Beckfoot

Subject: A-level Physics	Topic: Nuclear – types of radiation	Year Group: 13

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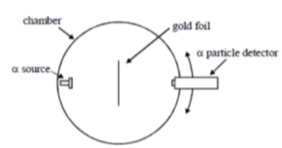
Rutherford's model of the atom

1	Rutherford fired alpha particles at a thin sheet of gold foil in a vacuum. It was in a vacuum to prevent alpha particles been absorbed by the air.	
2	The gold foil must be thin to prevent the alpha particles been absorbed by the gold and so that they are only scattered once.	
3	**Observation:** 1. Most alpha particles straight through the foil with little or no deflection. 2. Some alpha particles suffered large deflection/backscattering.	**Explanation:** 1. Nuclear radius much smaller than atomic radius. 2. Nucleus is positively charged and most of mass of atom is contained in nucleus.

Detecting radiation and safety

1	A Geiger-Muller (GM) tube is a device that registers a pulse of electricity each time an ionising particle enters it.
2	The GM tube is connected to a digital counter, which keeps count of the number of ionising particles entering the tube.
3	When measuring the count rate coming from a source it is necessary to account for background radiation by measuring and subtracting a count rate for background radiation. This gives you the corrected count rate.
4	When handling radioactive sources: •Always handle sources with tongs •Point the sources away from your body (and not at any anybody else) •Fix the source in a holder which is not adjacent to where your body will be when you take measurements •Replace sources in lead-lined containers as soon as possible •Wash hands when finished

α, β and γ radiation

1	Alpha (α)	Consists of 2 protons and 2 neutrons.	Stopped by paper and/or skin.	Range in air is a few cm.
2	Beta (β)	It is an electron.	Stopped by thin metal sheet.	Range in air is several m.
3	Gamma (γ)	It is high frequency EM radiation.	Intensity reduced by ½ by 5 cm of concrete or 1 cm of lead.	Ten to hundreds of m.
4	Alpha is the most ionising, gamma is the least.			
5	Alpha and beta deflect in opposite directions by electric and magnetic fields as they have opposite charges.			
6	Beta deflects more than alpha as it is lighter.			
7	Gamma is not deflected by magnetic or electric fields as it has no charge.			

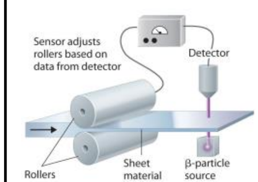
Medical uses of α, β and γ

1	Technetium-99 (γ source) is used as a **tracer** to make soft tissues show up through medical imaging processes. The tracer is either injected or ingested and a radiographer positions a detector outside the body which can produce a picture of the patient's internal organs. Changes in the amount of gamma **emitted** from different parts would indicate how well the isotopes are flowing.
2	Technetium-99 is used as it only emits γ rays meaning it can be detected outside the body and since it is the least ionising it causes little damage. It has a short enough half-life and will not remain active in the body after use. But its half life is long enough to remain active during diagnosis.
3	Treating cancer. Tiny amounts of radium-233 (α source) are injected into tumours to directly kill cancer cells. Iodine-131 (β source) is used to treat thyroid cancer. The cancer cells absorb radiation from the material and receive a high dose of energy. Doctors must work out the danger to nearby healthy tissue before giving this treatment.

Key Vocabulary

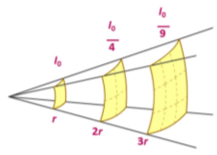
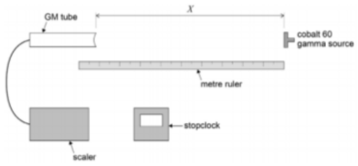
1	Atomic (proton) number	The number of protons in nucleus.
2	Mass (nucleon) number	The number of protons and neutrons in nucleus.
3	Isotope	Atoms of same element with different numbers of neutrons.
4	Background radiation	Nuclear radiation that is ever present. Sources include: radon, rocks, cosmic rays, nuclear fall out and medicine.
5	Avogadro constant	The number of particles in one mole of a substance. (6.02 x 10^{23} particles)
6	Mole	The amount of substance that contains 6.02 x 10^{23} particles.
7	Molar mass	The mass of one mole of an element or compound.

Uses of α, β and γ radiation

1	Uses of beta radiation 	To monitor and control the thickness of aluminium foil, paper and steel. If the material is too thick the count rate will fall and the rollers will be forced closer together. If the material is too thin the count rate will increase and the rollers will be forced apart.
2	γ radiation is used to sterilise medical equipment as it is the most penetrating meaning it can irradiate all sides of the equipment and equipment can be sterilised whilst in its packaging.	
3	Gamma emitters are also used as industrial tracers. E.g. a small amount of radioactive gas can be added to a pipeline system. By measuring the gamma intensity above the ground leaks can be detected in the pipes.	

Subject: A-level Physics	Topic: Nuclear - radioactivity	Year Group: 13

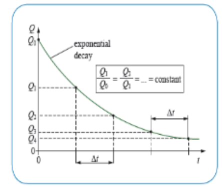
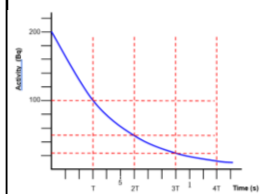
Inverse square law (including required practical)

1	For gamma radiation … The intensity decreases by a factor of one over the square of the distance, *r*, from the source. For example, doubling the distance from the source decreases intensity by a factor of four.	
2		Use this set-up to verify the inverse square law from gamma radiation.
3	**Method:** a) Use a GM tube connected to a counter to measure the count rate in the room with no radioactive sources present. This is your background count rate. b) Using a metre ruler place your gamma source 5 cm from the GM tube and measure the count rate. c) Calculate the corrected count rate by subtracting the background count rate from your count rate at this distance. d) Repeat for a range of distances. e) Plot a graph of corrected count rate against $1/x^2$. This will be a straight line that passes through the origin if the inverse square law is followed.	

Radioactive dating

1	Carbon dating is used to data artefacts that are made of organic material (things that were once living).
2	By comparing the amount of C-14 present now in a sample with the amount of C-14 likely to have been in the sample when it was alive, the time that has passed since the sample died can be determined.
3	Modern carbon dating methods use accelerator mass spectrometry to measure the ratio of C-14 to C-12 directly.
4	It is unreliable if the sample is less than 200 years old because it is difficult to measure accurately the small change in the ratio of C-14 to C-12.
5	It is unreliable is the sample is more than 60 000 years old because the activity would be very small compared to background/the ratio of C-14 to C-12 is too small.

Radioactive decay

1	An unstable nucleus attempts to become stable by emitting radiation. The decay is random.	
2	Radioactive decay is exponential. This means a quantity decreases by a constant factor in equal intervals of time.	
3	One way to prove data is exponential is to prove there is a constant ratio property as shown here. Or plot a graph of ln (data) on the y-axis against t e.g. ln (A) against t. If a straight line is produced the data is exponential.	
4	A graph of activity against time can be used to determine half-life. Half the initial activity. Read across from this to the line of best fit and then down to the time axis. This should give you the half-life. To check it is correct repeat the procedure by halving the activity again. Do this several times and calculate an average half-life. The gradient of ln(A) against t equals –λ.	

Decay equations

1	$N = N_0 e^{-\lambda t}$ You need to be able to rearrange for t and λ. $\ln\left(\frac{N}{N_0}\right) = -\lambda t$
2	If the decay constant is in s^{-1} time needs to be in seconds. If decay constant is in min^{-1} time needs to be in min.
3	Exam questions will often say things like the activity falls to 85% of its initial value in a 10 seconds, calculate λ. In this case recognise that $A/A_o = 0.85$.

Key equations

1	Inverse square law	$I \propto \frac{1}{x^2}$ OR $I = \frac{k}{x^2}$
2	Activity	$A = \lambda N = -\frac{\Delta N}{\Delta t}$
3	Radioactive decay	$N = N_o e^{-\lambda t}$ $A = A_o e^{-\lambda t}$ $C = C_o e^{-\lambda t}$
4	Half-life	$T_{1/2} = \frac{\ln 2}{\lambda}$

Key Vocabulary

1	Intensity	The radiation energy passing through a unit area per second.
2	Inverse square law	The intensity decreases by a factor of one over the square of the distance from the source.
3	Activity	The number of decays per second.
4	Becquerel	Unit of activity. 1 Bq is equal to 1 decay per second.
5	Decay constant	The probability of an individual nucleus of a particular radioisotope decaying per second.
6	Half-life	The time taken for the activity of a sample to halve OR time taken for half the radioactive nuclei to decay.
7	Corrected count rate	Counts per second minus background counts per second.
8	Carbon dating	A method of dating once living artefacts containing carbon by comparing the ratio of carbon-12 to carbon-14 atoms in a sample. Suitable for dating artefacts between 200 and 60 000 years old.

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Subject: A-level Physics	Topic: Nuclear – unstable nuclei	Year Group: 13

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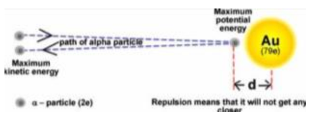
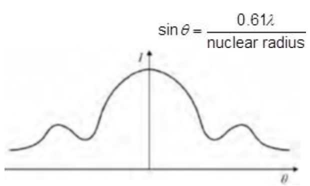
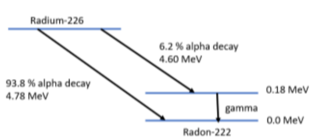
Nuclear radius

1	Nuclear radii are approximately 10^{-15} to 10^{-14} m.	
2	The nuclear radius, R, is given by the equation $\mathbf{R = R_0 A^{1/3}}$ where R_0 is a constant equal to the radius of one nucleon (usually = 1.05 fm) and A is nucleon number (not activity as for most of this unit).	
3	The equation has been confirmed experimentally using 2 methods.	
4	Closest approach method  $E_K = E_P = \frac{Qq}{4\pi\varepsilon_0 d}$	When an α particle makes a head on collision with the nucleus it is repelled backwards due to electrostatic repulsion. At the distance of closest approach (d) the α particle is stationary. All its kinetic energy has been changed to electric potential energy. If you know the initial E_K of the α particle you can solve for d.
5	Electron diffraction method 	A beam of high energy e^- is fired at a thin solid sample of an element. A detector measures the number of e^- scattered through different. The angle of the first diffraction minimum is given by the equation to the left allowing R to be determined.

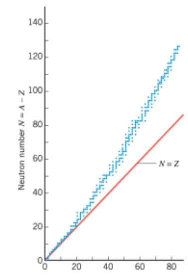
Nuclear excited states

1	After alpha and beta decays the daughter nucleus can be left in an excited state. To return to its ground state it emits a gamma photon.	
2	Here radium-226 is undergoing alpha decay. 6.2 % of the time this results in the daughter nucleus been created in an excited state. To return to its ground state it emits a gamma photon with energy 0.18 MeV. Therefore radium-226 emits alpha particles of two distinct energies, 4.78 and 4.60 MeV.	

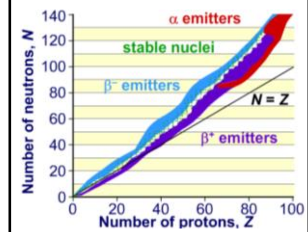
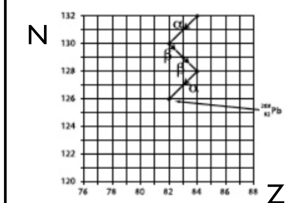
Decay equations

1	Alpha	$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$ An α particle (He nucleus) is emitted from the nucleus.
2	Beta minus	$^{A}_{Z}x \rightarrow {}^{A}_{Z+1}y + {}^{0}_{-1}e + {}^{0}_{0}\overline{\nu}_e$ A neutron changes into a proton, an electron and an antineutrino. The proton remains in the nucleus, the electron and neutrino are emitted.
3	Beta plus	$^{A}_{Z}x \rightarrow {}^{A}_{Z-1}y + {}^{0}_{+1}e + {}^{0}_{0}\overline{\nu}_e$ A proton changes into a neutron, a positron and a neutrino. The neutron remains in the nucleus but the positron and neutrino are emitted.
4	Electron capture	$^{A}_{Z}P + e^- \rightarrow {}^{A}_{Z-1}D + \nu_e$ The nucleus absorbs one of its inner orbital electrons, resulting in a proton changing into a neutron and an electron neutrino been emitted. An outer orbital electron will also fall down an energy level to replace the absorbed electron resulting in the emission of an X-ray photon.

Stable nuclei

1	The graph below shows neutron number, N, versus proton number, Z, for stable nuclei. If asked to draw this graph in an exam make sure: 1. line passes through N = 10/11 when Z = 10 and N increases as Z increases. 2. N = 115 → 125 when Z = 80 and that the graph bends upwards.	
2	In stable nuclei the electrostatic force pushing the nucleus apart is balanced by the strong nuclear force pulling it in.	
3	If nuclei are unstable they can emit alpha, beta and gamma radiation in an attempt to balance these forces.	

Decay graphs

1	Alpha decay occurs in only the most heavy nuclei. Beta-minus decay occurs in nuclei with too many neutrons (neutron rich nuclei). Beta-plus decay occurs in nuclei with too many protons. Electron capture occurs in proton rich nuclei.	A graph which nuclei decay by α, β^- and β^+ 
2	You need to be able to show decays on graphs such as the one to the right. The parent nucleus here has a proton number of 84 and a neutron number of 132. Often several decays are required for the nucleus to become stable as this shows.	
3	Initially it undergoes an alpha decay reducing both the proton and neutron number by 2. Then it undergoes a beta-minus decay which increase Z by 1 an decreases N by 1. And so on.	
4	Use arrows to show if N and Z are increasing or decreasing and always check the y-axis label to see if it is neutron number or mass number as either can be used.	

Key equations

1	Nuclear radius	$R = R_0 A^{1/3}$

Key Vocabulary

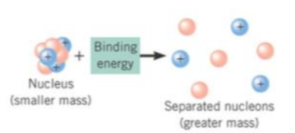
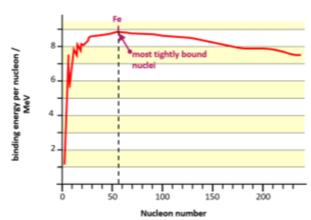
1	Metastable	An excited nucleus that returns to its ground state with a half-life longer than 1 ns. To show that a nucleus is metastable we put a m after its mass number e.g. barium-137m.
2	Parent nucleus	The nucleus which undergoes a decay event to produce one or more daughter nuclei.
3	Daughter nucleus	The nucleus formed from a radioactive decay event.

Subject: A-level Physics	Topic: Nuclear – nuclear energy	Year Group: 13

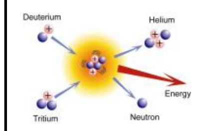
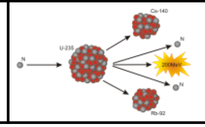
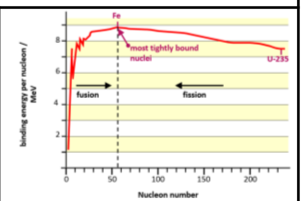
$E = mc^2$

1	The mass of an object is a measure of its energy content.
2	If energy is transferred to an object its mass changes as mass can be converted into energy and vice versa.
3	When a nucleus decays energy is released (either gamma photons or as the kinetic energy of the decay products).
4	Since energy is released this means some mass must have been converted into energy and therefore the mass after a decay should be less than the mass before.
5	The difference in mass (called the mass difference) is usually measured in atomic mass units, u.
6	1u = 1/12th mass of a C-12 atom = 1.661 x 10^{-27} kg = 931.5 MeV.
7	To determine the energy released in a decay determine the mass difference between the starting and the end nuclei in kg then use E = mc^2 to get an energy in J. OR find the mass difference in u and multiply by 931.5 to get an energy in MeV.

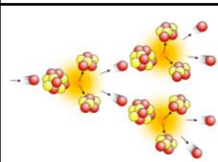
Binding energy

1	Energy has to be supplied to separate the nucleons in a nucleus because the strong nuclear force has to be overcome. Since energy has been supplied the mass must increase.	
2	Nuclei with more nucleons have the largest binding energy. But in order to judge how tightly bound a nucleus is we use binding energy per nucleon	
3	If you are asked to draw this graph in the exam be sure to: • Give the units for binding energy per nucleon as MeV. • Have the peak is at 8.7 MeV and nucleon number 56. • Have a sharp rise from origin and moderate fall not below 2/3 of peak height.	
4	The nucleus with the highest binding energy per nucleon is iron-56. Therefore this is the most tightly bound and most stable nucleus.	

Fission and fusion

1	Fusion: small nuclei join together, releasing energy.	
2	Fission: large nuclei split up into smaller nuclei, releasing energy.	
3	In both cases energy is released because the mass of the products is less than the mass of the reactants. (The difference in mass is released as energy.)	
4	This means the binding energy per nucleon of the products is greater than the binding energy per nucleon of the reactants.	
5	This condition can only be met by nuclei smaller than iron-56 fusing. OR by nuclei larger than iron-56 splitting/undergoing fission.	

Induced fusion

1	Spontaneous fission is rare. We can induce fission by bombarding heavy nuclei with neutrons, making them more unstable.	
2	This unstable nucleus then splits into two smaller nuclei called fission fragments along with a variable number of neutrons (usually 2 or 3).	
3	**^{235}U + neutron → fission fragments + neutrons + energy**	
4		This diagram shows how the neutrons produced in fission reactions can go onto create a chain reaction.
5	Not every neutron produced will go onto induce another fission reaction. Some maybe absorbed by a control rod, cladding, coolant or the neutron could escape from the reactor core.	

Key equations

1	Energy (J)	$E = mc^2$
2	Energy (MeV) *Not on data sheet*	E = mass difference in u x 931.5

Key Vocabulary

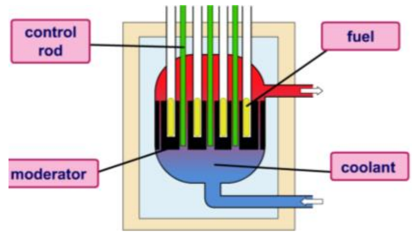
1	Atomic mass unit	1/12th of the mass of a carbon-12 atom. 1 u = 1.66043 x 10^{-27} kg.
2	Binding energy	The energy needed to separate all of the nucleons in a nucleus.
3	Binding energy per nucleon	The binding energy of the nucleus divided by the nucleon number.
4	Nuclear fusion	The joining together of small nuclei.
5	Nuclear fission	The splitting up of large nuclei into smaller nuclei.
6	Fission fragments	The atomic fragments left after a large atomic nucleus undergoes fission.
7	Critical mass	The minimum mass required to establish a self-sustaining chain reaction.
8	Critical chain reaction	Exactly one neutron from each fission event is allowed to cause another fission event.

Subject: A-level Physics	Topic: Nuclear - reactors	Year Group: 13

Nuclear waste

1	**High-level waste**	
	Examples	Spent (used) fuel rods.
	Radioactivity	Highly radioactive. Some will be radioactive for thousands of years. Generates a lot of heat.
	Storage	Placed in cooling ponds close to the reactor for a number of years. The plutonium/uranium is separated to be recycled. It can be vitrified/made solid into Pyrex glass. Then placed in steel/lead/concrete containers to be stored **deep** underground in a geological stable area.
2	**Intermediate-level waste**	
	Examples	Cladding that is removed from the outside of the spent fuel rods.
	Radioactivity	Lower levels of radioactivity than high level waste and it does not generate enough heat to require cooling.
	Storage	Some is stored in vaults and some is put in steel drums which are then encased in concrete and often stored underground. Thick concrete/bitumen walls are required to shield operators from high levels of radiation.
3	**Low-level waste**	
	Examples	Contaminated clothing (e.g. protective shoes and gloves). Considerable amounts of low level waste are produced by hospitals.
	Radioactivity	Has much lower levels of radioactivity then the other types of waste and does not generate heat.
	Storage	It is usually compacted to reduce its volume and then stored in steel drums.

Nuclear reactors

1		The main components of a nuclear reactor.

Fuel

1	The fuel used in nuclear reactors is either natural uranium (0.7% U-235 and 99.3% U-238) or enriched uranium (4% U-235 and 96% U-238).
2	It is U-235 that undergoes fission. It is the fissile material.
3	A movable neutron source rods provides the neutrons required for the initial start-up of the reactor.
4	It is not possible to use all the U-235 in the fuel rods as over time the U-235 percentage decreases as it undergoes fission and produces its decay products.
5	The fission fragments produced absorb neutrons which means there are too few neutrons to maintain the chain reaction.

Spent fuel

1	Fuel from a reactor which is no longer useful and is removed for reprocessing.
2	When U-235 undergoes fission it releases neutrons and produces fission fragments that are neutron rich.
3	The fission fragments are unstable and so often emit beta and gamma radiation.
4	The spent fuel is very radioactive and generates lots of heat.

Key Vocabulary

1	Fissile materials	A radioactive isotope which is capable of sustaining a chain reaction.
2	Thermal neutrons	A slow moving neutron which can be captured by a fissile nucleus.
3	Fast neutron	An energetic neutron produced in nuclear fission.

Coolant

1	Fission events generate lots of heat in the reactor core which is used to turn water into high pressure steam (to spin a turbine, to spin a generator and so on).
2	The coolant that passes through the core, absorbing the heat created by the fission events before transferring it to a secondary cooling system where high pressure steam is created.
3	Water and carbon dioxide are commonly used as it needs to be able to be pumped around and have good heat transferring abilities.

Moderator

1	The neutrons produced by fission events have lots of kinetic energy and are therefore moving quickly.
2	U-235 is much more likely to absorb a neutron that is travelling slowly (thermal neutrons).
3	The moderator (often water or graphite) slows the neutrons produced by fission events down without absorbing them.

Control rods

1	Rods used to control the rate of which fission occurs.
2	When lowered into the reactor they **absorb neutrons** slowing the rate of fission. When raised out, the rate of fission rises.
3	Contain cadmium or boron.