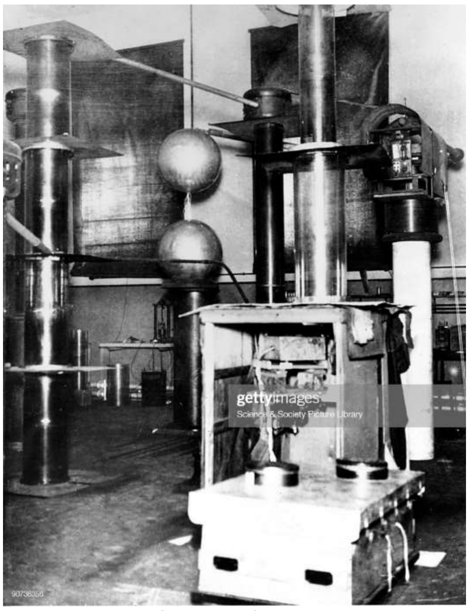
No. 2 in a series of essays on radioactivity produced by the
Royal Society of Chemistry Radiochemistry Group

After the Discovery of the Nucleus

All the ``early work was done using natural radioactivity, mainly α particles from radium.
This was a limitation because of the limited energies available (the maximum was 8 MeV) and there was a need to accelerate atoms (as charged particles) to higher energies in a controlled manner.

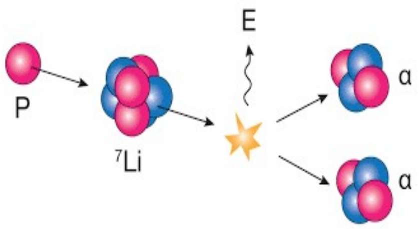
Walton and Cockcroft were employed by Rutherford to build such a machine, called an accelerator in a disused room in Cambridge.



Walton and Cockcroft Accelerator

A working prototype machine with a voltage multiplier system delivering several hundred kilovolts and a zinc sulphide (ZnS) detector was built. They were able to observe scintillations (flashes of light) characteristic of α particles when lithium was bombarded with hydrogen atoms (protons).

These experiments were confirmed by observation in a cloud chamber.

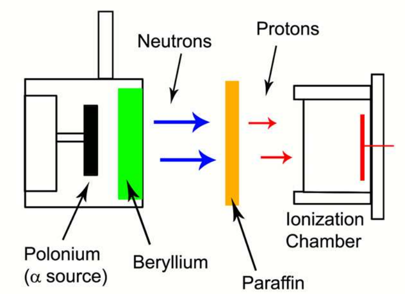


The lithium/hydrogen equation

Discovery of the Neutron

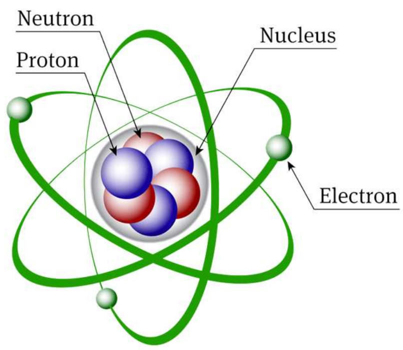
Further parts of the jigsaw puzzle of the structure of the atom came from the discovery of the neutron by Chadwick in 1932. This again was the result of bombardment experiments, where α particles bombarding Be produced an energetic neutral particle:

$$^{9}_{4}N + ^{4}_{2}\alpha \rightarrow ^{12}_{6}O + \ ^{1}n$$



Chadwick's Neutron Experiment

The neutron "appeared out of the blue", because it did not cause ionisation, being uncharged. But when focussed on a substance rich in protons (paraffin), protons were knocked loose which were easily detected by a Geiger Counter.



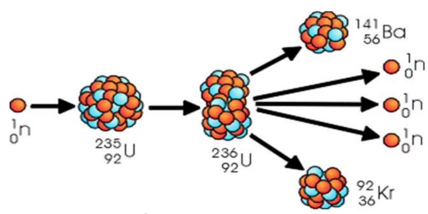
Structure of the atom

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. Moseley, and the proposal of quantum numbers by Neils Bohr gave further explanations of the atomic structure.

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



Fission of uranium by a neutron

In 1935 O. Hahn and F. Strassmann 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, fission. Subsequent work showed that beside producing fission products, 2 or 3 neutrons were produced with each fission event. The fission of ^{235}U does not produce the same products each time but occurs in a variety of different ways.

O. Hahn and F. Strassmann

Fission Yield from ^{235}U

Clearly for each fission taking place the sum of the masses of the two fission fragments plus the number of neutrons must equal 236 (from ^{235}U and capture of one neutron).

The fission of ^{235}U is initiated by slow neutrons (low energy), while 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 ^{235}U atoms thus creating a chain 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 using graphite as a moderator. The moderator reduces the energy of the fast neutrons. Thus, on December 2nd 1942 the operation of a controlled self-sustaining 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 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

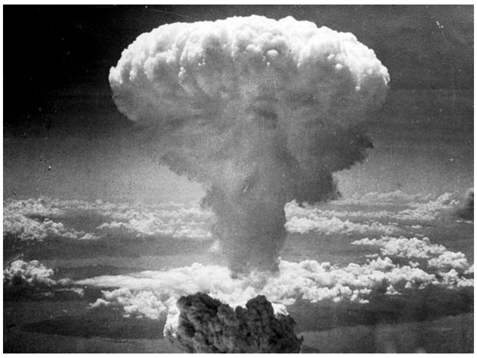
^{238}U is the most abundant isotope of uranium, present at 99.2 %, with ^{235}U being present at just 0.72 %.

Abelson, working for the US navy, realised that nuclear reactors would be ideal for submarines but would need to be physically much smaller. This could only be achieved by using fuel enriched in the ^{235}U isotope. (enrichment increases the ^{235}U content to above natural). He therefore started a programme of enrichment using gaseous uranium hexafluoride in diffusion cells. He produced uranium enriched in ^{235}U from 0.72 to 1 %. The Manhattan Project team so arranged to acquire the patent from Abelson for the sum of $1. It is said he is still waiting to be paid!

Production of ^{239}Pu

The early years of the Manhattan Project brought new discoveries with the production of transuranic elements (elements beyond uranium in the periodic table). The first, neptunium, was produced in 1939 through neutron bombardment of ^{235}U by McMillan and Abelson, producing ^{239}Np, which had a half-life of just 2.3 days. Its β decay product gave rise to the second transuranic element, ^{239}Pu. Subsequently, ^{239}Pu was found to be produced in a nuclear reactor by neutron bombardment of ^{238}U. In 1944 an atomic pile, designed to produce large quantities of plutonium, went critical.

Atomic Bomb

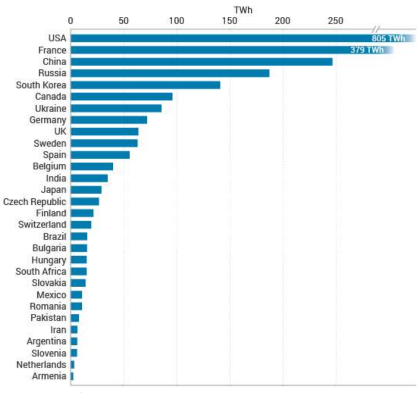


Atomic Bomb Explosion

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

Calder Hall

Following the Second World War a great emphasis was placed on the peaceful uses of radioactivity and nuclear 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.



Nuclear energy production by country in 2017

The Calder Hall reactor used natural uranium as a fuel source where the fission events generate heat. The amount of electricity generated across the world by country in 2017 is shown the Figure.

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 reaction took place. The heat this generated was removed by carbon dioxide to the boilers, Steam that was raised in the boilers was used to generate electricity. The basic design was subsequently used in the UK 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.

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

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 Pressurised 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 miniature PWR type reactors as they can be built on a compact scale.

A Pressurized Water Reactor (PWR)