BACKGROUNDER

Nuclear technologies allow us to see a world that was previously invisible, and are helping scientists to find solutions to global problems such as climate change, energy shortages and health issues.

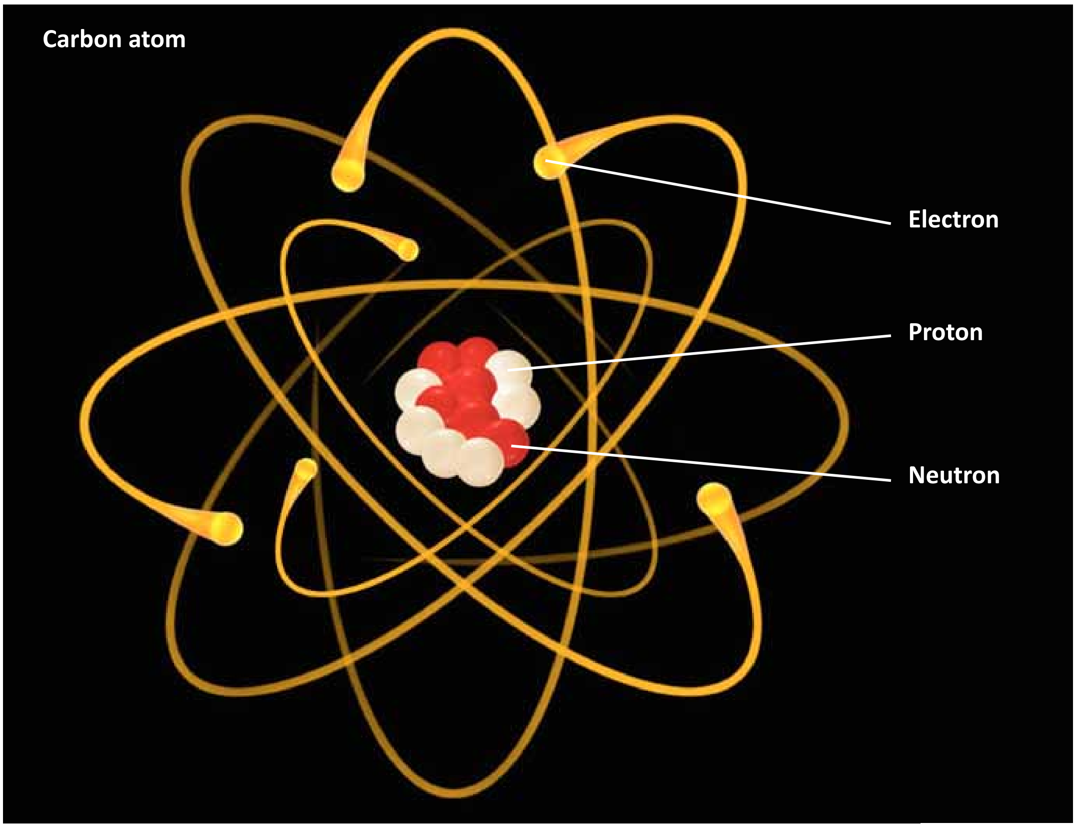
WHAT IS NUCLEAR SCIENCE?

Nuclear science is the study of the atomic world. Atoms make up everything – from our bodies and the Earth to the drugs that we take and the materials we use. Being able to see these atoms is crucial to understanding more about the world around us, as well as the structure of living organisms.

Atoms are constructed of three main building blocks (known as subatomic particles): protons, neutrons and electrons. Protons are positively charged, neutrons have no charge and electrons are negatively charged. The protons and neutrons are packed together in the centre of an atom to form a nucleus. They are held together by strong nuclear forces. The electrons move around the nucleus in shells with different energy states. Their negative charge keeps them separate from each other but near the nucleus, because they're attracted to the protons. In a stable atom with a balanced charge, the number of protons is the same as the number of electrons.

TWO ISOTOPES OF CARBON

The number of protons determines which element on the periodic table the atom will be. For this reason, the number of protons in the nucleus is known as the atomic number. If an atom gains or loses protons, it becomes an atom of a different element.



Carbon-12
6 protons
6 neutrons
Stable

Carbon-14
6 protons
8 neutrons
Unstable

If an atom loses or gains electrons, it can change its charge and become an ion. If an atom changes its number of neutrons it becomes an isotope of that element. There are hundreds of different isotopes – some are natural and some are artificial. A radioisotope is an isotope with an unstable nucleus because its nucleus is too big or the proportion of protons and neutrons make it difficult for the nucleus to hold together. This is called a radionucleus and it releases energy, which is emitted as radiation.

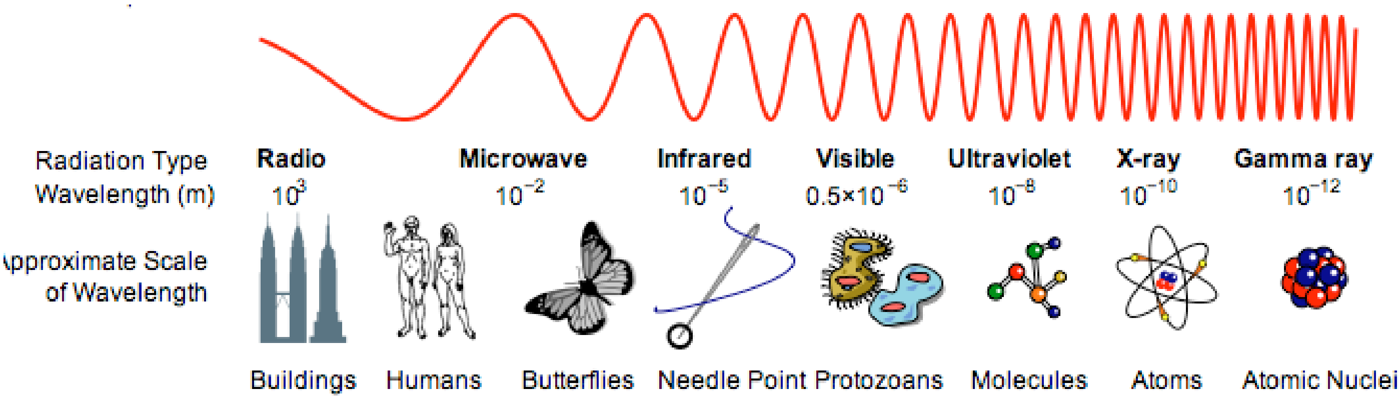
Nuclear science is also used to create many of the materials that we rely on every day – from medical radioisotopes to irradiated silicon used in industrial processes.

BACKGROUNDER

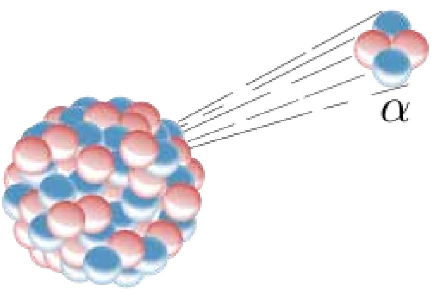
WHAT IS RADIATION?

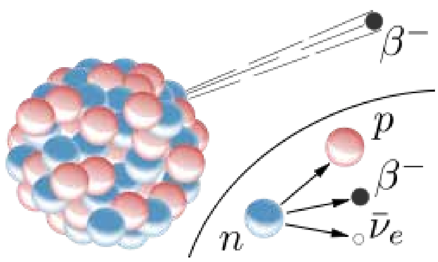
Radiation is energy that travels (or radiates) out in waves or particles from its source. Everything from heat, radio waves, X-rays and microwaves is a type of radiation, and every object in the universe emits radiation.
There are two categories of radiation: ionising or non-ionising.

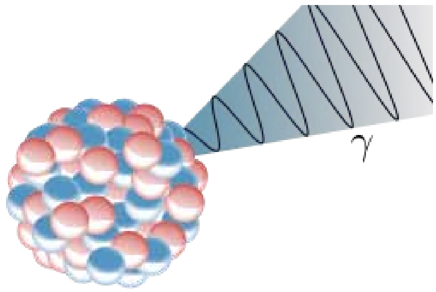
Non-ionising radiation includes low energy waves such as light waves or radio waves. Ionising radiation, on the other hand, changes the electron balance of a stable atom by either adding or knocking an electron out of the atom therefore changing the atom into an ion.



THREE TYPES OF NUCLEAR IONISING RADIATION







ALPHA RADIATION

In alpha radiation (also called alpha decay), the alpha particle (α) released from the nucleus has two protons and two neutrons, so it is essentially a helium nucleus.

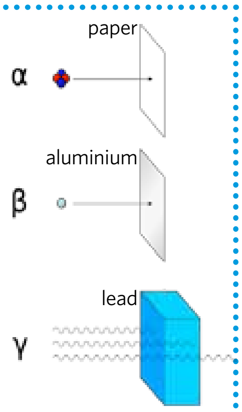
BETA RADIATION

In beta radiation, or decay, a neutron is converted to a proton and an electron. The electron is emitted (β^-).

GAMMA RADIATION

Gamma radiation is high-energy electromagnetic radiation (γ). Gamma radiation can be released by itself or along with alpha and beta radiation.

Alpha, beta and gamma radiation can penetrate different types of materials, so they can be used for different imaging purposes.



Nuclear reactors use a process known as nuclear fission, where an atom is split when it is hit by a neutron. Only certain elements will split in this way, such as Uranium-235, plutonium-239 and thorium-234. When one of these 'fissile' atoms is hit by a neutron, the atom splits into two smaller atoms and often, more than one free neutron, which can each knock into more fissile atoms, creating more splits and more neutrons. This 'chain reaction' needs to be controlled, but can be used to create great quantities of heat, such as in nuclear power reactors, or to create large quantities of neutrons, which can be directed into beams and used to research the nature of other materials.

Some amount of alpha, beta and gamma radiation is emitted by nuclear reactors but they are not used as a source of these particles, in fact the radioactive particles produced in reactors are absorbed by shielding such as water, lead, concrete or other materials.

WHAT IS NUCLEAR SCIENCE USED FOR?

Nuclear science is used for a range of different research fields, including medicine, the environment, materials engineering, archaeology and mining. And many people don't realise that the nuclear industry supplies or develops products that are used every day by society.

Nuclear science uses the beams of high-energy neutrons that are created in nuclear reactors by the ionising chain reaction process. Nuclear scientists direct these high-energy subatomic particles (created through nuclear technologies) at objects and observe how the particles either pass through to the other side, diffract due to the presence of the object or are reflected back. Scientists can learn a lot about the composition, age and structure of that object by observing how subatomic particles behave around it.

This knowledge can help scientists understand how atoms work together, leading to the development of more efficient materials and drugs. And it can also help them date how old fossil samples are, or work out what type of paint was used in an artwork. It can allow doctors to see what is going on inside a patient's body, and help to save thousands of lives. Basically, nuclear technologies can be applied to every single scientific discipline, and help researchers to see things in a different way.

Every Australian is expected to have at least one nuclear medicine procedure in their lifetime, normally a CT or PET scan that can image tumours and other diseases in a way that X-rays cannot. And we wouldn't know much about the development of the planet or the history of climate change without using nuclear technologies such as radiocarbon dating – a technology that helps scientists work out how old materials containing carbon are.

Nuclear science can also be used to generate nuclear power, providing an alternative to the burning of fossil fuels, which release a large amount of greenhouse gases into the atmosphere and have been shown to be linked to climate change.

WHICH MACHINES ARE INVOLVED IN NUCLEAR SCIENCE?

There are two main types of machines that can produce the high-energy particle beams used in research: reactors and accelerators.

REACTORS

Reactors are used to start, maintain and control the process of nuclear fission. Fission is when a neutron hits an atom, splitting it apart into smaller atoms and releasing more neutrons. If those neutrons then hit other atoms, they will also split and when this happens repeatedly this phenomenon is called a nuclear chain-reaction.

Only certain isotopes of certain elements are fissile (can be split by fission); for example, one isotope of uranium, U235, is fissile, while another isotope, U238, is not.

Nuclear fission also gives off energy, and large reactors are used in power plants to convert this energy into electricity. Smaller reactors are used by researchers to create neutron beams that help them visualise the atomic structure of most materials. Research reactors can also make radioisotopes and irradiated materials that are used in medicine and industrial processes.
In nuclear reactors, design features and control rods are used to regulate the chain reaction so it does not go too fast. Further, cooling systems are used to prevent the core of the reactor from getting too hot and melting down.

THE OPAL REACTOR

OPAL, or the Open Pool Australian Lightwater reactor, is a nuclear reactor devoted to research and commercial uses, operated by at the Australian Nuclear Science and Technology Organisation (ANSTO). The 20-megawatt reactor opened in 2007 and is considered state-of-the-art technology. The reactor has several key uses, including production of radioisotopes for use in medical imaging and cancer treatment and production of neutron beams for fundamental materials research.

ACCELERATORS

Rather than rely on nuclear fission, accelerators rapidly speed up particles (to almost the speed of light) and direct them into defined beams using electromagnetic fields. There are different types of accelerators, including synchrotrons and cyclotrons. While synchrotrons cannot be used to create radioisotopes, cyclotrons can produce neutron-poor isotopes that are mostly used in medical diagnostics. Particle accelerators can create very high-energy X-ray, proton, photon and electron beams that can be used for research and complement much of the work that can be done with reactors.

LARGE HADRON COLLIDER

The Large Hadron Collider is a huge particle accelerator. It sits 175 m below the ground on the outskirts of Geneva in Switzerland. It accelerates beams of protons and lead ions (also known as hadrons) to extreme speeds and smashes them into one another. The goal of the collisions is to recreate the conditions that were present just after the Big Bang. By doing this, particle physicists hope to fill in some of the gaps in knowledge about what fundamental particles make up the universe and how they interact with each other. The standard model of particle physics does this to a degree. However, an essential part of this is the Higgs boson – something that may not exist. The standard model predicts its existence, but to date, no definitive physical evidence of its existence has been found.

NUCLEAR SCIENCE IN AUSTRALIA

Australia has a synchrotron, several medical cyclotrons and a research reactor.

The Australian Synchrotron, which opened in July 2007, is located in Melbourne and provides high-energy light, from infrared to X-rays, to researchers and medical practitioners.

Australia's only research reactor is known as the Open Pool Australian Lightwater (OPAL) reactor and is housed at the Australian Nuclear Science and Technology Organisation (ANSTO). Using the neutron beams produced by the reactor and techniques such as neutron scattering, researchers are able to investigate areas like materials engineering, life sciences, climate change and mining. OPAL also produces radioisotopes for medical and industrial applications. Although it was only opened in 2007, OPAL is already one of the world's top five leading research reactors.

WHAT ARE THE SAFETY RISKS OF NUCLEAR SCIENCE?

Any ionising radiation can change the structure of an atom by ionising it. As our cells are made up of atoms, radiation can therefore alter our cells and lead to cancer, depending on exposure. While research reactors release radiation, it is contained and managed safely.

Many people are concerned with the risks of nuclear science (partially because of the negative associations with atomic bombs and nuclear war), but most nuclear facilities are research-focussed and extremely safe. For example, the water inside the OPAL reactor is not hot enough to boil a kettle, averaging at 40°C. And all reactors are designed to shut down at any sign of tremor or failure in the system.

However, there can be risks associated when a larger amount of radiation is produced. These risks are well-managed, but when unforseen circumstances occur there can be accidents. In March 2011, some of the nuclear reactors at the Fukushima Power Plant in Japan went into meltdown and released radiation into the atmosphere after a 9.0 magnitude earthquake and a 14.2 m tsunami. The Fukushima Daiichi nuclear power plant survived the earthquake intact and shut down automatically at the first sign of tremors, even though it was only built to survive a 7.9 magnitude earthquake and this one was 30 times more powerful. However, the 14.2 m tsunami that followed was too much for the 40-year-old plant and brought the reactor to the brink of meltdown, resulting in the release of radiation. The exact amount of radiation released and its impact is still being calculated.

In another famous incident in 1986, a nuclear power plant in Chernobyl, in the former Soviet Union, went into meltdown and released radiation into its surroundings after an accidental explosion. The initial explosion resulted in the death of 56 people, but the World Health Organisation (WHO) forecasts that the long-term number of deaths resulting from radiation exposure in the region could be as high as 4,000. As at 2005, WHO was only recognising the deaths of the 56 emergency workers.

While there have been tragedies in the nuclear industry, it's important to remember that nuclear isn't the only dangerous form of energy – coal-fired power plants kill nearly 24,000 people a year in the U.S. from asthma, cave-ins, and circulation and respiratory problems. Finally, the safety of nuclear reactors is continually being improved.

There are safety risks associated with radiation, but radiation is all around us constantly – it comes from the Sun and space, in the rocks and soil beneath our feet and even in certain foods. The nuclear industry is responsible for producing less than a thousandth of the radiation that we are exposed to on a daily basis.

BACKGROUNDER

NUCLEAR SCIENCE TIMELINE

A brief introduction to how nuclear science has developed.

1895 Wilhelm Röntgen discovers X-rays.

1898 Marie Curie discovers the radioactive elements radium and polonium.

1911 George von Hevesy conceives the idea of using radioactive tracers, which is later applied to medical diagnosis among other things. Von Hevesy won the Nobel Prize in Chemistry in 1943 as a result of his discovery.

1927 Herman Blumgart first uses radioactive tracers to diagnose heart disease.

1932 James Chadwick proves the existence of neutrons.

1938 Two German scientists, Otto Hahn and Fritz Strassman, demonstrate nuclear fission.

1939 Albert Einstein sends a letter to President Roosevelt telling him about German research that could potentially lead to a bomb. As a result, Roosevelt begins looking into a nuclear bomb for the U.S.

1942 The Manhattan Project is secretly formed to build a bomb before the Germans, and in December the first self-sustaining nuclear chain reaction is demonstrated under the squash court at the University of Chicago. Enrico Fermi supervises the design and assembly of an 'atomic pile' – an early nuclear reactor.

1945 The U.S. begins testing the first atomic devices and in August two bombs are dropped on Japan.

1946 Physicist Maria Goeppert Mayer develops her 'nuclear shell model' explanation of how neutrons and protons within atomic nuclei are structured. Her work explains why nuclei of some atoms are more stable than others, and why some elements have different atomic forms, called isotopes. She will go on to win a Nobel Prize in Physics in 1963 for her work.

1949 Radiocarbon dating (carbon-14 dating) is developed by J. R. Arnold and W. F. Libby; it becomes one of the most widely used and best-known methods of dating carbon-based material.

1951 The first usable electricity is produced from nuclear fission at the U.S. National Reactor Testing Station.

1958 Australia's first research reactor, the High Flux Australian Reactor (or HIFAR), begins operating.

1967 The Institut Laue–Langevin in France is founded; it is still the most powerful research reactor in the world.

1979 In March, Three Mile Island Nuclear Powerplant near Harrisburg, Pennsylvania suffers a partial core meltdown. Minimal radioactive material is released.

1986 The Chernobyl Nuclear Reactor meltdown and explosion occur in the former Soviet Union in April. There is a large amount of radiation released into the atmosphere.

1990s Research reactors continue to deliver breakthroughs for scientists and in a variety of fields, and nuclear power plants continue to grow in number, particularly in France and the U.S.

2005 Nuclear power provides 6.3% of the world's total energy.

2007 ANSTO's OPAL reactor is opened, as well as the Australian synchrotron.

2009 As of December, the world had 436 nuclear reactors – a slight decline from 2007.

2011 A 9.0 magnitude earthquake hits Japan, followed by a tsunami that puts the Fukushima nuclear power plant into meltdown.

FAST FACTS YOU MIGHT NOT KNOW ABOUT NUCLEAR SCIENCE

- There's more to nuclear science than power plants; nuclear technologies help scientists understand our bodies and the world around us and are used by doctors to save thousands of lives. Nuclear science is also used in archaeology, climate change research, environmental science, mining and material science.
- The nuclear industry releases less than one thousandth of the radiation we're exposed to – most comes from natural sources.
- Many research reactors, including Australia's OPAL reactor, produce only a small amount of contained radiation – less than enough to boil a kettle of water.
- On average, every Australian will have at least one nuclear medicine procedure in their lifetime.
- Australia does not have any nuclear power plants.

UNDERSTANDING WETLAND ECOSYSTEMS

It is often hard to work out the complex predator–prey relationships in wetlands. But scientists can use nuclear science to analyse the isotopic signature of different animals to work out what they eat and where they stand in the food web.

Every food contains naturally occurring radioisotopes and when animals eat, traces of these radioisotopes are incorporated into their tissues, leaving a signature of the food they've ingested.

Studying these isotopic signatures allows scientists to monitor changes in the food web under different environmental conditions, and see which parts of the ecosystem might be struggling. This can be useful in times of drought or flood, and researchers are currently using this technique on yabbies to monitor Australia's threatened Murray–Darling basin river system.


ANSTO

ANSTO and NSW Department of Environment and Climate Change scientists collecting samples for isotopic analysis

REVEALING THE INNER YOU


ISTOCK

Nuclear medicine scans can be used to examine our organs, tissues and bones. They can diagnose sports injuries, cancers, infections and other maladies. These scans are now so commonplace that, on average, each of us will have one during our lifetime.

One type of scan is SPECT (single-photon emission computed tomography) imaging. Patients undergoing a SPECT scan are injected with a radiopharmaceutical, a chemical that emits small amounts of gamma radiation. The drug travels through the body and is absorbed by the part of the body that needs to be examined, for example the lungs or the heart.

The patient is placed in the SPECT machine, which has a gamma camera. The camera moves slowly around the patient, detecting the gamma radiation emitted from their body. It then produces a 3-D image, which doctors can use to detect changes in the patient's body.