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AWE's Schools Liaison Scheme

Nuclear Physics

This resource can be used in support of the following curricula:
AQA: AS and A-level Physics - 3.2 and 3.8 **OCR:** A-level Physics - 6.4
Edexcel: A-level Physics – Topic 8

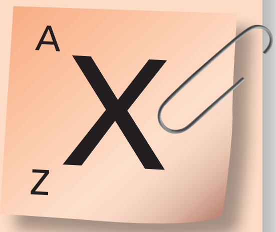
For Students:
Revision Notes

What is a nucleus?

The nucleus of the atom is made up of tightly-bound protons and neutrons, so the nucleus itself if positively charged. Negatively charged electrons surround the nucleus.

This structure was discovered by **Ernest Rutherford** in 1911. He fired a stream of positively-charged particles (called alpha particles) towards a film of gold a few atoms thick. He found that while most of the particles went straight through, a small number bounced back. This suggested that atoms were mostly empty space, but with a small positive 'ball' at the centre.

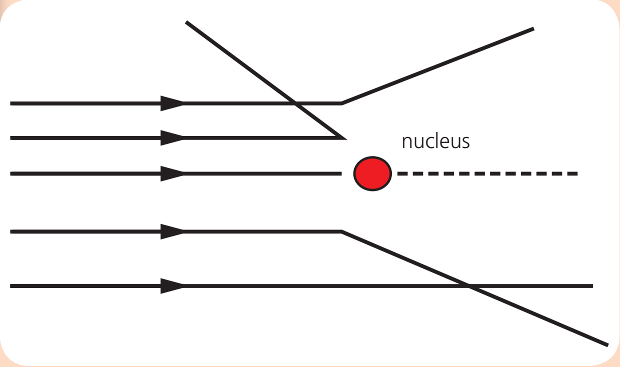
You're going to calculate the nuclear radius later, but first let's remind ourselves of the structure….

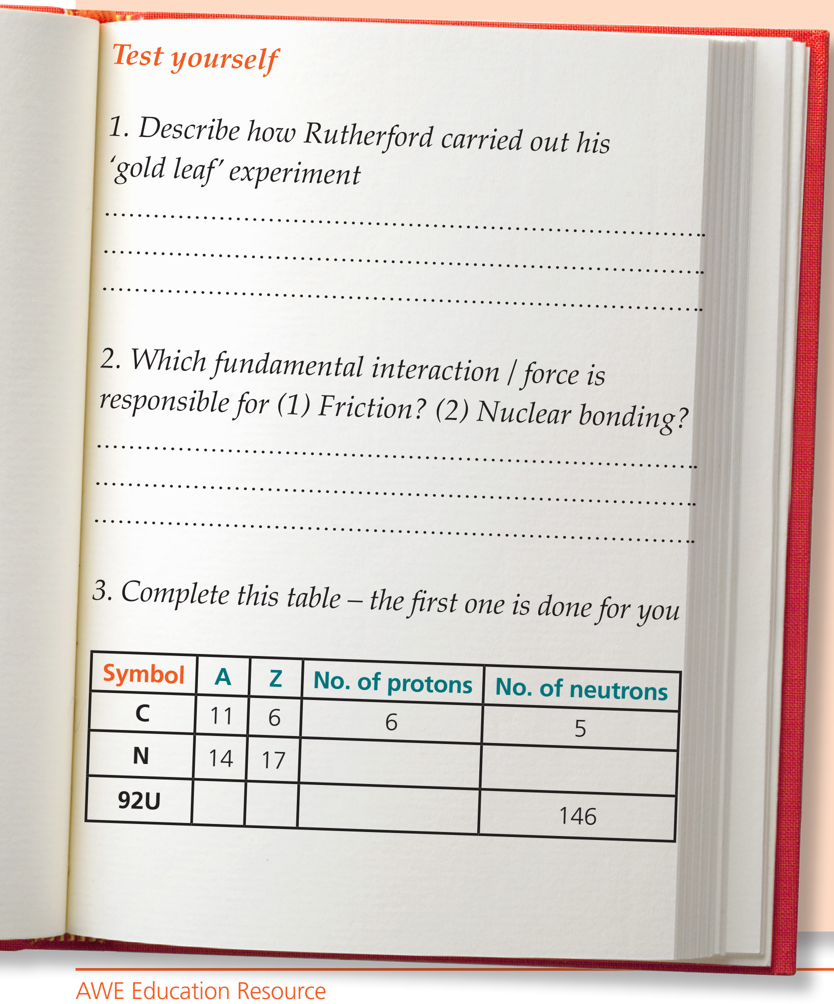


Proton number (Z): This is sometimes called the atomic number. It is the number of protons in the nucleus of an atom.

Nucleon number (A): This is the total number of nucleons (protons plus neutrons) in the nucleus of an atom. It is also known as mass number.

Isotopes of an element have the same number of protons but different numbers of neutrons in the nucleus. Some isotopes are more stable than others. Unstable nuclei can decay (or break down) emittingradioactive radiation.





Test yourself

1. Describe how Rutherford carried out his 'gold leaf' experiment

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2. Which fundamental interaction / force is responsible for (1) Friction? (2) Nuclear bonding?

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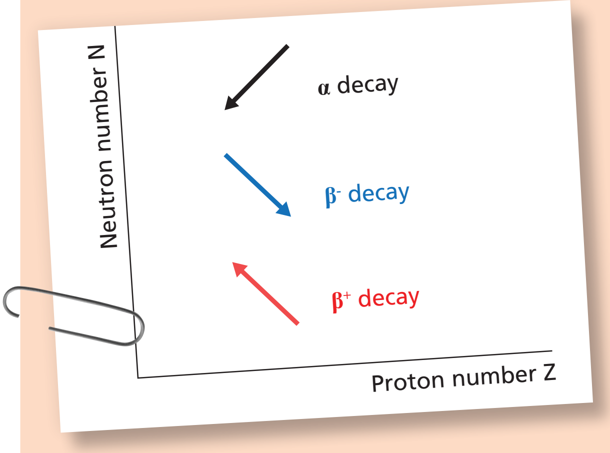
3. Complete this table – the first one is done for you

Symbol	A	Z	No. of protons	No. of neutrons
C	11	6	6	5
N	14	17		
92U				146

How does the nucleus decay?

Radioactive decay occurs because a nuclei is unstable. The nucleus can emit different forms of radiation to become more stable.



α decay: The unstable parent nuclei emits an alpha particle (2 protons and 2 neutrons)

β⁻ decay: In the parent nuclei a neutron changes into a proton and emits a beta, β, particle (electron)

β⁺ decay: In the parent nuclei a proton changes into a neutron and emits a beta+ β^+particle (positron)

γ decay: Gamma ray emission involves emitting a photon. It may happen at the same time as alpha or beta decay or it may occur a short while after. There is no change in the number of protons or neutrons.

Type of decay	α	β⁻	β⁺	γ	e⁻
Change in no. of protons	-2	+1	-1	0	-1
Change in no. of neutrons	-2	-1	+1	0	+1

The **decay constant**, λ, is the probability of an individual nucleus decaying per second.

The **activity** of a radioactive isotope is the number of nuclei that decay per second (measured in Becquerel, Bq).

The **half life** ($t_{1/2}$) is the time taken for the mass of the isotope to decrease to half the initial mass, or, time taken for the activity to half (measured in seconds/hours/years, etc.)

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

Nuclear Energy

Mass and energy are related to each other by a very famous equation. It tells us that a small amount of mass can contain large amounts of energy, and that it is possible to convert mass into energy and energy into mass.

$$E = mc^2$$

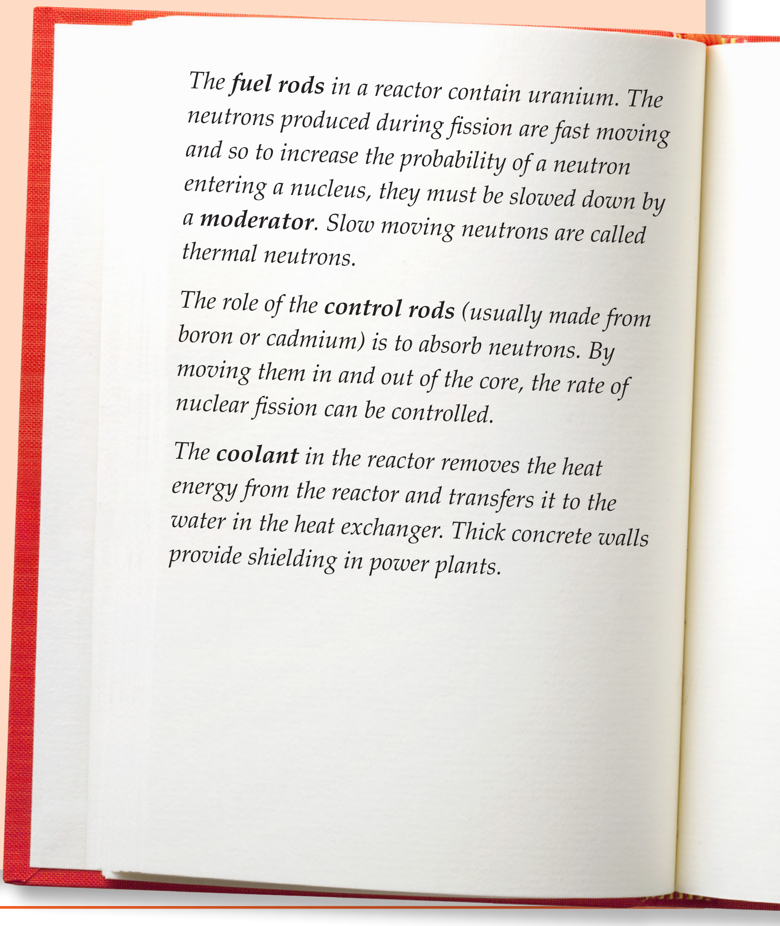
E = energy measured in joules (J), **m =** mass measured in kilograms (kg), **c =** the speed of light 3×10^8 ms^{-1}

There are two ways in which nuclei can be converted to energy – nuclear **fusion** and nuclear **fission**. Because uranium-235 can undergo induced fission (basically, it can be forced to decay), it tends to be the most commonly used isotope in nuclear applications.

Fusion: This involves two atomic nuclei joining to form a larger nucleus. This is what happens in stars - two hydrogen atoms are pushed together to fuse and make a helium atom. This also releases massive amounts of energy!

Fission: Nuclear fission of uranium-235 can be triggered by the nucleus absorbing a neutron. The uranium splits up into two lighter nuclei (barium & krypton) and two neutrons are released. If there is enough uranium present (so called ‘critical mass’), these two neutrons can collide with other uranium nuclei, leading to further fission… this is called a chain reaction and it is the process used in nuclear power plants.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{144}_{56}Ba + ^{90}_{36}Kr + 2^{1}_{0}n$$



*The **fuel rods** in a reactor contain uranium. The neutrons produced during fission are fast moving and so to increase the probability of a neutron entering a nucleus, they must be slowed down by a **moderator**. Slow moving neutrons are called thermal neutrons.*

*The role of the **control rods** (usually made from boron or cadmium) is to absorb neutrons. By moving them in and out of the core, the rate of nuclear fission can be controlled.*

*The **coolant** in the reactor removes the heat energy from the reactor and transfers it to the water in the heat exchanger. Thick concrete walls provide shielding in power plants.*

Did you know?

The annual dose level from discharges at AWE is currently less than 0.001 millisieverts (mSv). This is extremely low – putting it in context, a dose of 1 mSv is less than the equivalent radiation dose likely to be received from a single medical CT scan. The average annual background radiation dose in the UK is approximately 2.7 mSv.

Learn more!

- IOP worksheet on nuclear decay: https://www.tes.co.uk/teaching-resource/nuclear-equations-6041997
- Geiger counter experiments: https://www.nuc.berkeley.edu/sites/default/files/events/teachers-workshop/meter-exercises/teachers_guide.pdf
- BBC's Bang Goes the Theory talk about Brazil nuts: https://www.youtube.com/watch?v=Pt-SMAVN898
- http://www.awe.co.uk/app/uploads/2014/07/ORION-Fact_Sheet.pdf

For Students:

Exam-style question

1.Describe the changes made inside a nuclear reactor to reduce its power output and explain the process involved (2 marks)

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2.In a nuclear reactor, neutrons are released with high energies. The first few collisions of a neutron with the moderator transfer sufficient energy to excite nuclei of the moderator. Describe and explain the nature of the radiation that may be emitted from an excited nucleus of the moderator (2 marks)

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3.The subsequent collisions of a neutron with the moderator are elastic. Describe what happens to the neutrons as a result of these subsequent collisions with the moderator (2 marks)

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For Teachers: Experiment!

Nuclear Radius Challenge

This experiment uses a bag of ball pool balls (or similar) to **discuss the radius and density of the nucleus**, and to derive the relationship between nuclear radius and nucleon number $(r = r_o\, A^{1/3})$

Equipment

Set up in the centre of the classroom – see photo

- Ball pool balls (or similar – tennis balls, apples, etc…)
- Transparent bin-liner, netting or plastic bag
- Class set of meter-sticks or rulers
- String, scissors and tape

Students are challenged to estimate the number of balls within the bag without being allowed to touch it. They are provided only with a meter-stick (or ruler) and a representative ball-pool ball. The optimal strategy is for students to measure the diameter (and hence radius) of both their own representative ball and the bag itself.

Students can then calculate a ball volume and the bag volume $V_{Ball} = \frac{4}{3}\pi {r_{Ball}}^3$ $V_{Bag} = \frac{4}{3}\pi {r_{Bag}}^3$

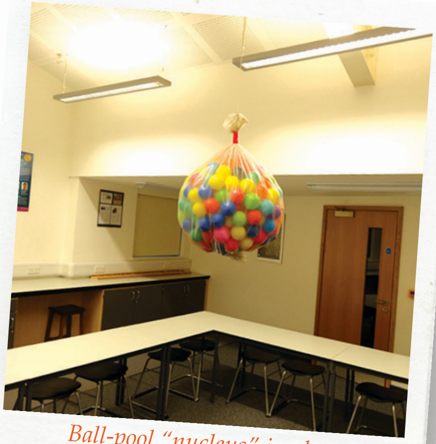
Finally, they can estimate the number of balls, N, by using:

$$N = \frac{V_{Bag}}{V_{Ball}} = \left(\frac{r_{Bag}}{r_{Ball}}\right)^3$$

Students should find that $r_{Bag} = {r_{Ball}}^{1/3} N^{1/3}$

Or $r_{Bag} \propto A^{1/3}$

Ask students how this would relate to the nucleus – what would the balls represent? What would the number of balls be equivalent to? This should lead students to the conclusion that $r = r_o\, A^{1/3}$



Ball-pool "nucleus" in place over a classroom

Things for students to consider

- *What would the 'volume of each ball' correspond to in the case of a nucleus?*
- *What are the limitations of the mode?What assumptions have been made in the calculations?*
- *Why is assuming that the number of balls is the ratio of bag and ball volumes only an approximation?*
- *The plastic bag held together the balls. What holds nucleons together in the nucleus? What tries to push them apart? Is the bag-of-balls a good model for nuclear forces?*

This experiment has been reproduced with the permission of Nic Harrigan - http://nicharrigan.com/