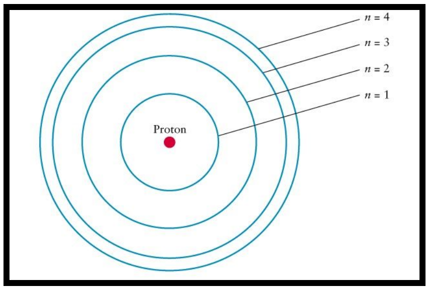
7.1 Discrete energy and radioactivity

Energy Levels

Electrons orbiting the nucleus of an atom are restricted to orbits with specific energies, rather than orbiting in any possible orbit around the nucleus. The energy levels are said to be **quantized**. When electrons gain energy, they are said to be **excited**, which allows them to jump between fixed energy levels

Transition between energy levels



When an electron in the hydrogen atom jumps from the ground state to the first excited state it must gain some energy; this cannot be any randomly chosen amount of energy - it must be exactly the right amount. The energy needed to excite an atom can come from the absorption of light by the atom. To understand this we must consider light to be a packet or **quantum** called a **photon**.

When n = infinity, the electron has left the atom, and the atom is said to be ionized. The energy required for this is known as the **first ionization energy**. Additionally:

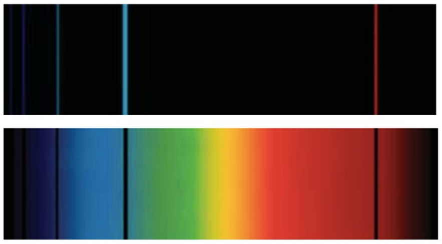
$$\mathbf{E = h\mathit{f}}$$

Where h is the Planck's constant = 6.63×10^{-34} J s

Absorption and Emission Spectra

When an object emitting a continuous spectrum is surrounded by a cool gas, the continuous spectrum is modified by the surrounding gas such that it is streaked by several dark lines.

Absorption occurs when an electron in the atom of the absorbing material absorbs a photon. The energy of this photon must be identical to the difference between the energy levels. The materials remove photons of this frequency from the continuous range of energies emitted by the light source. Naturally, this will make the absorber's atoms unstable and they will revert to a lower energy level by emitting photons.



NOTE:

Absorption occurs when electrons move up an energy level
Emission occurs when the electron is no longer excited and falls down energy levels. Can also be obtained with a spectrometer.

Nuclear structure

Mass number (A_r) - total number of protons and neutrons (nucleons) in the nucleus
Atomic number - the total number of protons in the nucleus

Isotopes

Isotopes are atoms with the same proton number but different mass numbers. Isotopes have the same chemical properties, as they have the same number of outer shell electrons, but they have different physical properties. The existence of isotopes is evidence for the existence of neutrons.

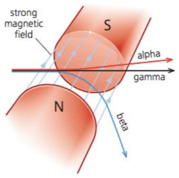
Interactions in the nucleus

There are two types of forces inside the nucleus:

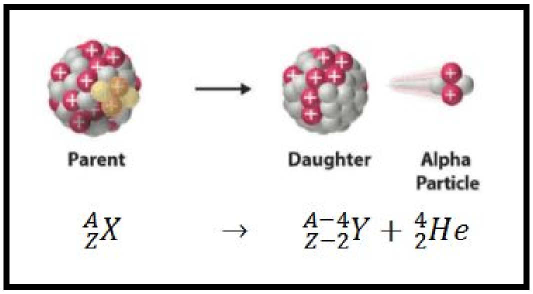
- Strong Nuclear Force (force between proton-proton, proton-neutron, neutron-neutron)
    - This is a short-range, attractive force
- Coulomb Force (force between +ve charged protons)
    - This is a repulsive force and is both short-range and long-range

Radioactive Decay

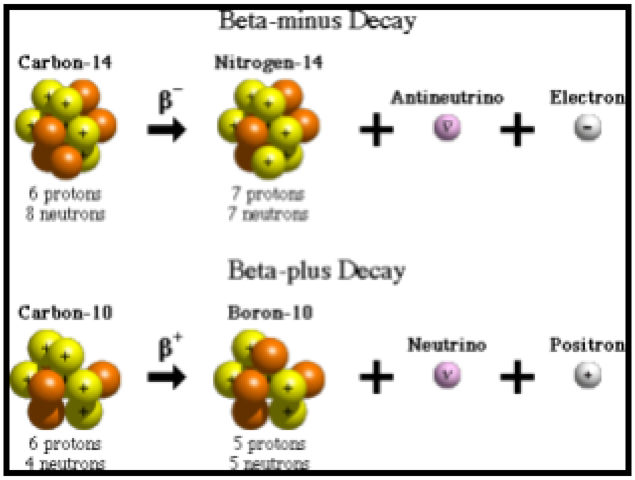
Radioactive decay is a naturally occurring process in which the nucleus of an unstable atom spontaneously changes into a different nuclear configuration emitting combinations of α-particles, β-particles, and ɣ-rays. The three types of emissions have different characteristics:

Type of radiation	**Alpha(α) particles**	**Beta(β) particles**	**Gamma(ɣ) particles**
Source	Nucleus	Atom shells	Nucleus
What is it?	$2p^{+}$ and $2n^{\circ}$ (He nucleus)	Electron	EM Ray
Mass (amu)	4	1/1836	0
Charge	2+	1-	0
Speed (c)	0.1	0.5-0.8	1
Ionization ability	**Very High** Greatest charge, so greatest force on electrons. Slow speed, so spend more time close to any electrons they pass	**Low** Low charge, smaller force exerted on electrons. Medium speed, so less time spent close to electrons passed	**Very Low** No charge, so very little force is exerted on electrons. Very fast, so they whizz past electrons quickly
Penetration power	**Very Low** Stopped by thick paper, skin, few cms of air	**High** Stopped by a few mm of Al or any other metal	**Very High** Only thick lead reduces the intensity
Effects of fields 	Deflected by magnetic and electric fields Positive charge, so equivalent to electric current.	Deflected by magnetic and electric fields Lighter than α particles, and negatively charged, so deflected more in the opposite direction	No deflection, as rays have no charge
Practical Uses	Smoke detectors	Monitoring the thickness of materials	Cancer treatment, testing equipment, sterilizing instruments, checking for leaks

Alpha (α) decay



Beta minus (β^-) and Beta plus (β^+) decay

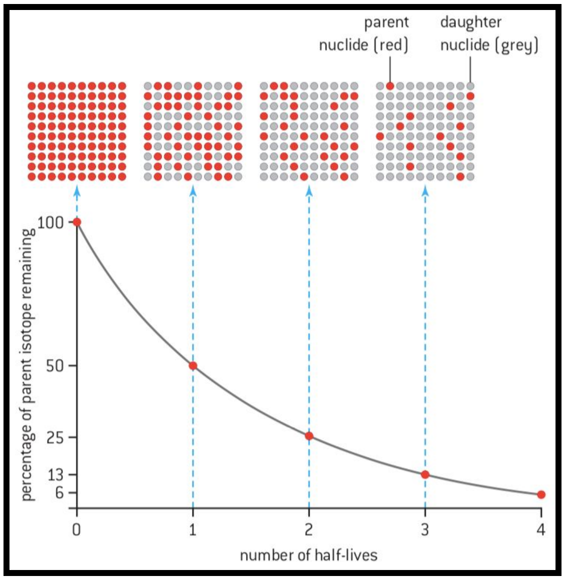


Gamma Ray emission

Gamma rays are high-energy photons often accompanying other decay mechanisms. Having emitted an alpha or beta particle, the daughter nucleus is often left in an excited state. It stabilizes by emitting gamma photons, thus losing its excess energy.

Half-life

Radioactive decay is a continuous but random process - there is no way of predicting which particular nucleus in a radioactive sample will decay next. However, the nuclide has a constant **probability of decay,** which does not depend on the size of the sample. **Activity** is the average number of disintegrations per second, measured in Becquerels (Bq). The **half-life** is the time taken for half the total number of nuclei initially in a sample to decay or for the initial activity of the sample to half. The half-life does not change with mass, but initial activity will change with mass.



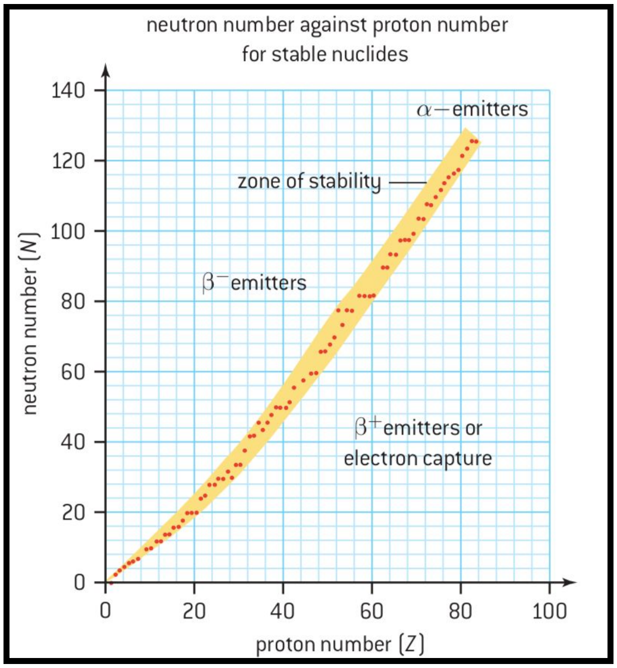
Measuring radioactive decay

A Geiger-Muller tube (GM tube) is used to detect the count rate near a source. When a GM tube is connected to its counter and switched on it will give a background reading even when a source of radioactivity is not present. This is known as **background radiation**. This is because radioactive material is found everywhere: in the air, rocks, and soil.

7.2 Nuclear Reactions

Patterns for stability in nuclides

Plotting the neutron number against the proton number, a clear pattern is formed. This is known as the **zone of stability**. Nuclides lying within the zone are stable, while those outside are unstable and will spontaneously decay into a nuclide tending towards the stability zone. In this way its possible to predict the mechanism for the decay: α, β^- or β^+:



As the proton number increases, the stability line curves upwards. This is because heavier nuclei need more and more neutrons to be stable. In a large nucleus, all the protons repel each other (long-range Coulomb forces), but nucleons only attract nearest neighbors. This makes the nucleus unstable, as forces are not balanced. Adding neutrons in between these gaps increases the attractive strong nuclear force, which gives the nucleus more stability. However, an excess of neutrons can also cause instability.

Unstable nuclides lying to the left of the stability line are **neutron-rich** and decay by β^- emission. Those nuclides to the right of the stability line are **proton-rich** and decay by β^+ emission. The heaviest nuclides are emitters of alpha radiation since the emission of both two protons and two neutrons reduce the neutron-proton ratio and bring the overall mass down.

Unified atomic mass unit (u)

The **unified atomic mass unit** is defined as 1/12 of the rest mass of an unbound carbon-12 atom in its nuclear and electronic ground state. It has a value of 1.661×10^{-27}kg or 931.5MeV c^{-2}.

Mass defect and nuclear binding energy

Mass defect is the difference in mass between the reactants and the products

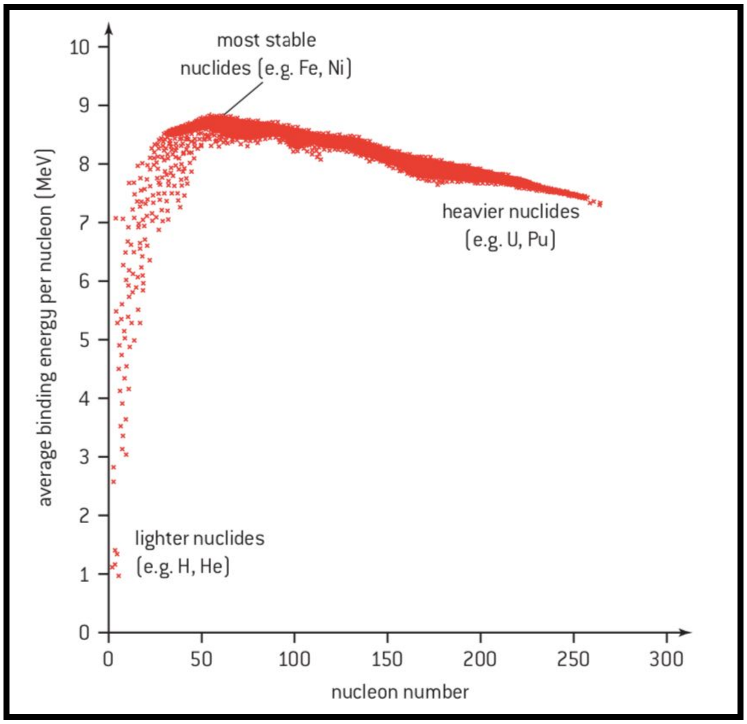
The **binding energy** of a nucleus is the amount of energy required to break the nucleus into its constituent nucleons. Energy is needed to deconstruct a nucleus and energy is given out when we construct a nucleus. The energy to construct is equal to what it takes to deconstruct.

The following equation links energy, mass, and the speed of light:
$E = mc^2$

When work is done on a system so that its energy increases by $+\Delta E$ then its mass will increase by amount $+\Delta m$. When work done by a system results in its energy decreasing by $-\Delta E$, then its mass will decrease by an amount $-\Delta m$.

These relationships are universal but are only significant on an atomic scale. As such, in scenarios on a larger scale, these can be ignored without jeopardizing calculations.

The **binding energy per nucleon** of a nucleus is the binding energy divided by the number of nucleons or the mass number. Plotting binding energy per nucleon against mass number allows us to spot trends in stability:



The trend shows that a greater binding energy per nucleon is an indication of more stable nuclei.

Nuclear fission and fusion

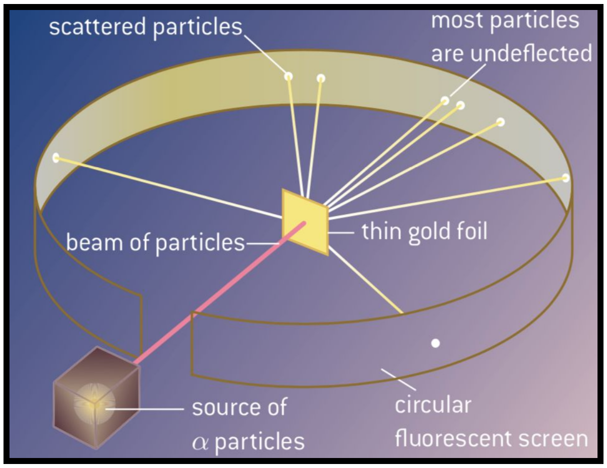
Fission is the splitting of a large nucleus into two smaller nuclei, and 2 to 3 neutrons. If these neutrons go on to strike other large nuclei, a chain reaction may start. A **chain reaction** is a self-sustaining fission reaction that is spread by neutrons.

Fusion involves the combining of two small nuclei into one larger nucleus. This can only occur at a high temperature, as only then there is sufficient energy to overcome large repulsive Coulomb forces between protons.

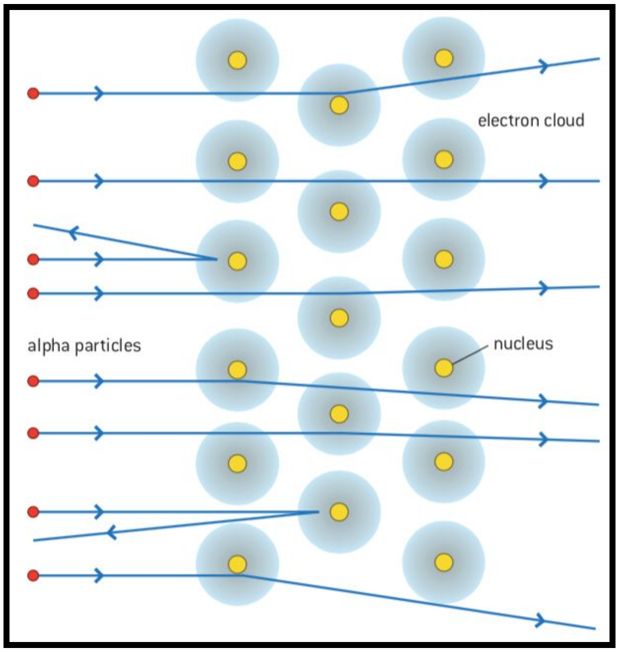
Products of fusion and fission are always more stable than the reactants. As such, fusion occurs for elements with mass numbers less than that of Fe. Fission occurs for elements with mass numbers greater than that of Fe.

7.3 The structure of matter

Scattering of alpha particles and Rutherford's gold foil experiment



A beam of **alpha particles** was aimed at **very thin gold foil** and their passage through the foil was detected. The scientists expected the alpha particles to pass straight through the foil, but something else also happened.



Some of the alpha particles emerged from the foil at different angles, and some even came straight back. The scientists realized that the positively charged alpha particles were being repelled and deflected by a tiny concentration of positive charge in the atom. This experiment proves that:

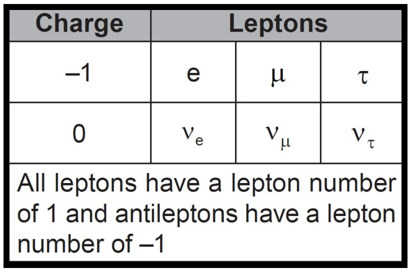
- The nucleus is very small compared to the rest of the atom
- There is lots of space in the atom
- All the positive charge is concentrated in the small nucleus

Classification of particles using the standard model

The standard model is a universal approach to classifying the numerous particles in nature. It is very successful in grouping particles but fails to incorporate relativistic gravitation or predict the accelerating expansion of the universe. It suggests that the only **fundamental particles** are leptons, quarks, and gauge bosons, with all other particles being combinations of quarks and antiquarks.

Leptons

Leptons are light and loosely bound particles. They are members of the electron family, consisting of the electron (e^-), the muon (μ), the tau (τ), plus 3 neutrinos for each of the 3 particles. Leptons only interact with the EM force carrier, the photon. Antileptons exist for each of the 6 particles, with reversed charge and lepton numbers. The table summarizes their properties. **Note**: to show an antiparticle, place a bar over what would be the original particle.

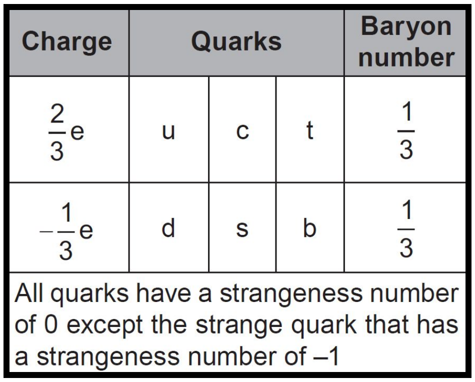


Charge	Leptons		
–1	e	μ	τ
0	ν_e	ν_μ	ν_τ

All leptons have a lepton number of 1 and antileptons have a lepton number of –1

Quarks

Quarks are heavier, tightly bound particles. There are six quarks and their antiquarks, which are labeled by their 'flavor'. These quarks are split into three generations of increasing mass. The first contains the up and down quarks, which are the lightest. The second contains the strange and charm quarks, and the third the bottom and top quarks - the heaviest. Quarks interact with photons as well as gluons, the force carriers for the strong force. Their properties are summarized in the table:



Charge	Quarks			Baryon number
$\frac{2}{3}e$	u	c	t	$\frac{1}{3}$
$-\frac{1}{3}e$	d	s	b	$\frac{1}{3}$

All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of –1

Quark confinement

A quark cannot be isolated from a baryon or a meson. The energy required to split quarks is so high in the first place that a new meson ends up being created instead of an isolated particle.

A **hadron** is a particle that participates in strong force.
A **baryon** is made of three quarks. Eg: proton - uud, neutron - udd
A **meson** is made up of a quark and an antiquark

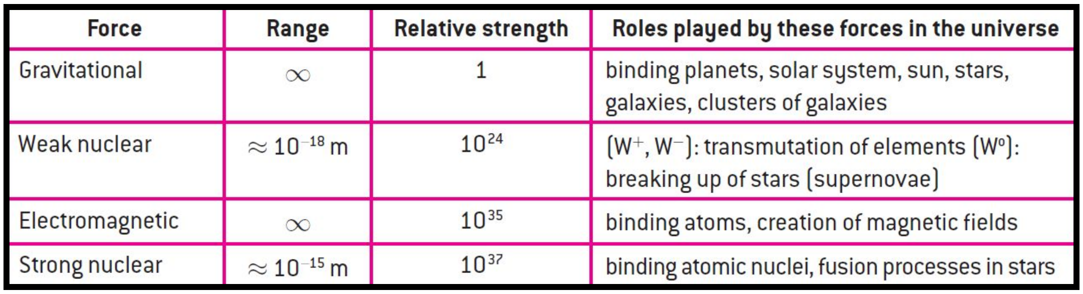
Conservation rules

For a reaction to occur, the baryon number, lepton number (and family), and charge must be conserved. Also, the strangeness must be conserved. Strangeness is equal to the number of antistrange quarks minus the number of strange quarks. The rules for strangeness conservation are slightly different. Strangeness is conserved in strong and EM interactions, but not in weak interactions.

Fundamental forces

There are four fundamental forces in nature (in order of increasing strength):

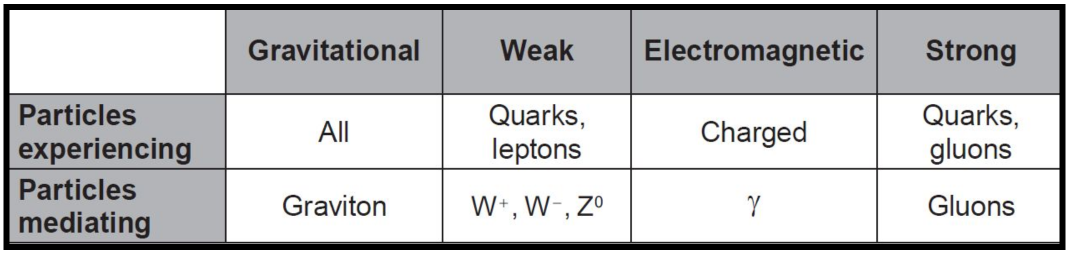
- **Gravitational force** is weak, has an infinite range, acts on all particles, and is always attractive Over astronomical distances it is the dominant force, whereas it is negligible at the atomic level
- **Weak nuclear force** is responsible for radioactive decay and neutrino reactions. It only acts over short ranges and acts between all particles
- **Electromagnetic force** causes electric and magnetic effects such as the forces between electrical charges or bar magnets. It also has an infinite range but is much stronger at short distances. It can be attractive and repulsive and acts between all charged particles
- **Strong nuclear force** is the strongest force in nature but has a very short range. It acts between hadrons, but not leptons. At this range, the force is attractive but becomes strongly repulsive at any smaller distances.



Force	Range	Relative strength	Roles played by these forces in the universe
Gravitational	∞	1	binding planets, solar system, sun, stars, galaxies, clusters of galaxies
Weak nuclear	$\approx 10^{-18}$ m	10^{24}	(W^+, W^-): transmutation of elements (W^0): breaking up of stars (supernovae)
Electromagnetic	∞	10^{35}	binding atoms, creation of magnetic fields
Strong nuclear	$\approx 10^{-15}$ m	10^{37}	binding atomic nuclei, fusion processes in stars

Exchange particles

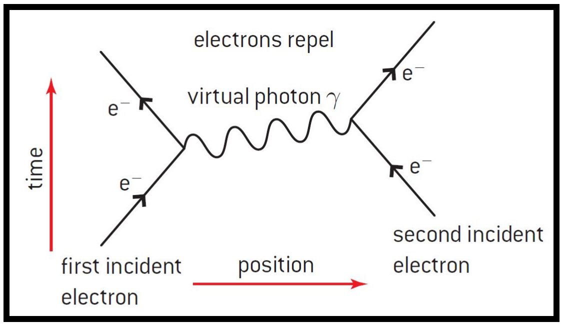
Exchange particles are **gauge bosons** that carry forces between compatible particles. Exchange particles whose range of influence is limited are known as **virtual particles**. Each fundamental force has a different range, which is determined by the boson responsible for each force. The mass of the boson establishes the range of the force. The larger the rest mass of the exchange particle, the lower time it can be in flight without being detected and, therefore, the lower the range of the force.



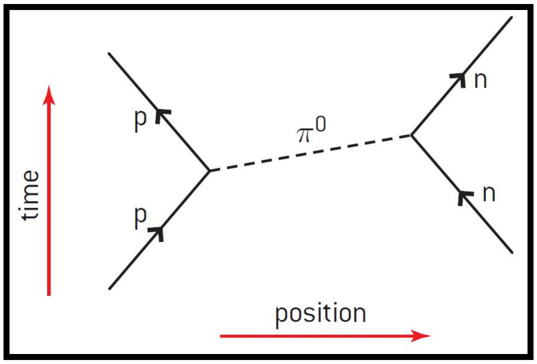
	Gravitational	Weak	Electromagnetic	Strong
Particles experiencing	All	Quarks, leptons	Charged	Quarks, gluons
Particles mediating	Graviton	W^+, W^-, Z^0	γ	Gluons

Feynman diagrams

Feynman diagrams are graphical visualizations of interactions between particles. The y-axis represents time, whereas the x-axis represents space (although these can be swapped). Straight lines represent particles and upwards arrows show particles moving forwards in time (downward arrows indicate an antiparticle - also moving forwards in time). Wavy lines with no arrows represent exchange particles. At each point where lines come together, conservation of charge, lepton number, and baryon number must be applied. The figure shows a Feynman diagram for when two electrons approach each other:



The next diagram shows the strong force between a proton and a neutron:

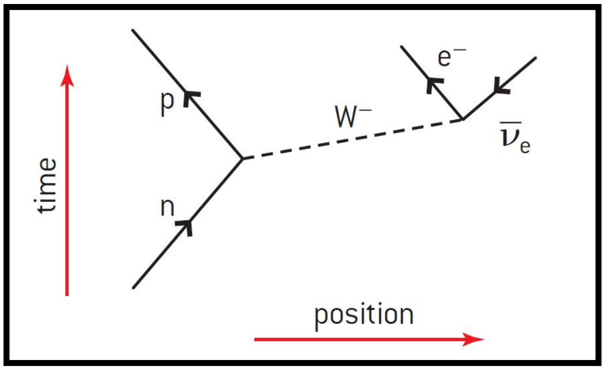


In this case, a neutral pion is exchanged between the proton and the neutron that ties them together. In hadrons, the pion carries gluons between the quarks - the gluons are the exchange particles for the color force acting between hadrons

We can also represent β^- decay:

Furthermore, the arrows for neutrons and protons can be replaced with three arrows showing their respective quark structure (uud for proton and udd for neutron)

Flipping the proton and neutron, replacing e^- with e^+ , W^- with W^+ , the antineutrino with a neutrino, and making appropriate changes to the arrow directions leaves us with a Feynman diagram for β^+ decay



The Higgs Boson

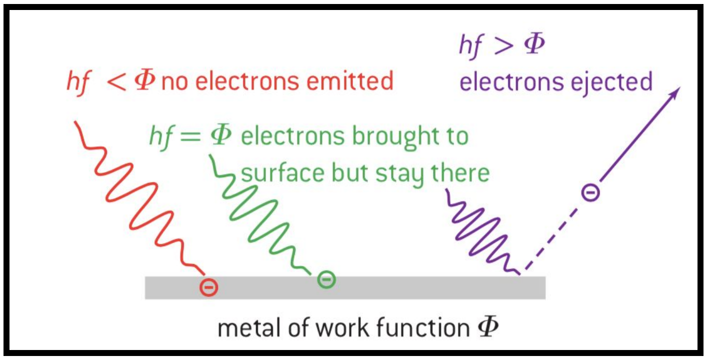
The Higgs Boson is a recently discovered particle. It is the particle that gives quarks and leptons their mass. The **Higgs mechanism** is the process by which particles gain mass by interacting with the Higgs field which permeates all space. As such, mass is not the property of the particle, but part of space itself. For this mechanism to work, the particle must be fully covered by a **Higgs field**. The particle associated with the Higgs field is the **Higgs Boson**. The Higgs Boson is boson-like, but it does not mediate any force.

12.1 The interaction of matter with radiation

The **photoelectric effect** is the phenomenon of the emission of electrons from the surface of a metal when light of a suitable frequency falls over it. This can be demonstrated using a **gold-leaf electroscope**.

Explanation of the photoelectric effect

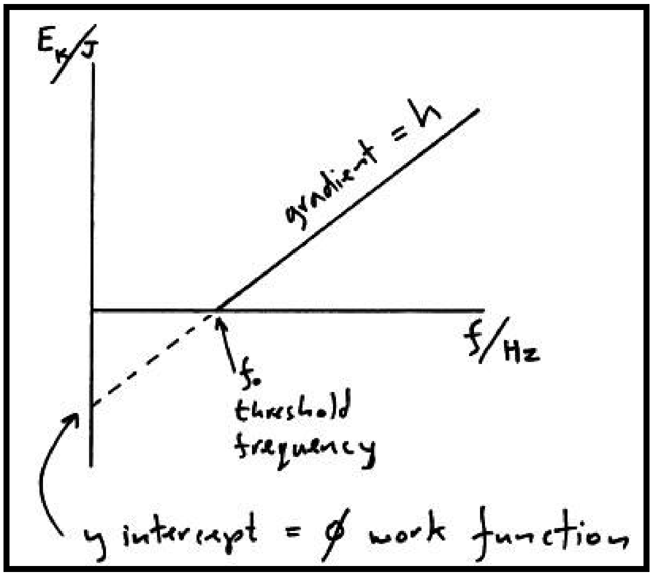
- Light can be considered to consist of photons, each of energy = hf
- Each photon can only interact with a single electron
- There is a minimum photon frequency - called the **threshold frequency** (f_o) below which no electron can be emitted
- Energy is needed to do the work to overcome the attractive forces that act on the electron within the metal - this energy is called the **work function (Φ).**
- Any further energy supplied by a photon becomes the KE of the emitted electron



Einstein's photoelectric equation

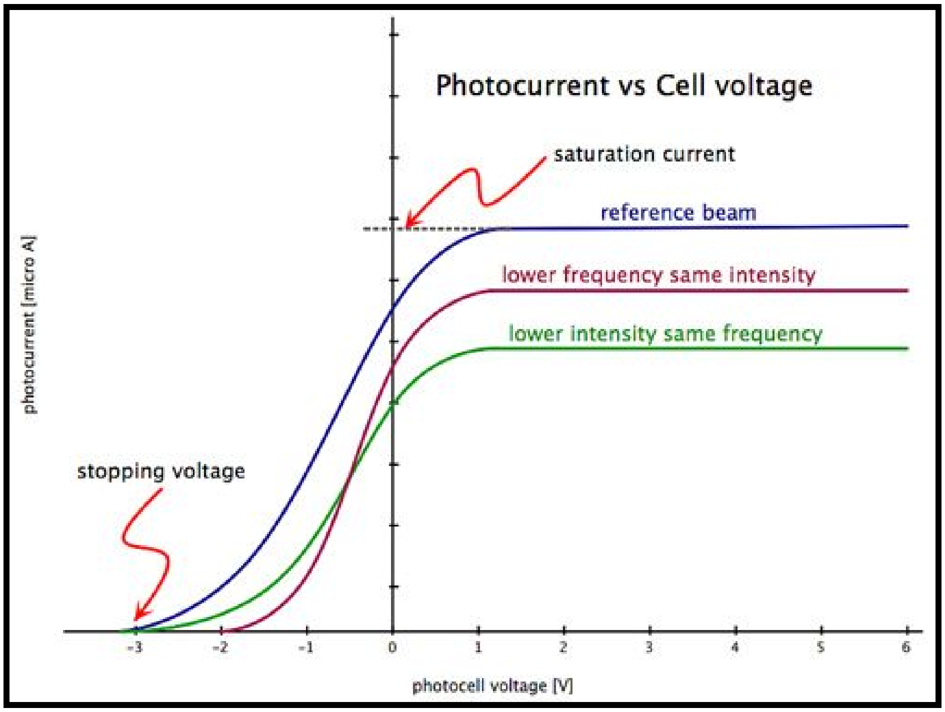
$E_{kmax} = hf - \Phi$

Φ is the work function. It gives the value for the energy required to pull electrons away from the nucleus. Subtracting the work function from the energy of the incident radiation gives the remaining maximum kinetic energy provided to the liberated electrons.



Factors affecting the photoelectric effect

- Nature of the photo surface (dependent on the electron configuration)
    - This affects the work function
- Frequency of radiation
    - Higher frequency provides higher photocurrent (only if the intensity is also increased)
    - Given E = hf, increasing frequency provides electrons with greater KE
- The intensity of the radiation
    - Higher intensity provides higher photocurrent
    - While KE remains the same, as the frequency is unchanged, the number of electrons increases, so greater current flow.



If the frequency is increased, but the intensity remains constant, then the photocurrent will decrease. While liberated electrons have greater KE, a fewer number of electrons are liberated, so the photocurrent decreases

The **stopping potential** is the energy required to stop electrons from reaching the collecting plate of a circuit. The stopping potential is not affected by the intensity of the light source.

Overall, when a photon hits a photo surface, 3 things can happen:

- The energy of the photon is not enough to remove the electron, so nothing happens
- The energy of photon = Ionization energy
    - Electron leaves the atom without any KE
    - No photocurrent flows
- The energy of photon > Ionization energy
    - Photocurrent can flow

Overall, light appears to have characteristics that can be attributed to either a wave or a particle - we call this **wave-particle duality**.

<u>Interpreting the observations of the photoelectric effect</u>

Observations	**Wave model**	**Photon model**
Emission of electrons happens as soon as light shines on a metal	Very intense light should be needed to have an immediate effect **(Fails to explain)**	A single photon is enough to release one electron
Even weak (low intensity) light is effective	Weak light waves should not affect (**Fails to explain)**	Low-intensity light means fewer photons are released, not low energy photons
Increasing the intensity of light increases the rate at which electrons leave the metal	Greater intensity means more energy, so more electrons released	Greater intensity means more photons per second, so more electrons released per second
Increasing the intensity does not affect the energies of electrons	Greater intensity should mean electrons have more energy **(Fails to explain)**	Greater intensity does not mean more energetic photons, so electrons cannot have more energy (E =hf)
A minimum threshold frequency of light is needed	Low-frequency light should work: electrons would be released more slowly **(Fails to explain)**	A photon in a low-frequency light beam has energy that is too small to release an electron
The increasing frequency of light increases the maximum KE of electrons	It should be increasing intensity, not frequency, that increases the energy of electrons **(Fails to explain)**	Higher frequency means more energetic photons; so electrons gain more energy and can move faster

<u>Matter waves</u>

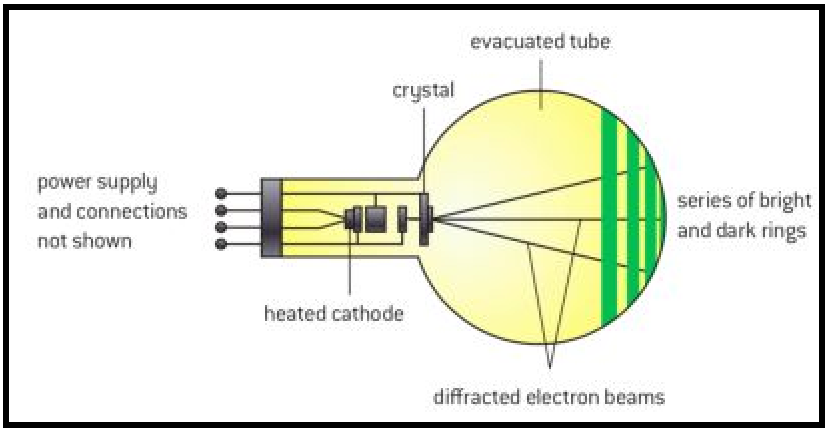
Louis De Broglie suggested that if something classically considered a wave could have particle-like properties, the opposite should also be true. The matter could, therefore, possess wave-like properties. He showed this but allowed particles to pass through a double slit, and obtained an interference pattern similar to that in Young's double-slit experiment. He suggested that the wavelength associated with a particle is given by:

$$\boxed{\lambda = \frac{h}{p}}$$

Where h is Planck's constant and p is the momentum of the particle (= mv). This wavelength is known as the **de Broglie wavelength**. The above equation is **NOT IN THE DATA BOOKLET**.

Electron diffraction

Two American physicists demonstrated de Broglie's hypothesis experimentally by observing interference maxima when a beam of electrons was reflected by a nickel crystal. Shown below is the arrangement:



Electrons from a heated cathode pass through a thin film of carbon atoms. If the electrons behaved like particles they would only be slightly deviated by collisions with the C atoms and would form a bright region in the center of the screen.

The bright rings indicate where the electrons land on the screen. A bright glow indicates a high probability of electrons reaching that point, whereas darkness indicates a low probability of electrons reaching that point. This pattern repeats and is very similar to the interference pattern obtained with light using a diffraction grating. This shows particles can also behave like waves.

Given $KE = 0.5mv^2$, we can rewrite the equation for the de Broglie wavelength. KE is equivalent to the work done to accelerate the particle through the electron diffraction.

First, we rearrange for v, changing energy to electron volts, so $v = \sqrt{(2eV/m)}$
Substituting this for v in $\lambda = h/mv$ leaves us with $\lambda = h/\sqrt{(2meV)}$

The Bohr Model

Niels Bohr proposed a model in which electrons could only occupy orbits of certain radii. The model has several postulates:

- Electrons in an atom exist in fixed stationary states, not radiating energy while in it
- Electrons may move from one stationary point to another by absorbing or emitting a quantum of electromagnetic radiation
    - $E = hf$ (this is the energy between stationary states)
- The angular momentum of an electron in a stationary state is quantized in integral values of $h/2\pi$
    - Angular momentum is the product of the momentum of a particle and the radius of its orbit, so for a particle in a circular orbit, the angular momentum is constant

$$\lambda = \frac{h}{p} \text{ and } \lambda = \frac{2\pi r}{n}$$

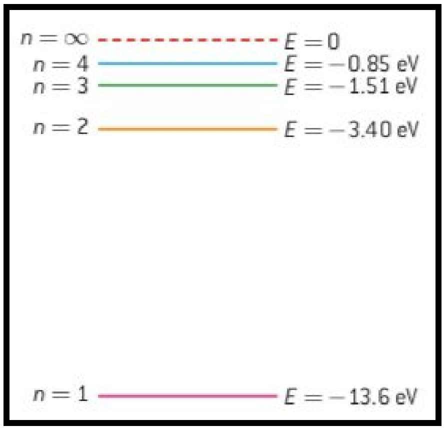
$$\frac{h}{p} = \frac{2\pi r}{n}$$

$$pr = \frac{nh}{2\pi}$$

$$mvr = \frac{nh}{2\pi}$$

Energies in the Bohr orbits

The Bohr model produced an equation that agreed with the equation for the spectrum of the hydrogen atom. By measuring total KE and PE of the H atom, an electron in the nth energy level (n≥1), the total energy in electronvolts at each level is given by:

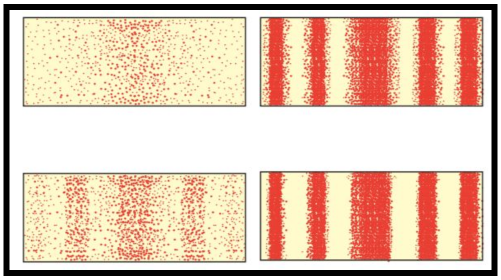


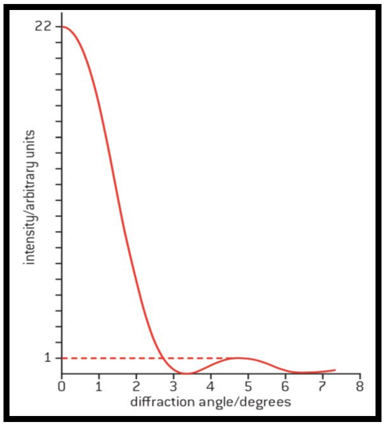
$$\boxed{E = -\frac{13.6}{n^2} eV}$$

The energy is negative because the electron is bound to the nucleus and energy needs to be supplied to the system to completely separate the electron from the proton.

Schrodinger's equation

Wave-particle duality explains a bright interference fringe as being the place where there is a high probability of finding a particle. Probability waves describe the position of particles. Like classical waves, probability waves superpose with one another to produce the expected interference pattern. At the principal maximum, the intensity of electrons is about 22 times that at the second max.





Schrodinger's wave equation describes the quantum state of particles. The wave function is not directly observable but its amplitude is very significant. With light waves, we observe the intensity, not the amplitude, and we have seen that the intensity is proportional to the square of the amplitude. For the wave function, where the square of the amplitude is maximum there is the greatest probability of finding a photon. When the square of the amplitude is zero there is zero probability of finding the photon. Ψ is thought of as the amplitude of the de Broglie wave, and:

$$\boxed{P(r) = |\psi|^2 \Delta V}$$

P(r) is the probability of finding a particle at a distance r from a chosen origin and V is the volume being considered. The higher the wave function, the higher the probability of finding a particle.

The Heisenberg Uncertainty Principle

If an electron behaves simultaneously as a wave and as a particle, we cannot divide physical objects as either particles or waves. There are two equations:

$$\boxed{\Delta x \Delta p \geq \frac{h}{4\pi}} \qquad \boxed{\Delta E \Delta t \geq \frac{h}{4\pi}}$$

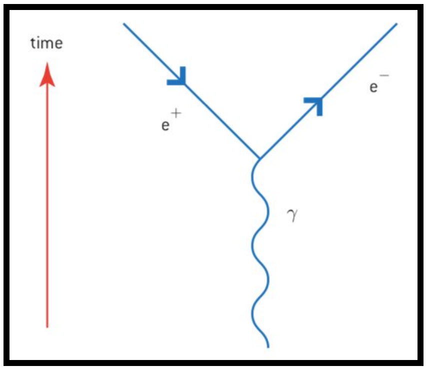
It is not possible to measure simultaneously the position and momentum of something with indefinite precision. This is due to the law of nature, rather than measurement uncertainties or errors in equipment. The same applies to energy and time relationships. Given how small the value of h/4π is, if Δx is 0, Δp is infinite and vice versa. Similarly, if ΔE is 0, then Δt is infinite and vice versa.

Pair production and annihilation

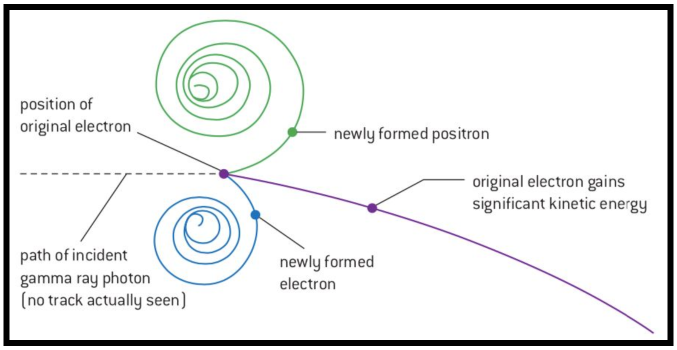
Close to an atomic nucleus, where the electric field is very strong, a photon of the right energy can turn into a particle along with its antiparticle. An electron is produced along with a positron, whereas a proton is produced along with an antiproton. The particle and antiparticle are said to be a "pair" and the effect is known as **pair production**. The antiparticle will have a mass e^+ equal to that of the particle meaning that the photon must have enough energy to create the masses of the two particles. The minimum energy to do this is:

$E = 2mc^2$ (because there are two particles)

Additionally, **both** energy and momentum are conserved during pair production

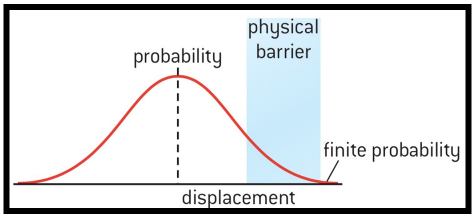


When a particle meets its antiparticle they annihilate, forming two photons, The total energy of the photons is equal to the total mass-energy of the annihilating particle. Sometimes a pair of particles annihilate but then one of the photons produces another pair of particles. The positron that is formed in the interaction quickly disappears as it is reconverted into photons in the process of annihilation with another electron in the matter.



Quantum Tunnelling

The process by which quantum particles (protons and electrons) can overcome a potential barrier deemed impossible according to classical physics.



12.2 Nuclear physics

Rutherford's scattering and the nuclear radius

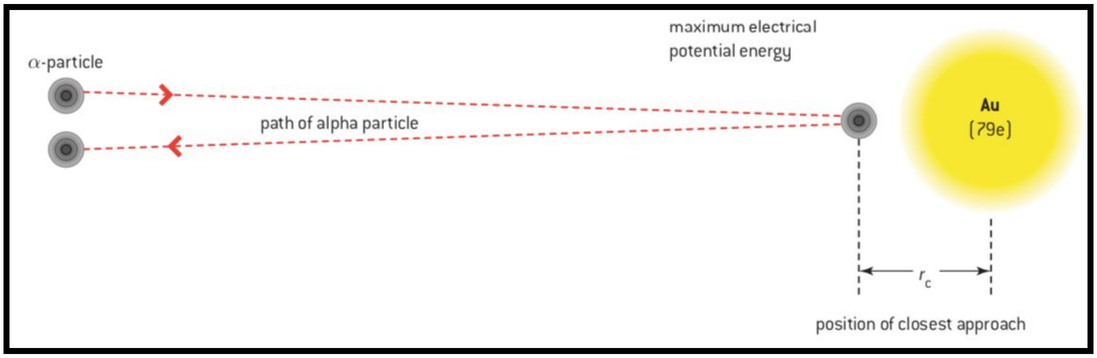
In Rutherford's experiment covered earlier:

- Most of the alpha particles passed through the gold leaf undeflected
- Some alpha particles were deflected through very wide angles
- Some alpha particles rebounded in the opposite direction

The interpretations of these results were:

- Most of the atom is space
- The atoms contain small dense regions of electric charge
- These small dense regions are positively charged

One way to determine the nuclear radius is by the method of the closest approach:



The diagram above shows an alpha particle incident head-on with a gold nucleus. As an alpha particle becomes closer to the nucleus, its kinetic energy falls, and its electric potential energy increases, as the charges of the nucleus and the alpha particle are both positive. When the alpha particle is closest to the nucleus, its kinetic energy has fallen to zero and it has momentarily stopped moving. At this point:

$$E_k = E_p$$

$$KE = \frac{kQq}{r}$$

$$KE = \frac{k(2e)(Ze)}{R_0}$$

$$KE = \frac{2Zke^2}{R_0}$$

$$R_0 = \frac{2Zke^2}{KE}$$

Where (2e) is the charge of an alpha particle, and (Ze) is the charge of the nucleus, with Z being the proton number of the relevant element. R_o is the distance of the closest approach, also known as the **Fermi radius**. (EQUATION ON THE LEFT IS NOT IN THE DATA BOOKLET)

Furthermore, as the volume V of a nucleus must be proportional to the number of nucleons, we would expect $V \propto A$ (where A is the nucleon number), and so the nuclear radius R would be $\propto A^{1/3}$.

$$\boxed{R = R_0 A^{\frac{1}{3}}}$$

The experimentally determined value for R_0 is 1.20×10^{-15}

Nuclear density

If the nucleus is assumed to be spherical, its volume can be calculated using the following equation:

$$\boxed{V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi\left(R_0 A^{\frac{1}{3}}\right)^3 = \frac{4}{3}\pi A R_0^3}$$

So the density of nuclear material will be given by:

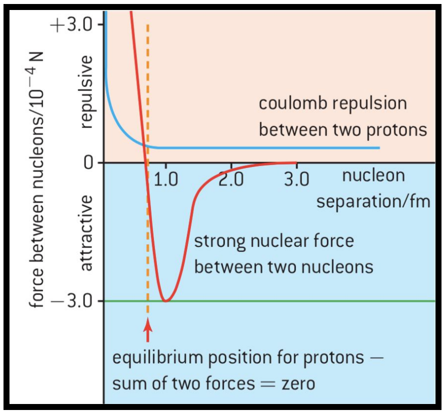
$$\boxed{\rho = \frac{m}{V} = \frac{Au}{\frac{4}{3}\pi A R_0^3} = \frac{3u}{4\pi R_0^3}}$$

Since, the 'A's cancel out, all the components of the expression are constants, which implies that the density of any nucleus is independent of the number of nucleons in the nucleus. Substituting the values in the equation gives:

$$\boxed{\rho = \frac{3u}{4\pi R_0^3} = \frac{3 \times 1.66 \times 10^{-27}}{4 \times \pi \times \left(1.2 \times 10^{-15}\right)^3} = 2.3 \times 10^{17}\, kg\ m^{-3}}$$

Deviation from the Rutherford model

The derivation is an approximation, as the nucleus has been treated as a point mass. If the alpha particle has high KE, it gets close enough to the nucleus for the strong nuclear force to dominate the Coulomb force. In Rutherford's experiments, using more energetic alpha particles found that the scattering relationship did not agree with experimental results. At higher energies, alpha particles can approach the target nucleus so closely that the strong nuclear attractive force overcomes the electrostatic repulsion. The figure shows how strong nuclear force and Coulomb force vary with distance:



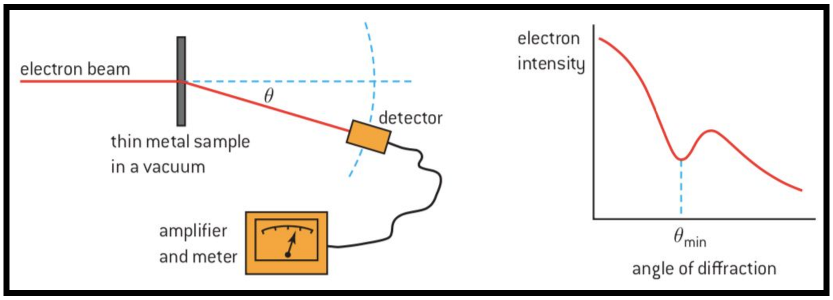
The method of the closest approach gives an approximation of the size of a nucleus. More reliable values for the size of a nucleus can be found using electron diffraction

Electron diffraction

As electrons are leptons (and not hadrons) they are not affected by the strong nuclear force but are affected by the charge distribution of the nucleus. High energy electrons have a short de Broglie wavelength of the order of 10^{-15}m. As this is also the order of magnitude of the size of a nucleus, it means that diffraction analogous to that observed with light incident on a narrow slit or small object can be observed. For a light incident on a small circular object of diameter D, the angle Θ that the first diffraction minimum makes with the straight-through position (Θ = 0°) is given by

$$\boxed{\sin\theta \approx \frac{\lambda}{D} \qquad \text{where } \lambda \text{ is the wavelength of the light}}$$

The elastic scattering of high energy electrons by a nucleus produces a similar effect:



Similar to light diffraction, the relationship can be approximated by:

$$\boxed{\sin\theta \approx \frac{\lambda}{D}}$$

Here D is the nuclear diameter, and λ is the de Broglie wavelength of the electrons. With angles greater than 10° the small-angle approximation sin Θ ≈ Θ cannot be applied to electron scattering.

For this experiment:

- Electrons work well because they don't respond to strong nuclear force in the nucleus
- Neutrons are not affected by Coulomb force, so they can also work well

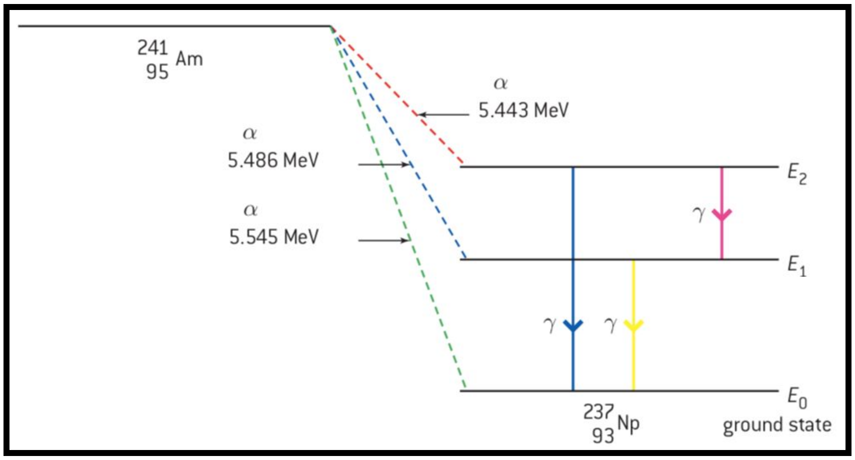
Using electrons of higher energies

When electrons of high energies are used, collisions are no longer elastic (the bombarding electrons lose KE), and the energy is "converted" to mass as mesons are emitted from the nucleus. At even higher energies, electrons penetrate deeper into the nucleus and scatter off the quarks within protons and neutrons - this is known as deep inelastic scattering and is evidence for the quark model of nucleons.

Nuclear energy levels

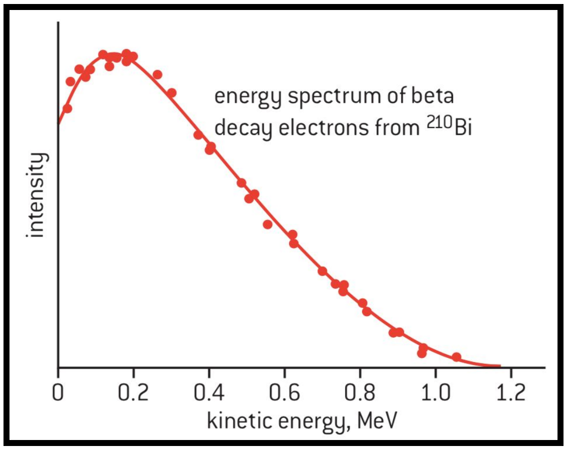
Much of the evidence for energy levels in the nucleus comes from the radioactive decay of nuclides. The emission of gamma radiation is analogous to the emission of photons by electrons undergoing energy level transitions. The emission of alpha or beta particles by radioactive parent nuclei often leaves the daughter nucleus in an excited state. The daughter nucleus emits one or more gamma-ray photons as it reaches the ground state.

The main evidence for the existence of discrete energy levels in the nucleus is the decay of alpha particles and gamma-ray photons, which decay in discrete amounts. Beta-decay is not discrete as beta decay will continue with the emission of neutrinos/antineutrinos, making it a continuous process.



Negative beta decay

The possible explanation for the continuous spectrum of beta decay was that mass-energy and momentum are not conserved in beta decay. These were very unlikely solutions since both of these principles are considered to be fundamental to physics. Pauli suggested that if a third particle was to be emitted in the decay, not only would this solve the mass-energy and momentum problems but it would also allow spin angular momentum to be conserved in the emission. The emission of an electron antineutrino meant that for a particular nucleus the energy would be shared between the electron and the antineutrino



The law of radioactive decay

The **law of radioactive decay** states that the number of nuclei that will decay per second is proportional to the number of atoms present that have not yet decayed.

The **decay constant**, represented by λ, is the probability of decay per unit time.

Given that the activity, A, is the number of disintegrations per second, the activity will be equal to the number of nuclei present multiplied by the probability that one will decay in a second. N will decrease with time, there is a minus sign:

$$\boxed{A = -\lambda N}$$

Activity is the rate of change of N, so:

$$\boxed{\frac{\mathrm{d}N}{\mathrm{d}t} = -\lambda N}$$

Upon integrating by bringing like terms together, and then manipulation, we end up with:

$$\boxed{N = N_0 \mathrm{e}^{-\lambda t}}$$

And given the $A = -\lambda N$:

$$\boxed{A = \lambda N_0 \mathrm{e}^{-\lambda t}}$$

Decay constant and half-life

At half life, $N/N_0 = ½$
So $½ = e^{-\lambda t}$
As such:

$$\boxed{t_{1/2} = \frac{-0.693}{-\lambda} = \frac{0.693}{\lambda}}$$

Measuring long half-lives

Some nuclides have very long half-lives. When a radioactive nuclide has a half-life that is long compared to the time interval over which radioactive decay observations are possible, there is no apparent rate of decay and it is not possible to measure the half-life in the manner suggested using a G-M Tube.

In this case, a pure sample of the nuclide in a known chemical form needs to be separated, its mass measured, and then a count rate is taken. From this reading the activity can be calculated by multiplying the count rate by the ratio:

$$\boxed{\frac{\text{area of sphere of radius equal to the position of the G—M tube window}}{\text{area of G—M tube window}}}$$

The decay constant is determined using the equation above.

To measure a long half-life, you only need the activity of the nuclide and the number of nuclide atoms. To know the number of nuclide atoms, you require the mass of the sample.