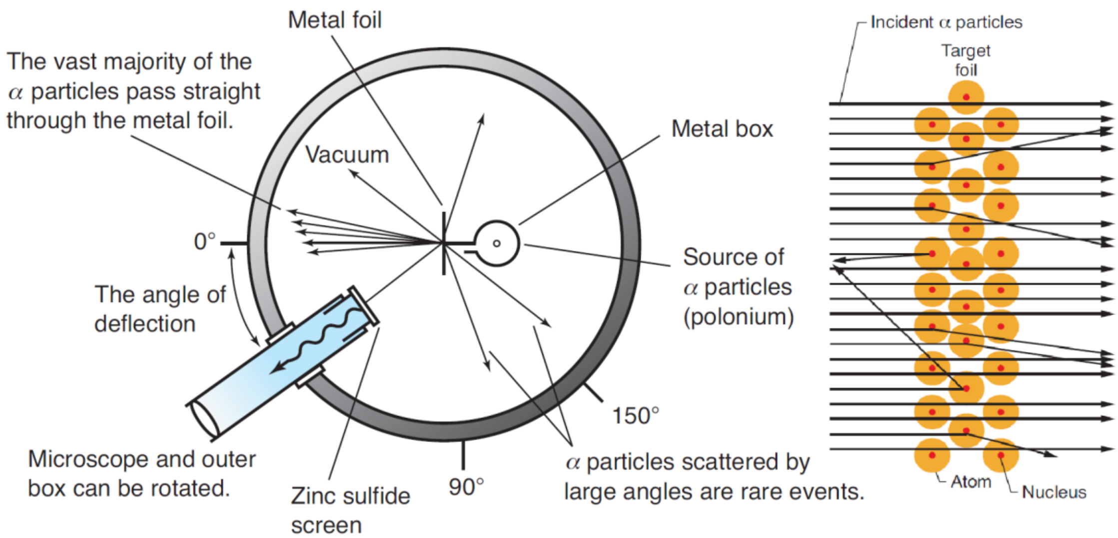
Option: Quanta to Quark

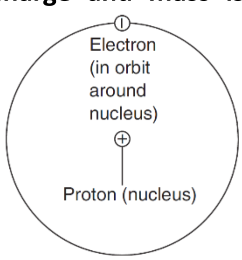
1. Problems with the Rutherford model of the atom led to the search for a model that would better explain the observed phenomena.

Students learn to:

- At the time that **<u>Ernest Rutherford</u>** (1871-1935) introduced his model of the atom, J. J. Thomson's **plum pudding model** was accepted where the atom had tiny negative charges embedded in a sphere of positive charge. However, in 1911, Rutherford's assistant, **Hans Geiger** and his PhD student **Ernest Marsden** conducted an experiment at Rutherford's suggestion where they fired **newly discovered alpha radiation at thin gold sheets** and measured the **<u>deflection of the radiation</u>**. The large majority of the radiation passed through with **little or no deflection**, as predicted by Thomson's model, however about 1 in every 8000 particles was reflected back at **greater than 90°**. This force was confirmed as an **inverse square force** and hence presumed as the electromagnetic force. The probability of explaining this through multiple small deflections was negligible meaning the interaction was with a **single atom**. By measuring the penetration and velocity of the particles, Rutherford concluded that that the positive charge must have been concentrated into an area **10,000 times smaller** than the atom to deliver the required force. Thus,



the positive charge must have been collected in a **<u>nuclear centre for the atom</u>**. Hence, Rutherford proposed a model for the atom, that a nucleus where the **positive charge and mass is concentrated** is "orbited" by electrons at a comparably large distance compared to the atom, as shown left. Thus most of the atom was **empty space** and whilst it was excellent at explaining the alpha scattering theoretically, it did not account for **why the nucleus was stable** with so much concentrated positive charge or even what it was. It did not explain the **structure of the orbits** or why the electrons weren't attracted to the nucleus. As the electrons orbiting would be also accelerating to maintain orbit, Maxwell required that they hence emit electromagnetic radiation and hence lose energy, become **unstable and collapse into the nucleus**. Thus, Rutherford's model was **<u>not complete.</u>**



- **<u>Neils Bohr</u>** (1885-1962) was a Danish physicist and a student of Rutherford's. Bohr recognised that every individual element had a **unique emission/absorption spectrum.** He also suggested that Planck's **atomic oscillators in Black Body radiation were electrons**. Thus he tried and failed to introduce quantum theories to the model of the atom. However when he was introduced to the

purely empirical Balmer equation used to explain hydrogen's spectral lines, Bohr realised how the electrons were **structured in the atom** and how he could use quantum ideas to explain the **structure of orbits** and the **observed spectral lines**. This was achieved by **quantising the electron orbits** and thus theoretically predicting the spectral lines of hydrogen. It was crucial to use hydrogen as it was the **simplest application of his model**. Thus, the spectral lines initiated Bohr's model.

- Bohr **assumed four postulates** (acceptance of phenomena that aren't explained) to make his model work:
  - Electrons orbit nuclei in **quantised metastable orbits** known as **stationary states** in which their **stability is inexplicable**.
  - In contradiction to **classical electrodynamics**, electrons orbiting (or accelerating) **do not emit radiation** when in their stationary states.
  - Electrons **must absorb or emit a photon** of the precise frequency that corresponds to the quantised energy difference between the states ($hf = E_1 - E_2$).
  - The angular momentum of the circular or **spherical orbits are quantised** as **integer multiples** of Planck's constant divide by two pi. That is, $L = mvr = n\frac{h}{2\pi}$.
- **Max Planck** investigated the '**ultraviolet catastrophe**' of infinite energies surrounding the concept of a **black body radiator**. He realised when he was processing **Boltzmann's calculations** that if he accepted that the energy generated by his **atomic oscillators** inside his atoms could only be emitted in **discrete quanta** instead of a **continuous wave spectrum**, then the mathematical equation before he integrated was the perfect description of the observed evidence. Thus, Planck developed this **mathematical trick** to describe black bodies and suggested that the **energy produced must be quantised**. **Einstein** later capitalised on this discovery confirming its validity and **Bohr** based his work on these two.
- The **Balmer Equation** was first derived by **Johann Balmer** as $\lambda = b(\frac{n^2}{n^2-2^2})$ to **describe empirically** the visible **spectrum of hydrogen** (now known as the Balmer series). **Rydberg** mathematically rearranged this formula into the familiar $\frac{1}{\lambda} = R_H(\frac{1}{{n_f}^2} - \frac{1}{{n_i}^2})$. These were both empirical descriptions of the phenomena. Bohr however assumed that the **electron orbits were circular shells** acted upon by **electrostatic attraction** from the nucleus (first postulate). Thus he equated **centripetal force** ($F_c = \frac{mv^2}{r}$) with **electro static attraction** ($F_q = \frac{k{q_e}^2}{r^2}$). By **quantising the angular momentum** (fourth postulate) and then substituting the above facts, he was able to **quantise radial orbits** such that $E_n = \frac{1}{n^2}E_1$. Bohr then calculated the **energy gaps** between his stationary states and equating them with **photon energ**y (third postulate) he was able to reach Rydberg's equation and his **theoretically derived constant** perfectly matched **Rydberg's empirical one**. Thus by **applying his postulates**, Bohr was able to reach an equation that matched experiment, a great strength of his model.
- The Bohr model of the hydrogen atom is a combination of quantum theory and classical theory which in itself provides contradictions. The model also fails to explain several phenomena listed below:
  - Only postulated on why electrons didn't emit radiation, no explanation.
  - **Spectra of Larger Atoms:** the Bohr model can only be applied to Hydrogen with its single electron, if more electrons are added it becomes too complex and breaks down.
  - **Relative Intensities of Spectral Lines:** when the spectra is observed, some of the spectral lines are of higher intensities than others. Bohr's model does not explain why some transitions would be favoured above others.
  - **Hyperfine Spectral Lines:** when the spectra were examined more closely with highly sensitive instruments, it was revealed that the spectral lines were actually made up of many hyperfine lines presumably caused by the splitting of the energy levels, however Bohr could not account for this.

- **The Zeeman Effect:** when an excited gas was placed in a magnetic field, each spectral lines split into many distinct lines. The Bohr model could not account for this.

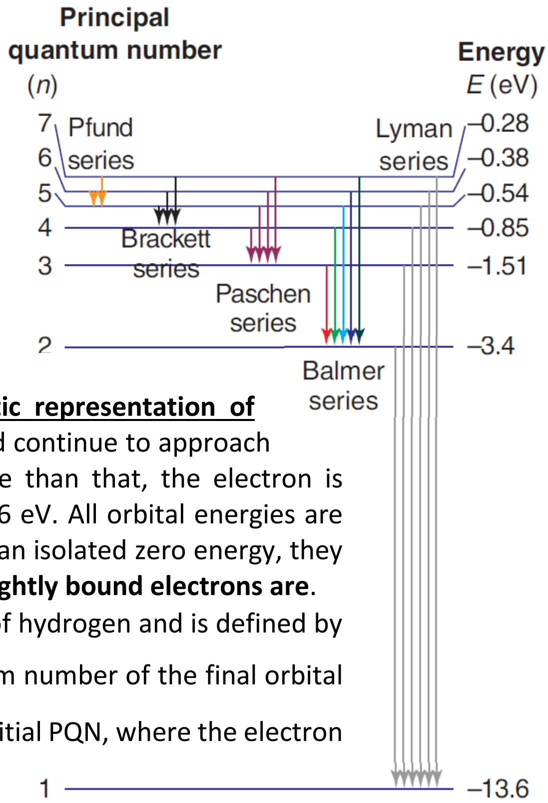
Whilst the Bohr model does not account for the above, it does make accurate predictions within it's limitations. It was very successful up until 1922 being able to predict many phenomena including the structure of the periodic table. The Bohr model's main success is its introduction of quantum theory into the atomic model, and whilst it was only the first step, it was a very important one.

Students:

- **Practical Investigation – Observing the Visible Spectrum of Hydrogen. Aim:** to observe the visible spectral lines of hydrogen gas and compare them to Blamer's equation. **Variables** – NA. **Method:** Setup an induction coil with DC power source connected to a hydrogen discharge lamp. Observe and record the visible spectral lines using a hand spectroscope. Calculate the theoretical values and compare. **Results:** as in table.

n_i	n_f	Predicted Wavelength	Observed Wavelength
3	2	656	670
4	2	486	490
5	2	434	435
6	2	410	415

- Bohr's orbitals are best represented as **quantised energy levels.** An electron is in its lowest possible energy state when in ground state. It must **gain energy** to be excited to upper orbitals. As electrons descend from orbital levels, they emit photons of light (third postulate) and the **Balmer series** is represented by the lines falling to **shell 2.** For the other series, Lyman, Paschen, Brackett, and Pfund, the energy gap is either much greater than Balmer producing an ultra violet series or much less producing infrared lines. Right is a **diagrammatic representation of Bohr's orbitals**. Theoretically, Bohr's orbitals could continue to approach 13.6 eV however if a photon ever delivers more than that, the electron is ionised. Thus **hydrogen's ionisation energy** is 13.6 eV. All orbital energies are **negative** as they are in a **bound state**, ie to reach an isolated zero energy, they must gain. Thus the ground state represent how **tightly bound electrons are**.

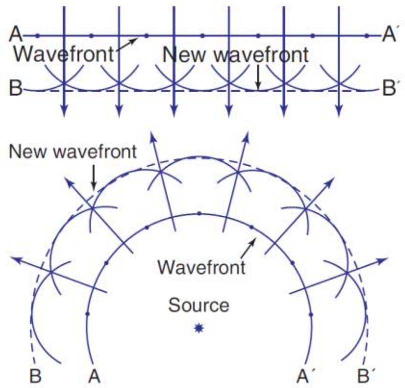


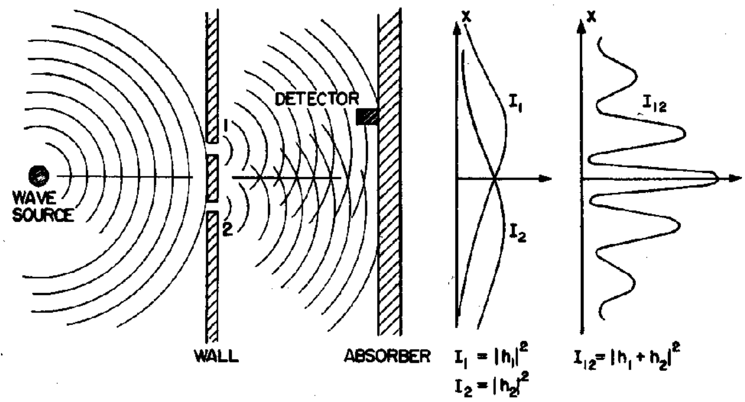
- The Balmer equation describes the spectral lines of hydrogen and is defined by $\frac{1}{\lambda} = R_H(\frac{1}{{n_f}^2} - \frac{1}{{n_i}^2})$. n_f is the principal quantum number of the final orbital shell, the one the electron descends to. n_i is the initial PQN, where the electron started. R_H is the Rydberg constant for hydrogen equal to $1.097 \times 10^7\ m^{-1}$.

2. The limitations of classical physics gave birth to quantum physics.

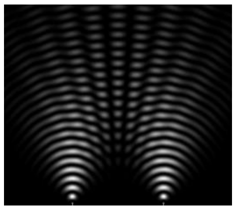
Students learn to:

- **Louis de Broglie** (1892-1987) further developed the idea of a **wave-particle duality**. He proposed that the reason why no one could reconcile the wave-particle duality of light was because on a quantum level all ***moving* particles** exhibited this behaviour. He suggested if waves carry energy dependent on frequency, then matter might also have a frequency depending on its energy. By rearranging the **momentum of light** quanta ($p = \frac{hf}{c}$, derived from $E = mc^2$), de Broglie reached the conclusion that for **all moving quantum particles**, they must have a **wavelength** of $\lambda = \frac{h}{mv}$. This proposal had an interesting impact as it had **no evidence to support it** and in the state of physics where every theory contradicted what they already knew, while de Broglie's maths was accepted, its **physical significance** was disregarded by most, except Einstein who commented "I believe it is a first feeble ray of light on this worst of our physics enigmas". This suggestion by de Broglie started a **quantum revolution** inspiring the likes of Heisenberg, Schrodinger, Dirac, Born and Pauli who developed **quantum mechanics**.

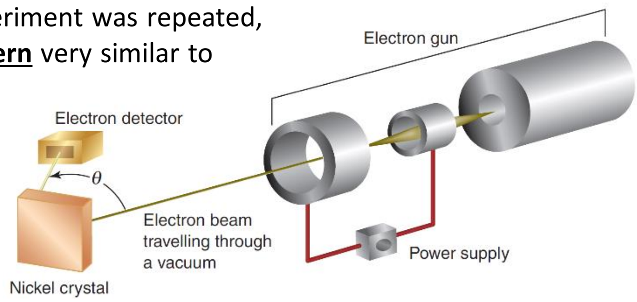




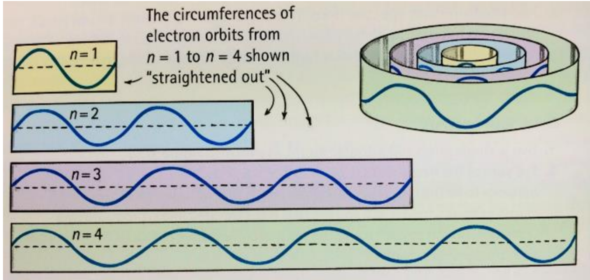
- **Diffraction** and **interference** is best explained with **Huygens' Principle** for wave transmission. It suggests that every point on a **wave front acts as a point source** and that the resulting wave could be calculated by considering the net effect of the point sources (as above). Thus, if a portion of the wave was blocked, then the point sources that made it through would **interact** on their own. This explains **diffraction,** the tendency of a beam of light to **deviate from rectilinear propagation** as a result of passing through a **narrow aperture or across an edge,** however it only occurs when the gaps are of similar size to the wavelength of the light, ie really sharp. **Interference** is the **pattern formed when two diffractions interact**. A common example is the double slit, where the two point sources caused by the splits interfere **constructively** and **destructively** at different points which creates different intensities on a surface detector and the pattern to the right.



- In 1927, **Clinton Davisson** and **Lester Germer** were studying the surface of a piece of nickel by **electron scattering**. They knew the structure was composed of **microscopic crystals** bonded at random angles thus the electrons should **scatter randomly**. However during the experiment, **air escaped into the vacuum chamber** forming an **oxide layer** on the nickel. In an attempt to remove the oxide layer, they heated the metal to just below its melting point which, unbeknownst to them, had the effect of **annealing the surface** forming **crystals** that were must **larger than the electron beam**. As a result, when the experiment was repeated, the electrons generated a **diffraction pattern** very similar to **X-ray diffraction** (X-rays have a similar wavelength to electrons). Thus, since **diffraction is a wave property**, Davisson and Germer **accidentally confirmed de Broglie's hypothesis**. This was independently confirmed by G.P. Thomson around the same time.



- One use of **de Broglie's wave theory** was to explain the **metastability of electron orbits** in the Bohr model. De Broglie suggested that the electron shells were actually similar to **standing waves**. If this was the case, then the orbits could only exist in circular waves and thus had to be **integral multiples** of a whole wavelength. Since the circumference of the circle is $2\pi r$, for a standing wave, $n\lambda = 2\pi r$. But since $\lambda = \frac{h}{mv}$, by substitution, $\frac{nh}{mv} = 2\pi r$. Rearranging, $mvr = \frac{nh}{2\pi}$ which was Bohr's **quantisation of angular momentum postulate**. Therefore the standing wave theory **satisfies Bohr's postulates** but also explains the **orbital metastability**, if the wave was not a standing wave then it would **destructively interfere** and the orbit would be unstable. Thus, orbits can only exist as the **stationary states** predicted by Bohr. As the electrons are not necessarily particles and hence not orbiting, they are not accelerating and **not required to emit radiation**. Thus, de Broglie's hypothesis solves one limitation of the Bohr model.



Students:

- With the introduction of **quantum theory** to **atomic theory**, theoretical physics began to make **predictions** before there was **evidence** to support it. The aspects of **quantum mechanics** were developed by many scientists, amongst who were **Werner Heisenberg** (1901-1976) and **Wolfgang Pauli** (1900-1958), and many did not appreciate the departure from the classical method.
  - **Heisenberg** made the most major contribution to quantum mechanics by removing it entirely from a **conceptual framework**. When considering Bohr's orbitals, Heisenberg decided to remove the idea entirely and **purely work on a mathematical framework** to describe the observations. He was successful at this and, as Max Born realised, had developed what was called **matrix mechanics** where he used matrices to describe the **current quantum model**. Erwin Schrodinger later developed what is called the **Schrodinger wave equation** which was proved to be **mathematically equivalent** to Heisenberg's matrices.
  - Pauli made one of his contributions by successfully applying, with difficulty, **Heisenberg's matrix mechanics to the hydrogen atom**. He was able to derive the **Balmer equation** and **Rydberg's** constant, just as Bohr had, but with a **mathematically coherent model**.
  - Pauli made a second contribution by realising the adding a **fourth quantum number**, **intrinsic spin**, in the description of particles, the **maximum capacity** of electron shells could be determined. By adding spin to the quantum numbers (the 1st, the principle qn; the 2nd, the azimuthal qn; the 3rd, the magnetic qn; the 4th, the spin projection qn. Do you think I should add how to determine the quantum numbers?), he could develop **Pauli's exclusion principle** which states that no **two identical fermions** (all electrons are identical) can occupy the **same quantum state simultaneously**, and as the quantum numbers describe the **position of an electron**, this limits the placing of electrons. This predicted the **hyperfine spectral lines** and accounted for the normal and anomalous **Zeeman effect**. He also proposed the existence of the **neutrino**.
  - Heisenberg had another big contribution known as the **uncertainty principle** where he states that for any given particle, the product of the **inherent uncertainties** of its momentum and position cannot be less than h bar. That is $\Delta x \times \Delta p \geq \frac{h}{2\pi}$. Thus you cannot both accurately measure a **particle's momentum and position** introducing an inherent uncertainty is present in quantum mechanics which confirmed the interpretation of Schrodinger's equations that particle behaviour must be considered in terms of **probability**.

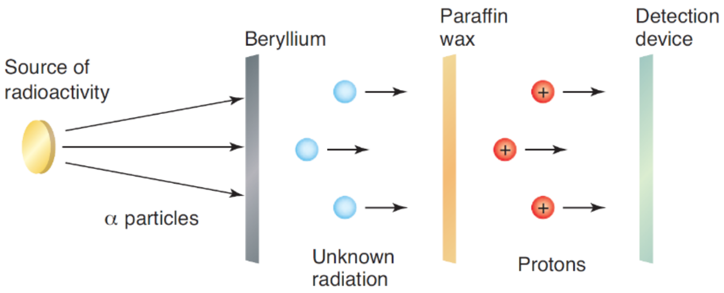
Many others contributed to the final **Copenhagen Interpretation** reached at the **Salvoy Conference of 1927.** Heisenberg granted quantum mechanics its two biggest strengths, it's **mathematical description** of events and its **probabilistic consideration**. Pauli **theoretically connected** Heisenberg's work and developed the **most important theory** for describing the atomic structure also **solving the problems** with the Bohr model. Thus, both Heisenberg and Pauli were major contributors to the **quantum mechanical model** of atomic theory.

3. The work of Chadwick and Fermi in producing artificial transmutations led to practical applications of nuclear physics.

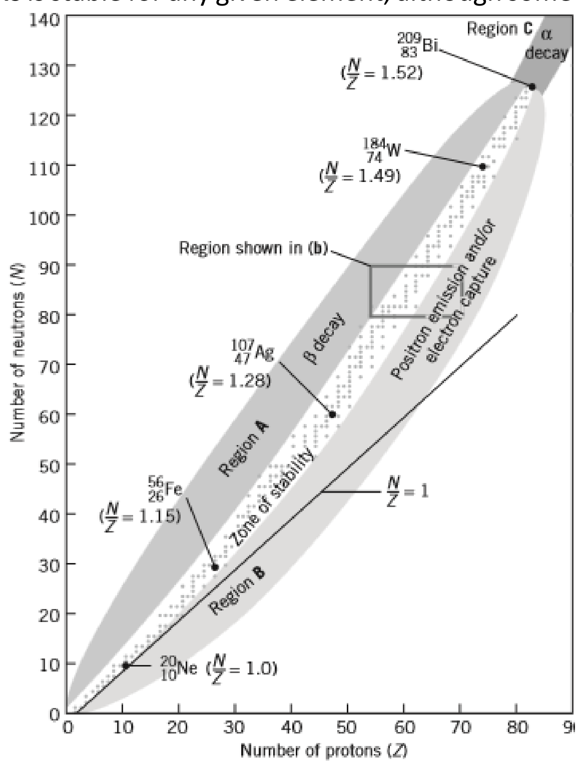
Students learn to:

Nucleon	Symbol	Charge (C)	Mass (kg)
Proton	^1_1p	$+1.602 \times 10^{-19}$	1.675×10^{-27}
Neutron	^1_0n	0	1.673×10^{-27}

- **Nucleons** are the components of a **atomic nucleus** and is the collective name for both **protons** and **neutrons**. Their **properties** contrast as right.
- In 1930, **Frédéric Joliot** and **Irène Curie** conducted an experiment where they fired **alpha particles onto beryllium** upon which a ***highly penetrating*** but ***non-ionising*** (neutral) radiation was produced. This radiation was hence directed at some **paraffin wax** (long chained hydrocarbon) which **ejected protons** with an energy of 5.3 MeV. Originally, it was thought the radiation was **gamma rays** (high pen, neutral). However **James Chadwick** read this paper, and applied two **conservation laws**. If **Conservation of Energy** applied, then the radiation need only have 5.3 MeV of energy, thus it was **possible** that the radiation was gamma. However if the **Conservation of Momentum** was to be applied, then because of **gamma's tiny momentum** as a massless particle ($p = E/c$), it would have had to interact with an energy of at least **50 MeV** assuming a **perfect inelastic collision**. Energy of this magnitude would have **decomposed** the beryllium nucleus entirely thus to realistically conserve momentum, Chadwick assumed that the radiation **must have had mass.** Chadwick proposed the **neutron**, with 1.15 times the mass of a proton. However there was doubt at the time whether the **conservation laws applied** on a nuclear scale and because Chadwick's reasoning relied solely on conservation laws, there was doubt as to it's accurateness.



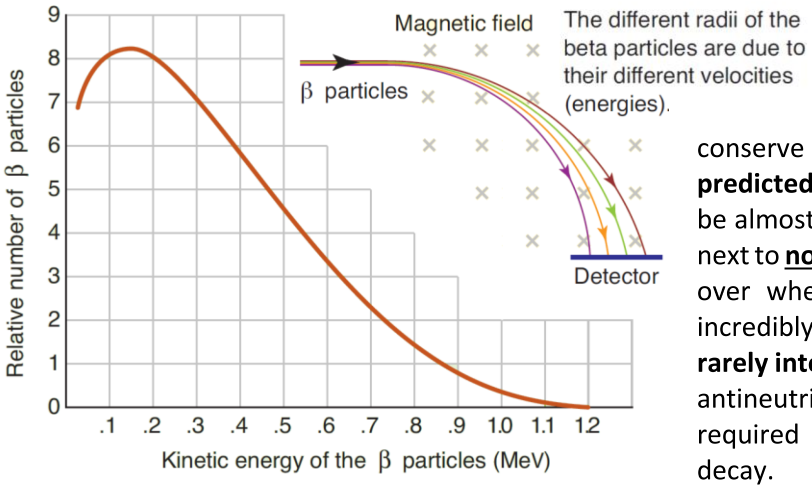
- **Transmutation** is the term describing a **nuclear reaction** where a **nucleus changes** from one type of **element/isotope** into another. This can occur **naturally** or **artificially** by alpha or beta decay.
- In **nuclear isotopes**, only a certain **ratio of nucleons** is stable for any given element, although some elements have no stable isotopes. The exact reason for this is a **quantum mechanical** phenomena however elements heavier than lead are unstable, there mass is too great. **Natural transmutation** occurs via **beta** or **alpha** decay, the exact type depends on the isotope's relation to the **zone of stability** (shown right). The general form for **alpha decay** is $^A_ZX \rightarrow {}^{A-4}_{Z-2}Y + {}^4_2He$ whilst **beta minus decay** is $^A_ZX \rightarrow {}^{A}_{Z+1}Y + {}^0_{-1}e + {}^0_0\bar{v}$ (everything reversed beta plus). In any nuclear reaction, mass charge are conserved.



- **Enrico Fermi** and his co-workers bombarded as many known elements as possible with the **neutron** after its discovery. As they recognised the neutron made a **better nucleus probe** to cause **transmutation,** most bombardments resulted in a **heavier isotope** causing beta decay. When they got to uranium, they wanted to use beta decay to produce a **transuranic element**. But when they tried to measure the

alpha radiation predicted from the transuranic elements they only found the **beta radiation**. They randomly then placed some rough **paraffin wax** in between the source and the target which acted as a **moderator** and greatly increased their **reaction rate**. They were able to produce the transuranic elements, ${}^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{92}U + \gamma \rightarrow {}^{239}_{93}Np + {}^{0}_{-1}e \rightarrow {}^{239}_{94}Pu + {}^{0}_{-1}e$. However they also discovered a lot of light elements from the **decomposition** of U-235, ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n$. Although they failed to realise it, they were the first to observe what was termed **nuclear fission**.

- **Alpha particles** are emitted from the same element at the **same speed;** they were ejected with equal energy. However observed energies in **beta emission** resulted in a **spectrum of energies**, as below, which promted whether beta emission occurred in a **continuous** or **line spectrum**. To solve this problem, **Pauli** suggested the existence of another **tiny neutral sub atomic particle**; the **neutrino**. The **distribution of energies** between the electron and neutrino would be random. **Fermi** developed this suggestion proving theoretically that it accounted for the **discrepancies in observed energies.** Fermi also concluded that electrons and neutrinos could come into and out of existence like a photon to conserve energy. However due to its **predicted properties** the neutrino would be almost **impossible to observe** as it had next to **no mass** (even now, there is debate over whether they have mass) and an incredibly high penetrating power, it **very rarely interacts with matter**. However the antineutrino was identified in 1953 via its required interaction in a reverse beta decay.

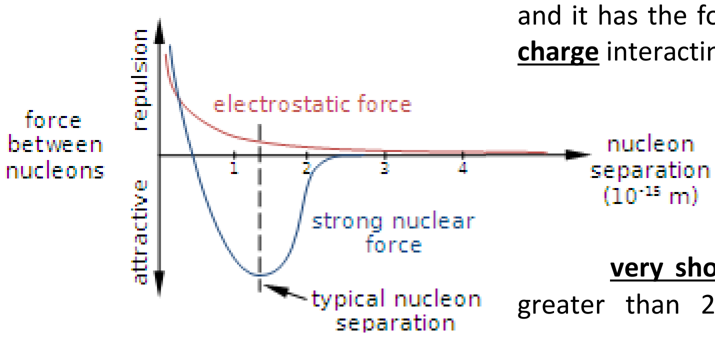


- Before the **strong** and **weak nuclear** forces, there was confusion as to why the **nucleus was stable** from considering the **relative contributions** of the **electrostatic and gravitational forces** to the nucleus. As they are **inverse square laws**, they are strong at small distances. The mathematics is considered right in a **helium nucleus** (gravity is doubled because of the effect of neutrons) where the nucleons are $1 \times 10^{-15}\ m$ apart. (ε_0 is the constant permittivity of free space equal to 8.854×10^{-12}) On a nuclear scale, the electrostatic force is 6.171×10^{35} times greater than the gravitational force, thus, gravity **could never account** for the stability of the nucleus.

$$F_g = G\frac{m_1 m_2}{d^2}$$
$$F_g = 2G\frac{(1.675 \times 10^{-27})(1.673 \times 10^{-27})}{(1 \times 10^{-15})^2}$$
$$F_g = 3.738 \times 10^{-34}\ N$$

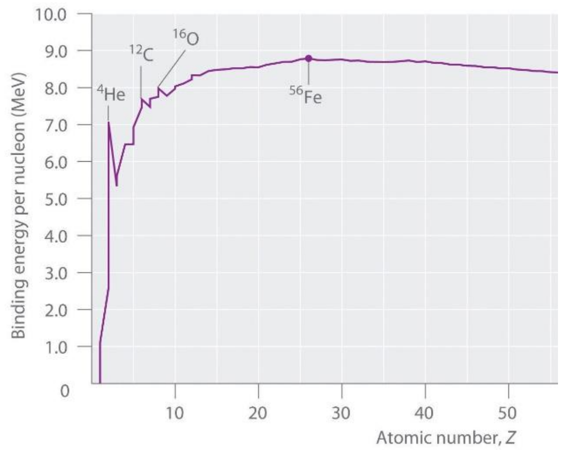
$$F_E = \frac{q_1 q_2}{4\pi r^2 \varepsilon_0}$$
$$F_E = \frac{(1.602 \times 10^{-19})^2}{4\pi(1 \times 10^{-15})^2(8.854 \times 10^{-12})}$$
$$F_E = 2.307 \times 10^2\ N$$

- Due to the reasons outlined above, there was a need for another force to be present to account for the **stability of the nucleus**. When discovered, the force was called the **strong nuclear force** and it has the following properties. It is **independent of charge** interacting with both nucleons equally. It is a **very strong attractive force** (although turns to repulsive at extremely short distances, as left) which forms a **stable equilibrium** at around 1×10^{-15} metres apart. When combined with its **very short range**, falling to zero over distances greater than 2.5×10^{-15} metres, this means every

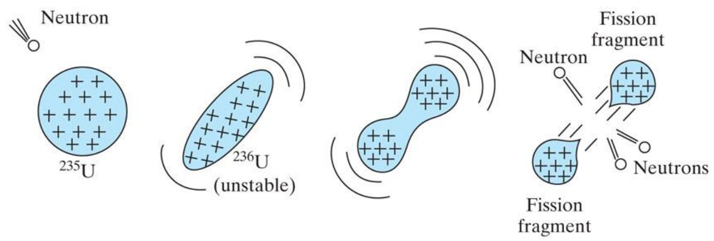


nucleon only **acts on its neighbours** which provides the **uniform density** of the nucleus and the uniform binding energy of nucleons. It also favours **pairing nucleons of opposing spin** and pairs of pairs with zero spin which explains the incredible stability of an alpha particle.

- It was found any nucleus weighed less than the sum of its **constituents**. This can be explained in terms of **binding energy** and **mas-energy equivalence**. When nucleons are bound in a nucleus by the **strong force**, they are more stable than when on their own, thus they have less energy in a nucleus due to the **binding effect**. All particles with energy have an **increase of mass** according to $E = mc^2$, particles **physically get heavier in higher energy states**. This difference in mass, or **mass defect**, allows us to calculate the **binding energy** (the strength of the strong force) for any nucleus. As the strong force affects all nucleons equally, we can hence derive the **average binding energy per nucleon** and determine how strongly the nucleons are attached. This allows us to plot the **stability of any nuclei**, as right. It is found that heavier nuclei are more stable to a point, then decrease in stability. **Iron-56** is the most stable nucleus of all. This concept also explains **fission** and **fusion**. By fusing two smaller nuclei together, you increase the binding energy and release energy. By splitting large nuclei, the same thing happens.



Nuclear Fission: is best explained using the **liquid drop model**. Here a **thermal neutron** impacts on a nucleus where the **nucleus absorbs it**. This causes the nucleus to become unstable and it starts to **elongate** as pictured below. It then splits into **two daughter nuclei** as below, often releasing **neutrons to balance the mass.** The split is most likely a **60-40,** empirically this is the most probable outcome. **Thermal neutrons** are also required as they are moving **slow enough to be absorbed**. This is from de Broglie wavelengths, a thermal neutron of 0.025 eV has a wavelength of $\sim 1.6 \times 10^{-11}\ m$ as opposed to a fast neutron of 1.0 MeV which has a wavelength of $\sim 2.5 \times 10^{-15}\ m$. Thus the thermal neutron can interact with the nucleus at 10,000 times the distance.

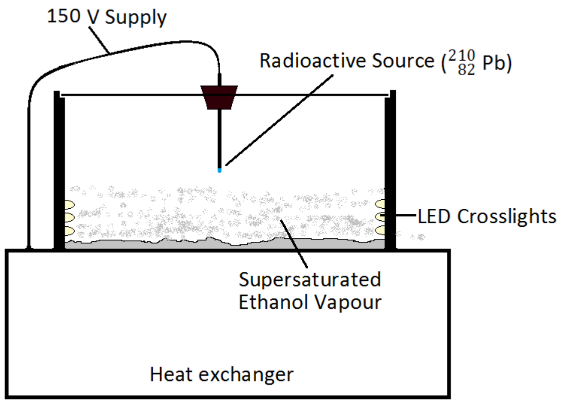


- **Fermi** headed the **American group** who demonstrated the **first controlled nuclear chain reaction** in 1942. It was not known whether a chain reaction could be started or controlled. They chose **U-235** for its **neutron multiplication** factor (produces 3 neutrons each reaction, only one required to start the next) which would **propagate a chain reaction** and release lots of heat. Fermi converted **old squash courts** at the University of Chicago where he used **6 tonnes** of **uranium metal** (the nation's entire supply) and **40 tonnes** of **uranium oxide** to provide enough U-235. He also recognised the need to **absorb some neutrons** to control the reaction and something to slow them down; he used 385 tonnes of **granite bricks as a moderator** (the only substance in the required purity and amounts) and **cadmium control rods** (known to be a good neutron absorber). By measuring the radiation, calculating and adjusting the control rods, they enabled the reaction to become **self-sustaining**, producing 0.5 W of power.
- For any **nuclear reaction**, a **critical mass** is required, where the size limits **neutron leakage** to an extent where a **critical reaction** can be sustained. Once a reaction is secured, the main difference is in a **controlled chain reaction**, the number of **neutrons is monitored** to ensure the reaction rate is constant, only one neutron from any fission goes on to cause another, which is termed critical. This is achieved through the use of **moderators** and **control rods**. The neutrons emitted from a fission are **fast neutrons** and are more likely of passing straight through or knocking a proton off

then combining, thus **moderators** slow down the neutrons to **thermal ranges** to allow the reaction to continue. The control rods are used to **absorb the neutrons** and can be adjusted. Due to the control applied, controlled reactions need only **3% enriched uranium**. In an **uncontrolled reaction**, the neutrons are promoted to cause more reactions thus the **rate of reaction increases exponentially,** termed **supercritical** with a few seconds releasing immense amounts of energy. Because there is nothing to slow the neutrons down, **much higher enriched uranium** is required (Weapons Grade > 93.5%). The large majority of the U-235 isn't reacted in uncontrolled reactions.

Students:

- **Practical Investigation – Wilson Cloud Chamber. Aim:** to observe radiation emitted from a nucleus using a Wilson Cloud Chamber. **Variables** – N/A. **Method:** set up cloud chamber as below. By cooling chamber, the ethanol vapour forms a **supersaturated vapour state** where the vapour is just on the verge of condensing. This is illuminated and sealed. A radioactive source is inserted with a high voltage (150 V) applied to ensure the chamber is cleared of any natural ions which could act as nucleation sites. **Results:** as the vapour is on condensation point, when the charged alpha/ beta particles pass through it and **ionise the gas**, the ions provide a **nucleation for the vapour to condense**, thus forming visible trails. Alpha particle form **thick, short trails** representing their high ionisation but low penetrating power whilst beta particles produce **long thin trails,** medium ionisation and penetrating power. **Safety:** Radiation is potential harmful medically to humans. Thus the radioactive source is kept in a **lead lined box**. The students will **not directly handle** the radiation and will limit exposure time. **Hands will be washed** afterwards and the room will be kept **ventilated** for the ethanol vapour.



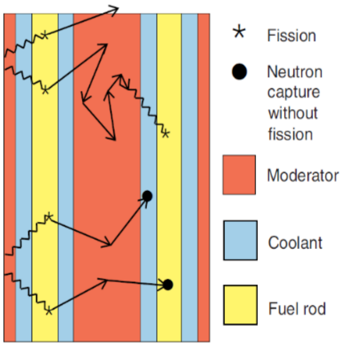
- You can **calculate** the **energy released by nuclear reactions** using **mass defects**. You can calculate both the energy of nuclear reactions and the **binding energy of atoms** this way. We can either consider the problems in kg or **atomic mass units**, $u = 1.66110^{-27}$. The amus of a proton, neutron and electron are below. Either way the mass defect or $\Delta m = m_{constituents} - m_{nucleus}$, so for an alpha particle formed by $2\,^1_1p + 2\,^1_0n \rightarrow \,^4_2He, \Delta m_\alpha = (2 \times 1.007276 + 2 \times 1.008665) - (4.002603 - 2 \times 0.000549) = 0.030376\,u$. From here, we have the mass in atomic units where we can convert to kilograms. However if we wish to find the **total binding energy**, we times by the conversion factor $931.5\ MeV/c^2$ to get energy in MeV. To get **average binding energy per nucleon**, we divide by the number of nucleons. Thus we have the mass defect and the energy released by the reaction.

$$m_p = 1.007276\,u$$
$$m_n = 1.008665\,u$$
$$m_e = 0.000549\,u$$

4. An understanding of the nucleus has led to large science projects and many applications.

Students learn to:

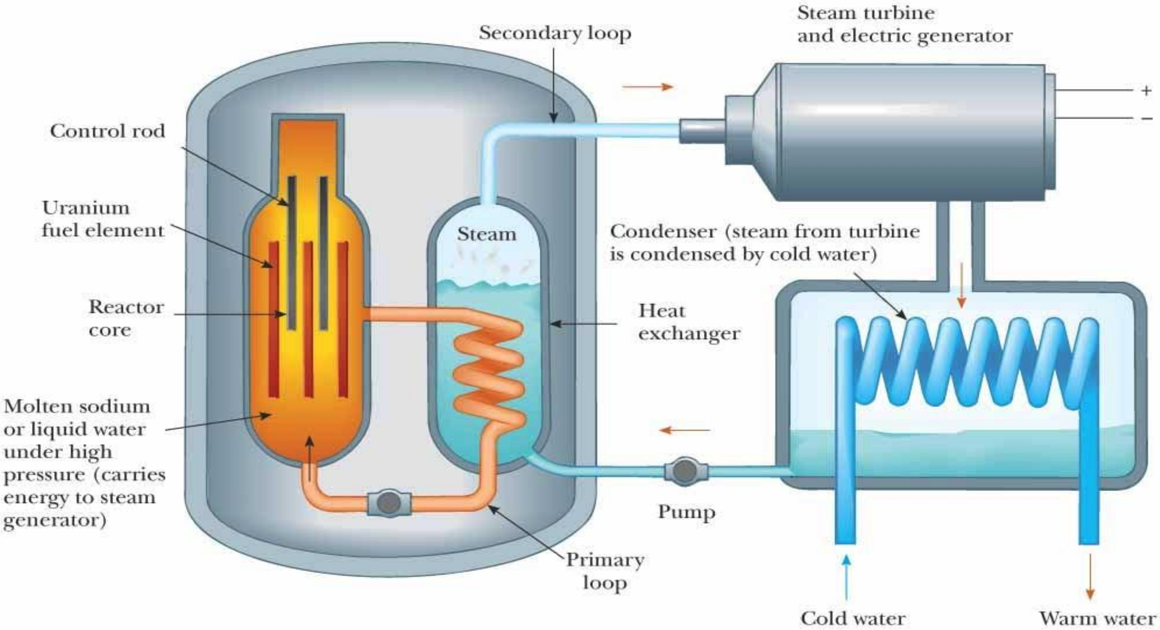
- A **fission reactor** are nuclear reactors relying on fission. There are three main types, **power reactors**, **research reactors**, and **breeder reactors**. They all share a **fission reactor core** where energy is produced, but have a different use for the result. In the core, there is the fuel rods themselves, the moderator, the coolant, and the control rods. The **fuel rods** are composed of **enriched uranium oxide** containing 3% fissile Uranium-235. The higher the enrichment, the less fuel needed to reach **critical mass** and **less efficient moderator** and **coolant** can be used. To prevent **neutron leakage** a **moderator** is required which slows the **fast neutrons** produced by fission to **thermal neutrons** were they can instigate a reaction. Ideally, the atoms used as



moderator should be approximately the **size of the neutron** thus **heavy water** (deuterium oxide) is used as it won't react with the neutron. However this is an **expensive moderator** so economically, **graphite** is used. To extract the thermal energy released by the fission in the rods, a **coolant** is required. **Heavy water** can be used if it is also the moderator otherwise normal **water** (despite absorbing some neutrons) can be used, as can **helium gas**; all **under high pressure**. The **control rods** are made of a **good neutron absorber** (generally have many stable neutron rich isotopes), commonly used are **hafnium, cadmium**, or **boron**, and are designed to control the **rate of reaction.** When that rate is one fission produces only one fission, it is termed **critical**. Reactors are designed to be **supercritical** but maintained as critical by the **control rods**. If in the event of catastrophe, the control rods can completely shut down the reactor by isolating the fuel rods. Around the core a **containment building** is constructed so even in the event of **total catastrophe**, all radioactive substances will be contained. There is a variety of designs, commonly a combination of **lead-graphite walls** to protect from radiation and reflect neutrons back inwards and a high density, **pre stressed concrete containment vessel**.

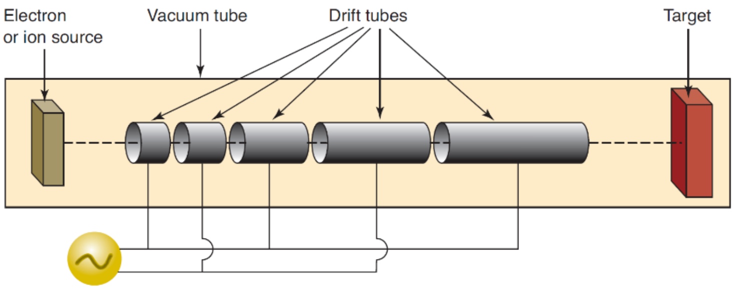
In a **power reactor**, what happens next is pictured on the next page. The coolant carries the **superheated water** away from the reactor and into a **heat exchanger** where fresh water is boiled into steam. That steam, under **extremely high pressure**, is then passed through a **turbine generator** to produce electricity. The steam is **condensed** back into water and recycled, with the **extracted heat** being released as **waste**. In both **breeder and research reactors**, the primary goal is the **production of neutrons** to be used to **irradiate samples**, whether this be **medical isotopes**, **silicon doping** for microchips or **scientific research**. Either way, some of the neutrons produced by the reactor are directed down **neutron guides** for these uses, or alternatively samples are placed near the core for irradiation. The steam is just dispersed, not used for energy production. In any reactor, only a **very small portion** of the uranium-235 undergoes fission which leaves you with a **radioactive mess** to dispose of. This is done by **reprocessing** where the used and unused components are separated, and then **recycled**. The small amount of waste must then be **immobilised** until it is no longer radioactive.

- **Neutron scattering** is used in the analysis of the **internal structure** and **properties of matter**. **Thermal neutrons** are passed through a crystal to **moderate their kinetic energy** and then fired at the sample. When the neutrons collide with the nuclei they form a **diffraction pattern** depending on the wavelength of the neutron (uniform) and the structure and the material. These

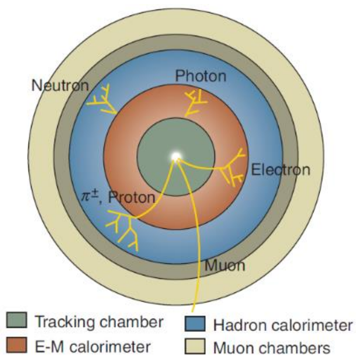


collisions may be **elastic or inelastic** depending on the sample or might even result in **absorption**. The scattering patterns are analysed by **diffractometers** (elastic) or **spectrometers** (inelastic) then put through **statistical analysis** to determine the structure of the sample. The properties of the neutron that make them so good at scattering include: The **de Broglie wavelength** of thermal neutrons is similar to that of **atomic spacing** in most matter required for diffraction patterns. They are **neutral** meaning they can **penetrate matter easier** and any **deviation in motion** is attributable to a physical collision, magnetic interaction or diffraction; giving a clearer, more accurate pattern. Neutrons also have a **magnetic moment** making them ideal for the **examination of magnetic** substances. There **vibrational energy** is similar to atoms in a **solid or liquid** thus can be used to study the **motion of atoms** in molecules in detail. They also **interact with the nucleus** strongly thus making them ideal for the **study of lighter isotopes** like hydrogen, normally missed by other methods, making them ideal for **studying organic materials** containing lots of hydrogen. 3Combined with their **non-destructive interactions**, this means neutron scattering is used geology, environmental science, biology, biotechnology, engineering, materials science, physics and chemistry. The **disadvantage** of neutron scattering is the most efficient method of producing neutrons is with a **fission reactor**. Australia uses the ANSTO's OPAL reactor at Lucas Heights.

- **Physicists** have been using **particle detectors** to study **matter** since the development of the atomic model. They started off with **Cloud Chambers** but progressed onto **Bubble Chambers** (using superheated liquid instead of supersaturated vapour) as much better detectors in the 19060's. As particle physics progressed, the need for **higher energy interactions** grew. There are a variety of **particle accelerators** used to this effect. **Linear Accelerators** use **electrostatic attraction** and **repulsion** to accelerate charge particles in a straight line. They have **drift tubes** attached to a **radio frequency alternating voltage** (RFAV) such that the particles are constantly being repelled and attracted and as such the tubes get longer (as right), which can accelerate electrons close to the **speed of light,** although high energy linear is not feasible.

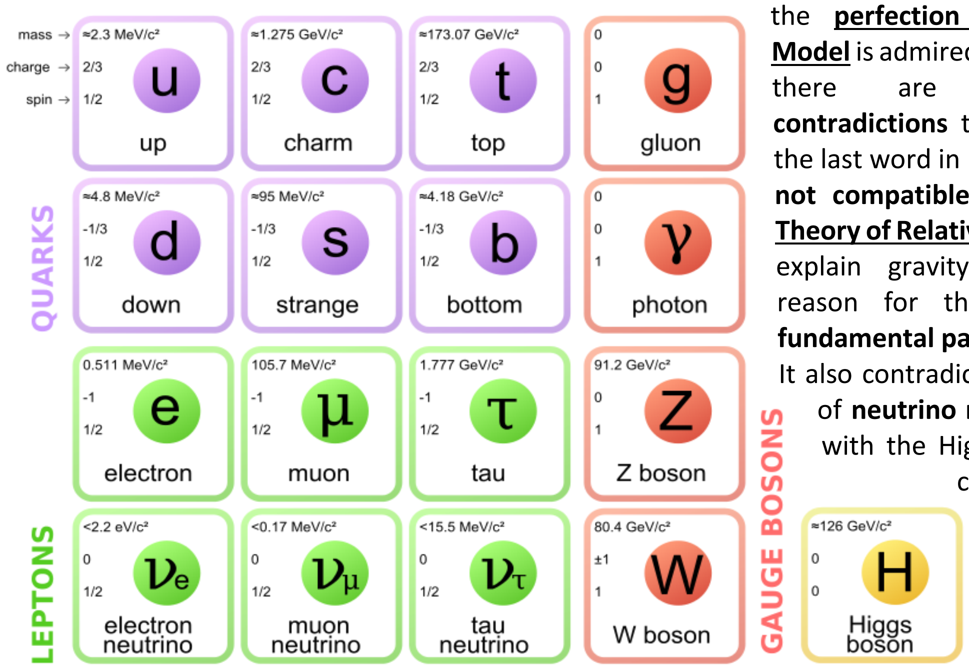


Cyclotrons are similar to Linears as they use an **RFAV** between two '**dees'** to accelerate the particle in a **spiral**. A **uniform magnetic field** is applied to the entire apparatus causing the spiral and when the particle reaches the edge it is **deflected** into the target. Again, high energy cyclotrons are **not possible**. **Synchrotrons** are the most commonly used accelerators today, of which the **LHC** is one. They use **variable magnets** (increasing with speed) to maintain their particles in an **evacuated tube** forming a **fixed radial ring** and accelerating them with a 'kick' using a **RFAV**. These accelerators can produce **massive energies** with the LHC being able to accelerate protons to 7 TeV and heavy ions to 1250 TeV. Collisions in any particle accelerator can either be **dual head on collisions** or **impact collisions.** Because **conservation of energy and momentum** must apply, impact collisions require the products to have **similar momentum** leaving **little energy** for the production of particles. Colliders however, especially using the collisions of **protons and antiprotons**, enable collision products to have **near zero momentum**, meaning **all the energy** of both incident particle groups can be used for particle production. As a result, **high energy accelerators** use collisions however this **limits the materials** used so impact collisions are still often used. The accelerators use **multicomponent detectors** (right) to electronically record **millions of collisions**. As the particles may spray anywhere, **cylindrical detectors** are used that measure **trajectory, energy** and **momentum**. Modern examples consist of 4 parts, an **inner tracking chamber**, and **electromagnetic calorimeter**, a **hadronic calorimeter** and a **muon chamber**. The



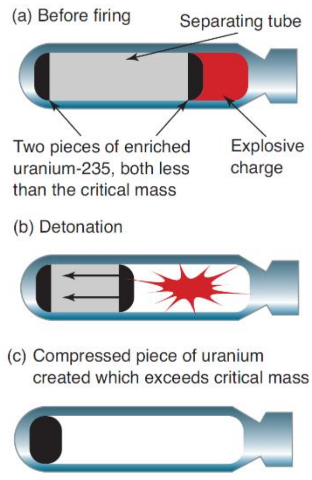
inner chamber contains a gas which measures **ionic interactions** with electric pulses, the **<u>calorimeters</u>** are dense materials interweaved with detectors that slow the particles so they never go past their detector. Accelerators like these are responsible for the **<u>development of particle physics</u>**.

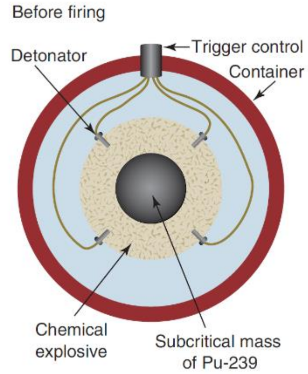
- The **<u>Standard Model of particle physics</u>** predicts the **interactions of all particles** in terms of **6 types (flavours)** of matter particles and 4 force particles. All interactions within the Standard Model are **<u>particle interactions</u>**, this is one of its greatest strengths. These particles (not necessarily fundamental) are divided into the following categories: **<u>Hadrons</u>** are particles that **experience the strong force**. **<u>Baryons</u>** are hadrons that have **half-integer spin** (also are fermions), eg nucleons. **<u>Mesons</u>** are hadrons with **zero or integer spin**, often a quark and antiquark. **<u>Fermions</u>** are particles with **half-integer spin** and hence obey Pauli's exclusion principle. **<u>Leptons</u>** are particles that **do not experience the strong force** (all fermions), eg electrons and neutrinos. **<u>Bosons</u>** are the **force carrying particles** which have zero or integer spin. The matter fundamental particles are all fermions and are listed in the table below with their properties and are **<u>quarks</u>** and **<u>leptons</u>**, which combine to form all matter. All hadrons are made of quarks which are **never found isolated** whilst leptons are **always found isolated**. **<u>Colour</u>** is a **property of quarks**, just like charge with **three varieties** (red, blue, green). Each quark can have one of these (antiquarks have anticolour) with **different colours attracting** and **same colours repelling**. The reason no quark can be isolated is that **all hadrons must be colourless**, so all baryons contain one of each whilst mesons have a normal and an anticolour. The **<u>four fundamental forces</u>** are carried by bosons, listed in the table below. These particles exchange properties, fermions can only interact through the exchange of bosons. All fermions interact with the **<u>weak force</u>** through W^+,W^-, and Z^0 bosons and it **changes their flavour** but only acts over 10^{-17} metres due to their large mass. The **<u>strong force</u>** technically is the **<u>colour force</u>** between quarks, the gluon **carries colour charge** changing the colour of quarks and thus mediating the colour force. The force between nucleons is the **<u>residual colour force</u>** and is mediated by **pion exchange**. **<u>Electromagnetism</u>** is an exchange force using the well-known photon. **<u>Gravity</u>** is **not explained** by the Standard Model but it is predicted there might be a graviton. Then finally there is **<u>the Higgs Field</u>**, which is the mechanism by which **particles are given mass**. The suggestion is that the Higgs Field **pervades the universe** and different elementary particles **interact** with it differently. Ie, a top quark would interact strongly, being slowed down from travelling at the speed of light and thus have lots of mass whilst a photon would pass through unaffected. The **<u>Higgs Boson</u>** is the predicted **excitation of this field** and the LHC has now confirmed the discovery of a Higgs Boson, but not necessarily the one we were looking for. Though the **<u>perfection of the Standard Model</u>** is admired by many scientists, there are some **glaring contradictions** that suggest it isn't the last word in particle physics. It is **not compatible** with the **<u>General Theory of Relativity</u>** and thus cannot explain gravity. It provides no reason for the **nature of the fundamental particles**, why 6 each? It also contradicts in its predictions of **neutrino masses**. And finally, with the Higgs Boson only just confirmed, there is still a way to go **confirming the theory**.



Students:

- **The Manhattan Project** was the codename for the project organised by **the US government** to develop the first **atomic bomb** during World War II. It was instigated by Leo Szilard who lobbied **Einstein** who in turn sent a letter to **President Roosevelt** urging him to construct atomic weaponry in response to the perceived threat of **Germany achieving it first**. All of the **best scientific minds** gathered at the secret laboratory **Los Alamos** for the project understood the gravity of the weapons they were constructing and most were **morally opposed** to their construction, however the **fear of Hitler** controlling it before they did and the excitement of **breaking new scientific ground** in the company of so many great minds drove them on. The first challenge was to collect **enough of the fissile U-235 and Pu-239.** There was various methods however for uranium, **gaseous diffusion** of **uranium hexafluoride** was used to commercial effect whilst Plutonium was assembled by the **neutron bombardment** of U-238. They developed two bombs; **the Little Boy**, dropped on Hiroshima on 6th August, 1945, used the **'gun method'** of forming supercritical mass of U-235 by using traditional explosives to fire to subcritical masses together and initiate fission (right). **The Fat Man**, dropped on Nagasaki on 9th August, 1945, used Plutonium surrounded by chemical explosives which when detonated **compressed** the subcritical Pu-239 into a supercritical mass initiating fission (right). The Manhattan Project has had **massive social implications**, both **positive** and **negative**, since its success in 1945. It is estimated that in the **bombing of Japan**, over 100,000 were killed instantly with another 200,000 killed by radioactive poisoning from the fallout. Some argue these killings **halted the war** and thus saved possibly even more lives from a **prolonged war**. However once the weapons got into the hands of politicians, it was generally considered a **negative** for the social environment of the globe. In the years to come of **Cold War,** the USA and USSR stockpiled over **80,000 nuclear warheads** of increasingly devastating potential, although ultimately, the only warheads used in war were in 1945. However there were some positives that emerged from the nuclear research. **Nuclear medicine** has now **saved millions of lives** and continues to be even more successful in both diagnosis and treatment. **Nuclear power** has also provided an **alternative to fossil fuels** and the Climate Change crisis as well as increasing our knowledge of the **physical universe**. Some argue that these things could have been achieved **without weapons** so whilst it is undoubted that the Manhattan Project had enormous significance to society, whether that was **positive or negative is open to debate**.





- **Radioisotopes** are commonly used for a variety of purposes in medicine, agriculture, and engineering. An example of each is below:
  - **Fluorine-18 in Medicine:** is used as a **diagnostic tool** in **Positron Emission Tomography** (PET) scans. The F-18 replaces a hydroxyl group in glucose to form **fluorodeaoxyglucose** (FDG). The patient is injected with FDG where the glucose is used by **energy intensive organs** in the body such as the **heart, brain**, and **liver** and any **fast growing tumour**, like cancer, is highly glucose intensive as well. The F-18 then decays into oxygen-18 through **positron emission** in these concentrated areas undergoing anhilation with a milimetre with an electron producing **two gamma rays** propagating in opposing directions. By measuring a **million emissions,** the PET constructs an image of the emissions and thus of the tumour. The F-18 only has a **half-life of 110 minutes** so has to be made on-site with a cyclotron by proton bombardment of oxygen-18 water, ${}^{18}_{8}O + {}^{1}_{1}p \rightarrow {}^{18}_{9}F + {}^{1}_{0}n$.

- **Phosphorous-32 in Agriculture:** because plants use **phosphate and nitrate fertiliser**, by inserting a radioisotope like P-32, the use of the fertilisers can be monitored. This enables a **more efficient** use of the fertilisers to be attained by understanding how the plants use the fertilisers. The P-32 has a **half-life of 14.3 days** and is a beta emitter decaying into Sulfur-32. The beta radiation has enough **penetrating power** to emerge from roots and stems to be measured. The P-32 is produced by **neutron bombardment**, ${}^{31}_{15}P + {}^{1}_{0}n \rightarrow {}^{32}_{15}P$.
- **Cobalt-60 in Engineering:** undergoes **beta decay** to ${}^{60}_{28}Ni$ producing **intense gamma rays** as well. These gamma rays can be **collimated** in a **portable measuring device** where it is used to **image weld lines**, jet engine turbine blades, etc. by passing the energetic waves through the metal and **exposing a photographic plate** behind. This creates an image revealing **structural weaknesses or impurities**. With its **half-life of 5.3 years** and its **chemically inert form**, the device requires little maintenance and thus is extremely effective. The cobalt is formed by **neutron bombardment**, ${}^{59}_{27}Co + {}^{1}_{0}n \rightarrow {}^{60}_{27}Co$.