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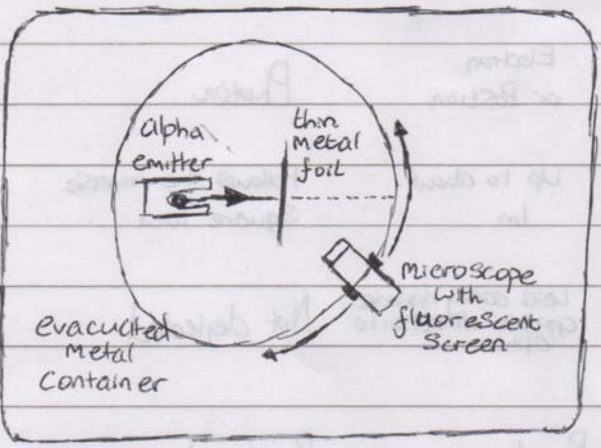
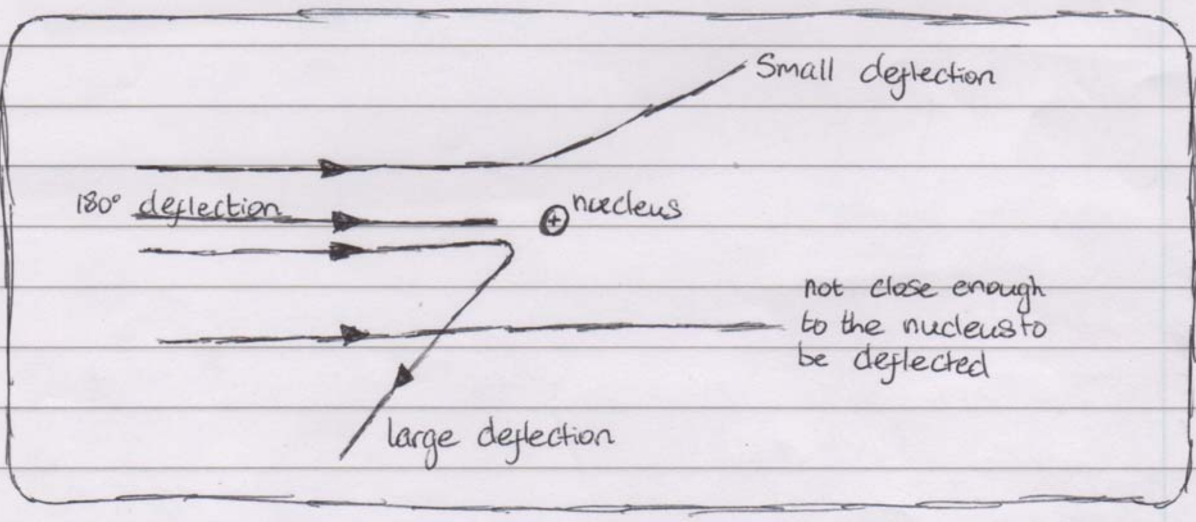
Rutherford Scattering



- Alpha emitter placed in vacuum
- Thin beam of alpha particles fired at metal foil
- Microscope used to count number of alpha particles deflected at each angle
- Most pass through foil with a deflection
- About 1 in 2000 are deflected and about 1 in 10000 are deflected at angles greater than 90°

Interpretation of Results

- Most of the atoms mass is concentrated in a small region, the nucleus, at the centre of the atom
- The nucleus is positively charged as it deflected positively charged alpha particles
- The closer to a head on collision with the nucleus, the greater the angle of deflection for the alpha particle



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Alpha, Beta, Gamma

Property	Alpha	Beta	Gamma
Nature	2 protons 2 neutrons	Electron or Postiron	Photon
Range	Depends on energy, up to 100mm	Up to about 1m	Follows the inverse square law
Deflection	Easily deflected	Less easily deflected, opposite direction to alpha	Not deflected
Absorption	By paper	By aluminium	By lead
Ionisation	Highly	Mid	Weak
Energy	Constant	Varies	Constant

- α emission : ${}^{A}_{Z}X \longrightarrow {}^{4}_{2}\alpha + {}^{A-4}_{Z-2}Y$
- B^- emission : ${}^{A}_{Z}X \longrightarrow {}^{0}_{-1}\beta + {}^{A}_{Z+1}Y + \bar{\nu}_e$
- β^+ emission : ${}^{A}_{Z}X \longrightarrow {}^{0}_{1}\beta + {}^{A}_{Z-1}Y + \nu_e$
- Electron Capture : ${}^{A}_{Z}X + {}^{0}_{-1}e \longrightarrow {}^{A}_{Z-1}Y + \nu_e$

Radioactive Decay

- The half life, $T_{1/2}$, of a radioactive isotope is the time taken for the mass of the isotope to decrease to half its initial mass
- The activity, A, of a radioactive isotope is the number of nuclei of the isotope that disintergrate per second
- The corrected count rate, C, of a sample is the count rate from a geiger counter with the background count taken away
- The decay constant, λ, is the probability of an individual nucleus decaying per second
- $\frac{\Delta N}{\Delta t} = -\lambda N$
- $N = N_0 e^{-\lambda t}$
- $A = \lambda N$
- $A = A_0 e^{-\lambda t}$
- $T_{1/2} = \frac{\ln 2}{\lambda}$

e.g. an isotope has a half life of 8 days, and a fresh sample contains 4.2×10^{16} atoms of the isotope. Calculate the decay constant and number of atoms remaining after 24 hours.

$$\lambda = \frac{\ln 2}{T_{1/2}}$$
$$= \frac{\ln 2}{8 \times 24 \times 60 \times 60}$$
$$= 1 \times 10^{-6} \ s^{-1}$$

number of atoms $= N_0 e^{-\lambda t}$
$$= 4.2 \times 10^{16} \times e^{-(10^{-6} \times 24 \times 60 \times 60)}$$
$$= 3.9 \times 10^{16}$$

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Radioactivity Uses

Radioactive Dating

- Living plants and trees have small amounts of $^{14}_{6}C$
- Carbon-14 has half life of 5570 years, so wont decay while the plant is alive
- Once the plant dies no more carbon-14 is produced
- Given the activity of the living plant is known the age of the dead plant can be calculated by measuring activity
- Ancient rocks contain argon gas as $^{40}_{19}K$ decays into $^{40}_{18}Ar$
- The half life of potassium-40 is 1250 million years
- The age of the rock can be calculated by measuring the proportion of potassium-40 to argon-40

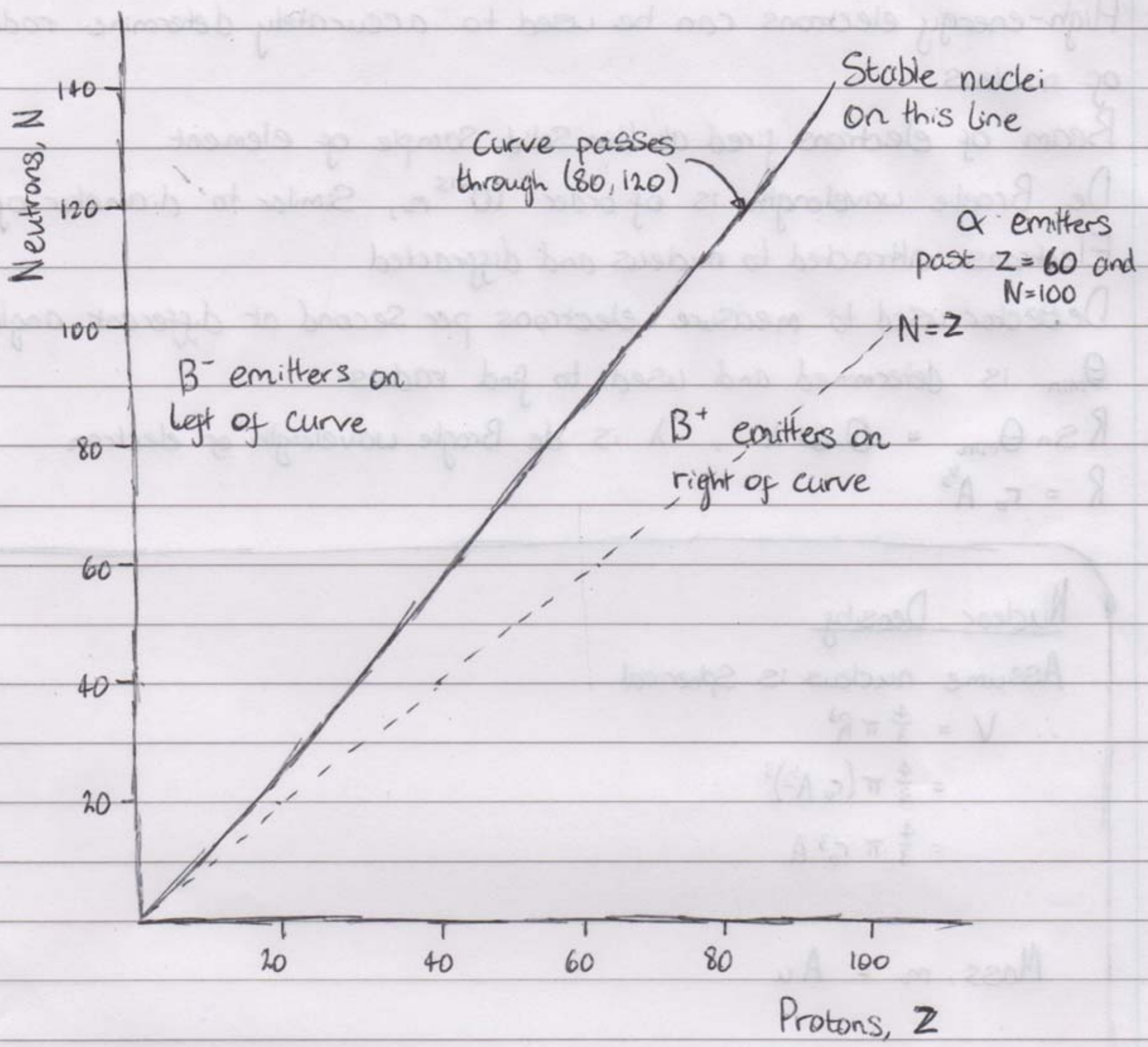
Radioactive Tracers

- Injecting a fluid containing β^- or γ emitters into an underground pipe can be used to detect a leakage (where most radiation gets through)
- A patient can be given a solution containing sodium iodine (β^- emitter) and activity can be measured to see how well thyroid glands absorb
- Plants can be watered with fertiliser containing phosphorus-32 and the radioactivity of the leaves measured to see how much fertiliser they get

Technetium - 99m

- Technetium generators are used in hospitals to produce sources of only γ
- $^{99}_{43}Tc$ forms after α and β emission to stay in a long excited state called the metastable state
- After β^- emission from molybdenum-99 (half life of 67 hours), technetium is formed with half life of 6 hours and decays by γ emission to ground state
- With a γ camera it can image internal organs and bones

N-Z Graph


Stable nuclei on this line
Curve passes through (80, 120)
α emitters past Z = 60 and N = 100
N = Z
β⁻ emitters on left of curve
β⁺ emitters on right of curve
Neutrons, N
Protons, Z
140
120
100
80
60
40
20
20
40
60
80
100

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Nuclear Radius

- High-energy electrons can be used to accurately determine radius of nucleus
- Beam of electrons fired at thin solid sample of element
- De Broglie wavelength is of order 10^{-15} m, similar to diameter of nucleus
- Electrons attracted to nucleus and diffracted
- Dettector used to measure electrons per second at different angles
- θ_{min} is determined and used to find radius
- $R \sin\theta_{min} = 0.61\lambda$, λ is de Broglie wavelength of electron
- $R = r_0 A^{1/3}$

Nuclear Density

Assume nucleus is spherical

$$\therefore \; V = \frac{4}{3}\pi R^3$$
$$= \frac{4}{3}\pi (r_0 A^{1/3})^3$$
$$= \frac{4}{3}\pi r_0^3 A$$

Mass, $m = Au$

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$
$$= \frac{Au}{4/3\,\pi r_0^3 A}$$
$$= \frac{u}{4/3\,\pi r_0^3}$$
$$= \frac{1.661\times10^{-27}}{4/3 \times \pi \times (1.05\times10^{-15})^3}$$
$$= 3.4\times10^{17}\ \text{Kgm}^{-3}$$

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Nuclear Energy

- $E = mc^2$
- When energy is released in a reaction the total mass decrease
- mass difference in u × 931.3 = energy released in MeV

e.g. The polonium isotope $^{210}_{84}Po$ emits an alpha particle and decays into $^{206}_{82}Pb$. Calculate the energy released.

$^{210}_{84}Po$ = 209.93667u

$^{206}_{82}Pb$ = 205.92936 u

α = 4.00150u

mass difference = 209.93667 − (205.92936 + 4.00150)

= 0.00581

energy released = 0.00581 × 931.3

= 5.41 MeV

Strong Nuclear Force

- Must be attractive force between nucleons to keep nucleus together
- Force is attractive at a few fm
- Force repulsive at distances less than 0.5 fm

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Binding Energy

- Binding energy of a nucleus is the work that must be done to separate a nucleus ~~from~~ into its individual protons and neutrons
- Binding energy per nucleon is the average work that must be done per nucleon to remove all nucleons from the nucleus
- The mass defect is the difference between the mass of the separated nucleons and the mass of the nucleus
- Binding Energy = Mass Defect × 931.3 (in MeV)

e.g. The mass of $^{212}_{83}Bi$ is 211.80012u. Calculate the binding energy of this nucleus.

mass of proton = 1.00728 u

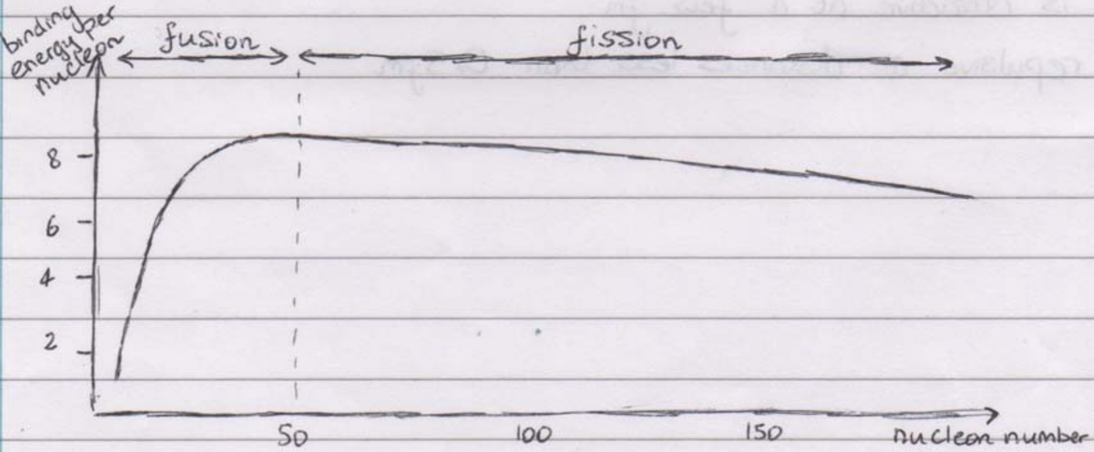
mass of neutron = 1.00867 u

mass defect = $(83 \times 1.00728) + (129 \times 1.00867) - 211.80012$

= 1.92255 u

binding energy = 1.92255×931.3

= 1790 MeV



- The higher the binding energy, the more stable the nucleus
- The maximum is roughly 8.7 MeV, for Iron
- Large atoms undergo fission to be more stable
- Small atoms undergo fusion to be more stable

Fission and Fusion

Fusion

- Fusion is when two small nuclei combine to form a larger one
- Energy released is equal to increase of binding energy
- Nuclei must travel at high speeds
- High speeds needed to overcome electrostatic repulsion
- Providing inputs are the same output will always be the same
- Energy from the Sun is produced by fusion with hydrogen nuclei
- To get heat and speed for nuclei on Earth makes this too costly to be worth it economically

Fission

- Fission is when a large nuclei splits into two smaller nuclei
- The result of fission is not always the same, but two products will be similar in size
- Energy released is equal to increase of binding energy
- Induced fission is forced fission by firing neutrons at nuclei to make them unstable
- Induced fisson is usually done with $^{235}_{92}U$ or $^{239}_{94}Pu$
- Induced fission causes two or three neutrons to also be released
- This can cause a chain reaction of more fission

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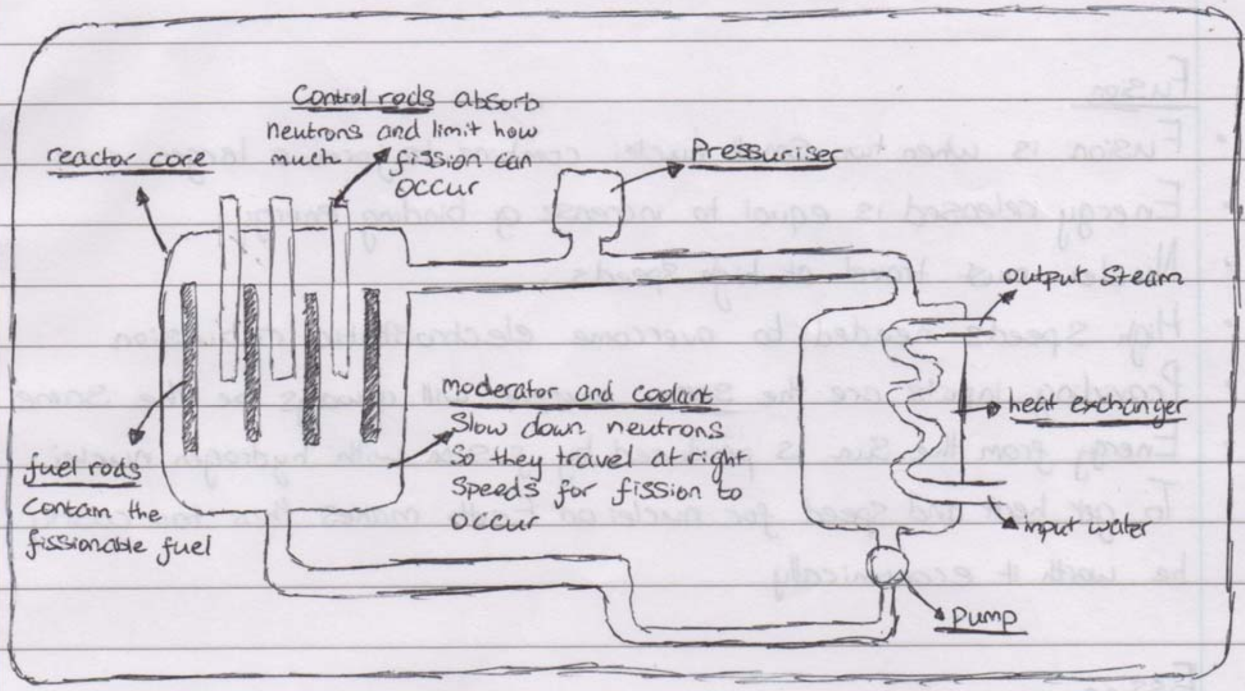
Thermal Nuclear Reactor



- The critical mass is the minimum mass that the fissile material must be for a thermal nuclear reactor, as some neutrons from nuclei will go away and not cause further fission

Safety Features

- Reactor core made to withstand high temperature and pressure in core, also absorbs some radiation
- Thick concrete walls around reactor
- Emergency Shut-down system will force control rods down completely
- Fuel rods are remotely placed in reactor so humans are not harmed

Radioactive Waste

- High-Level radioactive waste (fuel rods) are stored underwater for a year to cool them down, then are stored underground in metal containers for centuries
- Intermediate-level waste (containers and low activity material) is stored in specially constructed concrete buildings
- Low-level waste (protective clothing) is stored in metal drums

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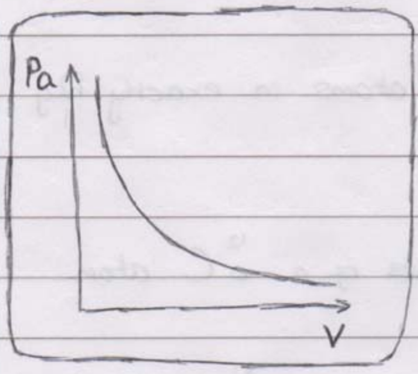
Gases

Pressure

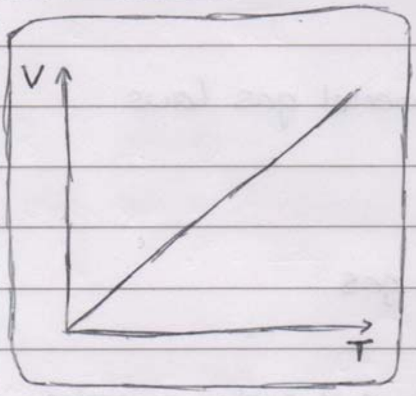
- Force per unit area a gas exerts on a surface
- Measured in pascals (Pa), $1\,pa = 1\,Nm^{-2}$
- Pressure dependent on temperature, volume and mass

Boyle's Law



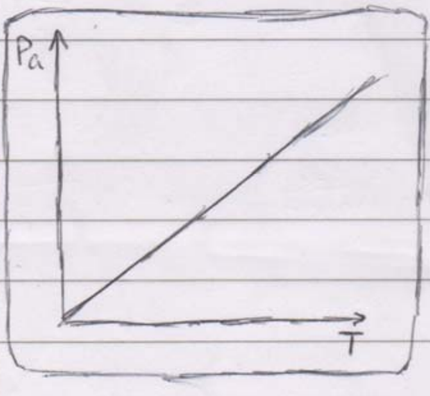
- Boyle's Law states pressure and volume are inversely proportional
- pV = constant
- a gas following this law is an ideal gas
- a change at constant temperature is an isothermal change

Charles' Law



- Charles' Law states volume and temperature are directly proportional
- $\frac{V}{T}$ = constant
- temperature must always be in Kelvin

Pressure Law



- Pressure Law states pressure and temperature are directly proportional
- $\frac{P}{T}$ = constant

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Brownian Motion

- Molecules of a gas move at random with different speeds
- They don't lose speed on collision with each other
- These collision exert a force, a pressure
- Placing a larger visible particle in the gas allows the effect to be seen under a microscope, usually a smoke particle
- The particles magnitude and direction will constantly change

Avogadro Constant and Molar Mass

- Avogadro constant, N_A, is the number of atoms in exactly 12g of carbon $^{12}_{6}C$
- $N_A = 6.023 \times 10^{23}$
- One atomic mass unit, u, is $\frac{1}{12}$ the mass of a $^{12}_{6}C$ atom
- $1u = 1.661 \times 10^{-27}$ kg
- One mole is the amount of substance that contains N_A particles
- Molar mass is the mass of 1mol of a substance

Ideal Gas Equation

- Ideal gas equation links the three experimental gas laws
- $\frac{pV}{T}$ = constant
- Must be a fixed mass of an ideal gas
- $pV_m = RT$, V_m is volume of 1mol of gas
- R is molar gas constant, 8.31 $J mol^{-1} K^{-1}$
- Equation can be written as $pV = nRT$, n is number of moles
- Can also write $pV = NkT$, N is number of molecules
- k is Boltzmann constant, $k = \frac{R}{N_A}$
- $k = 1.38 \times 10^{-23}$ JK^{-1}

Kinetic Theory of Gases

Molecular Speed

- Speed of individual molecules continuously changes
- Distribution of speeds stays the same, normal distribution
- Root mean square speed, $\bar{c} = \left[\frac{c_1^2 + c_2^2 + c_3^2 + \dots + c_N^2}{N}\right]^{1/2}$
- If temperature increases $\bar{c}$ increases

Kinetic Theory Equation

- $pV = \frac{1}{3} N m \bar{c}^2$
- N identical molecules, each of mass m
- For it to be true, the following assumptions are made:
  - volume of each molecules negligible compared to volume of gas
  - molecules do not attract each other
  - molecules move in random motion
  - collisions are elastic with container
  - collisions are much shorter time than time between impacts
- Average kinetic energy of a molecule is $E_K = \frac{3}{2} k T$
- Total kinetic energy for n moles is $E_K = \frac{3}{2} nRT$

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Thermal Physics

Internal Energy

- Internal energy of an object is the sum of the random distribution of the kinetic and potential energies of its molecules
- Internal energy changes when:
  - heat or energy transfer by radiation to or from the object
  - work is done on or by the object
- At absolute zero an object has minimum internal energy

Specific Heat Capacity

- Specific heat capacity, c, is the energy needed to raise the temperature of a unit mass by 1K without a change of state
- Energy, $Q = mc\Delta T$
- The specific heat capacity of water is approximately 4200 $J\,kg^{-1}\,K^{-1}$

Specific Latent Heat

- Specific latent heat of fusion is the energy needed to change the state of a unit mass of solid to liquid, or vice versa, without a change in temperature
- Specific latent heat of vapourisation is the energy needed to change the state of a unit mass of liquid to gas, or vice versa, without a change in temperature
- Energy, $Q = ml$ where l is specific latent heat in $J\,kg^{-1}$