- Topic 7 - Atomic, Nuclear, and Particle Physics
  - 7.1 Discrete energy and radioactivity
    - Equations
      - Photon energy - frequency relationship: $E = hf$
      - Planck relationship for wavelength: $\lambda = \frac{hc}{E}$
    - Energy levels
      - The orbiting electrons can't occupy any possible orbit around the nucleus in an atom.
        - Different orbits correspond to different amounts of energy, or energy levels, and the electrons in each specific orbital will be restricted to that specific energy.
        - Electrons change energy so that they can jump from one energy level to another, but they can only occupy allowed energy level.
      - Hydrogen atoms are the simplest of atoms and consist of a single electron held by a single proton using electromagnetic force.
        - Isotopes are the same atom where the only difference is the number of protons in an atom.
          - Chemical properties are the same, as that is affected by the # of protons.
      - The number of protons is what defines the atom to be a specific atom.
      - The energy levels of Hydrogen are:

Energy level (n)	Energy / eV
1	-13.58
2	-3.39
3	-1.51
4	-0.85
5	-0.54

      - An electron that occupies an energy level that is above the ground state is said to be "excited".
        - An electron in the second energy level is in the first excited level. 3 energy level, 2nd excited level, etc.
      - If you think of energy levels in terms of the Bohr model, then the first energy level (ground state) is the first shell which can hold 2 electrons
        - First shell = 2 electrons, second shell = 8 electrons, third shell = 18 electrons, Fourth shell = 32 electrons
        - Energy levels in atoms are said to be quantized meaning they have discrete finite values.
          - An electron in Hydrogen can't have -5.92 eV or -10.21 eV or any other value between -13.58 eV & -3.39 eV; it must have one of the energy levels in the table.
      - Transitions between energy levels.
        - When an electron in the hydrogen atom jumps from the ground state to n = 2, then it'll gain energy, this is an exact amount of energy meaning if the electron is moving from n = 1 to n = 2 it must gain 10.19 eV of energy.
          - Furthermore, the electron gains that electron all in one moment.
          - When the electron moves from one energy level to the other, it won't move in between the space between the two orbitals, it'll teleport.
          - The energy needed to to excite an atom can come from absorption of light by the atom.
            - The energy (E), carried by a photon (quantum (a packet)) is related to the frequency of the radiation by the equation: $E = hf$ (h = Planck constant $= 6.63 \cdot 10^{-34}$ Js), & f is frequency in Hertz).
          - The wave equation ($c = f\lambda$ (where c is the speed of electromagnetic waves in a vacuum), also applies to the photons and, by combining the two equations we get $E = h\frac{c}{\lambda}$ or $\lambda = h\frac{c}{E}$.
            - To find the wavelength of the electromagnetic radiation when an electron moves from one energy level to another is:
              - Convert eV to joules: $10.19\,eV \cdot 1.6 \cdot 10^{-19} J = \underline{\underline{1.6 \cdot 10^{-18} J}}$

$$\lambda = h\frac{c}{E} = \frac{(6.63 \cdot 10^{-34})(3 \cdot 10^{8})}{(1.6 \cdot 10^{-18})} = 1.2 \cdot 10^{-7} m$$

this radiation is in the ultraviolet part of the spectrum.

        - When an electron is excited and moves to a higher energy state, it will be very unstable, therefore, it will quickly fall back down.
          - To fall back down, it must lose the same amount of energy that it gained to move to the higher energy level.
        - When an electron is given the full 13.58 eV it is completely removed from the nucleus ($n = \infty$) and the atom is ionized. known as the first ionization energy.
        - Worked example
          - The reason that the ground state has a much higher value is because the electromagnetic force that acts on the electrons from the two protons is significantly higher compared to the one electron that attracts the one electron in Hydrogen.
          - $\Delta E = -10.2\,eV$

$$= -10.2 \cdot 1.6 \cdot 10^{-19} J$$
$$= 1.632 \cdot 10^{-18} J$$

Conversions between eV and Joules

$$E = hf$$
$$f = \frac{E}{h}$$
$$f = \frac{(1.6 \cdot 10^{-18})}{(6.63 \cdot 10^{-34})}$$
$$= \underline{2.41 \cdot 10^{15} Hz}$$

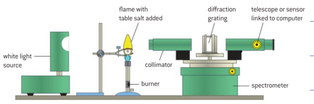
          - $\lambda = \frac{c}{\ }$

f

$= \frac{3\cdot10^{8}}{2.41\cdot10^{15}}$

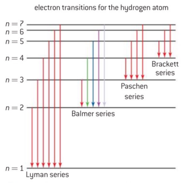
$= 1.25\cdot10^{-7}$ m (Ultraviolet region)

- Emission spectra (More research)
  - When energy is supplied to a gas of atoms at low pressure the atoms emit electromagnetic radiation.
    - Energy can be supplied by an electrical discharge (a current passing through the gas when a high voltage is set up between two electrodes across the gas).
  - If the radiation emitted by the gas is incident on the collimating slit of a spectrometer, it can then be dispersed by passing it through a diffraction grating or a glass prism.
    - Diagram
      -



▲ Figure 5 Demonstration of sodium absorption spectra.

  - Observing the spectrum will show a series of lines.
    - Each series of lines is dependent on the energy level that the electrons fall to.
    - The Lyman series shows the electrons fall to the ground state (n=1).
      - This series is in the ultraviolet region of the electromagnetic spectrum.
    - The Balmer series is the series where the electrons fall to the first excited level (n=2).
      - The series is in the visible light region.
    - The Paschen series falls to the second excited energy level (n=3).
      - The series is in the infrared region.
    - Diagram
      -



▲ Figure 3 Electron transitions for hydrogen.

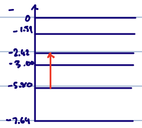
- Absorption spectra
  - Electrons in solids, liquids, & dense gases can also be excited - they tend to glow when heated to a high temp.
  - When the emitted light is observed its seen to consist of a spectrum of bands of colors rather than lines.
    - Solids will give out a continuous spectrum in which the colors are merged into each other and so aren't discrete.
      - This is due to the fact that in solids the atoms are closely packed, causing the energy levels in atoms to change value.
      - When there are many atoms, the overall energy levels combine to form a series of similar but different energies which make up an energy band.
  - The continuous spectrum is "streaked" by a number of dark lines.
    - E.g when a tungsten filament is heated then it will have black lines on its emission spectrum. These black lines correspond to the emission spectrum of hydrogen.
  - Absorption occurs when an electron in an atom absorbs a photon. The energy of this photon must be equal to the difference in energy levels (ΔE).
    - The material that is absorbing light will absorb photons of these specific frequencies from the continuous range of energies emitted by the light source.
    - This energy that is absorbed by the atoms in the solid means that the atoms will be more unstable as they move to a higher energy level. This means that the electrons will emit photons of the same energy that absorbed back so that they can fall back down to a more stable energy level.
      - The energy that they absorbed will be emitted in random directions rather than just in one direction. This will reduce the intensity of those specific frequencies in the original direction giving the black lines in the continuous light spectrum.
  - Why are there black lines on the emission spectrum? | What determines the number of lines?: They represent photon energies absorbed by electrons.
    - The reason that there are black lines on the emission spectrum is because when electrons absorb light in form of photons (packets of energy) they will have to absorb a specific wavelength which are absorbed from the electrons in the orbitals, forming the black line on the emission spectrum. Since the photons are released randomly, they won't make up the difference.
  - Worked example
    - Absorption spectrum is a continuous light spectrum that is emitted by substances when they absorb light. The reason that they have black lines is because when the electrons in the atoms fall back down to a more stable level they'll emit the photons in random directions rather than the original one.
      - The lines correspond to the frequencies of light that are absorbed by the material.
    - This may be observed by burning the material while passing white light through it, as the light passes through a diffraction grating you'll be able to see on a monitor that there will be black lines from where the electrons in the material absorbed the light.
    - $E = h\frac{c}{\lambda}$

      $= \underline{(6.63\cdot10^{-34})(3\cdot10^{8})}$

$\overline{(5.88\cdot10^{-7})}$

$= 3.38\cdot10^{-19}$ J

- The electrons in the atom would have to absorb the energy from a source such as light. The energy here must be equal to the difference between the levels, as this is an absorption of energy to move electrons to a higher state.
  - $-2.42 + 5.80 = \underline{3.38\cdot10^{-19}\text{ J}}$
  -



- Radioactive decay
  - Radioactive decay is a process where an unstable atom will spontaneously change into different nuclear configuration by the emission of alpha particles, beta particles, and gamma radiation.
  - There are fewer than 400 naturally occuring nucleides (nuclei w/ particular # of protons & neutrons) and approx. 60 of them are radioactive.
  - When an element changes due to radioactive decay, it'll become more stable.
    - The nuclide decaying is called the parent and the nuclide(s) formed is the daughter(s).
  - The nucleus of an atom contain protons and neutrons (known as nucleons), and they're held together by the strong nuclear force which must overcome the electrostatic repulsion between the positively charged protons.
    - The presence of neutrons moderates this repulsion.
    - The strong nuclear force (which has a very short range 10^{-15} m) acts equally on protons & neutrons.
  - Nuclei with few nucleons, having an approx equal amount of protons and neutrons will mean that nuclides being more stable and not radioactive.
    - Heavier nuclei need a greater proportion of neutrons in order to be stable.
  - Nuclide nomenclature
    - This is the method of describing the composition of a nuclide.
      - $^{A}_{Z}X$
        - A is the number of protons and neutrons (mass number)
        - Z is the number of protons
        - X is the elements nuclear symbol.
    - Isotopes are nuclides of the same element (w/ same # of neutrons) but with a different number of neutrons.
  - Alpha (α) decay (Emits ^4_2He (2 protons & 2 neutrons))
    - In alpha-particle decay, an unstable nuclide will emit a particle of the same configuration of Helium (2 protons, 2 neutrons, 0 electrons).
    - Many nuclides of heavy elements decay primarily by alpha-particle emission.
      - E.g $^{238}_{92}U \longrightarrow ^{4}_{2}He + ^{234}_{90}Th$. $^{234}_{90}Th \longrightarrow ^{4}_{2}He + ^{232}_{88}Ra$
        - The equations must be balanced so that there are equal numbers of protons and nucleons on either side due to the conservation of charge and mass-energy.
    - Alpha particle is written as $^{4}_{2}\alpha$. - The fact that they don't have any electrons means that have a positive charge (2+ charge).
  - Negative beta (β^-) decay (Electron emitted, neutron changes to proton, $\bar{\nu}$ released & $^{0}_{-1}\beta$ released)
    - In negative beta-particle emission, an unstable nuclide emits an electron.
      - Since electrons aren't counted towards the nucleon number, the number won't change
      - This decay occurs for those nuclides with too high a neutron-proton ratio. The decay is also accompanied by an electron antineutrino ($\bar{\nu}$).
    - A neutron is converted to a proton and an electron is ejected.
    - Example: $^{131}_{53}I \longrightarrow ^{0}_{-1}e + ^{131}_{54}Xe + \bar{\nu}$. $^{234}_{90}Th \longrightarrow ^{0}_{-1}e + ^{234}_{91}Pa + \bar{\nu}$.
    - The negative beta particle is written as $^{0}_{-1}\beta$.
    - The antineutrino has no proton or nucleon number ($^{0}_{0}\bar{\nu}$).

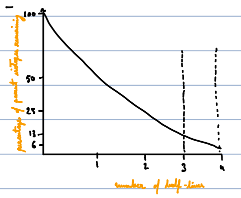
Why does a neutron convert to a proton when an electron is expelled?
This is in the form of a balanced equation, since β^- radiation is $^{0}_{-1}\beta^-$ an extra number at the bottom is necessary, meaning proton # increases.

  - Positron (β^+) decay (Positron expelled, proton converted to neutron, $^{0}_{+1}\beta^+$ & $^{0}_{0}\nu$ released).
    - In positron or positive beta-particle emission, the unstable nuclide emits a positron.
      - A positron is the antiparticle of an electron, having the same characteristics of an electron but with a positive charge rather than a negative one.
    - The emission of the positron doesn't change the nucleon number of the parent nuclide.
      - A proton is converted to a neutron and the positron is expelled.
    - This decay is for nuclides with too high proton-neutron ratio.
    - This reaction also releases an electron neutrino.
    - E.g: $^{11}_{6}C \longrightarrow ^{11}_{5}B + ^{0}_{+1}\beta + \nu$. $^{21}_{11}Na \longrightarrow ^{0}_{+1}\beta + ^{21}_{10}Ne + \nu$
  - Gamma ray emission
    - Gamma rays are high-energy photons often accompanying other decay mechanisms, then

- Having emitted an alpha or beta particle the daughter nucleus is often left in an excited state.
    - It stabilises by emitting gamma photon(s) thus losing its excess energy.
- Example:
    - $^{60}_{27}Co \rightarrow {}^{0}_{-1}\beta + {}^{60}_{28}Ni^{*} + \bar{\nu} + \gamma$
    - $^{60}_{28}Ni^{*} \rightarrow {}^{60}_{28}Ni + \gamma$
- The cobalt-60 decays by beta emission into an excited nickel-60 nuclide $^{60}_{28}Ni^{*}$, this decay of Cobalt-60 is accompanied by a gamma photon.
    - Another gamma photon is released after the decay of nickel-60 for the nickel atom to become stable.
- Gamma have no proton or nucleon number: $^{0}_{0}\gamma$.
- Cobalt decay in one step: $^{60}_{27}Co \rightarrow 2\gamma + \bar{\nu} + {}^{0}_{-1}\beta + {}^{60}_{28}Ni$

- Worked example
    - $^{90}_{38}Sr \rightarrow {}^{0}_{-1}\beta + {}^{90}_{39}Y + \bar{\nu}$
    - $^{55}_{26}Fe + {}^{0}_{-1}e \rightarrow {}^{55}_{25}Mn$ Why does a proton change to a neutron when an electron is added?
      Balanced equation

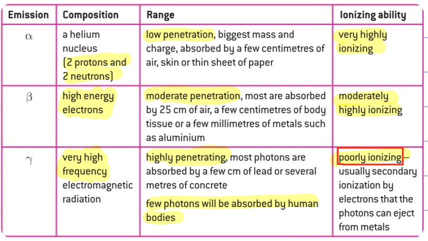
- Half-life
    - The half-life is the time taken for half the total number of nuclei initially in a sample to decay or for the initial activity of a sample to fall by half.
        - E.g Uranium-238 has a half-life of $4.5 \cdot 10^{9}$ years.
    - The nucleus of an atom has a diameter of the order 10^{-15} m and is essentially isolated from its surroundings.
        - This means that the decay of a nucleus is independent of the physical state of the nuclide and the physical conditions such as temp. & pressure.
        - Only nuclear interactions such as a collision with a particle in a particle accelerator can influence the half-life of a nuclide.
    - The graph showing the parent nuclei decay is the same for all radioactive isotopes. The shape is a square relationship.
        - The curve gets very near the x-axis but never intercepts it.
        - Parent nuclei decay



        - N_0 is the initial amount of radioactive material (Undecayed nuclei at $t=0$).
        - $\frac{N_0}{2}$ = Half-life
        - $\frac{N_0}{4}$ = two half-lives
        - $\frac{N_0}{8}$ = 4 half-lives
    - Measuring radioactive decay
        - To measure beta & gamma radiation you need a Geiger counter.
        - It's filled with a low-pressure gas.
        - One end of the tube has a thick piece of gas which allows radiation to pass through.
        - The radiation ionises the gas, the ions released will then be attracted to the electrodes creating a current that can be measured by a counting circuit.
        - Ionisation is when a radioactive particle pulls electrons with it.

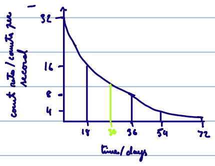
- Background Count
    - Radioactive materials are found everywhere.
    - Background count is the naturally occurring radiation in the surroundings.
    - The sievert (Sv) is a radiation unit that takes the ionising effects of different radiations into account.

- Absorption of radiation
    - Different radioactive emissions interact with materials according to their ionisation level.
    - Alpha particles ionise gases very strongly, have short range in air, and are absorbed by thin paper.
        - Due to massive masses, and have a charge of +2e.
    - Beta particles are poorer ionisers but have a range of several centimetres in air and require a few millimetres of aluminium to be absorbed.
        - They are much lighter than Alpha particles and have a charge of -1e or +1e depending on the type of Beta emission.
    - Gamma rays, being electromagnetic waves, barely interact with matter.
        - It takes many meters of air or several centimeters of lead to absorb gamma rays.
    - Table

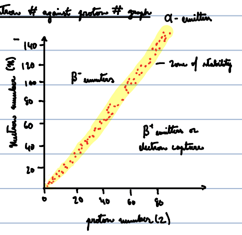


Emission	Composition	Range	Ionizing ability
α	a helium nucleus (2 protons and 2 neutrons)	low penetration, biggest mass and charge, absorbed by a few centimetres of air, skin or thin sheet of paper	very highly ionizing
β	high energy electrons	moderate penetration, most are absorbed by 25 cm of air, a few centimetres of body tissue or a few millimetres of metals such as aluminium	moderately highly ionizing
γ	very high frequency electromagnetic radiation	highly penetrating, most photons are absorbed by a few cm of lead or several metres of concrete few photons will be absorbed by human bodies	poorly ionizing – usually secondary ionization by electrons that the photons can eject from metals

- Worked example
  - A nuclide is a nucleus of a particular number of protons and electrons.
    - Half-life is the time when half of the reactive particles have decayed into nuclei of other elements.
  - Since Thorium-227 will release $^-\beta$ radiation when it decays, you can use a geiger-muller counter to measure the amount of radiation emitted.
  - $^{227}_{89}Ac \longrightarrow ^{227}_{90}Th + ^{0}_{-1}\beta + \bar{\nu}$
  - 4 days
  -



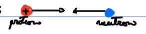
- 7.2 Nuclear reactions
  - Equations
    - The mass-energy relationship: $\Delta E = \Delta mc^2$
  - Patterns for stability in nuclides
    - To determine if there are too many neutrons compared to protons, or too many neutrons compared to protons a graph showing the variation of the neutron to proton number is plotted for stable nuclei.
      - The pattern formed is called the zone of stability.
        - Nuclides within the zone are stable, but if a nuclide is to the left or the right of the zone of stability will mean that the nuclide is unstable & will decay spontaneously so that it can reach the zone of stability.
    - Using the zone of stability and the graph we can predict the type of dec : α, β^-, β^+, or electron capture.
    - Nuclides having low proton numbers are most stable when the neutron-proton ratio is approx 1.
      - When a nuclide becomes heavier the neutron-proton ratio increases.
    - Neutron # against proton # graph



- Unstable nuclides lying to the left of the zone of stability are neutron rich, and decay with β^- radiation.
- Unstable nuclides to the right will be proton "rich", and will decay with β^+ radiation or with electron capture.
  - Electron capture is when a nucleus captures an electron and changes one of its protons to a neutron.
- The heaviest nuclides are alpha emitters since emission of both two protons & two neutrons decreases mass.
- Another factor that affects the stability of a nucleus is whether or not the number of protons and neutrons is even or not.
  - Almost half the known nuclides have both even protons & neutrons.
  - Only 5 stable nuclides have both odd protons & neutrons numbers.
- Whether the number of protons or neutrons is 2, 8, 20, 28, 50, 82, or 126 affects the stability.

- The unified atomic mass unit ← Is this how the weight of a neutron or proton is calculated?
  - The unified atomic mass unit (u) is a convenient unit for masses measured on atomic scale.
    - It's one-twelfth of the rest mass of an unbounded atom of carbon-12 in its nuclear & electronic ground state, having a value of $1.661 \cdot 10^{-27}$ kg.
      - Since C-12 = 6 protons & 6 neutrons, $\frac{1}{12}$ of C-12 will mean that you can find the weight of both neutrons & protons.
  - In chemistry, unified atomic mass is replaced with the "dalton" (Da).
  - Binding energy (It is the energy required to completely separate a nucleus).
    - The strong nuclear force between neighbouring nucleons is very short range ≈ 10^{-15} m or 1 fm.

- To completely dismantle a nucleus into its constituent nucleons work must be done to separate the nucleons and to overcome the strong nuclear force acting between them. This is known as the nuclear binding energy.
  - Forming a nucleus from individual nucleons would mean releasing energy as the strong force pulls them together. This energy is equal to the nuclear binding force needed to separate the nucleons.
- As you know from chemistry, forming bonds requires energy (endothermic) while breaking them is exothermic (release energy).

- Deutron
  - It's a stable particle composed of a proton & a neutron.
  - Process of formation
    - A free proton and a free neutron collide: 

    - The proton and neutron combine to form a deutron with the binding energy being carried away by a photon: 

    - A photon of energy greater than the binding energy of the deutron is incident on the deutron: 

Explain this → - The photon and neutron separate with their total kinetic energy being the difference between the photon energy and the binding energy needed to separate the proton & neutron.
  - The free photon and neutron have a greater total rest mass than the deutron ← Why? (284)

- Mass defect and nuclear binding energy
  - Energy and mass are different aspects of the same quantity & are shown to be interchangeable: $E = mc^2$
  - When work is done on a system so that its energy increases by an amount $+\Delta E$ then its mass will increase by an amount $+\Delta m$ given by:
    - $\Delta m = \frac{\Delta E}{c^2}$
  - When work is done by a system resulting in its energy decreasing by an amount $-\Delta E$ then its mass will decrease by an amount $-\Delta m$ given by:
    - $-\Delta m = -\frac{\Delta E}{c^2}$
  - These only work on an atomic scale.
    - When energy is supplied to accelerate a rocket, there will be an increase in the mass of the rocket.
  - In an exothermic reaction there will be a decrease in the mass of reactants.
  - The total mass of the individual nucleons making up a nucleus must be greater than the mass of that nucleus.
    - This difference is known as the mass defect, which is the "mass equivalent" of the nuclear binding energy.

- Mass and energy units for nuclear changes
  - Nuclear changes usually involve MeV (= eV · 10^6).
  - In $E = mc^2$ unit for MeV is MeV c^{-2}.
  - One unified atomic mass unit is equal to 931.5 MeV c^{-2}.

- Worked example
  - a) i) β^- decay

$m = 23.99096u - (23.98504 + 0.0053624863)$ Why do we have subtract from $^{24}_{11}Na$?

$m = 0.00055u$

ii) $E = mc^2$ $\left(\frac{5.002160 \text{ MeV}}{(6.242 \cdot 10^{12})}\right) = 8.01434 \cdot 10^{-13} J$

$m = \frac{E}{c^2}$

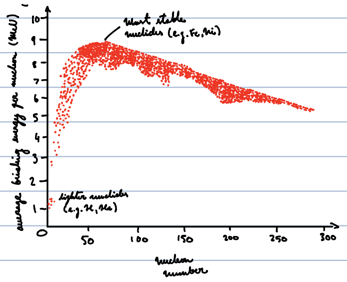
$m = \frac{(8.01434 \cdot 10^{-13})}{(3 \cdot 10^8)^2}$ $8.90482606 \cdot 10^{-30} kg \cdot 6.022 \cdot 10^{26} \approx \underline{0.0053624863u}$

$= 8.90482606 \cdot 10^{-30} kg$

How are we supposed to find the mass in the atomic mass unit without converting from kg to MeV? (285)

  - b) Na-24 because the strong force is stronger with more neutrons.

- Variation of nuclear binding energy per nucleon
  - The nuclear binding energy is higher for larger nuclei, and it tends to be smaller for smaller nuclei.
    - With greater number of nucleons there are more opportunities for the strong force to act between nucleons.
  - A larger nuclear binding energy means that more energy is needed to dismantle a nucleus into its component nucleons.
  - To find the average binding energy per nucleon is found by dividing the total binding energy for a nucleus by the number of nucleons in the nucleus.
    - Most nuclides have a binding energy of ≃ 8 MeV per nucleon.
  - Graph:



- On the left of the plot, the nuclides with low nucleon number, such as H-2 & helium, are less tightly bonded than the more massive nuclides.
- At the max binding energy per nucleon the nuclides have the most stable nuclei. This makes them the most abundant in the universe.
- The furthest to the right are the heaviest nuclei and are less tightly bonded together than the lighter ones.

- Nuclear fusion
  - The fusion of small nuclei gives out large amount of energy.
    - This is because the total nuclear binding energy of the fused nuclei is larger than the sum of total nuclear binding energies of the component nuclei.
  - The difference in binding energies is released as kinetic energy of the fusion products
  - The energy released can be thought of as the difference between the energy emitted in constructing the fused nucleus and the energy required in deconstructing the two nuclei.
  - When two nuclei of masses m_1 & m_2 fuse to form a nucleus of m_3.
    - Mass weight = $m_1 + m_2 > m_3$
      constituent particles
  - The loss of mass is emitted as kinetic energy of the fusion products → $\Delta E = ((m_1+m_2)-m_3)c^2$
    $\Delta E = \Delta m c^2$
  - Examples
    - $E=mc^2$ (He = 4.002602u)
      - mass of protons ·2 = 2.014552u
      - mass of neutrons ·2 = 2.01733u
        Total mass of nucleus: 4.031882u

        $\Delta m = 0.02928u \cdot 1.661\cdot10^{-27}$
        $= 4.863408\cdot10^{-29}$ kg
      - $\frac{0.02928u}{(6.022\cdot10^{26})} = m(kg)$ m (mass lost to k_E) = (4.031882 − 4.002602)
        = 0.02928 u
        $m = 4.86217204\cdot10^{-29}$ kg
      - $E = mc^2$
        $= (4.86217204\cdot10^{-29})(3\cdot10^{8})^2$
        $E = 4.37595484\cdot10^{-12}$ Joules

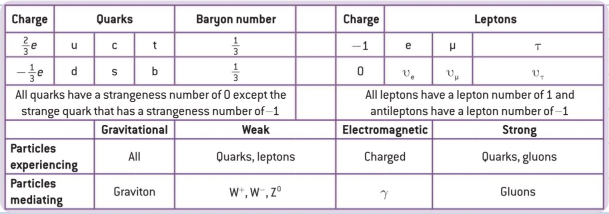
        MeV = $(4.37595484\cdot10^{-12})(6.242\cdot10^{12})$
        = 27.314 MeV ✓✓
  - There are many problems to trying to produce fusion. Initially, the repulsion between the protons means that energy must be supplied to the system in order to allow the strong nuclear force to do its work.
  - Joining two protons & two neutrons doesn't work, so earth-based fusion is between the nuclei of deuterium (H-2) & tritium (H-3).

- Nuclear fission
  - If we were able to take a large nucleus & split it into two smaller ones, the binding energy per nucleon will increase as we move from the right side to the center.
    - This means energy must be given out in form of kinetic energy.
  - The energy released is equivalent to the difference between the energy needed to deconstruct a large nucleus and that emitted when two smaller nuclei are constructed from its components.
  - Mass of two smaller nuclei is less than parent due to mass lost to kinetic energy.
    - $m_1 + m_2 < m_3$ then $\Delta E = (m_3-(m_1+m_2))c^2$.
  - Uranium-236 undergoes spontaneous fission to split into two lighter nuclides and at the same time emits two or three further neutrons.
    - ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n$

- Worked example
  - Nuclear fission is the splitting of a large nucleus into smaller ones while nuclear fusion is the fusion of smaller light nuclei to form a larger one.
    - In each case the total nuclear binding energy of products is larger than that of the reactant(s).
    - ΔE is emitted as k_E.
    - Mass of products is less than that of reactants due to k_E.
  - ${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + \text{energy}$
    - 4.002603 + 1.008665 (mass of neutron) = 5.011268 u
    - ${}^{2}_{1}H + {}^{3}_{1}H = 5.030152$ u
    - Mass lost to k_E = 5.030152 − 5.011268
      = 0.018884 u

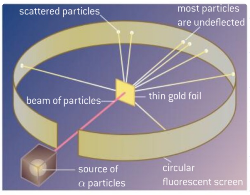
    $E = \left(\frac{0.018884}{6.022\cdot10^{26}}\right)c^2$
    $E = 2.82\cdot10^{-12}$ Joules

- 7.3 The structure of matter
  - Particle properties
    -

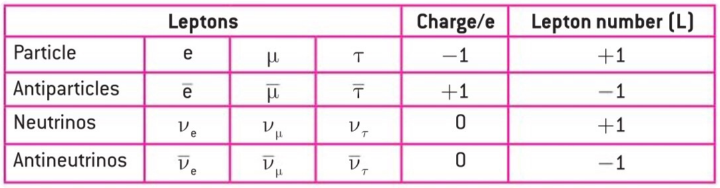


Charge	Quarks			Baryon number		Charge	Leptons		
$\frac{2}{3}e$	u	c	t	$\frac{1}{3}$		−1	e	μ	τ
$-\frac{1}{3}e$	d	s	b	$\frac{1}{3}$		0	υ_e	υ_μ	υ_τ
All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of −1						All leptons have a lepton number of 1 and antileptons have a lepton number of −1			

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

- Cathode rays are charged
- The scattering of alpha particles
  - The gold foil experiment was the following
    - Alpha particles where shot at the gold foil and $\frac{1}{8000}$ would have a diverted (0.0125%) course. This is because they must have hit a particle with a same charge. Since alpha particles are positively charged (2+ charge), then it will be repelled by the protons in the gold foil when they hit them.
  - Diagram of apparatus:
    - 

▲ Figure 3 The Rutherford–Geiger–Marsden apparatus.

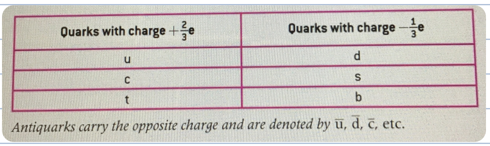
  - This showed that the diameter of a nucleus must be 10^{-15} m, while the whole atom would be 10^{-10} m in diameter.
  - The electrons that are accelerating because of circular motion should emit electromagnetic radiation and spiral into the nucleus.
    - This would mean that all atoms would collapse, but since thats not the case, the atom model is incomplete.
  - The particle explosion
    - A positron is an antiparticle of electrons.
    - An antiparticle is a particle that has the identical rest mass, but have reversed charges, spins, baryon numbers, lepton numbers, and strangeness.
      - If an electron curves in one direction, a positron will curve in the exact opposite way.
    - When an electron collides with a positron, they'll annihilate and their total mass is converted into a pair of photons of identical energy emmitted at right angles to each other.
      - Inverse of this process is called pair production. Pair production is when a photon interacts with a nucleus and produces a particle and its antiparticle.
        - For this to happen a photon must have a minimum energy equal to the total rest mass of the particle & antiparticle.
    - The antiproton is the antiparticle of a proton.
      - To form it protons must be accelerated to an energy of approx 6 MeV ($\frac{6}{6.242 \cdot 10^{12}} = 9.61306 \cdot 10^{-13}$) before colliding with another proton:
        - $p + p \longrightarrow p + p + p + \bar{p}$
        - E_k of reactants is sufficient to produce another proton & antiproton - using $E = mc^2$.
- Classification of particles - The standard model
  - Leptons
    - Leptons are members of the electron family & consist of the electron (e^-), the muon (μ), the tau (τ), their antiparticles plus three neutrinos associated with each of the particles and three neutrinos associated with the antiparticle.
      - Electrons (e^-), the muon (μ), the tau (τ) are negatively charged.
      - Their antiparticles are positively charged.
      - Neutrinos and antineutrinos are electrically uncharged.
    - Electron is $\frac{1}{1800}$ the mass of proton.
    - Muon is 200 times lighter than electron
    - Tau similar mass to proton.
    - Leptons have a lepton number +1 and antileptons -1.
    - 

Leptons				Charge/e	Lepton number (L)
Particle	e	μ	τ	−1	+1
Antiparticles	$\bar{e}$	$\bar{\mu}$	$\bar{\tau}$	+1	−1
Neutrinos	ν_e	ν_μ	ν_τ	0	+1
Antineutrinos	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$	0	−1

- Why doesn't the strong force apply on leptons?
  - Only quarks are affected by the strong nuclear force. Quarks have a property called "colored" (its not really colored), and the strong force is a force that acts on colored particles.
- Baryon number
  - Mesons, bosons, and leptons have baryon numbers of 0.

  - Quarks
    - Charges within nucleons are grouped in threes called quarks.
    - There are 6 quarks & 6 antiquarks.
      - Labelled by "flavor": up (u), down (d), strange (s), charm (c), bottom (b), and top (t).
    - They carry a charge of $+\frac{2}{3}e$ or $-\frac{1}{3}e$, and antiquarks carry $-\frac{2}{3}e$ or $\frac{1}{3}e$.

- Up and down quark are the lightest quarks, followed by strange & charm, and then bottom & top quarks (heaviest).
-



Quarks with charge $+\frac{2}{3}e$	Quarks with charge $-\frac{1}{3}e$
u	d
c	s
t	b

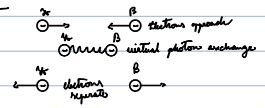
Antiquarks carry the opposite charge and are denoted by $\bar{u}$, $\bar{d}$, $\bar{c}$, etc.

- Quark confinement
  - Quarks only exist in groups called hadrons
    - Hadrons are formed from a combination of two or three quarks (called mesons and baryons) this is known as quark confinement.
  - To hold the quark in place they exchange gluons.
    - Gluons are an exchange particle that acts as the exchange particle for the strong force between quarks.
  - Moving a quark away from its neighbor in the baryon or meson stores more energy in the interaction between the quarks, and therefore requires increasing amounts of energy to increase their separation.

Have teacher explain. →

  - Adding more & more energy in the system won't break the force between quarks, it'll form more quarks instead.
    - This leaves original quark unchanged, but creates new meson or baryon by $E=mc^2$.
- Hadrons
  - Hadrons are particles composed of quarks, and include baryons (made up of three quarks) or mesons (comprise of quark-antiquark pairs).
    - Baryons are hadronic subatomic particles composed of 3 quarks, protons are composed of a Baryon.
  - The strong interaction acts on all hadrons but not on leptons.
  - Weak interaction acts on both leptons and hadrons.
    - Leptons are a subatomic particle which consists of an electron, a muon, and a tau with 3 neutrinos.
  - Some particles are theorised to be "pentaquarks" consisting of four quarks and an antiquark.
  - A baryon number is assigned to quarks to explain the outcome of observed interactions between particles
    - A quark is given a baryon number of $\frac{1}{3}$ and
  - "Strangeness" (s) was defined to explain the behavior of massive particles such as kaons and hyperons
    - Strange quarks have a charge of $-\frac{1}{3}e$.
    - These particles are created in pairs in collisions.
    - It has a lifetime of 10^{-10} s instead of normal 10^{-23} s. What they mean by strangeness is that the lifetime of quarks such as kaons & hyperons are so long compared to normal ones.
    - A strange quark has a strangeness of -1 while a strange antiquark has a strangeness of $+1$.
    - The property of strangeness is conserved when strange particles are created, but its not conserved when they decay.
    - Ask about The Eightfold Way with baryons and mesons.
  - Examples of baryons
    - Both protons and neutrons are baryons, they consist of 3 quarks and have a baryon number of $+1$.
      - The proton consists of two up quarks and a down quark. Its configuration is uud which means its baryon # is: $\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$
      - The neutron consists of two down quarks and one up quark (ddu) which gives charge: $-\frac{1}{3}-\frac{1}{3}+\frac{2}{3}=0$
      - When using antiquarks, the opposite charge is used, therefore, an antiproton will have a baryon number of -1, and it consists of two antiup quarks and an antidown quark: $\bar{u}\bar{u}\bar{d}$ with charge configuration: $-\frac{2}{3}-\frac{2}{3}+\frac{1}{3}=-1$
      - anti-proton ($\bar{p}$) $= \bar{u}\bar{u}\bar{d} = -1$ charge. Baryon (3 quarks).
      - Lambda (Λ) $= u\,s\,d = \frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$ charge. Baryon (3 quarks).
      - Omega (Ω^-) $= sss = -\frac{1}{3}-\frac{1}{3}-\frac{1}{3}=-1$ charge
        - Consists of 3 strange quarks. Furthermore, this is a baryon since it consists of 3 quarks.
  - Examples of mesons
    - Kaon (K^-) consists of $s\bar{u}$ (strange and antiup quark) with charge: $-\frac{1}{3}-\frac{2}{3}=-1$. Its a mesons as its a quark with antiquark. Strangeness of -1.
    - η_c (eta-c) consists of $c\bar{c}$ (charm quark and anticharm quark). Charge $=\frac{2}{3}-\frac{2}{3}=0$ charge. Meson.
    - π^+ (pion) consists of an up quark and an antidown quark: $u\bar{d}$, charge $=\frac{2}{3}+\frac{1}{3}=+1$. π^+ is meson as it only consists of a quark and antiquark.
    - Positive kaon (K^+) consists of $u\bar{s}$ (up quark and anti strange quark). With charge: $\frac{1}{3}+\frac{2}{3}=1$. Since s = strangeness -1, then $\bar{s}$ = strangeness 1.
- Conservation rules
  - As previously mentioned a change in mass due to interactions between particles or decay will be released in form of energy.
  - No interaction that disobeys the conservation of charge has ever been observed; the same is true for baryon numbers (B) and lepton number (L).
    - All leptons have a lepton number of $+1$ and antileptons have a lepton number of -1.

- Worked example
  - a) - Charge
    - Proton = +1, $\pi^- = -1$, neutron = 0, $\pi^0 = 0$
  - Baryon number
    - Proton = 1, $\pi^- = 0$, neutron = 0, $\pi^0 = 0$
  - $p + \pi^- \rightarrow 1 - 1 \rightarrow 0 + 0 \rightarrow n + \pi^0$

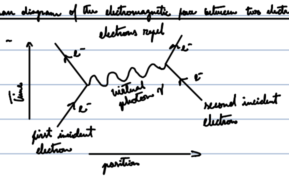
p. 298 (- b)) $uud + \bar{u}d \rightarrow udd + \bar{u}u$
    - π^0 will annihilate as they're a quark and its antiquark
  - No, there wouldn't be enough quarks to form a neutron, as well as this defies the laws of thermodynamics where it says that mass can't be created or destroyed.
- Fundamental forces
  - Gravitational force
    - This force is weak.
    - Has an infinite range and acts on all particles.
    - It's always attractive, and over large distances it's the dominant force.
      - On atomic & sub-atomic scale it's negligible.
  - Electromagnetic force
    - This is the force between electrical charges or bar magnets.
      - This causes electric and magnetic effect between electrical charges or bar magnets.
    - Infinite range, although unlike the gravitational force, it has a much shorter distance.
    - The force holds atoms and molecules together.
    - It acts on all charged particles, and it can either be attractive or repulsive depending on the particles.
  - The short nuclear force or strong interactions
    - This is an extremely strong force, but it has a very short range.
      - Only 10^{-15} m, and acts between hadrons but not leptons.
    - At 10^{-15} m the force is attractive but it becomes strongly repulsive at distances any smaller than that.
  - Weak nuclear force or weak interactions
    - This is responsible for radioactive decay and neutrino interactions.
      - Strong, electromagnetic, and weak interactions all cause particles to decay. However, only weak force causes decay of fundamental particles.
    - Without the weak interactions fusion wouldn't occur, and heavy nuclei could not be built.
    - Range $\approx 10^{-18}$ m and acts between all particles.
  - Exchange particles (Review)
    - The force between a pair of particles is transmitted by particles called gauge bosons.
      - Gauge boson is a force carrier
    - A different boson is responsible for a different force.
      - The mass of boson establishes range of force.
      - The bosons carry the force between particles.
    - As seen in the figure below, two electrons approach one another, this will result in a photon exchange leading to electromagnetic repulsion.
      - 

    - The reason the exchange particle is said to be virtual is because it's not detected during the exchange.
      - It can't be detected because detection would mean that it would no longer be acting as the transmitter of the force between the particles.
        - They can't be detected because they would become real particles if they would be detected.
      - The longer the rest mass of the exchange particle is, the lower the time it can be in flight without it being detected, therefore, the lower the range of the force.
      - A method of understanding how a repulsive force is produced by the transfer of a virtual particle is by thinking of two people in two different boats, and what effect a heavy ball that they would throw at one another.
        - As the ball is thrown at one another the change in momentum as the people throw & catch the ball will push them back. To someone who doesn't see the ball will think that there is a repulsive force between the two particles.
    - An attractive force between oppositely charged particles can be thought as two people with a boomerang, throwing it at one another with their backs to one another.

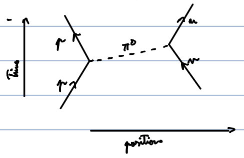
- In this case Δp will result in the boats being attracted to one another.
- Exchange particles of 4 fundamental forces
  -

Force	Exchange particle	Acts on
Gravitational	gravitons (undiscovered)	All particles
Weak nuclear	W^+, W^-, and Z^0 bosons	Quarks and leptons
Electromagnetic	photons	Electrically charged particles
Strong force	gluons (and mesons)	Quarks and gluons (and hadrons)

- Feynman diagrams
  - Represent interactions between particles.
    - the Time axes goes upwards, and the space or position axis to the right.
      - Some diagrams are drawn with the space or position axis as going up, while the Time axes is going to the right.
  - Straight lines represent particles and upwards arrows show particles moving forwards in Time (downwards arrows represent antiparticles also in the forward direction).
  - Wavy or broken lines that have no arrows represent exchange particles.
  - Points at which lines come together are called vertices and, at each vertex, conservation of charge, lepton number, and baryon number must be applied.
  - Example diagram
    - Feynman diagram of the electromagnetic force between two electrons
      -



    - Feynman diagram of the strong force between a proton and a neutron
      -



        - Neutral pion (π^0) is exchanged between a proton (p) and a neutron (n) mediating (transmitting) the strong nuclear force between these particles in the nucleus.
  - The electromagnetic force
    - As seen in the diagram of the electromagnetic force between two electrons, the exchange particle that gives rise to the force is the photon.
      - Photons have zero mass and this equates to the force having an 'infinite' range.
    - The diagram shows two electrons moving closer and interacting by the exchange of a virtual photon.