Year 12 Physics

Depth study guide

Introduction

We recommend that an ANSTO excursion becomes the starting point for a nuclear science depth study. ANSTO's Year 12 Physics excursion, together with the *ANSTO Year 12 Physics Excursion Workbook*, helps students cover content selected from Module 8: From the Universe to the Atom and Working Scientifically.

Our ANSTO Year 12 Physics Depth Study Guide provides students and teachers with ideas and resources for depth study activities after their excursion.

Year 12 Physics Nuclear Science Depth Study

An ANSTO excursion can be the ideal start for a nuclear science depth study. Students will 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.

Topic 1: Structure of matter, atomic theory and nuclear radiation

Suggested activities

- ANSTO scientists analyse the composition of gases trapped inside deep Antarctic ice to determine historical changes in our climate and atmosphere. Carbon-14, beryllium-10 and chlorine-36 are used routinely to determine the age of these ice core samples.

Carbon-14 half-life: 5730 years
Beryllium-10 half-life: 1,390,000 years
Chlorine-36 half-life: 301,000 years
$N_t = N_0 e^{-\lambda t}$
$\lambda = \ln(2)/t_{1/2}$
where N_t = number of particles at time *t*, N_0 = number of particles present at $t = 0$, λ = decay

Use the data and equations above to:

a) Calculate the decay constant for each isotope
b) Plot the decay curve for each isotope
c) Estimate the proportion of each isotope remaining in a sample of Antarctic ice 45,000 years old

- Alpha, beta and gamma radiation may be emitted when unstable nuclei decay. Radioisotopes are used for specific medical, industrial and agricultural purposes based on the properties of the radiation they emit.
  a) Select one example each of an alpha emitter, beta emitter and a gamma emitter. Explain how the properties of the radiation emitted make these isotopes suitable for their purpose in medicine, industry or agriculture.
  b) Explain what safety measures need to be taken when handling or using each of these isotopes.

- Design a poster to illustrate and explain different technologies that detect radiation. Indicate how each technology may be used to monitor radiation in the workplace.

- Chadwick discovered the neutron in 1932 when he bombarded beryllium with alpha particles from polonium.
  a) Explain how neutrons are generated to start the fission reaction inside a nuclear reactor.
  b) Explain how the properties of neutrons allow them to be used as a probe to investigate matter at ANSTO.
  c) X-rays and neutrons are both used for diffraction experiments to investigate materials. Use our current understanding of atomic theory to explain why x-rays and neutrons produce different but complementary diffraction data about a material.

d) Summarise a recent research project from the Australian Centre for Neutron Scattering, where scientists used neutrons to determine the atomic or molecular structures of materials.
e) Neutrons are a particularly penetrative form of radiation. Give examples of safety measures used by ANSTO staff to work safely with neutrons.

- From 1908 to 1913, Geiger and Marsden's gold foil experiments led to the discovery of positively charged particles in the nucleus of the atom, later termed "protons" by Rutherford.
  a) Explain, using labelled diagrams, how a cyclotron is used to accelerate protons at a target. Include the origin of the protons in your answer.
  b) Using balanced decay equations, give an example of a proton-rich, cyclotron-produced medical radioisotope and describe its use in patients.

  c) The first proton therapy unit in Australia is due to open in Adelaide in 2020. Describe how this process is currently used in other countries to treat cancerous tumours.

- Joseph Thompson discovered the electron in 1897 when he examined the deflection of cathode rays in electric and magnetic fields.
  a) ANSTO uses electron microscopes to develop new high-tech materials for industrial and medical applications. Explain how electrons are used to investigate materials in a scanning electron microscope.
  b) The Australian Synchrotron in Melbourne accelerates electrons to almost the speed of light. These electrons are then deflected through magnetic fields to create extremely bright light. Draw an annotated diagram to explain how the Australian Synchrotron works, and summarise one recent example of research performed using this machine.

Suggested resources

ANSTO. (2018). Historical temperature and greenhouse gas data from Antarctica. Data set. https://www.ansto.gov.au/education/secondary/workbooks-and-datasets

ANSTO. (2018). OPAL research reactor. Website. https://www.ansto.gov.au/about/how-we-work/how-safe-is-opal

Australian Microscopy and Microanalysis Research Facility. (2018). Myscope Outreach. Website. http://myscopeoutreach.org/

ANSTO. (2018). Latest news articles. Website. https://www.ansto.gov.au/news

ANSTO. (2017). Discoveries with light: A teacher resource on the Australian Synchrotron. Workbook. https://www.ansto.gov.au/education/secondary/workbooks-and-datasets

ANSTO. (2016). Cyclotrons and PET scans. Factsheet. https://www.ansto.gov.au/education/secondary/workbooks-and-datasets

ANSTO. (2015). Echidna – High resolution powder diffractometer. Video. https://www.youtube.com/user/ANSTOVideos

ANSTO. (2015). OPAL research reactor animation. Video. https://www.youtube.com/user/ANSTOVideos

ANSTO. (2015). PET scan animation. Video. https://www.youtube.com/user/ANSTOVideos

ANSTO. (2015). Radiocarbon dating on ANSTO's VEGA accelerator. Video. https://www.youtube.com/user/ANSTOVideos

ANSTO. (2014). Curiosity files (crystallography and neutron diffraction). Workbook. https://www.ansto.gov.au/education/secondary/workbooks-and-datasets

ANSTO. (2011). Production and decay of radioisotopes. Workbook. https://www.ansto.gov.au/education/secondary/workbooks-and-datasets

Topic 2: Applications of fission and fusion

Suggested activities

- Explain the requirements needed to achieve a sustained and controlled nuclear fission reaction in a fission reactor.
- Describe the demonstration of the first self-sustaining nuclear chain reaction at the University of Chicago in 1942.
- Fission reactions occur in both research reactors and power reactors.
    a) Construct a table to compare the structure and function of a research reactor (such as OPAL) with a power reactor.
    b) One fission reaction that occurs in a nuclear reactor is the bombardment of U-235 nucleus with a neutron to produce Ba-141 and Kr-92 as well as three neutrons.
        1) Write a nuclear equation for this reaction.
        2) Using data from the following website, calculate the energy released in this reaction (https://www.nist.gov/pml/atomic-weights-and-isotopic-compositions-relative-atomic-masses).
    c) The PRIS public web site (http://www.iaea.org/pris) provides information on global nuclear power reactor statistics to the general public. Create a poster to increase public awareness about the use of nuclear power, including the current use of nuclear reactors for the production of electricity throughout the world. Consider the future of this industry in terms of the proposed next generation (generation IV) of nuclear reactors.
- A particularly favourable fusion reaction for use in fusion reactors involves the fusion of deuterium (2H or D) and tritium (3H or T), producing a Helium nucleus (4He) and a neutron (n).
    a) Write a nuclear equation for this reaction. Using data from the PRIS public web site shown in the previous question, calculate the energy released in this reaction.
    b) Explain one way in which this reaction could be carried out in a reactor.
- Analyse progress in the development of fusion reactors. Discuss the availability of the fuel being used, the advanced materials required and an evaluation of the potential use of this reactor for the production of electricity.
- Write an opinion piece for the Sydney Morning Herald, justifying the need for scientific research into fusion reactors.

Suggested resources

ANSTO. (2018). How does OPAL work? Website. https://www.ansto.gov.au/about/how-we-work/how-safe-is-opal

ANSTO. (2018). Australia part of global renaissance in fusion power research symbolised by ITER experiment. News article. https://www.ansto.gov.au/news

Australian ITER forum. (2018). What is fusion energy? Website.
https://fusion.ainse.edu.au/home/what-is-fusion-energy/

Australian National University. (2018). Australian Plasma Fusion Research Facility. Website.
https://science.anu.edu.au/research/facilities/australian-plasma-fusion-research-facility

ITER. (2018). ITER. Website. https://www.iter.org/

Tollefson, J. (2018). MIT launches multimillion-dollar collaboration to develop fusion energy. Nature News. https://www.nature.com/articles/d41586-018-02966-3

Touran, N. (2018). Nuclear Power Plants. WhatIsNuclear Website.
https://whatisnuclear.com/reactors.html

Cartlidge, E. (2017). Europe pauses funding for €500 million fusion research reactor. Nature News.
https://www.nature.com/news/europe-pauses-funding-for-500-million-fusion-research-reactor-1.22165

Da Silva, W. (2017). Laser-boron fusion now 'leading contender' for energy. News article (UNSW).
https://newsroom.unsw.edu.au/news/science-tech/laser-boron-fusion-now-%E2%80%98leading-contender%E2%80%99-energy

Parliament of Australia. (2017). Generation IV Nuclear Energy – Accession. Parliamentary Inquiry.
https://www.aph.gov.au/Parliamentary_Business/Committees/Joint/Treaties/NuclearEnergy/Report_171/section?id=committees%2Freportjnt%2F024073%2F24682

Spyrou, A. and Mittig, W. (2017). Atomic Age Began 75 Years Ago with the First Controlled Nuclear Chain Reaction. The Conversation US (Dec 3, 2017).
https://www.scientificamerican.com/article/atomic-age-began-75-years-ago-with-the-first-controlled-nuclear-chain-reaction/

ANSTO. (2016). Nuclear techniques measure damage in superconducting cables for fusion energy research reactor. News article. https://www.ansto.gov.au/news

Gary, S. (2016). Fusion vs fission: clean, green nuclear energy technologies explained. News article (ABC Science). http://www.abc.net.au/news/science/2016-02-08/clean-nuclear-energy-are-we-there-yet/6777180

ANSTO. (2014). OPAL research reactor animation. Video.
https://www.youtube.com/user/ANSTOVideos

Ball, P. (2014). Laser fusion experiment extracts net energy from fuel. Nature News.
https://www.nature.com/news/laser-fusion-experiment-extracts-net-energy-from-fuel-1.14710

Topic 3: Accelerator science – cyclotrons, linear accelerators and synchrotrons

Suggested activities

- An early particle accelerator was developed by John D. Cockcroft and Ernest T. S. Walton. Describe this particle accelerator and outline a scientific discovery that they made with it.
- Cyclotrons are used at ANSTO to produce nuclear medicines for diagnostic scans
  a) Describe the construction of the first cyclotron by Ernest Lawrence
  b) Construct a table to compare a linear particle accelerator and a cyclotron, showing their similarities and differences
  c) Create an annotated diagram of a cyclotron to explain its operation and how it can be used in the production of fluorine-18
  d) Explain why very high energy cyclotrons are not possible
- Using references, write a mock conversation between Sir Mark Oliphant, an Australian physicist, and an interviewer to outline his contribution to particle physics.
- Construct a table to compare the Australian Synchrotron in Melbourne and the Large Hadron Collider near Geneva in terms of their purpose, scale, particles accelerated and structure.
- In 1964, two physicists independently proposed the existence of the subatomic particles known as quarks. Construct a timeline to summarise the events that confirmed the existence of quarks and the discovery of different types of quarks.
- Describe the discovery of two particles predicted by the Standard Model of particle physics.

Suggested resources

American Institute of Physics. (2018). Early particle accelerators. Website. https://history.aip.org/history/exhibits/lawrence/epa.htm

American Institute of Physics. (2018). The first cyclotrons. Website. https://history.aip.org/history/exhibits/lawrence/first.htm#epa

ANSTO. (2018). Cyclotrons. Website. https://www.ansto.gov.au/research/facilities/national-research-cyclotron

CERN. (2018). Fifty years of quarks by Cian O'Luanaigh. Website. https://home.cern/about/updates/2014/01/fifty-years-quarks

National Museums Scotland. (2018). Cockcroft-Walton generator. Website. https://www.nms.ac.uk/explore-our-collections/stories/science-and-technology/cockcroft-walton-generator/

CERN. (2018). The Z boson. Website. https://home.cern/about/physics/z-boson

Dowd, R. (2018). Synchrotrons and the Large Hadron Collider (LHC). Website (Australian Synchrotron). http://www.synchrotron.org.au/about-us/our-facilities/accelerator-physics/synchrotrons-and-the-large-hadron-collider

Nature Physics Portal. (2018). Beam time – the Cockcroft-Walton accelerator. Website. https://www.nature.com/physics/looking-back/cockcroft/index.html

O'Luanaigh, C. (2018). The Basics of the Higgs boson. News article (CERN). https://home.cern/about/updates/2013/05/basics-higgs-boson

Pralavorio, C. (2018). Long live the doubly-charmed particle. News article (CERN). https://home.cern/about/updates/2018/05/long-live-doubly-charmed-particle

Billings, L. (2017). LHC Physicists Unveil a Charming New Particle. Scientific American. https://www.scientificamerican.com/article/lhc-physicists-unveil-a-charming-new-particle/

Brewster, S. (2016). A primer on particle accelerators. Website. https://www.symmetrymagazine.org/article/a-primer-on-particle-accelerators

ANSTO. (2015). Not blarney: Irishman first to smash an atom. News article. https://www.ansto.gov.au/news

ANSTO. (2015). Cyclotrons and PET scans. Factsheet. https://www.ansto.gov.au/education/secondary/workbooks-and-datasets

Fermilab. (2014). Inquiring minds - The science of matter, space and time. Website. http://www.fnal.gov/pub/science/inquiring/matter/ww_discoveries/index.html

American Physical Society. (2003). This month in physics history – Lawrence and the first cyclotron. Website. https://www.aps.org/publications/apsnews/200306/history.cfm

Carver, J.H., Crompton, R.W., Ellyard, D.G., Hibbard, L.U. and Inall, E.K. (2003). Marcus Laurence Elwin Oliphant (1901-2000). Historical Records of Australian Science. 14(3). https://www.science.org.au/fellowship/fellows/biographical-memoirs/marcus-laurence-elwin-oliphant-1901-2000#6

Fermi National Accelerator Laboratory (2001). The Standard Model. Website. http://www-donut.fnal.gov/web_pages/standardmodelpg/TheStandardModel.html

Wilson, E.J.N. (Unknown). Fifty years of synchrotrons. Article. http://accelconf.web.cern.ch/accelconf/e96/PAPERS/ORALS/FRX04A.PDF

Topic 4: Medical physics – production, use and disposal

Suggested activities

- Prepare an annotated flowchart diagram to describe the life cycle of a commonly used radio-pharmaceutical, from production in OPAL to when it leaves the patient. Use quantitative evidence to assess the risks from radiation exposure to the patient and his/her family.

- Nuclear medicines fall into two main categories: diagnosis and treatment.
  a) Of the three types of radiation (alpha, beta and gamma), explain which type of radiation is emitted by diagnostic medicines, and which is emitted by therapeutic medicines. Consider the ionisation strength and penetration of each type of radiation to justify your answer.
  b) Select one example of a diagnostic and one example of a therapeutic nuclear medicine. Evaluate the effectiveness and safety of each example.
  c) Identify which type of radiation is least suited to medical procedures. Explain your answer.

- Write a dialogue between a patient and their doctor about a health condition requiring a nuclear medicine for diagnosis and/or treatment (300 words). Include in your dialogue:-
  - Symptoms experienced by the patient
  - Possible causes
  - Procedures required to diagnose the condition
  - Possible treatments

  Ensure the doctor explains how the nuclear medicine works, either in the diagnostic scan or as part of the treatment, and reassures the patient about any safety concerns that they may have.

- When identifying, or developing, a medical procedure that relies on a new radio-isotope, the scientists need to consider several factors before trials on patients can begin. Some of these factors are:
  - Toxicity of the isotope
  - Radiation dose delivered to the patient
  - Delivery methods to the target organ
  - The way it is excreted by the body
  - Risks to the family of the patient

  Choose a radio-isotope now being used in medicine and comment on its safety and design. Do not limit yourself to the factors listed above.

- Write two pages of FAQs (frequently asked questions) that patients may want to ask their doctor before they undergo treatment with a radio-pharmaceutical. Include the answer to each one.

- Write a news article, suitable for publication in the Sydney Morning Herald, explaining a clinical trial now underway in Australia of a new radio-pharmaceutical. Explain what it is, how the radiation is generated, how that radiation is delivered to the right organ in the body, in what way is it novel, the expected results from the trial and the advantages over current treatments.

- Write a feature article, suitable for publication in a weekend magazine, to justify the production of radio-pharmaceuticals in Australia, rather than importing them. Discuss impacts on both the patient and the broader community in your piece.

- Compare and contrast the following units to measure radiation: Sv, Bq, Gy. Identify the most relevant units when working in medical physics and explain your reasoning.

- The new ANSTO Nuclear Medicine (ANM) facility will increase Australia's production of molybdenum-99 to satisfy 25 to 30% of world demand. With the benefits of nuclear medicines comes the responsibility of managing the radioactive waste that results from the production process. Design a flyer for the local community living near ANSTO to explain how this waste is managed and to allay fears that people living near the site might have about it.

- ANSTO stores intermediate level waste from reprocessed spent reactor fuel and by-products of radiopharmaceutical production. This waste is often long-lived and requires secure and shielded storage. Compare and contrast the two main methods of storing intermediate level waste: immobilisation in glass (vitrification) and Synroc.

Suggested resources

- ANSTO. (2018). A day in the life of a radioactive waste worker. Video. https://www.youtube.com/user/ANSTOVideos.
- ANSTO. (2018). ANSTO fights cancer with a commitment to health research. News article. https://www.ansto.gov.au/news
- ANSTO. (2017). Managing waste at ANSTO (webpage). https://www.ansto.gov.au/education/nuclear-facts/managing-waste.
- Sydney Morning Herald. (2018). Radioactive injection trial aids in cancer treatment. News article. 9 May 2018, p. 10.
- Currie, G. (2017). Nuclear medicine explainer (video). https://www.youtube.com/watch?v=98zuh9S2L7o.
- Department of Industry, Innovation and Science. (2017). National Radioactive Waste Management Facility (webpage). radioactivewaste.gov.au.
- Currie, G. (2016). Nuclear medicine comes from nuclear reactors. Sydney Morning Herald (25/2/16). http://www.smh.com.au/comment/nuclear-medicine-comes-from-nuclear-reactors-20160225-gn3dlg.html.
- United Nations Environment Programme. (2016). Radiation: Effects and sources. Fact sheet. http://www.unscear.org/unscear/en/publications/booklet.html
- ANSTO. (2015). Safely managing Australia’s radioactive waste (brochure). https://www.ansto.gov.au/corporate-publications.
- ANSTO. (2015). Safely managing Australia’s radioactive waste (video). https://www.youtube.com/user/ANSTOVideos.
- ANSTO. (2013). How does Synroc work (video). https://www.youtube.com/user/ANSTOVideos.

Topic 5: Exploiting and Monitoring radiation

Introduction

Radiation needs to be monitored for two main reasons: to ensure we are all safe (i.e. not being over exposed to radiation) at work and elsewhere, and to ensure that the materials we create at ANSTO receive the correct dose.

ANSTO monitors four types of radiation: alpha, beta, gamma and neutron

Radiation needs to be measured to determine its intensity and the amount of damage it might cause.

The dose that is absorbed depends on the material that is receiving the radiation, the intensity of that radiation and the duration of exposure.

Different types of monitors are needed, depending on the reason for taking the reading.

Suggested activities

- Describe three examples of products that require radiation during production.
- Explain how different types of radiation cause different effects in human biological cells.
- Explain why some monitors measure instantaneous levels of radiation, while others measure accumulated dose. Describe a situation for each type when it is being used appropriately. What types of monitors are used routinely by ANSTO staff when working on site: **not** when working in a high radiation area.
- Write down the units used to measure a) the amount of radiation being released, and b) how much is being absorbed. Suggest an upper value of the latter for one radiation type that could be tolerated by a normal person without causing long term harm. Indicate how that value was determined.
- Compare and contrast the following units to measure radiation: Sv, Bq, Gy. Identify the most relevant units when working in medical physics and explain your reasoning.
- Write a news article, suitable for publication in the Sydney Morning Herald, explaining a clinical trial now underway in Australia of a new radio-pharmaceutical. Explain what it is, how the radiation is generated, how that radiation is delivered to the right organ in the body, in what way is it novel, the expected results from the trial and the advantages over current treatments.
- Write a feature article, suitable for publication in a weekend magazine, to justify the production of radio-pharmaceuticals in Australia, rather than importing them. Discuss impacts on both the patient and the broader community in your piece.
- The new ANSTO Nuclear Medicine (ANM) facility will increase Australia's production of molybdenum-99 to satisfy 25 to 30% of world demand. With the benefits of nuclear medicines comes the responsibility of managing the radioactive waste that results from the production process. Design a flyer for the local community living near ANSTO to explain how this waste is managed and to allay fears that people living near the site might have about it.
- ANSTO stores intermediate level waste from reprocessed spent reactor fuel and by-products of radiopharmaceutical production. This waste is often long-lived and requires secure and shielded storage. Compare and contrast the two main methods of storing intermediate level waste: immobilisation in glass (vitrification) and Synroc.

Suggested resources

- ANSTO. (2018). A day in the life of OPAL: www.ansto.gov.au/news/a-day-life-of-opal-multi-purpose-research-reactor%E2%80%94part-3-evening
- ANSTO. (2018). ANSTO fights cancer with a commitment to health research. News article. https://www.ansto.gov.au/news
- ANSTO. (2017). Managing waste at ANSTO (webpage). https://www.ansto.gov.au/education/nuclear-facts/managing-waste
- Sydney Morning Herald. (2018). Radioactive injection trial aids in cancer treatment. News article. 9 May 2018, p. 10.
- Currie, G. (2017). Nuclear medicine explainer (video). https://www.youtube.com/watch?v=98zuh9S2L7o.
- Department of Industry, Innovation and Science. (2017). National Radioactive Waste Management Facility www.aph.gov.au/Parliamentary_Business/Committees/Senate/Economics/Wastemanagementfacility
- United Nations Environment Programme. (2016). Radiation: Effects and sources. Fact sheet. http://www.unscear.org/unscear/en/publications/booklet.html
- ANSTO. (2013). How does Synroc work (video). https://www.youtube.com/user/ANSTOVideos
- ANSTO. (2018). Synroc waste treatment plant. https://www.ansto.gov.au/news/synroc-australian-innovation-increases-technology-readiness-for-waste-treatment-plant