, 99.2%. Uranium- 235 is 0.72%

Ableson, working for the US navy, realized that nuclear reactors would be ideal for submarines but would need to be physically much smaller. This could only be achieved by using fuelenriched in the uranium-235 isotope. (Natural uranium contains 0.72% of the 235 isotope, and enrichment produces higher values). He therefore started a programme of enrichment using gaseous uranium hexafluoride in gas diffusion cells. He produced uranium enriched in mass 235 from 0.72% to 1%. The Manhattan team so arranged to acquire the patent from Ableson for the sum of $1. It is said that he is still waiting to be paid!!

Production of Plutonium-239

The early years of the Manhattan programme brought new discoveries with the production of transuranic elements (elements beyond uranium in the Periodic Table). The first in 1940 was Neptunium, produced by deuteron bombardment of uranium-238 by G.T. Seaborg and his co-workers. The isotope produced was neptunium-238 which decayed by beta emission to plutonium-238, the second transuranic element to be reported. Subsequently, plutonium-239 was found to be produced in a nuclear reactor by neutron bombardment of uranium-238.

In 1944 an atomic pile, designed to produce large quantities of plutonium, went critical.



Cross-section of a reactor

Atomic bomb

In order to make a nuclear explosion it was necessary for the Manhattan Project to make a chain reaction proceed at an uncontrolled rate. This necessitated the enrichment of a critical mass of uranium in the isotope 235, and then keeping it subcritical for safety. For the explosion to take place the critical mass had to be regenerated for a long enough time. This has been described as the requirement to build "a bomb within a bomb with a bomb outside it".

A tall order but, in August 1945 two such weapons were dropped on Japan with the well known outcome.

Atomic Explosion, Hiroshima

Calder Hall

Following the second World War a great emphasis was placed on the peaceful uses of radioactivity and of Atomic power. It resulted in the first token use of a nuclear power reactor at Argonne National Laboratory, USA in 1951. However, it is widely accepted that the first Nuclear Power Reactor to be connected to a local electricity grid was operated at Calder Hall, Cumbria, UK in 1956.

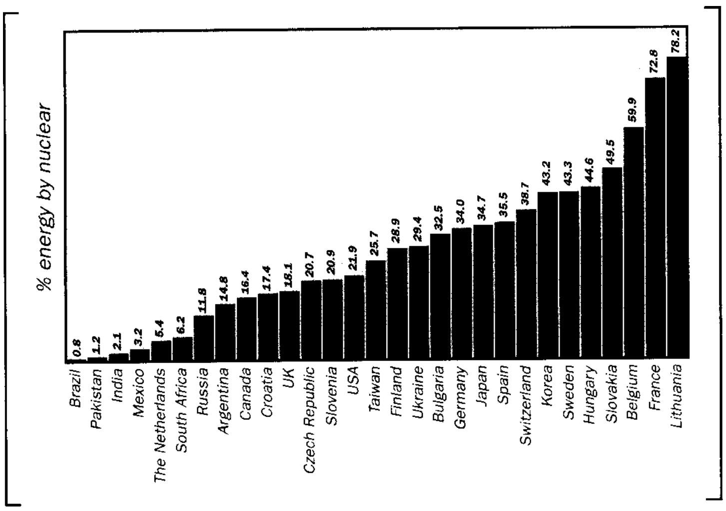
The Calder Hall reactor used natural uranium fuel as a source of fission which generates heat. The worldwide generation pattern is:

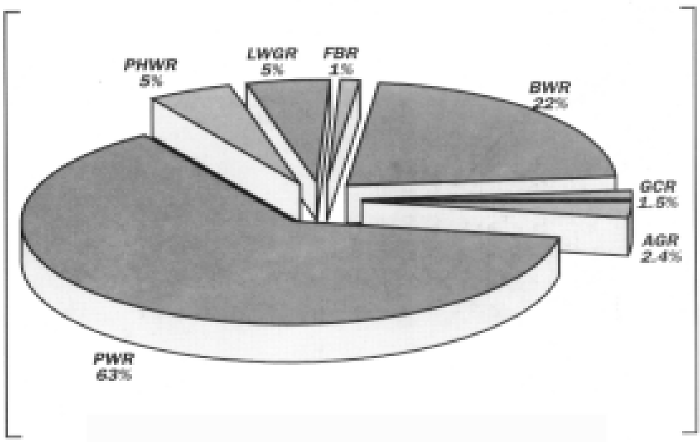
The development of isotopic enrichment described earlier allowed uranium fuel with a higher than normal uranium-235 concentration to be manufactured. This led to the second tier of nuclear reactors, the Advanced Gas Cooled Reactor (AGR) in the UK.

Meanwhile the rest of the world had been experimenting with water cooled reactors. Again the advent of enriched fuel meant that normal high purity water could be used as the moderator and as the coolant. Development led to the Pressurized Water Reactor (PWR) becoming the World's most popular reactor.

The first nuclear powered submarine

Nuclear power has not been confined to electricity production, it has been used as a power source for a range of ships. Nuclear powered submarines are perhaps the most well known. These were first launched in 1954 by the USA. All such vessels use water cooled and water moderated reactors as they can be built on a compact scale.





Graphite was used as a moderator to slow down the fast neutrons produced in fission. The slower neutrons induced further fissions and the design of the reactor ensured a controlled fission chain reactor took place. The heat generated was removed by carbon dioxide to the boilers. Stearn raised in the boilers was used to generate electricity. This basic design was subsequently used for the Magnox Nuclear Reactors operated by the Central Electricity Generating Board, the first of which went critical in 1962 passing electricity to the grid at Berkeley, Gloucestershire and Bradwell in Essex.

In 1992 18% of electricity is produced by nuclear power in the UK. The major sources of uranium are Canada, Niger, Namibia and Australia.

Proposed fusion reactor

Fission of the heavy elements produces energy as seen above. Energy can also be produced by the fusion of light elements. For example, the fusion of deuterium and tritium to form helium produces a large amount of energy per unit mass. As with many scientific discoveries however, converting the theoretical dream to a practical reality takes much effort, time and finance. The race is still on to build the first fusion reactor for the production of electricity.