Revision Guide for Chapter 17

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Student's Checklist

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I can show my understanding of effects, ideas and relationships by describing and explaining cases involving:

the use of particle accelerators to produce beams of high energy particles for scattering (collision) experiments (knowledge of the construction details of accelerators not required) Revision Notes: Accelerators	
evidence from scattering for a small massive nucleus within the atom Revision Notes: Alpha scattering Summary Diagrams: Rutherford's picture of alpha scattering; Distance of closest approach	
evidence for discrete energy levels in atoms (e.g. obtained from collisions between electrons and atoms or from line spectra) Revision Notes: Evidence for energy levels Summary Diagrams: Spectra and energy levels	
a simple model of an atom based on the quantum behaviour of electrons in a confined space Revision Notes: Model of the atom Summary Diagrams: Standing waves in atoms	
a simple model of the internal structure of nucleons (protons and neutrons) as composed of up and down quarks Revision Notes: Quarks	
pair creation and annihilation using $E_{rest} = mc^2$; interaction as exchange of particles (bosons) Revision Notes: Pair production and annihilation; Subatomic particles Summary Diagrams: Exchange of photons	

I can use the following words and phrases accurately when describing effects and observations:

energy level, scattering Revision Notes: Evidence for energy levels; Alpha scattering; Summary Diagrams: Spectra and energy levels; Rutherford's picture of alpha scattering	
nucleus, nucleon, quark, gluon, lepton, antiparticle, neutrino Revision Notes: Subatomic particles Summary Diagrams: Fundamental particles	

I can sketch and interpret:

diagrams showing the paths of scattered particles Summary Diagrams: Rutherford's picture of alpha scattering	

I can make calculations and estimates making use of:

the force *F* = *q v B* on a charged particle moving in a uniform magnetic field See Revision Guide Chapter 16	
the kinetic and potential energy changes as a charged particle approaches and is scattered by a nucleus or other charged particle Summary Diagrams: Rutherford's picture of alpha scattering; Distance of closest approach	

Revision Notes

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Accelerators

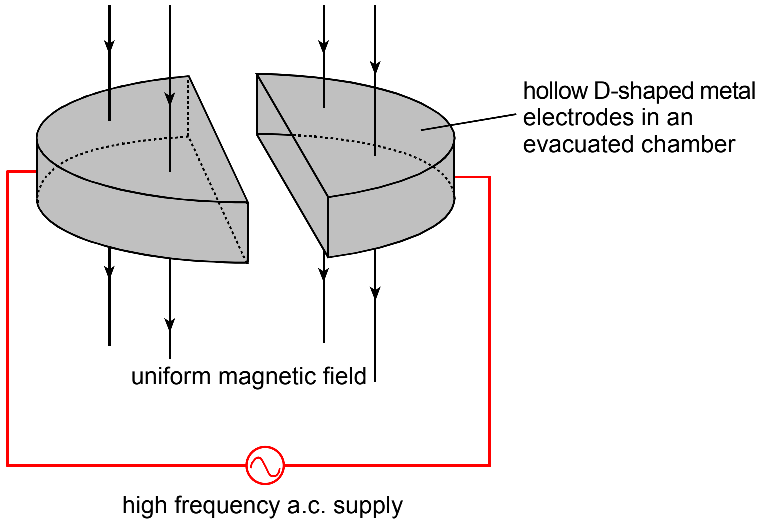
An accelerator is a linear or circular device used to accelerate charged particles. Particles are given energy by electric fields. They are steered using magnetic fields.

A **Van de Graaff accelerator** consists of a large isolated metal dome kept at a high potential by the accumulation of charge from a continuously moving belt. Ions created inside the dome in an evacuated tube are repelled. The work W done on a particle of charge q is $W = q\,V$, where V is the potential of the dome.

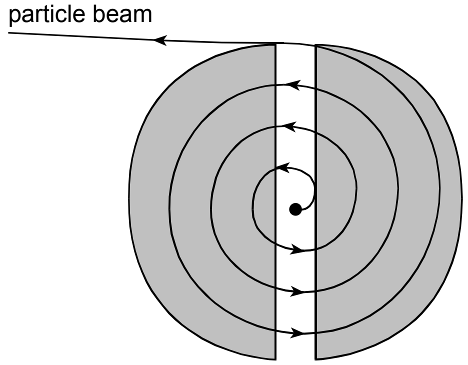
The largest Van de Graaff accelerators can accelerate protons to energies of the order of 20 MeV. Although the maximum energy is low, it is stable and can be accurately controlled, allowing precision investigations of nuclear structure.

A **cyclotron** consists of two hollow evacuated D-shaped metal electrodes. A uniform magnetic field is directed at right angles to the electrodes. As a result, charged particles released at the centre are forced to move round in a circular path, crossing between the electrodes every half turn. A radio-frequency alternating p.d. between the electrodes accelerates the charged particles as they cross the gap between the electrodes. The charged particles spiral out from the centre, increasing in energy every half-cycle.

The cyclotron



construction



particle paths

The following equations apply if the speed of the particles remains much less than the speed of light. The magnetic force on a charged particle q is equal to $B\,q\,v$, where v is the particle's speed and B is the magnetic flux density. Thus

$$Bqv = \frac{mv^2}{r}$$

where m is the particle's mass and r is the radius of the particle orbit.

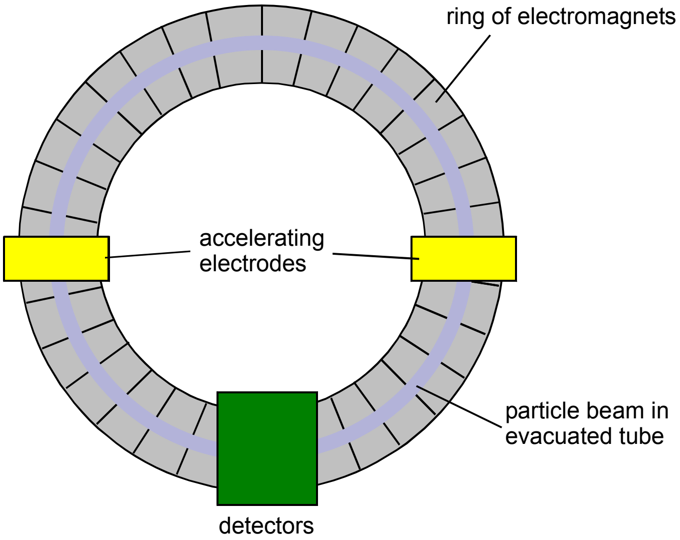
Thus the momentum of a particle is $m\,v = B\,q\,r$ and the frequency of rotation is

$$f = \frac{v}{2\pi r} = \frac{Bq}{2\pi m}.$$

This is independent of radius r and is the constant frequency of the alternating p.d.

Relativistic effects limit the maximum energy a cyclotron can give a particle. At speeds approaching the speed of light the momentum of a particle is larger than the classical value mv. The frequency of orbit in the magnetic field is no longer constant, so the alternating accelerating potential difference is no longer synchronised with the transit of a particle between the two electrodes.

Synchrotron Accelerator



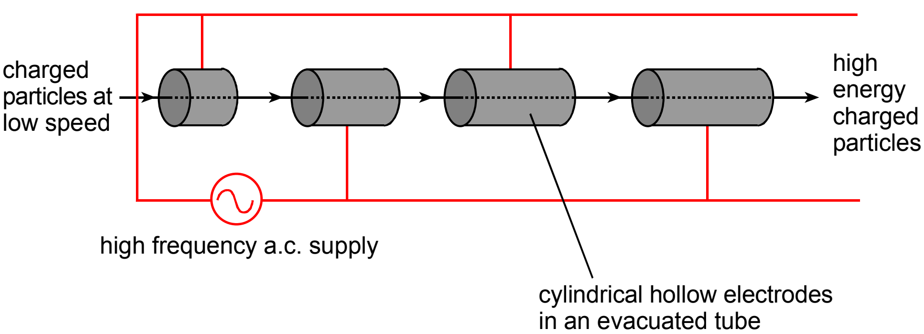
The **synchrotron** makes particles travel at a fixed radius, adjusting the magnetic field as they accelerate to keep them on this fixed path. The frequency of the alternating accelerating potential difference is also adjusted as the particles accelerate, to synchronise with their time of orbit.

The machine consists of an evacuated tube in the form of a ring with a large number of electromagnets around the ring. Pairs of electrodes at several positions along the ring are used to accelerate charged particles as they pass through the electrodes. The electromagnets provide a uniform magnetic field which keeps the charged particles on a circular path of fixed radius.

In a collider pulses of particles and antiparticles circulate in opposite directions in the synchrotron, before they are brought together to collide head-on.

A **linear accelerator** consists of a long series of electrodes connected alternately to a source of alternating p.d. The electrodes are hollow coaxial cylinders in a long evacuated tube. Charged particles released at one end of the tube are accelerated to the nearest electrode. Because the alternating p.d. reverses polarity, the particles are repelled as they leave this electrode and are now attracted to the next electrode. Thus the charged particles gain energy each time they pass between electrodes.

The linear accelerator



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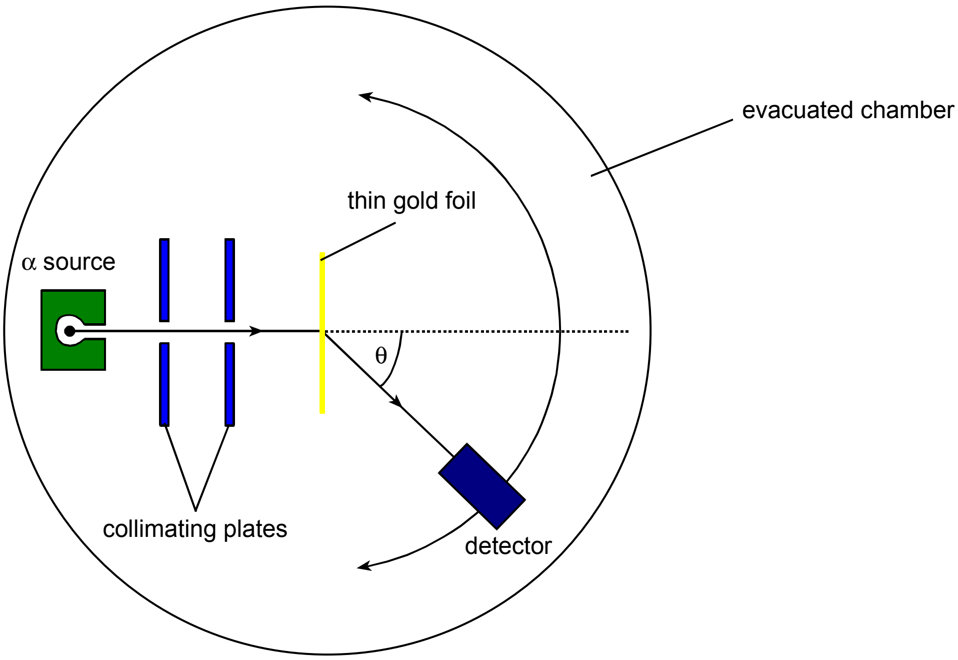
Alpha scattering

Rutherford, working with Geiger and Marsden, discovered that most of the alpha particles in a narrow beam directed at a thin metal foil passed through the foil.

α scattering



They measured the number of particles deflected through different angles and found that a small number were deflected through angles in excess of 90°. Rutherford explained these results by picturing an atom as having a small massive positively charged nucleus.

The fraction of particles scattered at different angles could be explained by assuming that the alpha particles and nucleus are positively charged and so repel one another with an electrical inverse square law force.

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Evidence for energy levels

Confined quantum objects exist in discrete quantum states, each with a definite energy. The term **energy level** refers to the energy of one or more such quantum states (different states can have the same energy).

The existence of discrete energy levels in atoms has been confirmed in electron collision experiments using gas-filled electron tubes. The gas atoms exchange energy with the electrons in discrete amounts corresponding to differences in energy levels of the atoms.

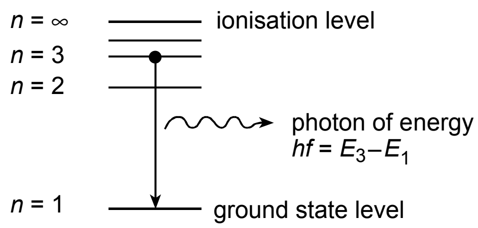
Evidence of discrete energy levels in atoms also comes from the existence of sharp line spectra. A line emission spectrum is seen if the light from a glowing gas or vapour is passed through a narrow slit and observed after it has been refracted by a prism or diffracted by a diffraction grating.

The energy of a photon $E = h\,f = h\,c\,/\,\lambda$, where f is the frequency of the light, c is the speed of light and λ is its wavelength. If an electron goes from energy level E_1 to a lower energy level E_2, the emitted photon has energy $h\,f = E_1 - E_2$.

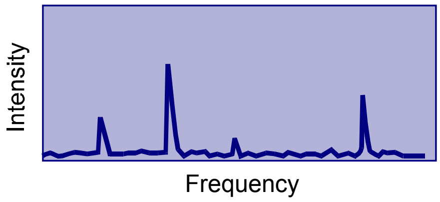
The energy levels of an atom may be deduced by measuring the wavelength of each line in the spectrum then calculating the photon energies corresponding to those lines.

Energy levels and line spectra

(a) Energy levels



(b) Spectrum



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Model of the atom

A simple model of the atom explains why the electrons have discrete energy levels.

The quantum properties of the electron are responsible for limiting its energy in the atom to certain discrete energy levels. Any quantum particle confined to a limited region of space can exist only in one of a number of distinct quantum states, each with a specific energy.

One way of thinking about this is to associate wave behaviour with the quantum particles. A particle is assigned a de Broglie wavelength, $\lambda = h / m v$, where m is its mass, v is its velocity and h is the Planck constant.

An electron trapped in an atom can be thought of as a standing wave in a box such that the wave 'fits' into the box exactly, like standing waves fit on a vibrating string of fixed length.

Consider a model atom in which an electron is trapped in a rectangular well of width L. Standing waves fit into the well if a whole number of wavelengths fit across the well. Hence $n \lambda = L$ where n is a whole number.

De Broglie's hypothesis therefore gives the electron's momentum $m v = h / \lambda = n h / L$. Therefore, the kinetic energy of an electron in the well is:

$$\frac{1}{2}mv^2 = \frac{m^2v^2}{2m} = \frac{n^2h^2}{2mL^2}.$$

Thus in this model, the energy of the electron takes discrete values, varying as n^2.

This simple model explains why electrons are at well-defined energy levels in the atom, but it gets the variation of energy with number n quite wrong. Optical spectra measurements indicate that the energy levels in a hydrogen atom follow a $1/n^2$ rule rather than an n^2 rule.

A much better model of the atom is obtained by considering the quantum behaviour of electrons in the correct shape of 'box', which is the 1 / *r* potential of the charged nucleus.

The mathematics of this model, first developed by Schrödinger in 1926, generates energy levels in very good agreement with the energy levels of the hydrogen atom.

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Quarks

Quarks are the building blocks of protons and neutrons, and other fundamental particles.

The nucleons in everyday matter are built from two quarks, each with an associated antiquark:

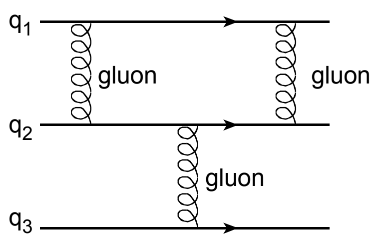
1. The **up** quark ($+ {}^{2}/_{3}\ e$) and the **down** quark ($- {}^{1}/_{3}\ e$).

A proton, charge +1*e*, is made of two up quarks and one down quark **uud**. A neutron, charge 0, is made of one up quark and two down quarks **udd**. A **meson** consists of a quark and an antiquark. For example, a π meson consists of an up or a down quark and an up or down antiquark.

The first direct evidence for quarks was obtained when it was discovered that very high-energy electrons in a beam were scattered from a stationary target as if there were point-like scattering centres in each proton or neutron.

Quarks do not exist in isolation. They are bound together by the exchange of gluons.

Gluon exchange



Beta decay

β^- decay occurs in neutron-rich nuclei as a result of a down quark changing to an up quark (udd → uud) and emitting a W^-, which decays into an electron (i.e. a β^- particle) and an antineutrino.

β^+ decay occurs in proton-rich nuclei as a result of an up quark changing to a down quark (uud → udd) and emitting a W^+, which decays into a positron (i.e. a β^+ particle) and a neutrino.

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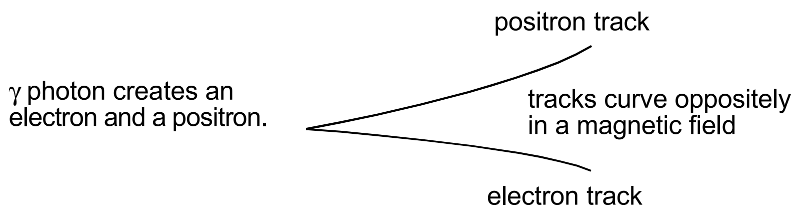
Pair production and annihilation

The positron is the antiparticle of the electron. It differs from the electron in carrying a charge of + *e* instead of – *e*. The masses of the two are identical. One point of view in quantum mechanics regards positrons as simply electrons moving backwards in time.

A gamma-ray photon of energy in excess of around 1 MeV is capable of creating an electron and a positron. Energy and momentum must always be conserved in a pair production event. The photon energy must exceed the rest energy $E_{rest} = mc^2$ of the electron and of the positron, which is about 0.5 MeV for each (actual value 0.505 MeV). To conserve momentum, the creation event must take place close to a nucleus which recoils, carrying away momentum.

Pair production



A positron and an electron annihilate each other when they collide, releasing two gamma photons to conserve momentum and energy. The energy of each gamma photon is half the total energy of the electron and positron. For example, if a positron of energy 1 MeV was annihilated by an electron at rest, the total energy would be approximately 2 MeV including the rest energy of each particle. Hence the energy of each gamma photon would be 1 MeV.

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Subatomic particles

Subatomic particles divide into two main groups:

Leptons: particles not affected by the strong interaction, including electrons, positrons, neutrinos and antineutrinos.

Hadrons: composite particles, made of quarks, held together by the exchange of gluons (strong interaction).

Whereas protons and neutrons contain three quarks, intermediate particles such as pions are made of one quark and one antiquark.

A further fundamental distinction is between bosons and fermions.

A **boson** is the general name given to particles (such as photons and gluons) which carry the interaction between other particles. Bosons have integer spin, and do not obey the exclusion principle. (Some particles made of fermions – e.g. certain nuclei – also have integer spin.)

A **fermion** is the general name given to particles (such as electrons and gluons) which function as particles of matter. Fermions have a half integer spin, and obey the exclusion principle (no two particles can be in the same quantum state).

The bosons such as the photon which 'carry' the forces or interactions between matter particles are called **exchange particles**. In quantum physics, all interactions are understood in terms of the exchange of such particles.

It used to be said that there are four different fundamental kinds of interaction between particles: gravity, electromagnetism, the weak interaction and the strong interaction. Electromagnetism is due to the exchange of massless virtual photons between charged bodies. The weak nuclear interaction is responsible for beta decay. However, electromagnetism and the weak interaction have now been brought together into one unified theory. The strong nuclear force is the residual effect of the exchange of gluons between the quarks in a nucleon. There are hopes, not yet fulfilled, of bringing all the interactions together into one unified theory.

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Summary Diagrams (OHTs)

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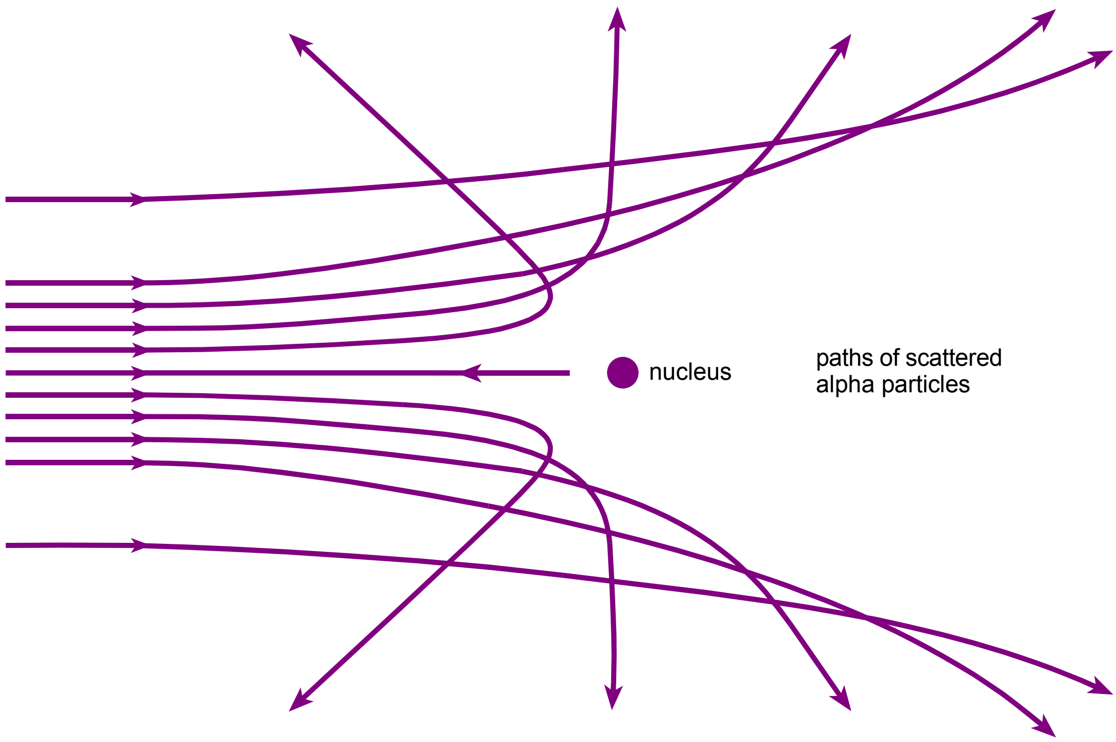
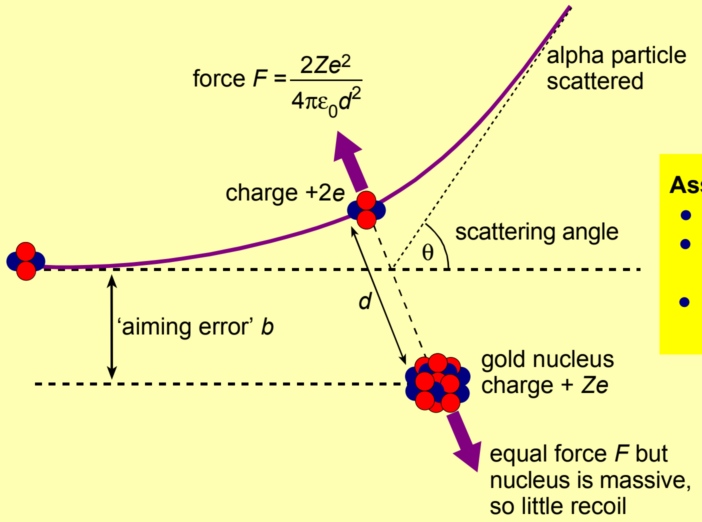
Rutherford's picture of alpha scattering

Rutherford's picture of alpha scattering



Rutherford's picture of alpha scattering

For calculations



Assumptions:

- alpha particle is the He nucleus, charge +2e
- gold nucleus has charge + Ze, and is much more massive than alpha particles
- scattering force is inverse square electrical repulsion

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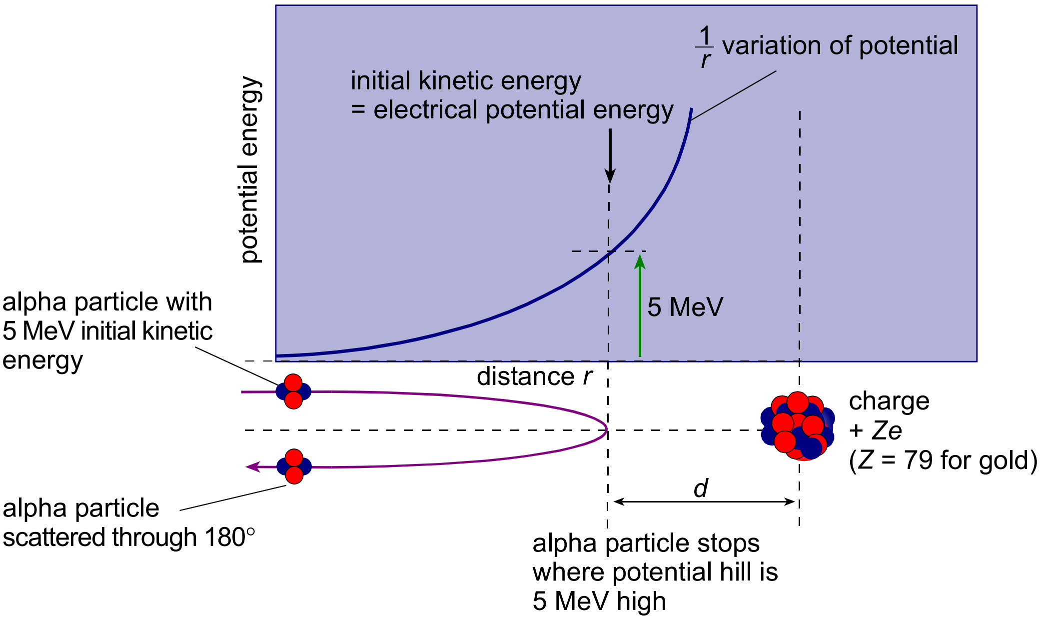
Distance of closest approach

Distance of closest approach



Where does the alpha particle stop?

Initial kinetic energy

= 5 MeV

$= 5 \times 10^{6}$ eV $\times 1.6 \times 10^{-19}$ J eV^{-1}

$= 8.0 \times 10^{-13}$ J

Electrical potential energy

$$V = \frac{+\,2\,Ze^2}{4\pi\varepsilon_0 d}$$

$Z = 79$, $e = 1.6 \times 10^{-19}$ C,

$\varepsilon_0 = 8.9 \times 10^{-12}$ C^2 N^{-1} m^{-2}

Alpha particle stops where

initial kinetic energy = electrical potential energy

$$8.0 \times 10^{-13}\ \text{J} = \frac{+\,2\,Ze^2}{4\pi\varepsilon_0 d}$$

substitute values of Z, e, ε_0:

$d = 4.5 \times 10^{-14}$ m

Radius of gold nucleus must be less than of the order of 10^{-14} m

Atoms are 10 000 times larger than their nuclei

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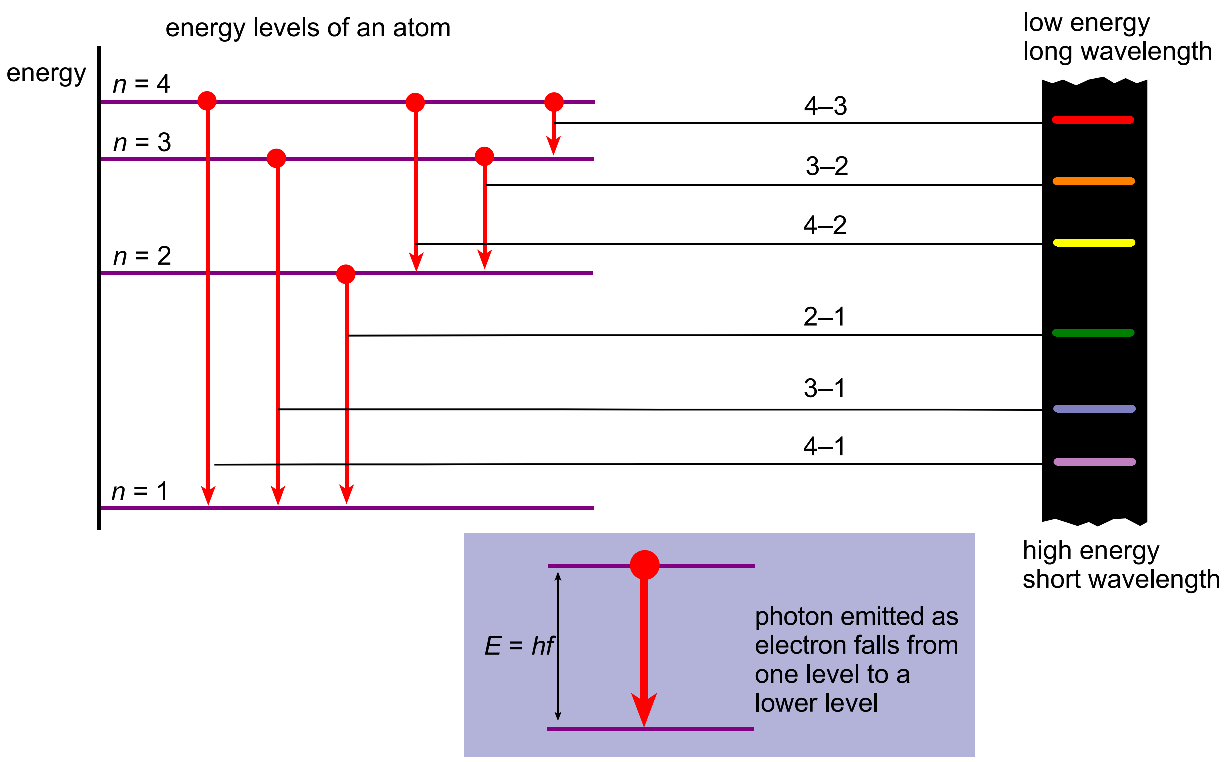
Spectra and energy levels

Spectral lines and energy levels



Spectral lines map energy levels
***E* = *hf* is the energy difference between two levels**

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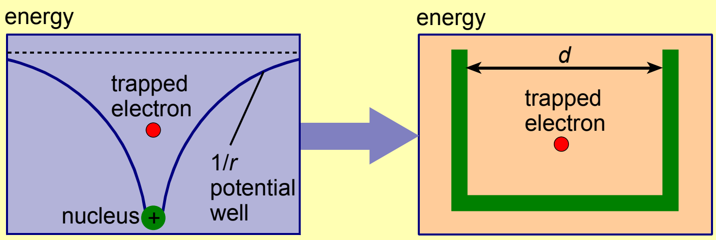
Standing waves in atoms

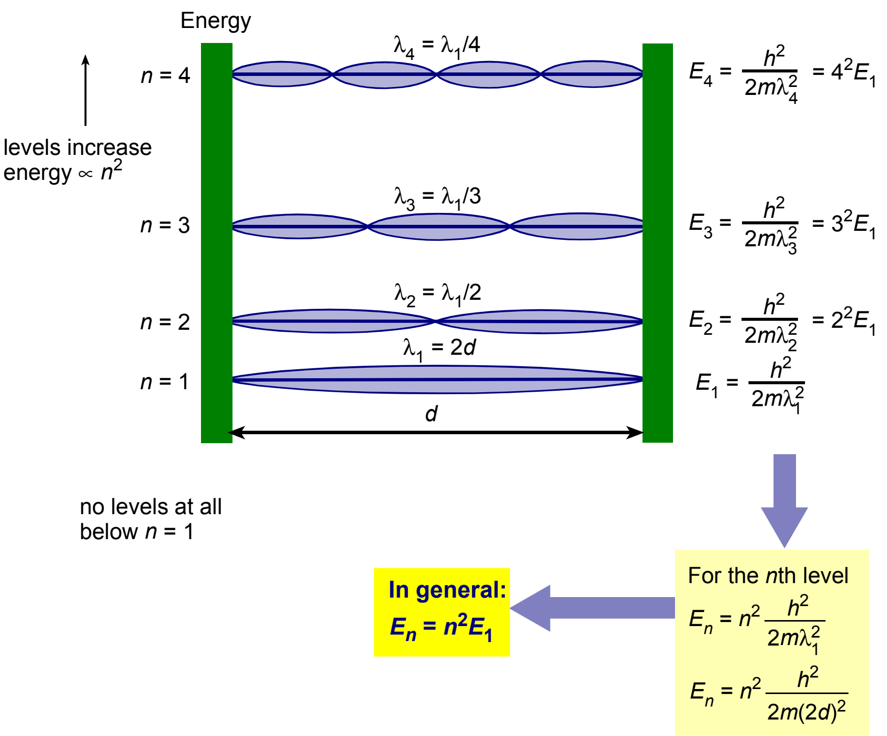
Standing waves and energy levels

A guitar–string atom

Simplify:

Change the 1/*r* potential well of the nucleus into a pair of fixed high walls





Each level has a quantum number *n*.
The energy depends on the quantum number

Note that in a real one-electron atom (hydrogen) the energy of the levels varies as $1/n^2$, not as n^2.

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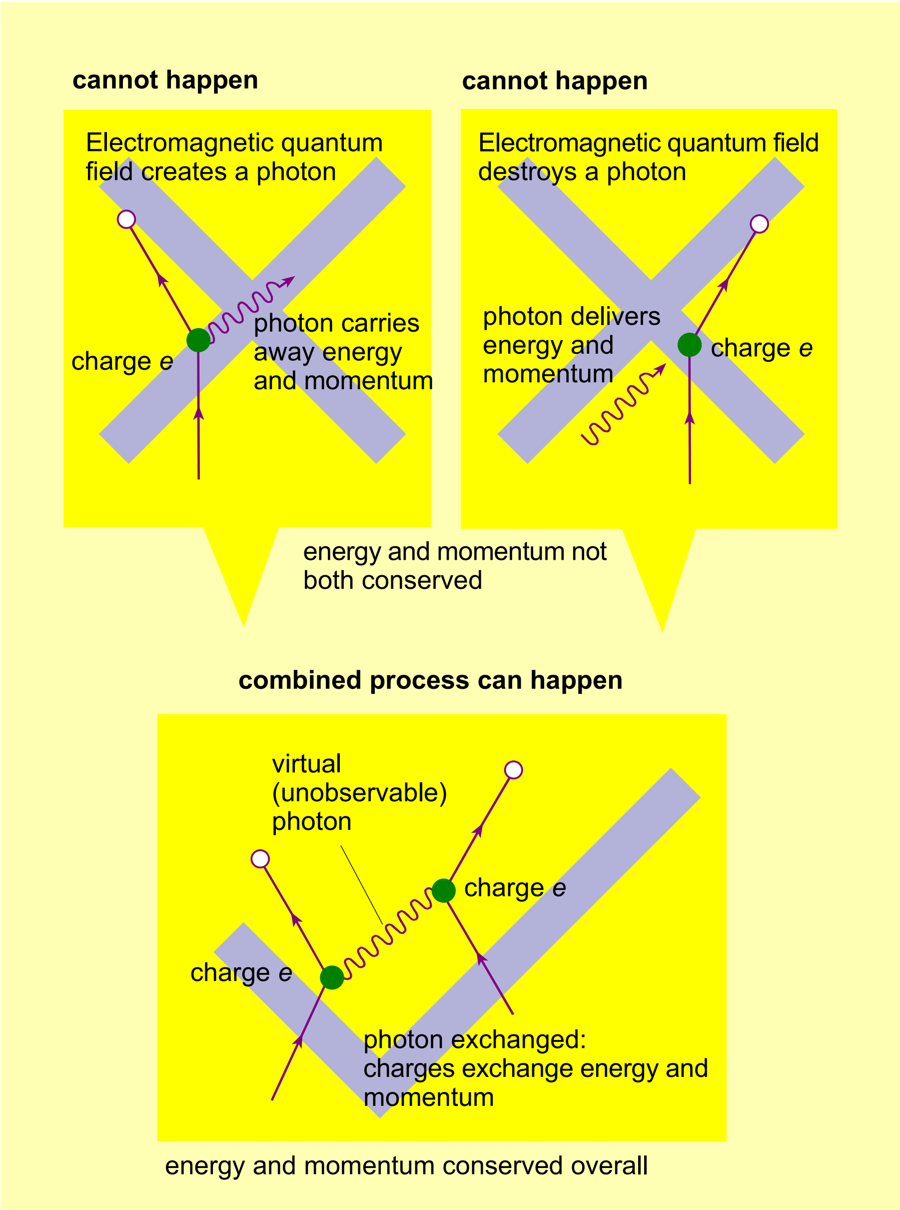
Exchange of photons

Quantum fields create and destroy particles



Forces between charges arise from the exchange of momentum through exchange of virtual photons

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Fundamental particles

The particles of the everyday world
Everything you touch around you is made of just these particles:

The world around you	Leptons	charge	rest energy / MeV	Quarks	charge	rest energy / MeV
	e^- electron	–1	0.511	u up	$+\frac{2}{3}$	5?
	ν_e neutrino	0	0?	d down	$-\frac{1}{3}$	7?

A complete picture of your world should include their antiparticles too:

The world around you	Leptons	charge	rest energy / MeV	Quarks	charge	rest energy / MeV
particles	e^- electron	–1	0.511	u up	$+\frac{2}{3}$	5?
	ν_e neutrino	0	0?	d down	$-\frac{1}{3}$	7?
antiparticles	e^+ positron	+1	0.511	$\bar{u}$ anti-up	$-\frac{2}{3}$	5?
	$\bar{\nu}_e$ antineutrino	0	0?	$\bar{d}$ anti-down	$+\frac{1}{3}$	7?

To account for all known matter, the pattern of a pair of leptons and a pair of quarks repeats three times:

Generation	Leptons	charge	rest energy / MeV	Quarks	charge	rest energy / MeV
1 The world around you	e^- electron	–1	0.511	u up	$+\frac{2}{3}$	5?
	ν_e neutrino	0	0?	d down	$-\frac{1}{3}$	7?
2	μ^- muon	–1	106	s strange	$-\frac{1}{3}$	150?
	ν_μ muon-neutrino	0	0?	c charmed	$+\frac{2}{3}$	1200?
3	τ^- tau	–1	1780	b bottom	$-\frac{1}{3}$	4700?
	ν_τ tau-neutrino	0	0?	t top	$+\frac{2}{3}$	90 000?

The other particles that make up the world are the bosons, the carriers of interactions:

interaction	force carrier	electric charge	rest energy / GeV	explains
electromagnetism	photon	0	0	Everyday interactions including all chemistry
weak interaction	Z^0 W^+ W^-	0 +1 –1	93 81 81	Radioactive decays; changing particle nature
strong interaction	8 different 'colour combinations' of gluons	0	0	What holds nucleons and mesons together
gravity	'graviton'	0	0	Conjectured, but not detected

The hunt is on for another particle, the Higgs boson, which is thought to be responsible for particles having mass.

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