# NATBC0815 “Return to the Centre of the atom” – Briefing notes for teachers

## Introduction

These notes are intended to form a briefing relating to Nuclear and Particle Physics and their applications. They are by no means exhaustive and scratch the surface in terms of the diversity of the subject. References and weblinks are provided to much more detailed resources.

## The nucleus

The story of nuclear physics is just over 100 hundred years old. Arguably our present picture can be dated to the famous gold foil scattering experiment (1909) of Geiger and Marsden, in which alpha particles were fired at a gold foil. Most passed through the foil with minimum deflection but a few were deflected back towards the source. This was later interpreted by Rutherford as showing that most of atoms is empty space and that the mass is concentrated in a dense central core – the atomic nucleus, which also had a positive charge balancing the negative charge of the electrons. The positively charged particles that made up this nucleus were called protons. It took another twenty years before later experiments showed that a further uncharged particle  - the neutron also made up the nucleus and that under certain circumstances these could be expelled from the nucleus and be detected. Later work showed that protons can transform themselves into neutrons via the weak interaction (beta-decay) and that therefore the proton and neutron are aspects of the same particle – the nucleon. As physicists probed these particles at increasingly higher energy, it turned out that they were in turn made of quarks. This lower level of description is not so important for discussing most of the properties of atomic nuclei.

Understanding the nucleus continues to challenge physicists as it is a “*mesoscopic system*”. In other words, for all but the lightest nuclei whose properties can be solved exactly, the nucleus has around 100 particles in it for which it is not possible to apply a statistical approach.  Indeed, at some level the nucleus feels the effects of all the four forces: the strong and weak nuclear forces, electromagnetism and gravity.

The chemical element is defined by the *atomic number*, Z, i.e. the number of protons which make up its nucleus, which has a one-to-one matching with the number of orbiting electrons for a neutral atom. *Isotopes* of a given element have the same atomic number but varying numbers of neutrons. The sum of the number of protons and neutrons gives the *atomic mass* (A). For lighter nuclei, the most stable isotopes are often those with equal numbers of protons and neutrons (N=Z). For heavy nuclei, this line bends over as it is easier to add more neutrons. There are about 300 stable isotopes in nature of elements from Hydrogen (Z=1) to Uranium (Z=92). A small number of the elements in this range such as Technetium (Z=43) have no stable isotope. As shown in figure 1, there are many thousands more isotopes which are to greater or lesser extent unstable and undergo radioactive decay. A good many of them have been observed by nuclear physicists in the lab. Somewhat embarrassingly, a similar number should exist but are far more difficult to study and their properties are only theoretical.

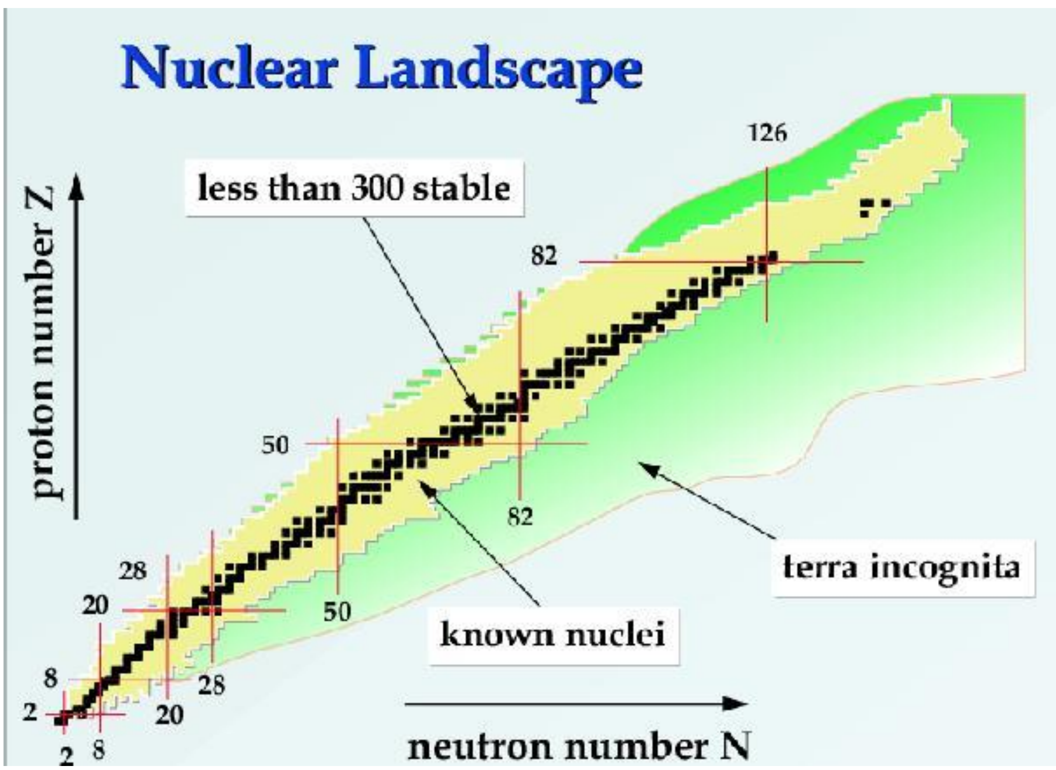


**Figure 1: The nuclear landscape as a function of proton and neutron number. Those isotopes which we know to exist and have been studied in the laboratory are shown in the yellow region. Those which should exist according to nuclear models but are yet to be observed are in the "terra incognita" region marked in green.**

## Nuclear Stability and Radiation

All the types of radiation are associated with a given nucleus becoming more stable i.e. finding a lower energy configuration. An exotic (i.e. unusual N/Z ratio) nucleus may undergo a whole series of such decays often in rapid succession.

$\alpha$ - Alpha decay is the spontaneous emission of a helium nucleus from a heavier (using very heavy A>200) nucleus. The alpha particle, comprising two protons and two neutrons, is the most stable nuclear configuration we know about. In some sense, the alpha particle must be bouncing around pre-formed inside the nucleus waiting to come out. This has led some theorists to try and interpret the properties of heavy nuclei as clusters of alpha particles. As they are a relatively heavy, charged particles, alpha particles do not easily penetrate matter and are stopped by a sheet of paper. A well-known application of alpha decay is the use of the alpha-decaying isotope Americium-241 in smoke detectors.

$\beta$ - Beta decay is the spontaneous conversion of a proton into a neutron by emitting a positron, or capturing an orbiting electron; or conversion of a neutron into a proton by emitting an electron. In each case, the process is accompanied by emission of a neutrino or anti-neutrino. Beta decay seeks to restore a more stable ratio of protons to neutrons in the nucleus. Electrons and positrons are more penetrating than alpha particles. Beta-decaying isotopes are relevant to medical imaging like PET scanning,

$\gamma$ - Gamma ray emission is a form of electromagnetic radiation involving a very high energy photon. Gamma rays can be extremely penetrating, often requiring 10s of cms of material before they lose all their energy. Often gamma-ray emission accompanies beta-decay of radioactive isotopes. There are also long-lived *isomers* in some nuclei. Gamma-rays are emitted when such isomers decay, changing the way the protons and neutrons arrange themselves, but not the numbers of them. Gamma rays are harnessed extensively in cancer treatments.

**Fission/neutrons** – Fission is the process where a nucleus spontaneously splits into two parts. In general, this occurs favourably only for very heavy nuclei like uranium. Fission is usually accompanied by emission of a few neutrons. Fission neutrons, having no electric charge, are very penetrating through material and need a large amount of material to be thermalized and stopped.

For some very exotic nuclei, it is not unknown for protons or neutrons to be directly emitted and in some heavy nuclei, emission of heavy particles like Carbon-14 nuclei has been observed!

## Physics Topics

### Nuclear Astrophysics

The astronomer Carl Sagan famously said “We are all made of star stuff” and this is certainly true: all the atoms in our bodies have been processed through a number of generations of stars before they got into us. It is also a remarkable feature that certain elements like aluminium and iron are very abundant in the earth’s crust while others are extremely rare like platinum and gold. In a sense, these abundance patterns are the impact of the properties of the nucleus writ large in the world. Nuclear physicists support astrophysicists in evolving models of stars and stellar explosions. This discipline is known as nuclear astrophysics and focuses on reproducing the nuclear reactions taking place in stars here on earth.

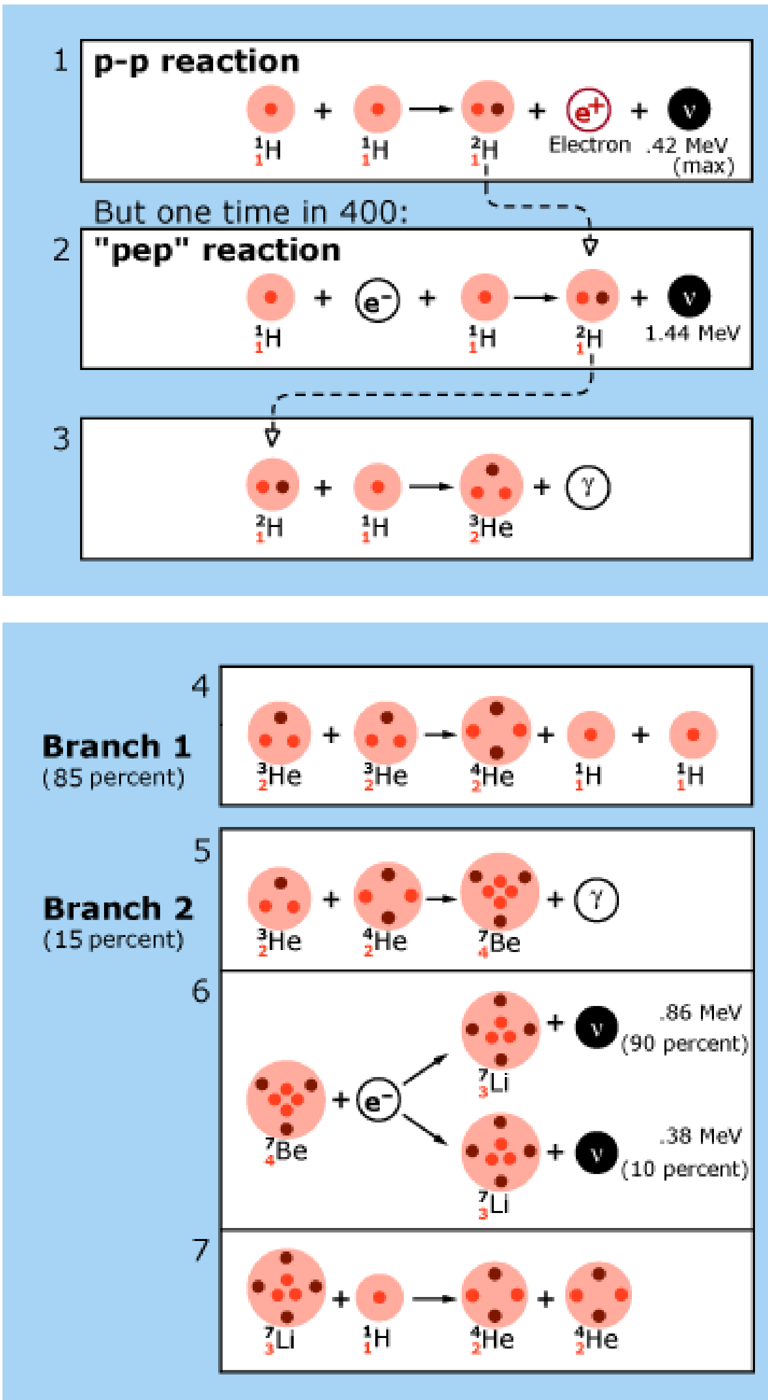


Figure 2" The p-p chain which converts hydrogen into helium in stars

Certainly, the range of chemical elements we know about were not produced at the outset. Indeed, so-called big bang nucleosynthesis which is believed to occur only for a short period minutes after the Big Bang could have produced only the first three chemical elements: Hydrogen, Helium and Lithium. This is because no stable isotopes exist which have an atomic mass of 5 or 8. In order to bridge these gaps, we need the much slower cooking that takes place in stars. In stars, the temperature is high enough to overcome the Coulomb repulsion between nuclei and for nuclear fusion to take place. The most important process is the conversion of four hydrogen nuclei into one helium nucleus, through successive fusion and beta-decay processes. This takes place through the p-p chain (see figure 2).

A key process as far as our existence here on earth is concerned is the production of carbon. Carbon has a unique and complex chemistry and without it, it would be hard to see how any life could form. This presented a problem in the 1950s when it was realised that in order to produce Carbon-12, it would be necessary to fuse three Helium-4 nuclei together but the intermediate system Beryllium-8 is unbound. The production rate for Carbon-12 would therefore be expected to be very small. The British astronomer, Fred Hoyle realised that the fact that we know that there is a significant quantity of Carbon-12 in the universe must mean that something makes this fusion process proceed much more readily, and suggested that there must be a *resonance* in this reaction, which, in other words, corresponded to the prediction of an excited state of Carbon-12 with just the right properties in a very narrow energy range. This prediction was later vindicated experimentally. It forms an interesting variant of the *anthropic principle* since if the properties of the Carbon-12 nucleus were different, would be here to see it?

Massive stars can produce elements up to iron and nickel (Z=28) but this is where the fusion processes end, as nickel is the most stable element, having the greatest binding energy per nucleon. The production of heavier elements therefore requires a much more energetic and dramatic environment. Physicists currently believe that this environment is provided by the supernova, where a massive star blows itself apart in an unimaginably powerful explosion. How this process works in detail is not so well understood and this question was listed in the US as one of the 11 great open questions for Physics.

Not only do supernovae produce the heaviest elements, but also these massive explosions distribute the debris into space, where it is incorporated into later generations of stars. Later stars therefore become successively enriched in heavier elements and if it were not for this process a terrestrial environment like ours could not exist. We are therefore “all made of star stuff”.

Nuclear physicists seek to understand the fusion processes at work in stars and exploding stars like supernovae. The burning in stars is extremely slow and this poses challenges in measuring the fusion process between light nuclei like hydrogen and helium. Much of this work is done using particle accelerators in deep underground laboratories where the small signal of gamma rays emitted from fusion is not masked by false signals from cosmic rays. In supernovae, the process is extremely dramatic and involves nuclei lying in the "terra incognita" of figure 1. This poses a separate set of challenges that physicists hope to address in the coming decades at a range of new facilities:

http://www.gsi.de/fair/index_e.html

http://www.ganil.fr/research/developments/spiral2/index.html

http://www.triumf.info/public/about/isac.php

http://isolde.web.cern.ch/ISOLDE/

**Superheavy elements**

A fascinating question actively pursued by nuclear physicists is whether there is a so-called island of stable superheavy nuclei far beyond the last elements like uranium which are found in the earth. Figure 2 shows one set of predictions of where this island might appear. Most theories suggest N=184 is a particularly stable number for neutrons, but the number of protons thought most stable varies between about 114 and 126 depending on the model.

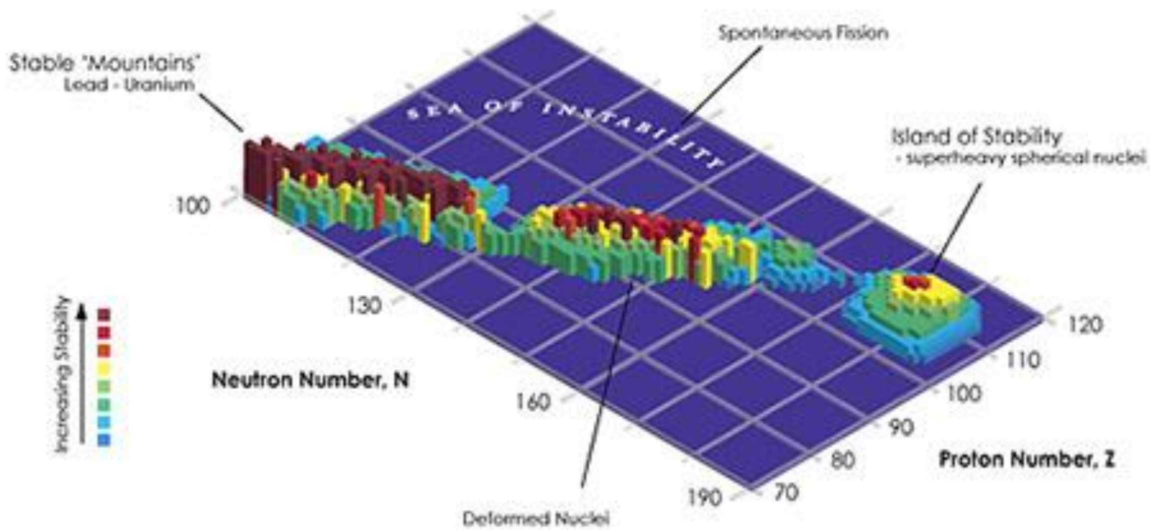


**Figure 3: Predictions of the relative stability of isotopes above lead (Z=82). Note the island of stability where more stable superheavy nuclei are expected to reappear.**

In the 1940s and 1950s, the search for elements heavier than uranium was led by Glenn Seaborg at the Lawrence Berkeley National Laboratory in California. They used the cyclotron accelerator designed by Lawrence to fuse alpha particles with successively higher mass nuclei and discover new chemical elements. Seaborg and his group were "nuclear chemists" – they produced weighable amounts of these new elements and used chemical techniques to separate them. They were aided in this by a good guess as to the Chemistry of the new elements from the periodic table. In this way, elements up to 98 (Californium) were produced and their chemistry studied.

Progress in this area from the late 1950s relied upon the availability of heavy ion beams i.e. accelerated beams of nuclei heavier than helium. The first such element synthesised in this way was element 102 – Nobelium. This technique became successively more difficult with each heavier element reached. This is due to the *cross-section i.e.* the probability for fusion becoming smaller. The number of detected nuclei of a new element in such experiments might be at the level of one every few weeks! Progress in the 1960s and 1970s was driven by competition between US scientists at Berkeley and Dubna in the Soviet Union. In the 1980s the main group working in this area were at GSI in Darmstadt, who pushed up to element 112.

Heavy element research has often been dogged by controversy and dramatic claims which were later retracted. In 2001, a Berkeley team led by Viktor Ninov announced the discovery of element 118. This announcement was something of a sensation in the field as it seemed much easier to produce this element than most models would otherwise have suggested. The announcement was later retracted among allegations that the original data had been manipulated and the discovery events fabricated. This debacle has raised major questions about the responsibility of scientific collaborators when they put their name to a publication:

http://yclept.ucdavis.edu/course/280/Ninov_Yashar.pdf

At the present date, the heaviest known element is 118 discovered by the Dubna laboratory in Russia but it is yet to be verified. The measurements at Dubna involve bombarding actinide e.g. plutonium/curium targets with a Calcium-48, a very neutron-rich but stable isotope. The Calcium-48 is a hugely expensive material and it is also extremely difficult to handle radioactive targets. It is therefore difficult for other laboratories to repeat the Russian work at the present time.

At the time of writing (May 2008), a further controversy has been opened by claims of the discovery of a few atoms of element 122 in a sample of thorium. The quality of this work has been strongly questioned by experts in the field:

http://space.newscientist.com/article/dn13828-has-the-heaviest-element-been-found.html

**Getting to the origins of mass – the Large Hadron Collider**

The Large Hadron Collider (LHC) which should start up in the summer of 2008, is arguably the most exciting scientific project at the present time. It seeks to answer fundamental questions about the origin of mass and the mass scale, for example, why the proton is around 2000 times heavier than the electron. Although it seems somewhat counterintuitive from our perspective, it is far from obvious why anything should have a mass. One explanation for the existence of mass is the Higgs mechanism mediated by the so-called Higgs boson. The LHC is intended to produce and determine the mass of the Higgs boson. The extremely high energies accessible at the LHC may also potentially shine light on other Physics beyond the standard model, or the origin of Dark Matter.

The LHC accelerates two beams of protons in opposite directions around a ring 27km in circumference reaching energies up 7 TeV, which corresponds to 99.9999991% of the speed of light. These beams are made to intersect at four different points around the ring. The enormous energy of the collision may be transformed into the creation of very massive particles. These decay through a shower of hundreds/thousands of lighter particles. This complex process is recorded in very large detector systems such as ATLAS and CMS. The events are reconstructed to determine what was created in the collision.

http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/

Everything about the LHC is on a fantastic scale. The tunnels are 27 km in circumference and 4m across. They lie around 100m below the surface, straddling the border of France and Switzerland. The whole machine operates at liquid helium temperature. The data produced will be so extensive that major new computing initiatives such as the so-called GRID are necessary to deal with it. The total cost of the project is between 3 and 5 billion pounds, funded by the CERN member states.

# Societal and medical applications

There have been a whole range of spin-offs from research in Nuclear Physics from medicine to energy generation. A selection of these are discussed below:

**Cancer treatment**

A well known application of ionizing radiation in medicine is in the context of cancer treatment. The radiation kills cancer cells and shrinks tumours but strong side-effects can often result. Important isotopes for radiation therapy are Cobalt-60 and Cesium-137. These isotopes were discovered in Berkeley as a by-product of the work of Seaborg on superheavy elements described above.

http://gammaknife.org/

**Heavy-ion therapy**

Heavy-ion therapy is a very valuable treatment for certain cancers of the head, which particularly affect younger patients. This treatment derives from developments in accelerators for Nuclear Physics. The principal example of such a facility is at the GSI laboratory in Darmstadt , Germany. Heavy ion (carbon-12) beams are used to destroy the cancer. This takes advantage of the fact that heavy ions deposit most of their energy towards the end of their trajectory - the so-called *Bragg peak.* This allows the energy to be deposited at some depth within the head, treating the cancer while barely harming surrounding tissue and delicate organs like the eye. No such treatment currently exists in the UK.

http://www.gsi.de/forschung/bio/heavyiontherapy_e.html

http://www.nupecc.org/iai2001/report/B31.pdf

**Medical imaging**

PET scanning exploits a type of beta-decay where a positron (anti-electron) is emitted. This positron annihilates with an electron to produce two gamma-ray photons which are emitted back-to-back. The detection of these gamma-rays therefore locates the point of their production. Scintillator crystals like Bismuth Germanate (BGO) are used for detecting the photons.

A very common radioactive source for PET scanning is Fluorine-18 whose half-life is 110 minutes. This isotope has to be produced nearby or on-site using a small cyclotron. The short-lived nature of the radioisotope used and the small dose make it tolerable to use this procedure without excessive risk. The procedure is particularly valuable for imaging cancers within the body.

http://www.radiologyinfo.org/en/info.cfm?pg=PET

http://www.nupecc.org/iai2001/report/B23.pdf

MRI used to be called nuclear magnetic resonance and while it relies on aligning the spin of nuclei in a large magnetic field, it is not really a nuclear application in the same sense as PET; the latter exploiting radioactive decay.

http://www.nupecc.org/iai2001/report/B21.pdf

**Archaeology and art**

The key technique for dating human artefacts is radiocarbon dating. This makes use of the characteristic 5700-year half-life of Carbon-14 found in organic samples. High energy cosmic rays produce secondary neutrons in our atmosphere. These neutrons react with Nitrogen-14 to produce Carbon-14. This latter material is taken up into biological materials principally as $CO_2$. When the organism dies, no further $CO_2$ is taken in and the Carbon-14/Carbon-12 ratio declines over time as the Carbon-14 decays. In principle, it would be possible to measure the rate of decay of a sample to see how much Carbon-14 is in it. In practice, it is much more accurate to use *accelerator mass spectroscopy*. This technique derives the ratio of Carbon-14 to regular Carbon-12 nuclei in a sample by producing an accelerated beam of carbon ions. The dating procedure can be calibrated using tree-ring samples which give us an absolute calibration back to about 50000 BP (before present).

Famous examples of the application of this technique include the dating of the Shroud of Turin, which turns out to be medieval and not from the time of Christ. (How the Shroud was produced still continues to puzzle archaeologists.) A second example is the dating of the iceman, Oetzi, whose excellently-preserved body was found in the Austrian Alps in 1991. Radiocarbon dating suggests a date for the body between 3500 and 3000 BC. For more detailed discussion of this, see: http://www.nupecc.org/iai2001/report/B44.pdf

Clearly, it is highly fortuitous that the half-life of Carbon-14 (5700 years) is very suitable for dating periods in human history. It is interesting to note, however, that most theoretical nuclear models would suggest a half-life of hours for this isotope, and it is not clear at present what effect leads to the retardation of this decay.

# Nuclear energy

### Nuclear Fission

Nuclear power will always be a controversial topic in the Western World, and several countries have decided to avoid it completely. Nevertheless, a number of European countries rely heavily on nuclear power, and some have recently moved into this area for the first time, notably, Finland. Fears of climate change and the urgent need to reduce carbon dioxide emissions have restored nuclear power to the political agenda in the UK, in particular, when it seemed to be completely unacceptable only a few years ago. Modern reactor designs are increasingly safe with multiple levels of safety features that rule out accidents of the type which occurred at Chernobyl. Moreover, the improved designs produce significantly less waste than older reactors and so a reinvigorated nuclear power generation industry in the UK would add little to the existing store of radioactive waste, which our country will have to pay to deal with in any event.

Nuclear physics experiments are helpful in continuing to improve our understanding, for example, of fission products and to further refine reactor models. It is worth noting that there is a serious skills shortage in areas related to nuclear power due to the run down of the nuclear power industry in the UK over the last twenty years, and many of those entering this industry at a more senior level are trained through MSc and PhD programmes in experimental nuclear physics. If the UK decides to re-enter nuclear power generation in a serious way, then there will be extensive employment opportunities for Physics and Engineering graduates.

http://www.world-nuclear.org/info/inf84.html

An important possible contribution to the problem of nuclear waste stemming from research by nuclear physicists is *accelerator-driven transmutation*. What is envisaged here is to bombard the very long-lived actinide material, comprising the most serious category of nuclear waste, and transmute it into short-lived fission products. Several initiatives are ongoing worldwide to try to bring this idea to reality:

http://www.guardian.co.uk/commentisfree/2007/jul/26/comment.nuclear

http://www.nea.fr/html/trw/index.html

**Nuclear fusion**

For the past fifty years, physicists and engineers have been working to try to harness nuclear fusion, which powers stars as a viable energy source on earth. From the nuclear physics perspective, it is very clear which is the most suitable reaction in terms of energy output and we know very well the rate of this reaction at different energies/temperatures. The reaction involving deuterium and tritium (heavy isotopes of hydrogen) is shown in figure 4.

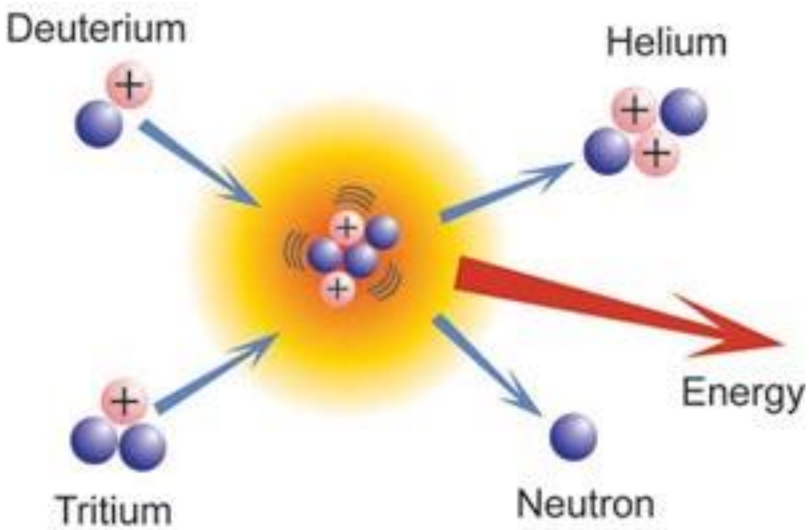


Figure 4: The d-t fusion reaction

The Nuclear Physics issues in terms of obtaining energy from nuclear fusion are well understood. The challenge is to reproduce what stars achieve effortlessly under their enormous gravity, namely to confine the fuel in a suitably dense, hot plasma to achieve continuous energy generation. Fusion has been achieved in an experimental setup but only for a matter of seconds. The next step is a prototype reactor called ITER, which is under construction in Cadarache in France. This enormous Physics and engineering project is drawing on efforts from a very broad international scientific community:

http://www.fusion.org.uk/

http://www.iter.org/

## Further reading and teaching resources

http://www.lbl.gov/abc/wallchart/teachersguide/title_page.html

http://www.particlephysics.ac.uk/index.html

Atom – P. Bizony (accompaniment to BBC series with Jim Al-Khalili)

Nucleus: A Trip into the Heart of Matter, J. Al-Khalili (2001, ISBN 0801868602)

The Transuranium People: The Inside Story – D. Hoffman, A. Ghiorso and G.T. Seaborg

Imaginary Weapons – Sharon Weinberger (Avalon Publishing Group, 2007)