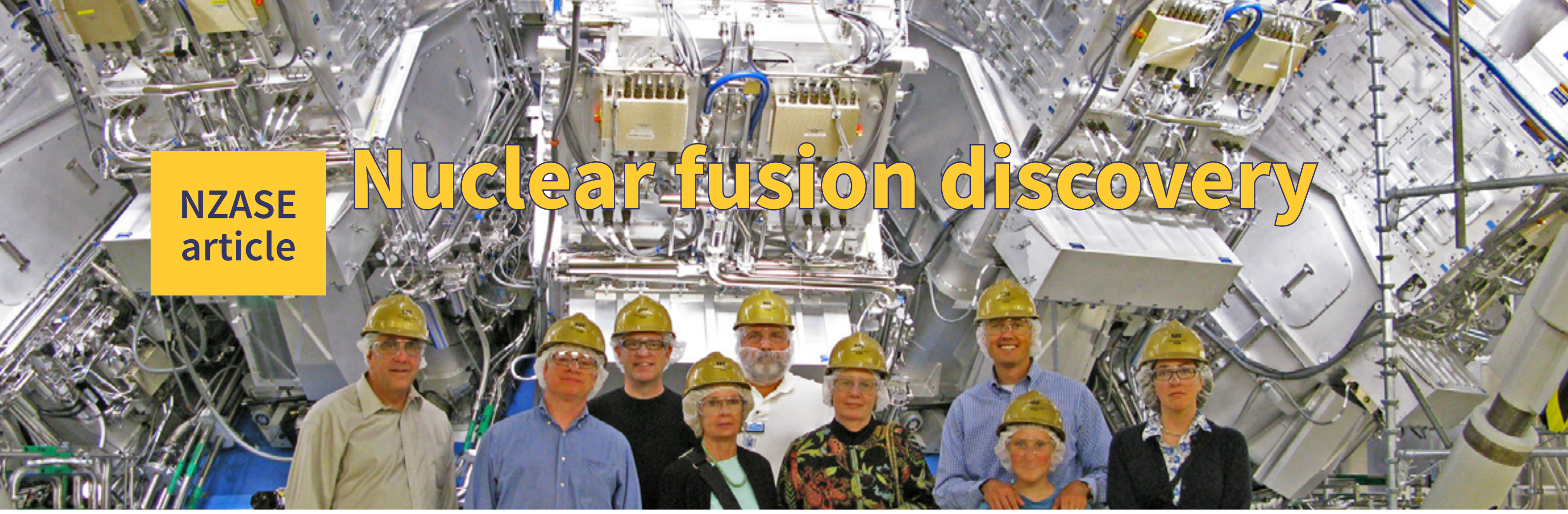
NZASE article

Nuclear fusion discovery



Lawrence Livermore National Laboratory staff and nuclear fusion reactor, USA. Steve Jurvetson, Flickr.

Scientists recently announced an important breakthrough in fusion experiments. What did they achieve and why is it important? NZASE Science Communicator Mike Stone investigates.

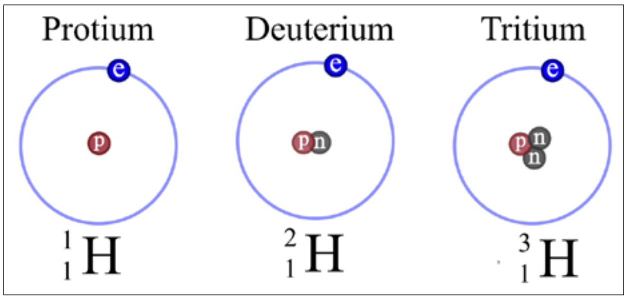
Atomics

An atom's nucleus is held together by a balance of two opposing forces: an attractive force (called the Strong Nuclear Force) holding the protons and neutrons tightly together, and a repulsive force between positively charged protons.

For nuclei smaller than Fe-56 there are relatively few protons, and so the net force is attractive. Larger nuclei are held together less strongly, as the attractive force can only act over a short distance. Both small and large nuclei can be unstable and release energy in nuclear reactions.

The energy released in nuclear reactions is much larger than in chemical reactions, because the forces holding the nucleus together are much greater than the force holding electrons to a nucleus.

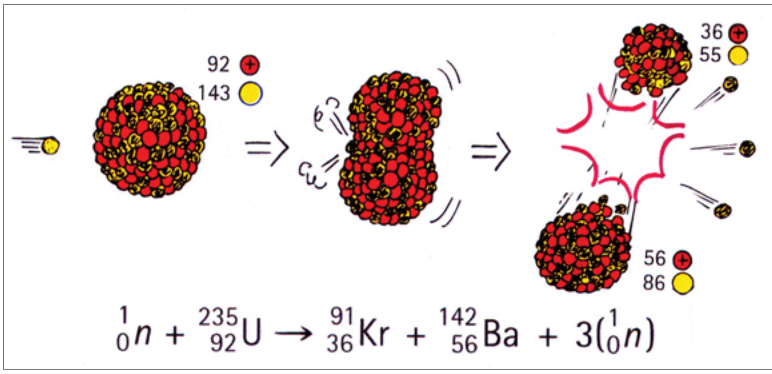
Hydrogen holds a key role in some nuclear reactions. Hydrogen has three isotopes, with varying numbers of neutrons. On average over 99.98% of hydrogen atoms are protium, about 0.02% are deuterium, and tritium makes up about 10^{-18} of a percent. Protium is the hydrogen atom we are more familiar with (H-1), and has a lone proton in its nucleus, like all isotopes of hydrogen. Deuterium's nucleus also has one neutron (H-2), while tritium has two (H-3), and these two substances are considered heavy hydrogen nuclei.



The isotopes of hydrogen., by Wayne Breslyn.

These heavy isotopes are found in a percentage of all molecules that contain hydrogen, including, importantly, water. This percentage, though, differs in different water sources – so analysis of hydrogen isotopes can be used to identify the origin of any water tested.

Fission



A typical uranium fission reaction. National Science Teaching Association, USA.

Nuclear fission occurs in fairly large nuclei, where an imbalance between the attractive and repulsive forces means the nucleus is unstable. Here, the two sides of a nucleus are far enough apart that the strong nuclear force can't hold it together and the positive repulsion breaks the nucleus apart.

These nuclei break up into several fragments – smaller nuclei and neutrons. For example, when it absorbs a neutron, U-235 can split into Kr-92 and Ba-141. The reaction also produces several free neutrons and gamma rays.

However, the composition of the products from these reactions is unpredictable; sometimes the fission of uranium produces Xe-134 and Sr-100 plus a neutron.

Fission was discovered in Germany in

1938 by Otto Hahn, Fritz Strassmann and Lise Meitner. Scientists fleeing Nazi persecution brought the knowledge to America and became their research leaders. The US Manhattan Project used fission to create the world's first atomic bomb, testing it in the Nevada Desert in 1945.

The significance of fission is that the reaction releases a large amount of energy, both as electromagnetic radiation and the kinetic energy of the fragments. In this reaction, the products have measurably less mass than the reactants. Using Einstein's equation, $E = mc^2$, the energy released from that lost mass can be calculated. One fission reaction can release 3.2×10^{-11} J, which may seem small, but it means a 1 kg mass can generate 9×10^{16} J, enough to allow a Boeing 737 to cross the Atlantic 90,000 times.

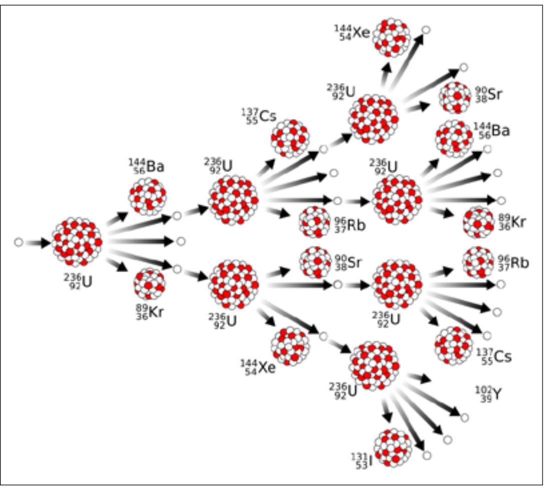
This energy can be harnessed for use in nuclear power as well as nuclear weapons. Both of these rely on self-sustaining chain reactions: neutrons released by one reaction trigger other reactions and those neutrons also start others, spreading very quickly.

The isotopes that can sustain a fission chain reaction are called nuclear fuels, and are said to be fissile.

As well as being induced synthetically by a neutron, nuclear fission can happen naturally, although this is rare. It is mostly seen in elements with mass numbers of 230 or more, such as uranium, plutonium, thorium and others.

Remember, any lump of uranium will be a mix of isotopes, and only the rarest of these will undergo fission, natural chain reactions are uncommon. Radioactive elements release nuclear particles of different types, called alpha or beta decay. Elements that undergo synthetic fission show exponential decay and have half lives.

Fission chain reaction. Mike Run, CC BY-SA 4.0

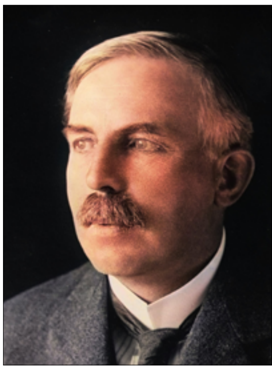


The release of neutrons from fission of the Californium-235 isotope can be used to inspect airline luggage for hidden explosives or measure moisture levels in soils or grains stored in silos. It works by measuring and analysing the gamma-ray signature returned by every component in a targeted item after they are hit by neutron bursts.

The Grafenrheinfeld nuclear reactor, in the spherical building, with its distinctive cooling towers, Germany, 2013. By Avda, CC BY-SA 3.0.

Old smoke detectors used to use the slow fission of Americium, sounding an alarm when the smoke reduced the amount of radiation detected by the sensor.

Rutherford's contribution



Ernest Rutherford, a scientist from Aotearoa New Zealand, made three important breakthroughs in our understanding of the atomic nucleus and its decay, from 1898 to 1919.

- He showed that larger nuclei have a tendency to decay into smaller nuclei, in the process discovering alpha and beta rays. This work gained Rutherford the 1908 Nobel Prize for Chemistry, and also heralded carbon dating techniques that are still important today.
- From his famous gold leaf experiment, Rutherford realised the atom was a tiny nucleus surrounded by orbiting electrons, with empty space between the two.
- Rutherford created the first artificial nuclear reaction, using alpha rays to split nitrogen into an oxygen atom and a hydrogen nucleus, releasing energy. While he became known as the first to split the atom, his process was not the same as fission, which was discovered after his death.

He was also part of developing the science behind Geiger counters and modern smoke detectors. As an important scientist, when he died in 1937, Rutherford's ashes were interred in Westminster Abbey.

Fusion

Nuclear fusion is a reaction where two small nuclei are merged to form a single, heavier nucleus. Energy is released from the mass lost in this reaction, by Einstein's equation above. If the new product is small, lighter than Fe-56, the fusion reaction will release energy (exothermic). A nuclear fusion reaction making heavier nuclei is endothermic, as instead of being released, the energy is used to hold the nucleus together.

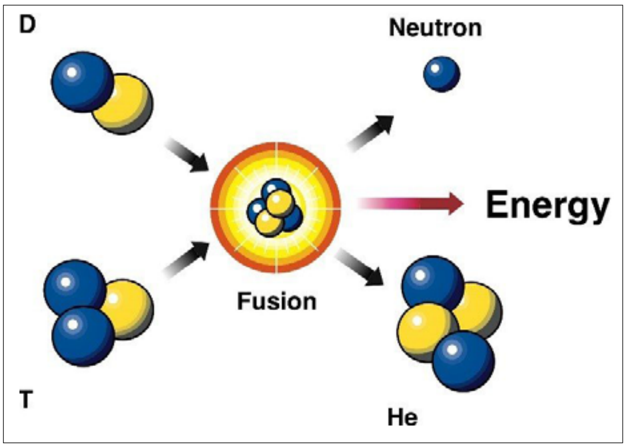
Scientists are most interested in fusing deuterium and tritium, because this reaction occurs at lower temperatures and releases much more energy than other reactants. This reaction forming helium is the main reaction releasing large amounts of energy in the sun and other stars.

There are two main types of reactors for nuclear fusion. Magnetic confinement reactors, such as a tokamak, use a magnetic field to confine the heated plasma and are usually shaped like a doughnut. Inertial confinement reactors fire laser pulses at a tiny pellet. The explosion of the outer pellet compresses the inner layers and triggers fusion.

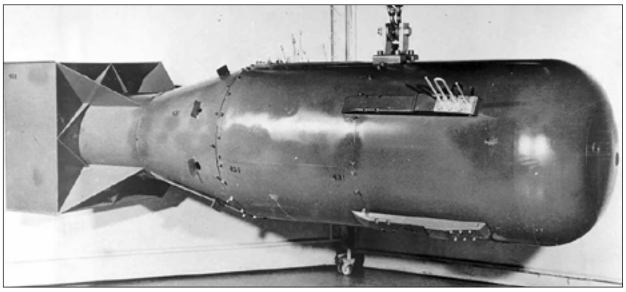
There are some difficulties with generating fusion that we have not fully overcome.

- These reactions require high enough temperature and pressure (100 million °K, 203 kPa) to create plasma, a hot cloud of ions and their free electrons. So far, creating the right conditions uses up more energy than is generated.
- The neutrons released in the reaction degrade many fo the materials commonly used to construct the reaction chamber.

The deuterium (D) and tritium (T) fusion reaction, which produces a helium nucleus (or alpha particle) and a high energy neutron. Office of Science, US Department of Energy.



After the reactions powering the sun were worked out in the 1920s and 1930s, scientists began trying to recreate this reaction on Earth. Nuclear fusion was first achieved in 1952, in a hydrogen thermonuclear bomb test, as part of the Manhattan Project – but this reaction used more energy than it released.



The Little Boy atomic bomb, the type dropped on Hiroshima. US Department of Defense.

Comparing fission and fusion

Nuclear fission uses lighter elements, such as hydrogen and helium, which are in general more fusible, while the heavier elements, such as uranium, thorium and plutonium, are more fissible.

As a source of power, nuclear fusion would have advantages over fission.

- There is less waste product and it is not as dangerous. Fusion's waste product is inert helium, rather than radioactive material. The process uses tritium, and while radioactive (it's a beta emitter) it has a short half-life and only a small amount is used. However, neutrons can damage the reactor chamber.
- The fuel hydrogen is plentiful compared with uranium, which is hard to get and expensive.
- Fusion cannot cause a nuclear accident, as there are no chain reactions. Any disruptions tend to cause the plasma to cool and the nuclear reactions to stop.
- Fusion reactions produce more energy per unit mass than fission, so need less fuel.

However, only fission is currently being used in nuclear power stations.

2022 breakthrough

Scientists, working at Lawrence Livermore National Laboratory (LLNL) in California, claim to have successfully generated a nuclear fusion reaction. This means their fusion reactions generated more energy than was put in.

Deuterium and tritium both have a positively charged nucleus and they need to be pushed together against the force of their repulsion. This was done by heating the isotopes in a plasma to temperatures where the nuclei are going so fast they can overcome the repulsion and fuse together.

An array of lasers delivered 2.05 MJ of energy to a tiny cylinder holding a pellet of frozen deuterium and tritium, and in a fraction of a second, the nuclear fusion released 3.15 MJ.

While this is momentous, the energy difference might be only enough to boil a jug. And critics point out that the lasers needed 500 MJ of energy to deliver their pulse, so the energy output was, in fact, less than the input.

As nuclear fusion promises safely to free us from fossil fuels for power generation, scientists in many labs around the world are working to improve the process. They need to turn the one short pulse into one continuous pulse, compensate for losses in the input infrastructure, and engineer stronger materials capable of withstanding the harsh fusion environment for long periods of time.

Although fusion power generates no greenhouse gases and minimal nuclear waste, it is unlikely to be at scale soon enough to save us from climate change. Nuclear fission and renewable energy will be the main energy sources to take over from fossil fuels, at least initially. Scientists hope that fusion power might be the long-term answer.

Glossary

Alpha particle: A helium nucleus, i.e. two neutrons and two protons.
Beta particles: Electrons that fly out of the nucleus when a proton changes into a neutron.
Electromagnetic radiation: An electric and magnetic disturbance travelling through space at the speed of light; eg, radio waves, microwaves, infrared, light, ultraviolet, X-rays, and gamma rays.
Endothermic: Reactions that absorb energy; if in a test-tube, it will feel cold.
Exponential decay: As nuclei in a lump of, say, uranium undergo fission, the proportion of unstable nuclei in that lump gradually decreases over time.
Gold leaf experiment: Rutherford fired alpha particles at a very thin sheet of gold and found most passed right through, while others deviated or even rebounded.
Half-life: The time it takes for half the nuclei in a radioactive sample to have undergone fission.
Isotopes: Different forms of an atom, with varying quantities of neutrons, and therefore different mass numbers.
Kinetic energy: The energy of things that are moving.
Molecule: Particle made up of two or more atoms covalently bonded together. The atoms may be the same or different; eg, N_2 or H_2O.
Radioactive: Substances that contain nuclei that undergo fission spontaneously.
U-235: One way to write the mass number of an element (uranium).

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Ngā Kupu

Hauwai – Hydrogen
Honokarihi – Fusion
Huanga whaiwhai – Chain reaction
Irahiko – Electron
Iramoe – Neutron
Kanoirite – Isotope
Karihi – Nucleus (of an atom)
Konukarihi – Uranium
Pūhohe karihi – Nuclear reactor
Tauhohe karihi – Nuclear reaction
Wehekarihi – Fission.

From Paekupu