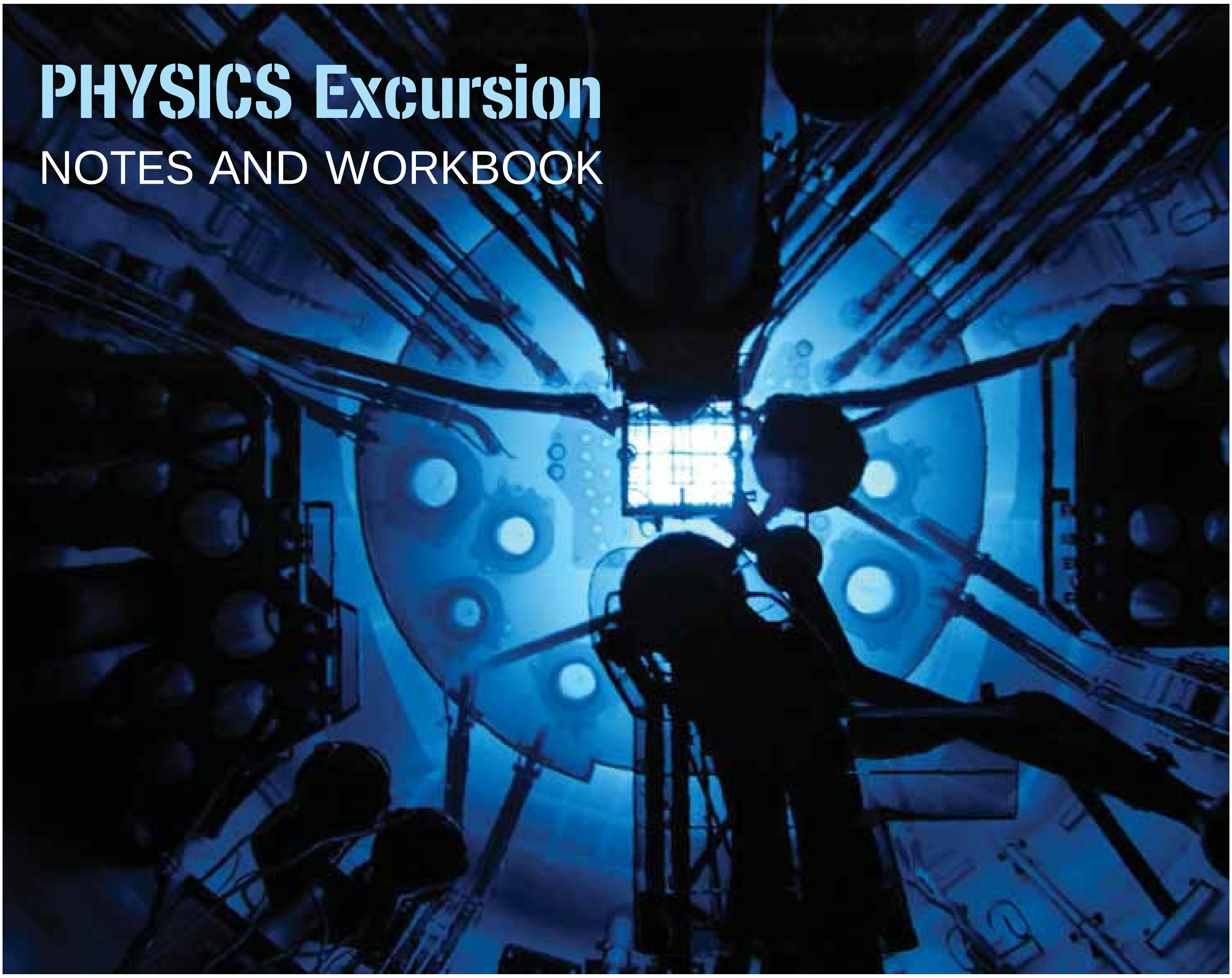
Australian Government

Nuclear-based science benefiting all Australians

Welcome to ANSTO

(Australian Nuclear Science and Technology Organisation)



PHYSICS Excursion

NOTES AND WORKBOOK

An outcomes-based resource manual for NSW HSC Physics students

Student notes and excursion activities covering material from HSC Options:

- **Quanta to Quarks** (9.8.3 and 9.8.4)
- Aspects of **Medical Physics** (9.6.3)

Prepared by Peter L. Roberson with assistance from ANSTO Education Officers, 2007

Introduction

The material covered in this document is to support a Yr12 Physics class excursion to ANSTO where students will be taken on a guided tour of OPAL, our new research reactor, and related facilities. This document combined with the excursion to ANSTO, is of particular relevance to those studying the option Quanta to Quarks, but also supports certain aspects of the Medical Physics option. The document contains much of the important theory that relates to the material contained in the NSW HSC Physics course outcomes shown below, and includes activities and questions for students to complete as preparation for the excursion and during their tour of the ANSTO facilities.
The notes contain information on the following:

- **Review** of the relevant ideas on radioactivity studied previously in Stage 4 and 5

- Sections of the **Medical Physics** option:

9.6.3.

- Outline properties of radioactive isotopes and their half lives that are used to obtain scans of organs
- Identify that during decay of specific radioactive nuclei positrons are given off
- Discuss the interaction of electrons and positrons resulting in the production of gamma rays.

- Sections of the **Quanta to Quarks** option:

9.8.3.

- Define the components of the nucleus (protons and neutrons) as nucleons and contrast their properties
- Define the term ‘transmutation’
- Describe nuclear transmutations due to natural radioactivity
- Describe Fermi’s initial experimental observation of nuclear fission
- Discuss Pauli’s suggestion of the existence of neutrino and relate it to the need to account for the energy distribution of electrons emitted in β decay
- Solve problems and analyse information to calculate the mass defect and energy released in natural transmutation and fission reactions
- Account for the need for the strong nuclear force and describe its properties
- Explain the concept of a mass defect using Einstein’s equivalence between mass and energy
- Describe Fermi’s demonstration of a controlled nuclear chain reaction in 1942
- Compare requirements for controlled and uncontrolled nuclear chain reactions.

9.8.4.

- Explain the basic principles of a fission reactor
- Describe some medical and industrial applications of Radioisotopes
- Identify data sources, and gather, process, and analyse information to describe the use of:
  - a named Radioisotope in medicine
  - a named Radioisotope in agriculture
  - a named Radioisotope in engineering
- Describe how neutron scattering is used as a probe by referring to the properties of neutrons
- Identify ways by which physicists continue to develop their understanding of matter, using accelerators as a probe to investigate the structure of matter.

A Note for Teachers:

In order to benefit most from the excursion and their time at ANSTO, students should have covered much of the theory BEFORE they go on the excursion. This will allow the excursion to reinforce their understanding and provide the opportunity for them to have questions answered.

Apart from covering aspects of the relevant theory for their HSC Physics, the excursion also offers the opportunity for students to explore important aspects of nuclear technology and to gain first-hand experience of Australia's nuclear reactor and the research being conducted on-site. This experience may prove useful to provide a greater understanding of the issues involved with nuclear reactors and provide students with ideas they can use if asked the question, 'Discuss the contribution of nuclear science and reactors to society.'

The following theory, covering the components of the HSC course as indicated, is provided as the answer to a series of relevant questions. Each theory element is followed by questions for the student to answer. Although most of the required detail is provided to cover the points in the HSC course as indicated, they are not directly referred to in the following text. The material is presented in an order to attempt to allow students to build their overall knowledge and understanding as they work through the contents and complete the excursion. This document is designed to support your teaching of the relevant syllabus points but individual teachers must ensure they use the material as they consider most appropriate for their students, and provide appropriate guidance on which material is the most relevant to students and how they can best use this resource.

Section 1 – Preliminary ideas to be explored BEFORE excursion.

What is radioactivity?

To understand radioactivity we first need to consider the nucleus of an atom.
The particles found in the nucleus, protons and neutrons, are termed **nucleons**. The neutron and proton are similar in mass but a neutron has NO electric charge while a proton has a positive charge.
The number of protons in the nucleus, known as the atomic number (Z), determines what element the atom is, e.g. hydrogen atoms always have just one proton in the nucleus, carbon atoms always have 6 protons in the nucleus, iron atoms always have 26 protons in the nucleus, and uranium atoms always have 92 protons in the nucleus.
The nucleus of the same element can contain different numbers of **neutrons**. This produces atoms that have different masses termed isotopes. The atomic mass (A) of an isotope is equal to the total number of nucleons (protons plus neutrons) found in the nucleus. Except for the most common isotope of hydrogen which has a nucleus of just a single proton, the nuclei of all other elements contain both protons and neutrons. For the common isotope of the elements we find in greatest abundance on Earth, the huge electrostatic repulsion experienced between the positively charged protons in the nucleus is contained by the strong nuclear force, and this is combined with the correct balance between the number of protons and neutrons to result in the nucleus remaining stable.

Radioactivity is a property of certain isotopes (radioisotopes) where the nucleus of the isotope has internal instabilities that eventually lead to the nucleus decaying. This results in the nucleus emitting energy in the form of 'ionising' radiation. In most cases this decay leads to a 'transmutation' where the nucleus changes to become a new element. A transmutation was originally defined as 'changing from one element to become another'. Natural radioactivity is the result of nuclei of certain isotopes, found naturally on earth, which are not completely stable and eventually this results in the nucleus decaying and emitting ionising radiation. Where this decay forms a new element it is an example of a **natural** transmutation of an element.
Artificial transmutations can be produced by bombarding the nuclei of a target element with particles, e.g. neutrons or protons. The collision of the particle with a target nucleus results in a nuclear reaction that may lead to the creation of a new element (usually radioactive). A radioactive isotope is referred to as a **radioisotope** while the nucleus of a radioactive atom is termed a **radionuclide**.

Questions:

1. Define a nucleon.

2. Compare a neutron with a proton.

3. The most common isotope of uranium is U-238. The 238 represents the atomic mass of the isotope, and a uranium nucleus contains 92 protons. Outline how this information can be used to determine the number of neutrons in the nucleus of an atom of U-238.

What causes a nucleus to be radioactive and what is the ionising radiation emitted?

Why a particular nucleus (radionuclide) is radioactive is generally explained by one of two things:

1. When the nucleus of the element contains a very large number of protons, the electrostatic repulsion between the protons can become so great that, long term, even the nuclear strong force cannot maintain its grip and, in an attempt to resolve the problem, four nucleons, two protons and two neutrons, are ejected from the nucleus as an ALPHA particle α. All isotopes of the elements with more than 83 protons in their nucleus are radioactive.

(Interesting note: Fairly recent research suggests that the isotope of bismuth, element 83, Bi-209, that was formerly considered a stable element, is actually radioactive with a huge half life of about 1.9×10^{19} years.)

2. To remain stable, a nucleus must contain the appropriate ratio of protons to neutrons otherwise the interactions between the nucleons will result in one of the two forms of BETA DECAY (β) occurring. The type of beta decay that occurs depends on whether the imbalance is caused due to an excess of neutrons or by an excess of protons. beta decay involves weak nuclear interactions. In a nucleus where there is an excess of neutrons compared to protons, a neutron transmutes to become a proton with a BETA minus particle (electron) and an anti-neutrino emitted from the nucleus. When there is an excess of protons compared to neutrons, a proton transmutes to become a neutron with a BETA plus particle (positron) and a neutrino emitted from the nucleus.

Note: Most radioisotopes that produce alpha or beta radiation, usually follow this with the release of gamma-radiation (γ-photons) as excess energy is lost from the daughter nucleus. Gamma rays are very high frequency electromagnetic radiation similar to X-rays. Lower energy gamma rays are indistinguishable from X-rays.

Radioactive substances produce ionising radiation. This means the radiation released can cause the matter it encounters to become electrically charged, i.e. it can remove electrons from atoms.

Questions:

1. The common, stable isotope of carbon-12 can be represented by the symbol $^{12}_{6}\mathrm{C}$.
   Describe the nucleons that would be found in the nucleus of an atom of this stable form of carbon.

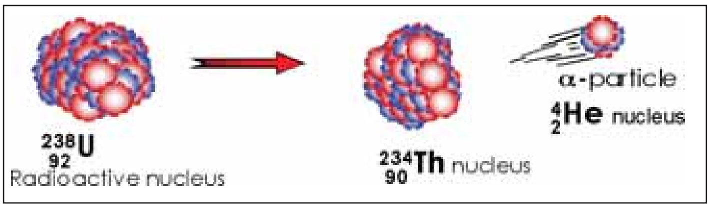
2. Another isotope of carbon found naturally has the symbol $^{14}_{6}\mathrm{C}$. This isotope is radioactive.
   Based on the nucleons in the nucleus of this isotope of carbon, with a reason for your answer, predict the type of radiation produced when a nucleus decays.

What are the properties of the common ionising radiations emitted from radioactive materials?

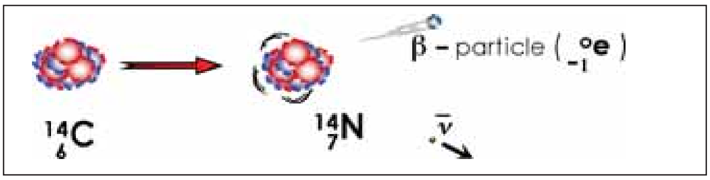
The following table shows the three forms of ionising radiation emitted from natural radioactive isotopes.
Note: The energy of the different ionising radiation can vary considerably dependent on the parent radionuclide they are emitted from. Radiation emitted with a higher energy can penetrate further through matter and produce greater ionisation, e.g. beta particles from P-32 with a maximum energy can penetrate about 7m through air.

Name of radiation	Identity of radiation	Penetration through matter (energy dependent)	Ability to cause ionisation	Behaviour of path in magnetic field
ALPHA (α)	Helium nucleus, i.e. two protons and two neutrons	Very weak; average alpha can only penetrate about 5 cm through air, stopped by sheet of paper or skin.	Produce intense ionisation	Show deflection in strong magnetic fields and exhibit a positive charge
BETA (β)	β-minus – negative; electron and anti-neutrino β-plus – positive; positron and neutrino	Moderate; penetrate about 1 to 2 m through air, stopped by a few mm of aluminium.	Produce moderate ionisation	Easily deflected by magnetic fields, exhibit negative charge (β-minus) or a positive charge (β-plus)
GAMMA (γ)	Very high frequency electromagnetic radiation	Very powerful penetration; not really completely stopped by anything. Higher energy rays are reduced 50% by about 12mm of lead	Very weak effect in causing ionisation	Not deflected by magnetic fields, exhibit NO electric charge.

Diagrams representing an α and β decay



In this decay, just like the parent U-238 nucleus, the Th-234 nucleus formed is also radioactive.



In this decay, unlike the radioactive parent C-14 nucleus, the N-14 nucleus formed is stable.

Questions:

1. A student has a sample of radioactive material. They find that when a Geiger counter is held about 20 cm from the sample the count recorded is very small but, when they bring the Geiger counter very close to the sample, the Geiger counter goes wild and huge amounts of radiation are detected. Outline one conclusion the student might make about the radioactive material.

2. Smoke detectors, which act to warn occupants of a fire, contain an electric circuit that relies on a small sample of a radioisotope to emit radiation into a small air gap to ionise the air and allow the electric circuit to be completed. When the radiation is blocked by the particles in smoke, the circuit is broken and a very loud alarm is activated. With reasons for your choice, identify the form of radiation that would be emitted from the radioactive element used in a smoke detector.

How do you write nuclear equations to determine the products from different types of radioactive decay?

When writing equations to show nuclear reactions you present the information using the appropriate symbols to show the particular isotope, i.e. the atomic mass (A), and the atomic number (Z), e.g. the isotope of uranium-238 would have the symbol ${}^{238}_{92}\mathrm{U}$. If you know the type of radiation the element produces when it decays, the nuclear equation can be easily written by taking into account what is emitted from the radioactive nucleus (parent) as it decays. The following example shows the equation for alpha-decay of uranium-238.

$${}^{238}_{92}\mathrm{U} \longrightarrow \text{Daughter nucleus} + {}^{4}_{2}\alpha$$

To work out what the daughter nucleus is, we just need to make sure the total mass (equivalent to the number of nucleons) and the total electric charge are both the same on each side of the equation, i.e. for the decay of U-238, for the daughter nucleus, for the mass, we use $238 = A + 4$, and for the charge on the nucleus, i.e. number of protons, we use $92 = Z + 2$. From this we can determine that the daughter element has an atomic mass, A= 234, and a proton number, Z= 90. We can then use a Periodic Table of the elements to find out what element has 90 protons in its nucleus, i.e. No.90 is thorium. Thus the final equation is:

$${}^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha$$

Note: The decay of U-238 to Th-234 also results in the release of a gamma ray.

To write the equation for an isotope that undergoes beta decay, the same technique is employed, e.g. for strontium-90.

$${}^{90}_{38}\mathrm{Sr} \longrightarrow {}^{90}_{39}\mathrm{Y} + {}^{0}_{-1}\beta + \bar{\upsilon}$$

The beta-particle in the equation is an electron which is considered to have negligible mass compared to a nucleon, but it does carry a negative electric charge. The anti-neutrino (originally just called a neutrino) that comes off with the beta-particle is considered to have no mass and has no electric charge. Notice how the mass and charge on either side of the equation are equal.

Questions:

1. The following table shows some information on the radioactive decay of several radioisotopes. The first row of the table is complete but there are FOUR empty spaces with missing information. Use a Periodic Table of the elements to help you fill in the missing details.

	PRODUCTS of decay of parent nucleus	
Radioactive parent isotope	Daughter element	Symbol for radiation emitted
${}^{238}_{92}\mathrm{U}$	${}^{234}_{90}\mathrm{Th}$	${}^{4}_{2}\alpha$
${}^{230}_{90}\mathrm{Th}$		${}^{4}_{2}\alpha$
${}^{40}_{19}\mathrm{K}$		${}^{0}_{-1}\beta + \bar{\upsilon}$
${}^{226}_{88}\mathrm{Ra}$	${}^{222}_{86}\mathrm{Rn}$	
${}^{18}_{9}\mathrm{F}$		${}^{0}_{+1}\beta + \upsilon$

What are neutrinos?

When Einstein developed the equation $E=mc^2$, the scientific community could finally explain the perplexing problem as to where the energy emitted by radioactive isotopes was coming from. Measurement of the masses of the parent nucleus, compared to the combined mass of the daughter nucleus and alpha particles produced as products, showed that the products had slightly less mass than the parent nucleus. For a particular alpha-emitter, the loss of mass equated nicely using $E=mc^2$ to the measured kinetic energy of the alpha particles plus the energy of the associated gamma ray. When they applied this technique to study the beta-radiation coming from a pure sample of a radioisotope emitting beta particles they found that, rather than all having the same energy like the alpha particles coming from particular alpha-emitters, the beta particles were being emitted with a range of different energies. This discrepancy from the expected energy for the beta rays suggested an apparent tiny 'lost mass'. To explain the observed variation in the energy of the beta particles released by a particular radionuclide, in 1933 Wolfgang Pauli suggested that there might be a neutral particle being emitted along with the beta particle that could account for their variation in energy. The Italian, Enrico Fermi, adopted this idea in 1934 and his mathematical analysis of the results from experiments with beta radiation led to him proposing the 'neutrino' (Italian for 'little neutral one'). His mathematical model worked very well in explaining observations of β decay and scientists were quick to adopt neutrinos in their thinking, but even though neutrinos carry energy, because they basically have no mass and no electric charge, it took more than 30 years before they were actually detected in experiments. Note: Originally the anti-neutrino produced in β decay was just called a neutrino.

What are positrons?

Physicists now think that all particles of matter have their own anti-matter equivalent. The positron is the anti-particle to an electron. It is exactly the same mass and has the same sort of physical properties as a normal electron except it bears a positive rather than negative charge. A positron and neutrino are emitted during beta-plus decay. This form of β^+ decay occurs when there is an excess of protons compared to neutrons within the nucleus. A proton in the nucleus is involved in a nuclear weak interaction and transmutes to become a neutron as it emits the positron and neutrino. Anti-matter particles do not normally exist for very long in our matter world and the positrons released from β^+ decay fairly quickly interact with a normal electron. This interaction leads to matter being turned into energy and causes 'annihilation' of an electron with the positron, where the two particles end up disappearing as they are converted into energy in the form of two identical gamma rays (photons) that travel off in opposite directions.

Questions:

1. The electron and positron both have a rest mass of 9.109×10^{-31} kg. Considering $E=mc^2$, and annihilation of a positron with an electron converts all the mass to energy, calculate the amount of energy released as gamma rays when a positron and electron undergo annihilation.

2. Describe what actually happens within the nucleus of a radio isotope when the nucleus decays and releases a positron and neutrino.

What is meant by half-life?

The rate at which a particular radioactive element decays depends on the interactions between the different nucleons in the nucleus and the action of nuclear forces. Some very radioactive isotopes have so much instability in their nucleus that they decay almost as soon as they form. Other isotopes have only a very small imbalance and it can take many millions of years before this leads to the decay of the nucleus. When measurements are made of radioactivity we are generally dealing with countless millions of radioactive atoms. When a pure sample is studied, it is found that it doesn't matter how big the sample is, it will take exactly the same time for half of the radioactive atoms present in the sample to decay.

The time taken for half the atoms in a pure sample of a radioisotope to decay is known as the isotope's half-life. If you start with a mass of 1.0 kg of a pure radioactive isotope then, after a time equal to the half-life of the isotope, you will have 0.50 kg of the isotope still remaining in the sample. After waiting the same time again so another half-life has elapsed, there will now be 0.25 kg of the isotope still remaining in the sample.

Questions:

1. The half-life of the isotope U-238 is 4.51 x 10^9 years. The age of the earth is estimated to be about 4.6 x 10^9 years. Based on this, predict how much of this isotope of uranium would be found on earth today compared to when the earth first formed.

2. The regular half-life exhibited by radioactive isotopes makes them ideal for dating. Carbon-14 is a naturally occurring isotope of carbon that is radioactive. All living things absorb carbon from the environment while they are alive, and then stop taking it in when they die. By analysing the carbon found in ancient remains derived from once living things (artefacts), the amount of C-14 can be compared to the other isotopes of carbon (C-12 or C-13) in the sample and, based on the amount of the different isotopes of carbon found naturally in the environment, an age for the artefact can be determined. Carbon-14 has a half-life of about 5730 years.
   An ancient wooden artefact from a human settlement is analysed and found to only contain about $12^1/_2$ % of the C-14 that would be expected if it were alive in the environment today. Based on this result, calculate an approximate age for the ancient artefact.

What is the nuclear strong force and its properties?

The nuclear strong force was proposed to explain how nucleons could be held together within the nucleus. The electrostatic force of repulsion between the positively charged protons in a nucleus is absolutely enormous when the size of a proton is considered. If we consider just two protons together in a nucleus, i.e. a helium nucleus, the protons are considered to be just over 10-15m apart in a nucleus, and each proton has a charge of + 1.602 x 10^{-19} C. Using this information the repulsive force acting between the two protons can be calculated using Coulomb's law, i.e.

$$F_\varepsilon = \frac{k_\varepsilon\, q_1\, q_2}{d^2} \quad \therefore \quad F_\varepsilon = \frac{9\text{x}10^9 \text{ x } (1.602\text{x}10^{-19})^2}{(10^{-15})^2} = 231 \text{ N}$$

With this absolutely enormous force acting on them, the protons should accelerate at over 1029 ms-2 but instead, they remain held within the stable helium nucleus. When the nucleus was first studied, this force seemed to be far stronger than any force known to science so it was called the nuclear strong force. It is about 20x stronger than the electromagnetic force, the next strongest known force. Studies showed that the nuclear strong force had the following properties:

- the strongest of all known forces
- only has an effect over a very short range, ~ 3 x 10^{-15} m
- only acts on nucleons
- force only creates ATTRACTION between nucleons and acts between pairs of nucleons irrespective of charge

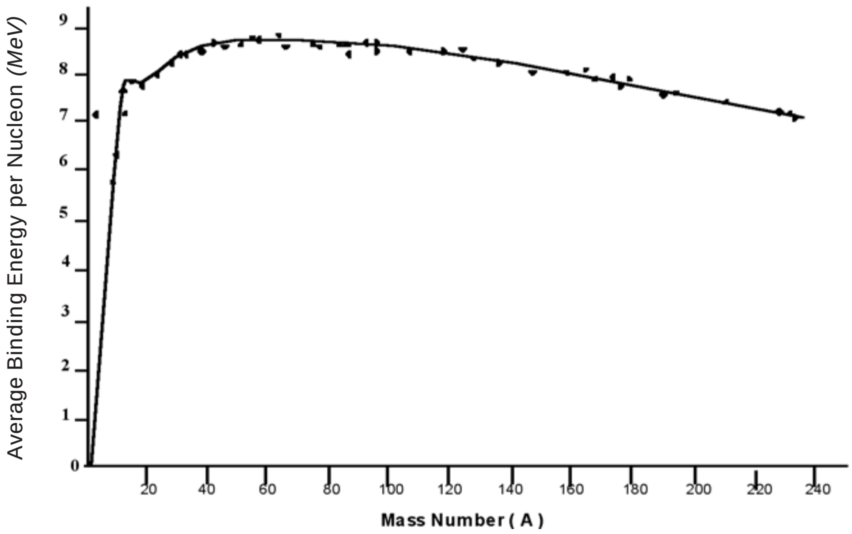
Questions:

1. Inside the core of stars, the enormous pressure and the kinetic energy of the hydrogen nuclei (protons) are so large that the protons can come close enough for the nuclear strong force to have an effect. When this occurs the electrostatic repulsion between the protons is overcome and they are combined together by the nuclear strong force to form a larger nucleus. One of the protons immediately goes through a beta decay to become a neutron with a positron and a neutrino emitted. This process of small nuclei joining to form a larger nucleus is known as nuclear fusion.
   In the space below, write the correct equation to describe this nuclear fusion reaction of hydrogen.

Where does nuclear energy come from?

When scientists first encountered natural radioactivity they could not explain where the energy was coming from. When in 1905, Einstein showed the equivalence of mass and energy with his equation $E=mc^2$, physicists realised that here was the answer to the origin of the energy observed in radioactivity, i.e. during the decay of a natural radioisotope the original parent nucleus is slightly more massive than the products that form when it decays. This showed that 'nuclear energy' was the result of mass being converted into energy. Over time, studies were done to measure the mass of different isotopes and, based on the number of nucleons and the known rest mass for a single proton and neutron, the total mass defect for each isotope could be calculated. Using this information the following graph was created:

'Average Binding energy per Nucleon' *versus* 'Atomic Mass (Number of nucleons)'



Using $E=mc^2$, the total mass defect for a particular isotope can be used to calculate an equivalent energy value. This energy became known as the 'binding energy' of the nucleus. The values plotted onto the vertical axis of the above graph were obtained by dividing the total binding energy of that isotope by the number of nucleons found in the nucleus of the isotope. When this graph is examined closely, several important implications from nuclear reactions are suggested:

1. If very small nuclei were fused together to create a larger nucleus, the average binding energy per nucleon in the new nucleus that forms would be much greater than it was for the smaller nuclei that fuse. This reaction produces a 'mass defect' for the product which results in energy being released. This is nuclear fusion and is the source of the energy coming from stars, e.g. the sun.

2. If a very large nucleus was split to create two smaller nuclei, the average binding energy of the original nucleus would be less than the average binding energy of the nuclei formed. This reaction produces a 'mass defect' for the products which results in the release of energy. This is nuclear fission and is the source of the energy produced in a nuclear fission reactor.

3. The nuclei that have the highest binding energy per nucleon (about 60 nucleons) have the greatest mass defect and represent nuclei that would CONSUME energy if they were to undergo either fission or fusion. As such, these nuclei represent the most STABLE nuclear structures, e.g. iron.

Questions:

1. Nuclear fusion of hydrogen in the core of the sun can be summarised by the following equation;

$$4\ {}^{1}_{1}\text{H} \longrightarrow {}^{4}_{2}\text{He} + 2\ {}^{0}_{+1}\beta + 2\upsilon$$

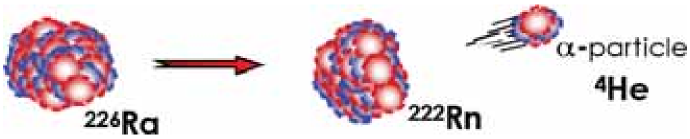
The information below shows the mass of the various components in the equation.
The masses are given in atomic mass units (u), where 1.0 u = 1.6605×10^{-27} kg

Rest mass of proton (hydrogen nucleus) - 1.007267 u
Rest mass of helium nucleus - 4.001506 u
Rest mass of positron - 0.0005486 u
Rest mass of neutrino - ~ 0.0000 u

(a) Determine the mass of the reactants and the mass of the products, and then use them to calculate the amount of mass lost (mass defect) in this solar reaction.

(b) Using Einstein's equation, calculate the energy in joules, released from this fusion reaction.
(Note: The mass must be in kg before you use the equation.)

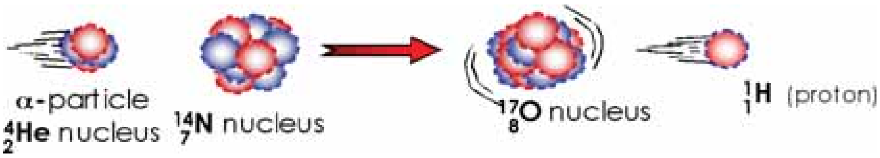
2. The diagram below represents the natural radioisotope, radium-226, undergoing a radioactive decay where it emits an alpha particle to become radon-222. This is an example of a natural transmutation and the large kinetic energy carried away by the α-particle can be explained by the mass defect, where the mass of the original radium nucleus is greater than the mass of the products formed.



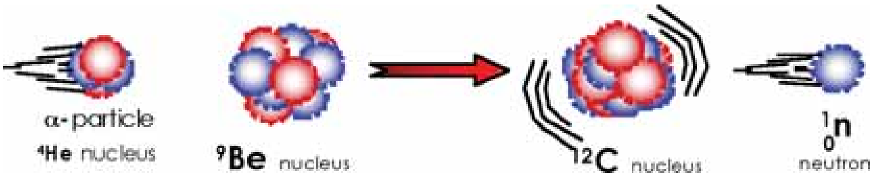
The mass of the radium-226 nucleus is 226.0254 u and the α-particle has a mass of 4.001506 u. If the α-particle is ejected with a kinetic energy of 7.665×10^{-13} J, and you assume it receives all the energy produced by the decay, explain how the mass of the radon-222 nucleus could be determined and calculate a result in atomic mass units. Think about it and be sure to use masses in kg.
(Note: In the actual decay of a Ra-226 nucleus, the alpha particle does not really receive all the energy involved, with a gamma ray also released [not shown]).

How did humans come to use nuclear reactions to produce energy?

When scientists first began to explore the nucleus, they tried to use energetic α-particles fired at different elements to create nuclear reactions. In 1919 Ernest Rutherford was successful in producing the first artificial transmutation when he bombarded a sample of gas containing nitrogen with α particles, i.e.



This artificial transmutation was very significant in that it was the first experimental confirmation that the hydrogen nucleus was a component of larger nuclei and this led to Rutherford naming it the ‘proton’. With this information and his knowledge of relative atomic masses, in 1920 Rutherford suggested that the nucleus must also contain a neutral particle he termed the ‘neutron’. With the development of the mass-spectrograph by F.W. Aston, it became possible to make very accurate measurements of the mass of different isotopes. Over the next decade many experiments were carried out bombarding different elements, including using protons as the probe. John Cockcroft and Edward Walton built a device to accelerate protons to even higher energies than the most energetic α-particles and, when they directed the proton beam at a target made of lithium, the term ‘splitting atoms’ was born with the proton causing the lithium nucleus to break into two parts, equivalent to two α-particles, (He nuclei). Another very important contribution came from the development of much more sensitive radiation detectors for use in experiments, e.g. Geiger-Mueller counters. In 1932 James Chadwick used the accumulated information about the nucleus, and results from some recent experiments, to design the famous experiment where he was able to confirm the ‘neutron’ and identify its properties. In doing this, not only did he fill in an important piece in the puzzle of the nucleus, but he also made people aware of how they could produce neutrons using energetic α-particles fired at a beryllium target, as represented by the diagram below:



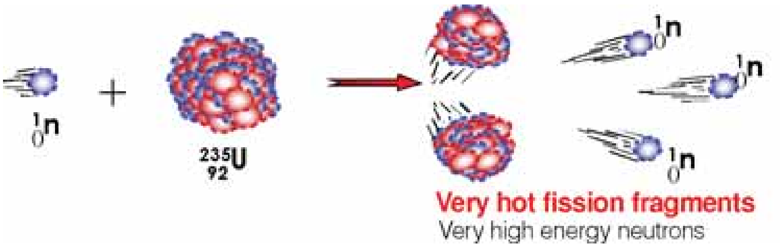
Scientists immediately realised that here was a new particle to fire at nuclei to try to create nuclear reactions and the neutron provided a significant advantage because it has NO electric charge and as such, will not be repelled by the positively charged nuclei.

Questions:

1. In the space below, write the correct equation to show the nuclear reaction produced by Cockcroft and Watson when they bombarded lithium, $^{7}_{3}$Li with protons, $^{1}_{1}$H. In your nuclear equation indicate the nucleus that would have formed first, and then almost immediately, split to form two alpha particles.

How did scientists first work out they could cause nuclear fission of uranium?

Although some scientists had suggested that energy could be produced for humans using nuclear reactions, the direction of studies using neutrons as probes originally started in a different direction. Enrico Fermi in Rome was one who was quick to use neutrons to begin a methodical search, starting with the smallest atoms, exploring what would happen when neutrons were fired at the different elements. This led to the discovery of many new radioactive isotopes and ultimately provided evidence to show that the positron (an anti-matter particle) was produced when certain radioactive isotopes decay. In Germany, similar studies using neutrons were being conducted by Otto Hahn and Fritz Strassmann using uranium as a target. They found some unexpected results and communicated the puzzling presence of barium and lanthanum as elements found after the neutron bombardment. This result was also observed by Fermi in 1934, but because barium is in the same group on the Periodic Table as radium, their very similar chemical properties had, to this point, led to researchers assuming it was radium. When Austrians Otto Frisch and Lise Meitner heard of the barium in the result they set about doing calculations using the known properties of uranium. The results suggested that on absorbing a neutron a uranium nucleus could become so unstable that it would split to form two new smaller nuclei and, the barium that had been found in the experiment was just the right mass to be one of the products. Frisch later named this nuclear reaction ‘fission’. As the news spread of these findings, including to Fermi in America, Frisch set about collecting the materials to conduct an experiment to confirm the prediction. In January 1939 he generated neutrons using Chadwick’s technique and directed the beam towards a sample of uranium. Just as he suspected, the experiment showed evidence of uranium atoms having been split by the neutrons to become two smaller, radioactive nuclei. With Hitler and the Nazi party in power in Germany and war imminent in Europe, Fermi, and now Bohr, had fled to take refuge in America. With the news of the fission reaching the U.S.A it caused a lot of excitement combined with a concern that it was already known about in Germany and the Nazis might try to use the knowledge to develop a weapon. A number of experiments were quickly performed which confirmed that absorption of a neutron by a uranium atom could split the atom into two smaller nuclei and Frisch’s nuclear fission was possible. The following diagram shows a possible nuclear fission of the isotope U-235.



Questions:

1. If one of the fission fragments produced in the above fission reaction is an isotope of barium, $^{141}_{56}\text{Ba}$ write the nuclear equation for the reaction and use a Periodic Table of the elements to identify the other isotope produced as a fission fragment with the barium.

2. A stable isotope of barium shown in the Periodic Table has 137 nucleons in its nucleus while the barium produced by this fission reaction has 141 nucleons and is very radioactive. With reasons for your answer, explain what form of radioactive decay you would expect to be exhibited by this barium isotope produced by the fission reaction.

How did humans come to be able to use fission to extract nuclear energy for use?

The experiments confirming fission of uranium at the start of 1939 began intensive studies. In order to extract useful amounts of energy it was realised that it was necessary to produce a ‘chain reaction’ in the fission of uranium nuclei. Experiments had already shown that the speed of neutrons could be reduced by passing them through a material rich in hydrogen e.g. paraffin wax, and the chances of the neutron being captured by a nucleus increased significantly with slower neutrons. They had also found that the fission with neutrons only took place in a small percentage of the uranium atoms in the sample. When this was studied closely it was realised that the atoms of the U-235 isotope, present as less than 1% in natural uranium, would readily undergo fission when a nucleus captured a neutron. They also found that some nuclei in the atoms of the common U-238 isotope were capturing a neutron and, rather than undergoing fission, the U-239 nucleus forming from the neutron capture would fairly soon undergo β decay to form a new element with an atomic number 93 and then, some time later, this nucleus also decayed to form yet another new element with atomic number 94. These new, transuranic elements were named Neptunium and Plutonium respectively and were the first artificial elements created. Experiments also showed that in each fission of a uranium nucleus the result was that, not only were fission fragments produced (smaller nuclei), but the fission could also produce 2 or 3 neutrons that, in theory, could then go on to cause the fission of other uranium nuclei. The ‘chain-reaction’ to extract nuclear energy now seemed like it was really possible. With the outbreak of war in Europe, as time passed, news filtered through to the USA of the Nazis taking over uranium mines and, having invaded France in 1940, they had captured Frederic Joliot who was a leader in research into nuclear reactions and, just after Frisch and Fermi, had conducted one of the earliest experiments to confirm fission. The Nazis had managed to get copies of all his experimental work and had drawn together a team of some of the best German scientists with Hitler directing them to conduct research so they could build a weapon using nuclear energy. The scene was now set for nuclear energy, originally called atomic energy, to have a truly significant impact on human society with scientists working to develop the required technology to allow them to use a chain reaction of nuclear fission and, according to $E=mc^2$, convert mass into energy.

Questions:

1. In the space below, show the equation for the beta decay that occurs in the U-239 isotope which results in the uranium transmuting to become element 93, Neptunium.

2. Suggest a possible reason why passing the neutrons through a material rich in hydrogen could act to slow down the neutrons and increase their chance of being captured.

What were the essential components in the first nuclear reactor?

The start of the war in Europe prompted Leo Szilard to convince Einstein to write a letter to the U.S President, Franklin Roosevelt, warning of the potential threat of Hitler obtaining nuclear weapons from the fission of uranium, and advising the President that they should work with haste to build an atomic bomb using a chain reaction of fission in uranium. This started the so called Manhattan project which culminated in the creation of the first nuclear reactor and the first atomic bombs (nuclear weapons).

The first nuclear reactor was constructed in a squash court of Chicago University. In a collaborative effort involving many scientists from Europe, Britain and America, the construction of the nuclear reactor was led by Enrico Fermi. The components required for Fermi's team to build the first nuclear reactor, to produce a CONTROLLED chain reaction of nuclear fission in uranium, correspond closely to the components found in a modern nuclear reactor which include:

- **FUEL RODS** – These consist of enriched uranium, i.e. the common isotope U-238, with an increased concentration of the much more fissionable isotope U-235. It is within the fuel rods in the core of a reactor that fission of the uranium nuclei occur. The fuel used in the core of the OPAL reactor is enriched to about 20% U-235.
- **MODERATOR** – This is a material to slow the speed of the neutrons produced by fission in the fuel rods. This gives the neutrons a much greater chance of being captured and creating fission in other uranium nuclei. Fermi used blocks of graphite as a moderator while many modern reactors, including OPAL, use 'heavy' water where much of the hydrogen in the water molecules is the isotope known as deuterium which has a neutron as well as a proton in the nucleus ($^{2}_{1}H$).
- **CONTROL RODS** – These are rods made from an element that has a high neutron capture coefficient, e.g. cadmium, boron and hafnium. The control rods act to regulate the number of neutrons available to create fission. When the control rods are lowered into the reactor core they absorb neutrons making them unavailable to the fission reaction. When the control rods are raised, more neutrons become available to create fission in the fuel. In this way the control rods act to maintain the rate of fission reactions going on in the reactor core.
- **HEAT-EXCHANGER** – This is a system to extract the energy produced from the fission reactions and acts to transfer the heat produced in the reactor core while also cooling the core to prevent overheating.

Questions:

1. When a neutron encounters the nucleus of different isotopes there can be different results depending on the isotope the neutron encounters:
   - the neutron can bounce off the nucleus in an elastic collision or,
   - the neutron is captured by the nucleus with three different results possible,

   i. the neutron capture results in fission of the nucleus, or,
   ii. the neutron capture results a in a new, radioactive nucleus, or,
   iii. the neutron capture results in a new, stable isotope forming.

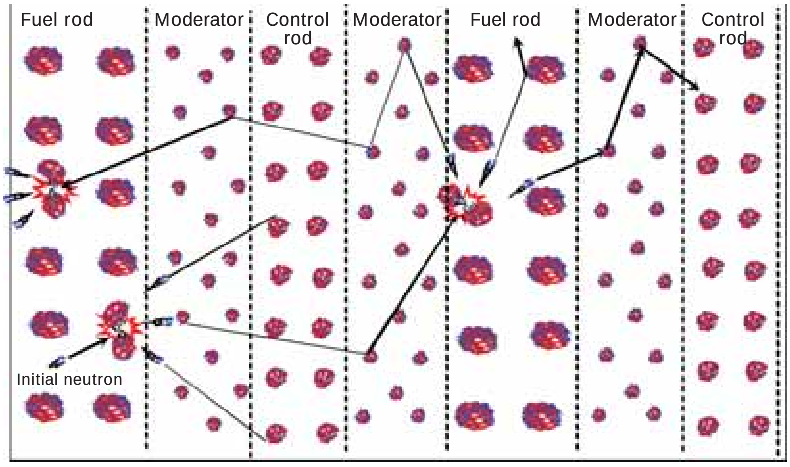
   Identify which of these properties an isotope would need to have for it to be a good choice to use in a nuclear fission reactor as:

   - the fuel

   - the moderator

   - the control rods

What is the difference between a CONTROLLED and UNCONTROLLED chain reaction of fission?

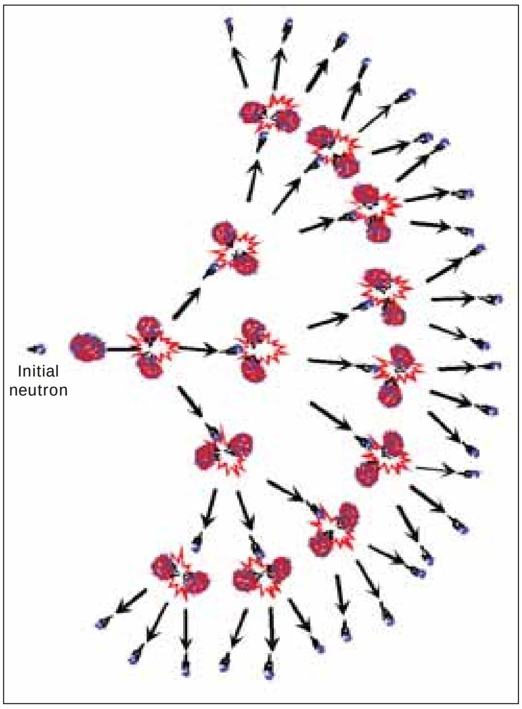


Each fission of a uranium nucleus produces 2 or 3 neutrons which can go on to create further fission reactions. For a CONTROLLED chain reaction, some of the neutrons produced by fission must be captured by the nuclei of the element in control rods so they are taken out of the reaction. The control rods can be lowered if too many neutrons are present in the core, or raised to allow the rate of fission reactions to increase. In this way the control rods help to regulate the amount of energy being released from fission.

The idea is represented in a very simplified form in the diagram alongside where the nuclei of the different components in a reactor core have been shown. In this case it can be seen that different components in a reactor core have been shown. In this case it can be seen that only 1 of the 3 neutrons produced in the initial fission goes on to create fission of another uranium nucleus, while the other two end up captured by nuclei in the control rods. (Note: The path of the neutron is indicated by the arrows.)

In an UNCONTROLLED chain reaction each neutron produced in fission goes on to rapidly create fission of another nucleus, with the neutrons produced in these fissions each going on to create even more fission reactions. In this way enormous amounts of energy are released very rapidly.

It is uncontrolled fission that occurs in a nuclear weapon. The first nuclear weapons, known as atomic bombs, that were developed in the Manhattan project, used an uncontrolled chain reaction in almost pure U-235 (Hiroshima) and in plutonium-239 (Nagasaki).



Questions:

1. According to the diagram of CONTROLLED nuclear fission, outline what occurs when neutrons encounter the nuclei of the moderator atoms.

2. The fission of one uranium-235 nucleus yields an average energy of about 200MeV = 3.2 x 10^{-14}J. Considering that 1.0kg of pure uranium 235 contains approx 2.56 x 10^{24} uranium atoms, calculate the total energy released if the nucleus of every atom in the 1.9kg of uranium undergoes fission.

What role can a nuclear fission reactor play to benefit science?

A nuclear fission reactor provides a valuable research tool for scientists. In a research reactor, it is not the energy released in fission which is most important but rather, it is the neutrons produced by fission reactions that are most useful to scientists. The neutrons can be directed at particular targets to create useful radioisotopes for use in a wide range of applications or, using the neutrons in a beam allows them be used as probes in neutron scattering experiments. (Discussed later)

Using a nuclear reactor to produce radioisotopes

When a particular target isotope is exposed to neutrons, the nuclei of the target can capture the neutron to become a new isotope. With the right exposure of certain targets, a specific radioactive isotope can be formed. Radioisotopes produced in reactors can be used for a range of applications in agriculture, medicine and industry. Examples of medical radioisotopes produced in a nuclear reactor are technetium-99m (from molybdenum-99) used for diagnosis and Iodine-131, used in the treatment of thyroid cancer. (Note that molybdenum-99 is usually produced from fissioning uranium-235 rather than the neutron irradiation of a target.)

Using a particle accelerator to produce radioisotopes

Cyclotrons, which are machines which use magnetic fields to accelerate charged particles in a circular path, have been developed to extend the range of radioisotopes which can be used in medicine. Cyclotrons use charged particles such as protons to bombard targets and make radionuclides with specific properties which make them very useful for diagnosis of medical problems. e.g. the radioisotope Fluorine-18 is produced in a cyclotron where protons are accelerated to collide with a target nucleus. fluorine-18 decays by beta-plus decay, emitting a positron and decaying to form a stable isotope of oxygen. This makes it a suitable radioisotope to use in Positron Emission Tomography (PET) scans which are proving to be an extremely valuable diagnostic tool.

Questions:

1. During a PET scan, the positrons produced are almost immediately annihilated in a collision with an electron. This annihilation leads to TWO gamma rays (γ) which travel off in opposite directions.
   Based on the mass defect, calculate the minimum energy of the photons of γ radiation produced by the annihilation of the positron with an electron.

What are some of the radioisotopes manufactured for use in medicine, agriculture, and engineering?

The radioisotopes produced in a nuclear reactor or cyclotron can be very useful in a wide range of applications and have uses in medicine, industry, engineering, agriculture, and also play a significant part in many areas of scientific research. You will have the opportunity to explore many of these applications and discuss examples of the radioisotopes used when you complete the excursion to ANSTO. (You will find more information in a booklet ‘Radioisotopes:/their role in society today’ available when you visit ANSTO.)

Medicine:

Radioisotopes have many roles in medicine, being used both for diagnosis and treatment. The large majority of medical uses of radioisotopes are in a diagnostic role (approximately 90%). Radioisotopes can be produced in a nuclear reactor or cyclotron so they have specific properties which allow them to be used safely.

Any radioisotope taken internally as part of a medical treatment must be carefully chosen so it has a relatively short half-life, produces only the desired form of radiation, and the daughter isotope produced from the decay is harmless or rapidly expelled by the body, This non-invasive technique uses radioisotopes which have been incorporated into particular molecules so when used with the patient, they will be concentrated in particular regions of the body, e.g. C-11 can be incorporated in glucose to allow activity within the brain to be studied. As discussed before, PET scans rely on the emitted positrons undergoing annihilation with an electron to produce two identical gamma rays that travel off in opposite directions. A scanner around the patient records the gamma rays and then a powerful computer uses tomography to construct an image based on the data from the gamma sensor.

Radioisotopes can be used for radiotherapy treatments of cancer, with cancerous cells tending to be far more susceptible to the effects of the radiation than normal body cells. In one example, the radioisotope cobalt-60, which undergoes beta decay followed by a gamma-emission, is placed in a specially designed device and used to supply gamma rays which are collimated to concentrate at the site of the cancerous tissue in the patient.

Agriculture:

Radioisotopes are used in agriculture to monitor the way various agricultural chemicals move into crops and into ground water. Phosphate and nitrate are essential nutrients required for plant growth. By incorporating radioisotopes of nitrogen or phosphorus, e.g. P-32, into the fertiliser, the movement of the fertiliser from ground into the crop plant can be traced. The information gained by monitoring how the fertiliser is being used by different crops can then be used to improve and maximise the use of fertiliser, and can lead to greater efficiency and reduced costs.

Engineering:

A common use of radioisotopes in engineering is to assess the integrity of metal objects. Higher energy gamma rays have a shorter wavelength than X-rays and are more penetrating. A radioisotope emitting gamma rays can be conveniently used in the field. An appropriate radioisotope emitting gamma rays, e.g. iridium-192, can be contained within a specially designed container that acts to shield the operators from the radiation, but when being used, allows a collimated beam of gamma rays to be produced. The beam can then be passed through a metal object to create an image on a special photographic film placed on the other side of the metal. In this way welds can be carefully checked for their strength and, objects such as the rotor blades for a jet engine, can be closely scrutinised for any flaws.

How scientists use natural radioisotopes

Radiosotopes which are found in nature can be used by scientists to find out interesting and useful facts. Carbon-14 occurs in all organic material and can be used to measure the age of artifacts made for example out of bone. This is called carbon dating. Naturally occurring chlorine-36 is used to measure the age of water up to two million years old. Hydrogen-3 (tritium) is used to measure the age of young groundwater up to 30 years old.

Apart from producing radioisotopes, what role can a nuclear research reactor have in allowing scientific research to be carried out?

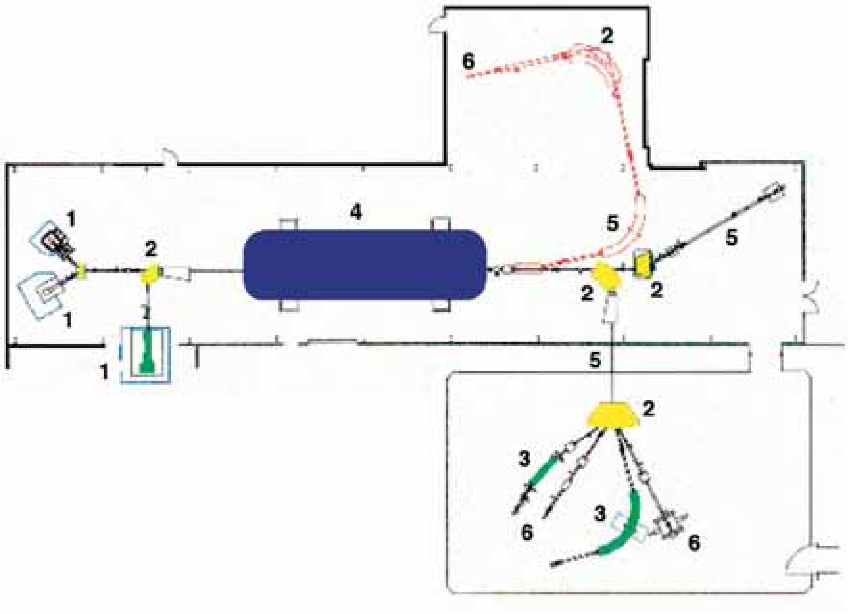
What is neutron scattering and why is it so useful?

Neutron scattering involves using neutrons as probes to explore matter. The process is similar to X-ray crystallography which you have previously studied but neutrons have the advantage that they are able to penetrate electron clouds to reveal details on the nuclei in the target atoms. Neutrons generally have a very small de Broglie wavelength. Generally the resolution in images increases with smaller wavelengths, but it is often more appropriate to use neutrons with a much longer wavelength. The neutron wavelength can be increased by cooling to slow the neutrons down, e.g. the de Broglie wavelength for a cold neutron at 20K is about 10x the radius of a hydrogen atom. The source of the neutrons for neutron scattering experiments is a nuclear fission reactor. A research reactor such as OPAL, that is designed for neutron scattering experiments, supplies beams of neutrons using various guides that direct the neutrons produced in the reactor core to supply a collimated beam of neutrons at a particular energy which can be directed at a target material for analysis. Neutron scattering is a powerful technique used to study the structure and behaviour of materials at the crystalline, molecular, atomic and sub-atomic levels.
(You will view OPAL's neutron scattering facilities on your excursion.)

What are particle accelerators and why are they so useful in our research into matter?

Many of the early breakthroughs in nuclear science were made possible using a particle accelerator. There are many forms of accelerator but their purpose is, using electric and magnetic fields, to accelerate and control charged particles so they can be directed at very high speed to collide with a target. It was through the evidence collected from experiments with accelerators that the Standard model of matter was produced, and continues to be tested. You should familiarise yourself with the common particle accelerators and the techniques involved to accelerate and control the charged particles being used.
(You will have the opportunity to examine ANTARES, a particle accelerator on your tour.)

> The building blocks that make up ANTARES
> The ANTARES facility is made up of several functional units. They are the ion sources (1) where the ion beams to be accelerated are formed; magnetic (2) and electric (3) analysers that are used to select ion mass, energy and electrical charge; the high voltage accelerator (4), which is surrounded by insulating gas inside the large pressure vessel, necessary to stop the millions of volts discharging to the surrounding environment; the beamlines (5), which provide a highway down which the ion beam travels to its final destination while being focussed and directionally aligned; and the target stations (6) where the high energy beam of ions is measured for its isotopic components, or information is gathered from a surface targeted by the ion beam.



EXCURSION QUESTIONS:

These questions will be completed as your complete your tour at ANSTO.
Note that your tour may not be in the order shown.

Part 1 - The Education and Tour Centre: Introduction and overview of nuclear physics

1. Identify THREE areas where radioactive isotopes are found in everyday materials.

2. Identify what is required to start a nuclear fission reaction.

3. With an example for each, describe what is meant by the terms fissile and fertile when referring to the elements found in the fuel used in a nuclear reactor.

4. Outline the principal role of the ANSTO facilities at Lucas Heights.

5. State an example of a radioisotope produced at ANSTO that is used in:

   - medicine for diagnostic purposes

   - medicine for treatments

   - in industry or engineering

6. Describe the features of a medical radioisotope which are required to make it suitable to be administered internally to a patient.

7. Molybdenum-99 is not administered to patients but it is a very useful radiopharmaceutical, i.e. a radioactive substance used in a medical application. Describe how Mo-99 is used in a medicine.

Part 2 - OPAL: The functional components of Australia's research reactor and the neutron and X-ray scattering facilities.

1. Describe the nuclear fuel assemblies found in OPAL's reactor core.

2. Identify the substance that is used as the moderator in OPAL.

3. Identify the materials used in the control rods.

4. Explain the purpose of the hot water blanket at the top of the pool above the reactor core.

5. Describe how the people working above the reactor are protected from radiation.

6. Identify the blue glow observed in a reactor core and outline why it is produced.

7. Explain the purpose of the large delay tank incorporated into OPAL’s construction.

8. State the purpose of the reflector vessel.

9. Explain why the neutron beam guides are not pointing straight towards the reactor core.

10. Why is silicon irradiated in OPAL?

Neutron Guide Hall:

10. Outline how cold neutrons are produced.

11. State reasons why scientists use both X-rays and neutrons to study materials.

12. Describe the technique used to separate gamma rays and high energy neutrons from the thermal neutrons that are used for experiments.

Part 3 - : Junior Caves – Production and safe handling of radioisotopes.

1. Describe the design features present which allow the operator to safely handle radioactive substances.

2. Identify the target isotope used to manufacture iodine-131.

3. Outline the process used to manufacture iodine-131 including what this radioisotope is used for.

Part 4 - : ANTARES – A tandem particle accelerator.

1. Outline how ANTARES acts to accelerate particles to allow them to be studied.

2. State two analytical techniques that use a tandem accelerator.

3. Describe how the tandem accelerator is used to monitor an environmental problem.

4. Explain the purpose of the electromagnets in a tandem accelerator.

Part 5 - : Building 3 – Dealing with nuclear waste.

1. Identify the sources of nuclear waste.

2. Describe a technique for locking up radioactive waste so they are safe to the environment.

3. Once radioactive waste has been treated and placed in an appropriate container, outline the other safety precautions that must be followed to ensure the safety of humans and the environment.

4. Describe a spin-off that has arisen from nuclear waste disposal technology.