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Nuclear-based science benefiting all Australians

Year 12 Physics

Excursion Workbook

Ver 0.8

Your visit to ANSTO

On site, you will visit:

- The OPAL (Open Pool Australian Lightwater) Research Reactor
- The Australian Centre for Neutron Scattering
- The Centre for Accelerator Science
- The ANSTO Nuclear Medicine Facility

Back at the Discovery Centre, you will:

- Draw traces left by alpha particles, beta particles and protons in the cloud chamber
- Observe demonstration of a scintillation counter and how radiation varies with distance from source and with shielding thickness
- Consider other instruments for detecting radiation (thermo-luminescent device, personal dosimeter)
- Process information to learn how the Australia Synchrotron accelerates electrons to produce intense light for research purposes
- Attend lecture to understand more about ANSTO science work, future directions of nuclear technology and nuclear waste management

The tour will conclude at the Discovery Centre. We have a number of brochures that you may wish to collect or they can be accessed on our website.

Year 12 Physics: Nuclear Science Depth Study

We recommend that this excursion becomes the starting point for a nuclear science depth study. ANSTO's Year 12 Physics excursion helps students cover the following syllabus content:

Module 8: From the Universe to the Atom

Students:

● analyse the spontaneous decay of unstable nuclei, and the properties of the alpha, beta and gamma radiation emitted (ACSPH028, ACSPH030)

● examine the model of half-life in radioactive decay and make quantitative predictions about the activity or amount of a radioactive sample using the following relationships:

$$N_t = N_0 e^{-\lambda t}$$

$$\lambda = \ln(2)/t_{1/2}$$

where N_t = number of particles at time t, N_0 = number of particles present at t = 0, λ = decay constant, $t_{1/2}$ = time for half the radioactive amount to decay.

● model and explain the process of nuclear fission, including the concepts of controlled and uncontrolled chain reactions, and account for the release of energy in the process

● analyse relationships that represent conservation of mass-energy in spontaneous and artificial nuclear transmutations, including alpha decay, beta decay, nuclear fission and nuclear fusion

● account for the release of energy in the process of nuclear fusion

● predict quantitatively the energy released in nuclear decays or transmutations, including nuclear fission and nuclear fusion, by applying:

– the law of conservation of energy

– mass defect

– binding energy

– Einstein's mass–energy equivalence relationship $E = mc^2$

● investigate the operation and role of particle accelerators in obtaining evidence that tests and/or validates aspects of theories, including the Standard Model of matter

Working Scientifically

- Questioning and predicting
- Planning investigations
- Conducting investigations

We recommend students use our *Year 12 Physics Depth Study Guide* for ideas and resources for depth study activities after their excursion.

NESA requirements for Depth Studies

- A minimum of 15 hours of in-class time is allocated in both Year 11 and Year 12
- At least one depth study must be included in both Year 11 and Year 12
- The two Working Scientifically outcomes of Questioning and Predicting, and Communicating must be addressed in both Year 11 and Year 12
- A minimum of two additional Working Scientifically skills outcomes, and further development of at least one Knowledge and Understanding outcome, are to be addressed in all depth studies.

Pre-work Questions – to be attempted ***before*** your visit

Question P1

Use the online Atom Builder program (www.ansto.gov.au/games) and the Periodic Table poster (www.ansto.gov.au/posters) to help complete the table.

Name of atom	Number of protons	Number of neutrons	Mass number	Notation
nitrogen-14				
	3		7	
				$^{19}_{9}F$
		14	27	

Question P2

Most unstable nuclei with a large number of protons (more than 82) decay via alpha radiation. Nuclei with too many neutrons, when compared to the stable isotopes of that element, decay via beta (β^-) radiation, while those with too few neutrons often decay by positron emission (β^+). State the common stable isotope of each element and use it to predict the type of radiation produced when the following nuclei decay:

a) C-14		
b) U-238		
c) F-18		
d) Co-60		
e) I-131		

Question P3

Answer the following questions using the information in the table below:

Name of radiation	**Identity of radiation**	**Penetration through matter (energy dependent)**	**Ionising power**	**Behaviour of path in magnetic field**
Alpha (α)	Helium nucleus (two protons and two neutrons)	Very weak; average alpha can only penetrate about 5cm through air, stopped by a 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 1-2m through air, stopped by a few mm of aluminium or perspex	Produce moderate ionisation	Easily deflected by magnetic fields, exhibit a 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 12mm of lead	Very weak effect in causing ionisation	Not deflected by magnetic fields, exhibit no electric charge

a) A student has a sample of radioactive material. They find that when a Scintillation counter is held about 20 cm from the sample the count recorded is very low, but when they bring the counter very close to the sample, high counts are detected. Outline one conclusion the student might make about the radioactive material.

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b) Smoke detectors contain a small sample of a radioisotope that emits radiation into a narrow air gap between two electrodes. The air is ionised and completes an electric circuit. When smoke enters this air gap, fewer air particles are ionised and the current drops, activating the alarm. Identify the form of radiation that would be emitted from the radioactive element used in a smoke detector. Give reasons for your answer.

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Question P4

The following table shows some information on the radioactive decay of several radioisotopes. Use the ANSTO periodic table of the elements (www.ansto.gov.au/posters) to help you fill in the missing details

	Products of decay of parent nucleus	
Radioactive parent isotope	Daughter element	Symbol for radiation emitted
${}^{230}_{90}Th$		${}^{4}_{2}\alpha$
${}^{241}_{95}Am$		${}^{4}_{2}\alpha$
${}^{131}_{53}I$		${}^{0}_{-1}\beta + \bar{v}$
${}^{18}_{9}F$		${}^{0}_{1}\beta + v$
${}^{14}_{6}C$	${}^{14}_{7}N$	
${}^{36}_{17}Cl$		${}^{0}_{-1}\beta + \bar{v}$

Question P5

The following equation allows you to quantitatively predict the remaining radioactivity of a sample using its half-life:

$$N_t = N_0 e^{-\lambda t}$$

$$\lambda = \ln(2)/t_{1/2}$$

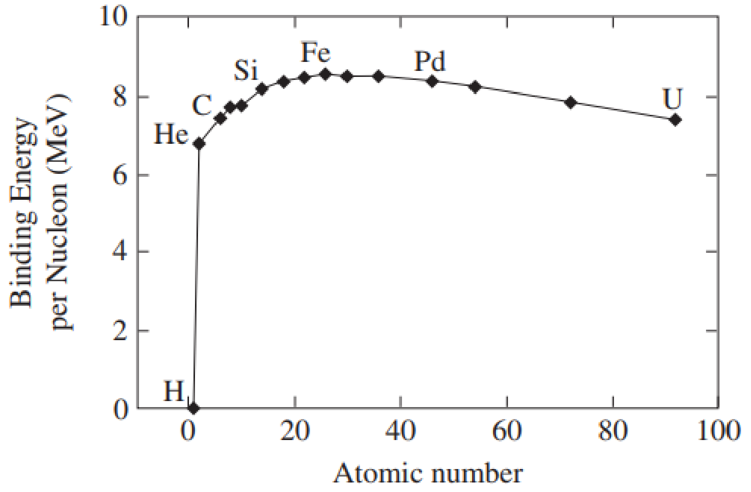
where N_t = number of particles at time t, N_0 = number of particles present at t = 0, λ = decay constant, $t_{1/2}$ = time for half the radioactive amount to decay.

a) The half-life of the isotope U-238 is 4.51×10^9 years. The age of the Earth is estimated to be about 4.6×10^9 years. Based on this, predict what proportion of this isotope of uranium would be found on Earth today compared to when the Earth first formed (N_t/N_0).

b) 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, the ratio of C-14 to other isotopes of carbon (C-12 or C-13) in the sample can reveal the age of an artefact up to 50,000 years old. Carbon-14 has a half-life of about 5,730 years.

   An ancient wooden artefact from a human settlement contains about 12.5% 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.

Question P6



Source: 2014 HSC Physics Exam, New South Wales Education Authority.

a) Using the diagram above, explain the concepts of mass defect and binding energy

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b) Nuclear fusion of hydrogen in the core of the Sun can be summarised by the following equation:

$$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}^{0}_{1}\beta + 2\nu$$

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 x 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

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c) The natural radioisotope, radium-226, undergoes a radioactive decay where it emits an alpha particle to become radon-222. 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 x 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. 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, because a gamma ray is also released).

d) Different fission fragments are produced during the fission of uranium-235. Fill in the blanks in the example fission equation below:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{\square}_{56}Ba + ^{92}_{36}\square + 3^{1}_{0}n + \gamma + heat$$

e) 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 1.0kg of uranium undergoes fission.

Question P7

Fission in a nuclear reactor is controlled, whereas fission in a nuclear weapon is uncontrolled. Controlled fission in a reactor requires:

- The correct **fuel** composition, usually a mixture of fissionable U-235 and U-238.
- A **moderator** to slow the speed of the neutrons from the fission reaction, increasing the chance that neutrons are absorbed by neighbouring uranium nuclei for further fission events.
- **Control rods**, which, when inserted into the reactor core, regulate the number of neutrons available to create fission events via neutron capture.
- **Coolant and heat exchangers** to cool the core to prevent overheating.

Isotopes have different properties when they interact with neutrons. When a neutron encounters the nucleus of different isotopes either

- the neutron can bounce off the nucleus or
- the neutron is captured by the nucleus, with three different results possible:

  1) the neutron capture results in fission of the nucleus, or
  2) the neutron capture results in a new, neutron-rich radioactive nucleus, or
  3) the neutron capture results in a new 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:

  i) the fuel

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  ii) the moderator

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  iii) the control rods

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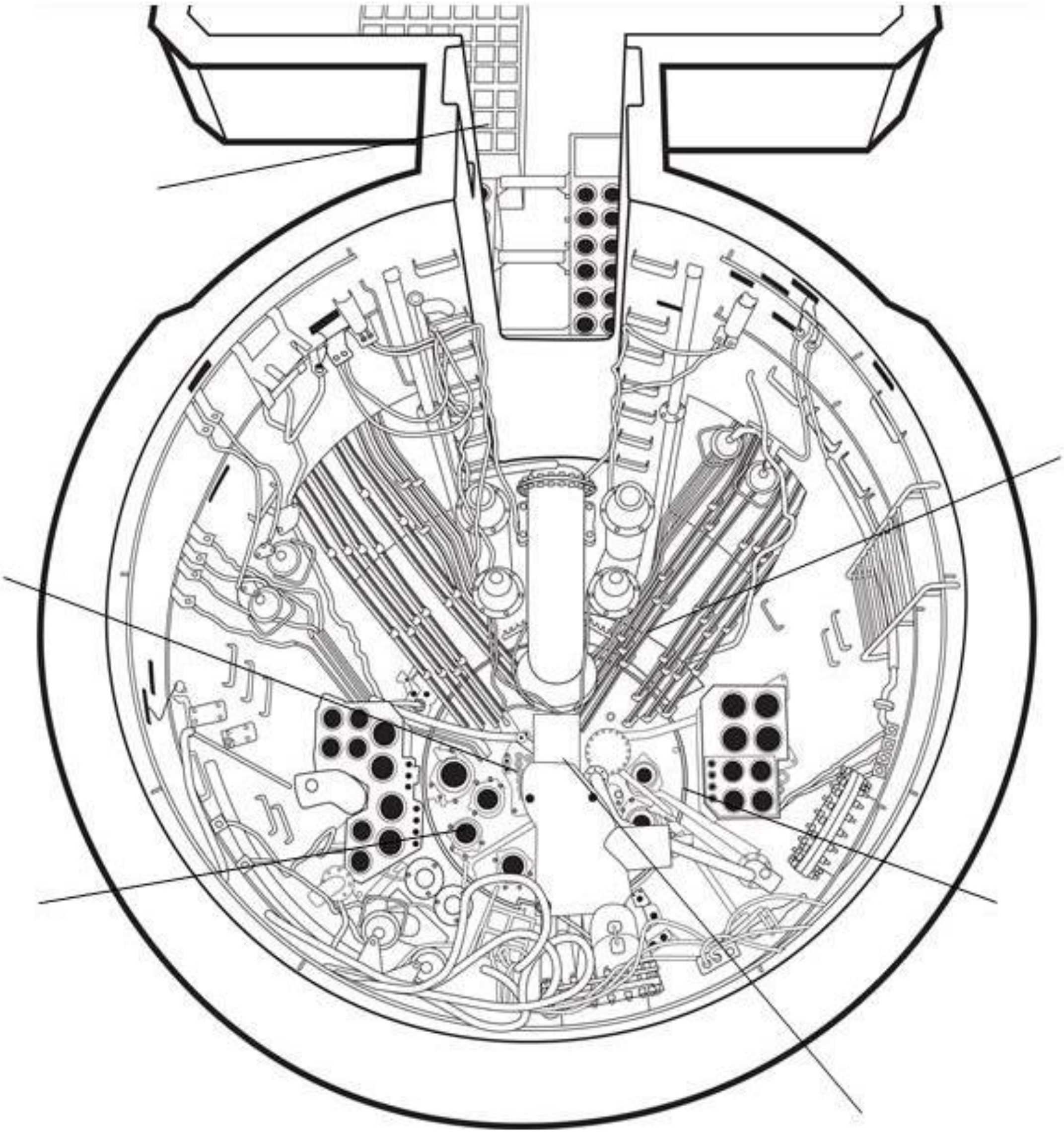
On-site tour - **During-excursion questions**:
Information will be available on the tour to enable you to answer them

Question T1 – OPAL research reactor

Label the diagram and complete the table below:



Material	Reactor component	Function
Heavy water		
Hafnium (encased in stainless steel)		
Light water		
Uranium		

Question T2 – Australian Centre for Neutron Scattering

1. Identify three properties of neutrons that make them suitable for studying materials. Explain how each property allows scientists to use neutrons as a probe for investigating matter.

Property of neutrons	How property enables investigation of matter

2. Why does ANSTO use both thermal and cold neutrons?

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3. Summarise one example of neutron research

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Question T3 – ANSTO Nuclear Medicine Facility

1. If technetium-99m is the radioisotope used for diagnostic scans, why does ANSTO manufacture and distribute molybdenum-99? Consider the half-life of each isotope.

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2. Target plates are very radioactive when they come out of the reactor. Describe two safety measures used to work safely with radiation during the manufacture and distribution of molybdenum-99

   a) ____

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   b) ____

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3. What are the benefits of Synroc as a waste storage solution?

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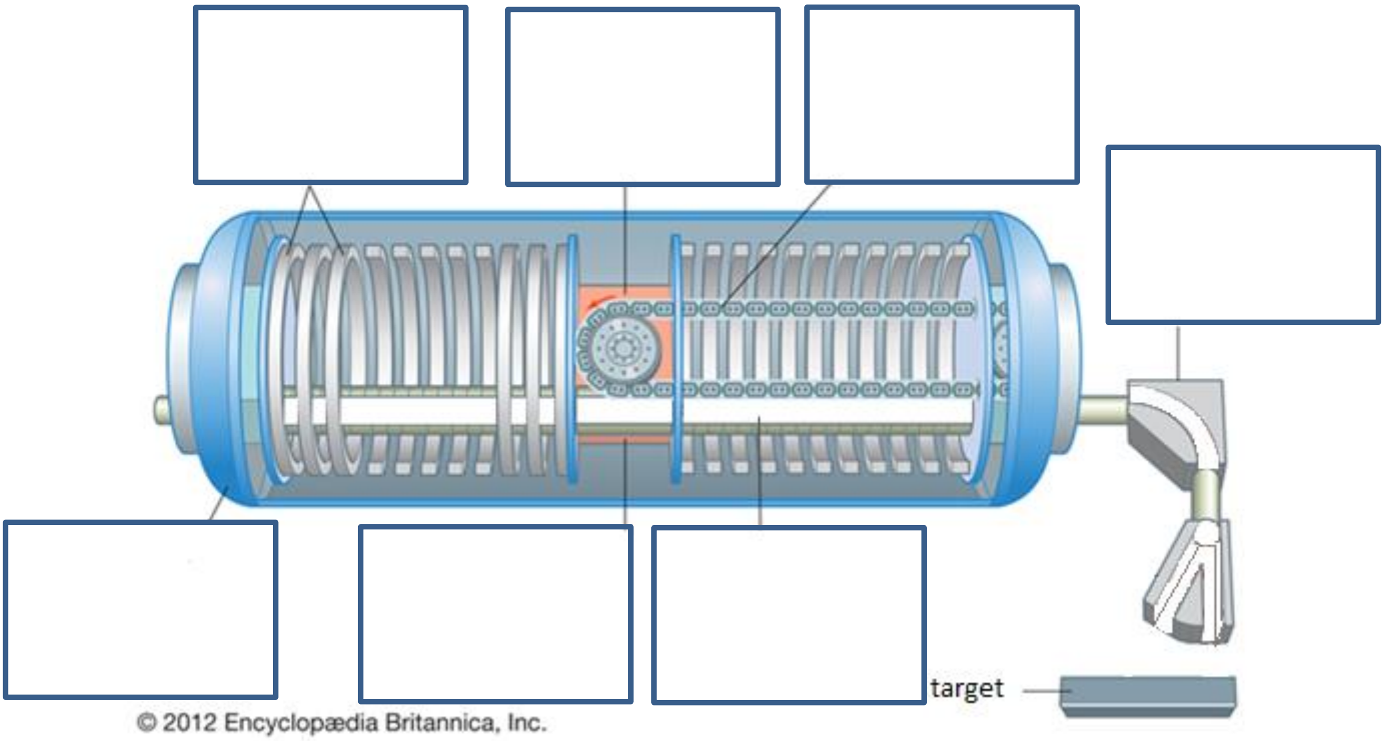
Question T4 – Centre for Accelerator Science

1. a) Choose from the following list to label the diagram of the tandem accelerator below.

   positive high voltage terminal, steel pressure tank, charging chain, evacuated accelerator beam tube, stripping chamber, equipotential rings, magnet.

   b) Annotate each of the components to describe or state the purpose of that component.

   c) Indicate the flow and charge of the ions on the diagram.



2. In the tandem accelerator, what is the purpose of each of the following:

electric field	
magnetic field	

3. Complete the following paragraph:

In the accelerator beam tubes, ion beams travel in _______________ lines until they enter a _____________________ which changes the __________________ of their travel. The physics equation that relates the magnetic field strength, the velocity of the ions and the magnetic force which acts on the ions is

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The strength of the magnetic field used depends on the _________________ and the ________________ of the ions and the ______________________ to which their paths will be bent. The path of a lower mass ion entering a set magnetic field will bend _______________ than the path of an ion of higher mass.

4. Explain why the accelerator beam tubes need to be evacuated.

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5. Explain why the accelerator tank is filled with sulfur hexafluoride gas at 500 kPa.

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6. Describe one use of ANSTO accelerators.

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At the Discovery Centre:

Station 1 – Measuring radioactivity – (10 mins)

Your Education Officer will demonstrate how to use a scintillation counter to measure radioactivity from a range of objects.

1. Which object is the most radioactive?

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2. What sound is made by the scintillation counter when it detects each of the following types of radiation?

Alpha: ____

Beta: ____

Gamma: ____

3. Move the scintillation detector further away from the source

   a) How does the sounds produced by the scintillation counter change? Why?

   b) How does the reading on the dial change?

   c) Sketch a graph to illustrate how radioactivity changes as distance from the source increases.

4. Increase the thickness of a shielding material between the source and the detector, record how the detected level decreases. Is the decrease linear?

Monitoring radiation

At ANSTO, we use different portable devices to monitor levels of radiation.

Next to the picture of each device below, write the name of the device and a sentence or two to explain how it works.

	Name of the device and how it works
	
	
	

Station 2 - Cloud Chamber – (5 mins)

A **cloud chamber** allows us to see the effect of different nuclear radiation. Radioactive particles move through the supersaturated alcohol vapour in the cloud chamber and strip electrons from surrounding atoms in the air. The alcohol vapour then condenses on the charged particles, leaving a trail of droplets along the path. These tracks disappear almost immediately.

Read the information about the different types of nuclear radiation.

1. Name three particles whose tracks you have identified. Draw an example track for each particle and describe them.

Particle name	Track diagram	Description

2. Look for muon tracks. Muons are leptons with a charge equal to that of an electron, but they are about 200 times heavier. They have a half-life of 2.2 microseconds (µs). They are produced about 15 km above the surface of Earth and travel at 0.99C (2.99x10^8 m/s).
   At this speed, we expect them to take 15000/3x10^8 sec (=50 µs) to reach us. This is ~20 times their ½ life: hence fewer than 10^-6 should survive. However, we can usually see some muons in our cloud chamber.

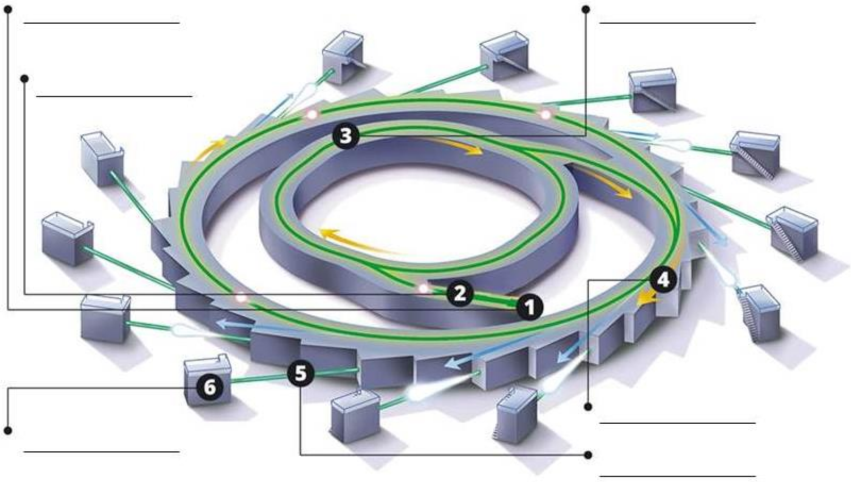
   Suggest a plausible explanation for their appearance on earth.

Station 3 – Australian Synchrotron – (10 mins)

Observe the interactive model of the Australian Synchrotron in the Discovery Centre.

1. Label the diagram below with the following options:

End station	Electron gun	Booster ring
Linear accelerator	Storage ring	Beamline



2. Fill out the blanks in the flow chart with the following options:

Beamlines	Electromagnets	Electrons
Linear accelerator	Synchrotron light	

__________ are produced from a heated tungsten matrix cathode in an electron gun.

→ The __________ accelerates the electrons to 99.9987% the speed of light.

→ In the booster ring, bunches of electrons are propelled to their maximum energy (3 GeV) using a carefully timed alternating voltage. __________ steer and focus the electron beam inside a ring-shaped vacuum chamber.

→ Electrons circulate in the storage ring for 30-40 hours. Electrons generate extremely bright __________ as powerful magnets force them to travel in a circular orbit.

→ Synchrotron light is channelled down __________ to end stations, where it is used to examine materials at atomic and molecular scales.

3. Summarise one example of research done at the Australian Synchrotron

Station 4 – Virtual Reality experience of OPAL – (5 mins)

Small groups will use the "Go" headsets, where available, and appreciate how OPAL operates.

Presentation in DC theatre – (30 mins)

Suggested topics may include any, or all, of the following:-

- Comparison of research reactors with power reactors
- Comparison of Fission and Fusion reactors
- Overview of different types of power reactors
- Future directions in nuclear technology
- Nuclear waste management in Australia and Synroc
- Managing safety in nuclear operations
- Uses of radio-pharmaceuticals

All schools are invited to suggest topics that they would like to receive and that are appropriate to the new Year 12 Physics syllabus. NB: only 30 minutes is available