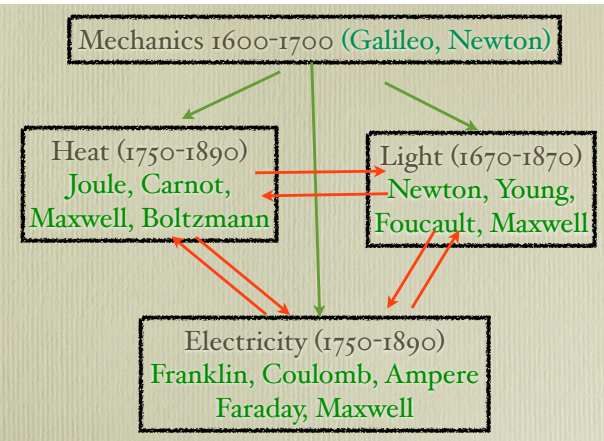
The End of Certainty

Peter Watson

First picture of single xenon atoms (1989)



All fundamental Discoveries in Physics have already been made, and subsequent development will be in the sixth place of decimals Michelson (1895)

PW

Basis of Success

- Newton's Laws of Motion valid for everyday objects,
- but also for very large
- Falling Apple ➠ Planets ➠ Galaxies
- and very small
- Conservation of Momentum and Energy ➠ Kinetic Theory of gases ➠ Heat

PW

Or Common Sense

- The layer of prejudices we acquire before we are sixteen" A. Einstein
- So what could go wrong?

PW

Energy

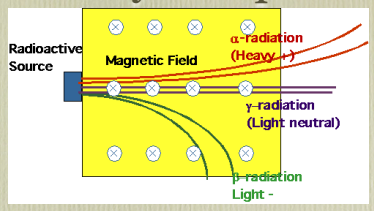
- Human sized objects: energy in joules
- Energy you get by dropping 1 kg from 10 cm
- Will measure energy in electron-Volts (eV)
- 1 electron-volt (eV) = 1.6×10^{-19} J
- 0.00000000000000000016 J
- most chemical processes involve energies of a few eV per molecule

PW

X-rays

- Röntgen (1895)
- Very penetrating rays produced by vacuum tube
- passes through solids, fogs photographic plates
- very short-wave radiation ($\lambda \sim 1$ nm)

Radioactivity Becquerel (1896)



- "Something" penetrating given off by certain materials (e.g. uranium salts).
- consists of a mixture
- (alpha) α-rays ~heavy, positively charged
- (beta) β-rays ~ light, negatively charged
- (gamma) ɣ-rays ~ neutral, light

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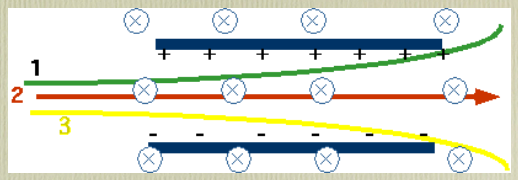
Discovery of Electron

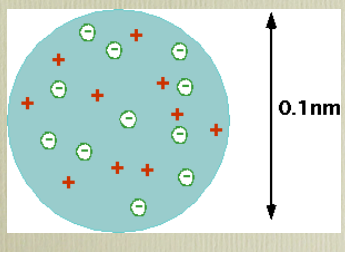


- J. J. Thomson (1899) measured properties of "cathode rays" with "velocity separator":
- suggested made of negatively charged particles called electrons
- electrical and magnetic fields both accelerate particles
- by balancing them can measure charge/mass

PW

Discovery of Electron

- Millikan (1909) measured charge of electron
- and hence found mass = 9.1×10^{-31} kg
- mass of H. atom = $1.67\ 10^{-27}$ kg
- (Thomson) proposed currant bun model of atom,: electrons imbedded in positively charged material.



PW

- Subsequently saw that
- α-rays = helium nucleus
- β-rays ~ electrons
- ɣ-rays ~ X-rays (but higher energy)
- Note we will use ɣ (gamma) as the universal symbol for a photon

PW

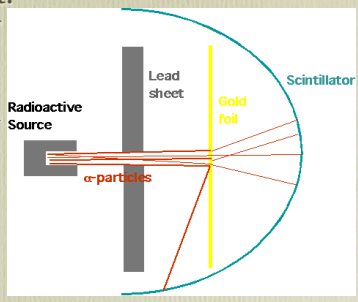
Problems:

1. What is this radioactivity that Becquerel discovered?
2. Why is the electron so much lighter than an atom?
3. What is the positive "stuff" that must be in the atom?

PW

The Nucleus (Rutherford 1909)

- Lead block with radium salt: α-particles are produced by radium,
- collimated to narrow beam
- pass through gold foil and are
- detected by scintillator (produces spark of light when hit by charged particle



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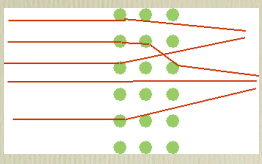
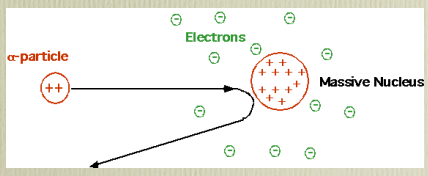
- Expected to see most of them deflected by a small angle
- Discover some deflected by more than 90°
- How could this happen?
- must hit something very small and very heavy





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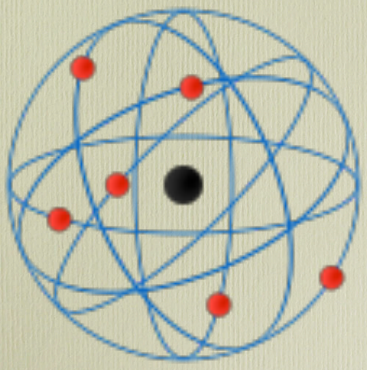
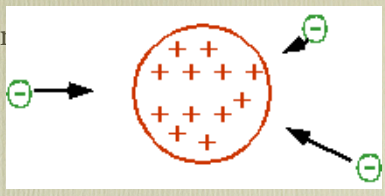
- Gives us something like our "child's model" of atom
- Electrons move round tiny heavy nucleus



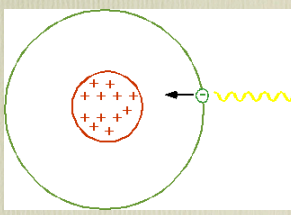
PW

- Why don't the electron fall into nucleus?



Maybe electrons are in orbit

But an accelerating charge emits E.M. radiation, so orbiting electrons would lose energy.



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Why

1. don't the electrons fall into nucleus?
2. are all atoms the same?
3. do specific atoms emit radiation of definite wavelength?
4. do we get emission and absorption spectra?

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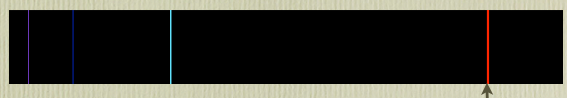
Back to hydrogen

Planck's constant $h = 4.1\times10^{-15}$ eV s



$\lambda = 656$ nm

$f = c/\lambda = 4.57\times10^{14}$ Hz

$E = hf = 1.89$ eV

- Note that since each line has a definite λ
- the photon must have a definite energy
- so energies must be "hidden" in the atom

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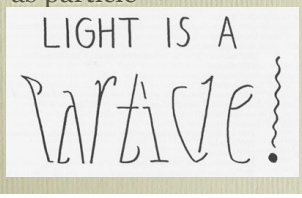
The Bohr atom (Bohr 1917)

- First Model for Hydrogen atom: explains
- Spectrum : This implies only photons of certain definite energies are emitted . . .
- Rutherford's observation of massive nucleus
- Stability
- Bohr model of electron in orbit round nucleus lets us explain spectrum of H but not other atoms

PW

But you told me light was a wave.....! What is light?

- Particle? Newton, Descartes
- Wave? Young, Huyghens
- Yes? Planck, Einstein
- Light travels as wave, but arrives and departs as particle



Douglas R. Hofstadter

Wave-Particle Duality
De Broglie (1924)

- You cannot ask:
- Is light a wave or a particle?
  answer is "yes"
- so maybe electron (particle) has some wave properties.....

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- What is wave-length of electron?
- de Broglie guessed for an electron wavelength $\lambda=h/mv$
- if v = 1000 ms^{-1}, ➠ λ = 500 nm (like yellow light!)

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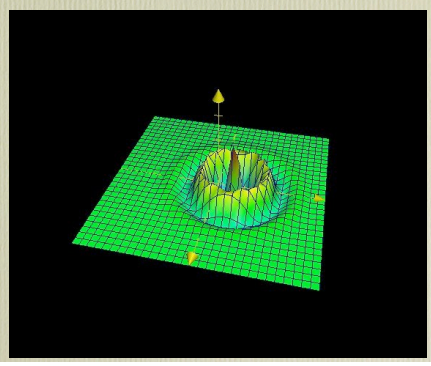
- Wave - particle duality:
- All fundamental (i.e small!) particles also act like waves (what is an electron?...)
- waves act like particles.
- or a wavicle!



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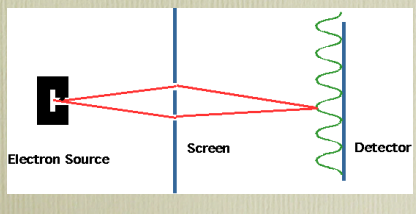
Is it true?

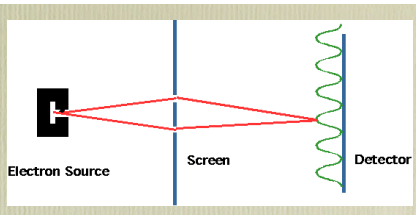
- A simple experiment is now possible:
- the electron analog of Young's slits.
- Very low energy electrons pass through slits
- hit detector (e.g. photo plate) and give 2-slit interference pattern

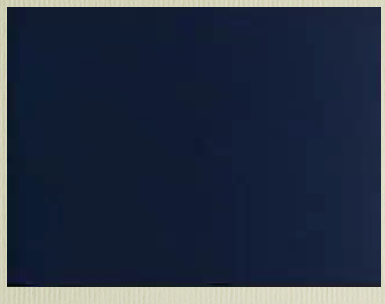


PW

- We can now do this with electrons:
- Very low energy electrons pass through slits and hit detector (e.g. photo plate) and give 2-slit interference pattern

You can even watch how it builds up, one electron at a time





- G.P. Thompson carried out series of experiments using weaker and weaker sources, until he had less than one electron in apparatus at any one time
- Pattern unchanged:
- i.e. **not** one electron interfering with second, but one electron interferes with itself.
- Huh?

Note in passing JJ Thompson discovered the electron was a particle.
GP Thomson was his son
He discovered it was a wave!

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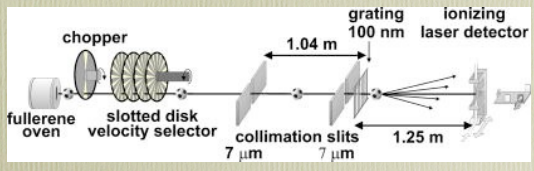
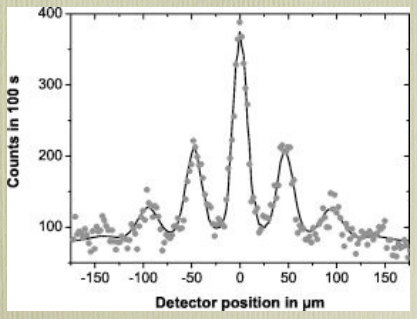
- A dramatic recent example uses a buckyball C_{60}
- Apparatus uses a diffraction grating:velocity v = 117 ms^{-1}



Nairz, Arndt, and Zeilinger

But

- A buckyball C_{60} has a $\lambda \sim 10^{-11}$m
- its "size" is 100 times bigger (~ 10^{-9} m~ 1nm)



Nairz, Arndt, and Zeilinger

How can something be bigger than its wave?

Two tiny problems

1. Which slit did the electron go through??
2. What waves??

PW

Model for H. atom must explain

- This implies only photons of certain definite energies are emitted . . .
- Rutherford's observation of massive nucleus
- Stability

$$\frac{1}{\lambda} = R\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

$$n = 1 \Rightarrow m = 2,3,4.....$$
$$n = 2 \Rightarrow m = 3,4,5....$$
$$n = 3 \Rightarrow m = 4,5,6.....$$

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Let's build an electric solar system!

- De Broglie suggested that allowed orbits have an integral number of waves fitted into one orbit

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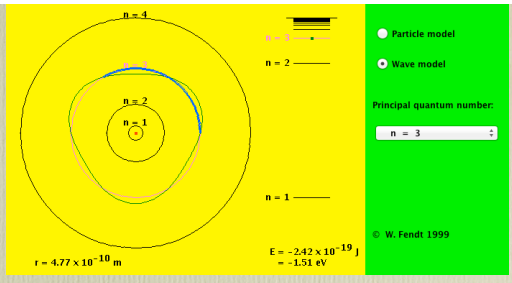
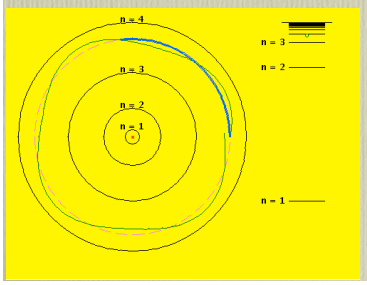
- Allowed n=3 level





Forbidden n ~ 3.5 level

Walter Fendt

- Repeating Newton's calculation for the falling moon (but changing gravity to electricity!)

Fit a given number of wavelengths into orbit

$$\lambda = \frac{2\pi r}{n} = \frac{h}{mv}$$

Gives radius of n'th orbit in agreement with knowledge of size of atoms

$$r_n = n^2 r_0, r_0 \approx 0.05nm$$

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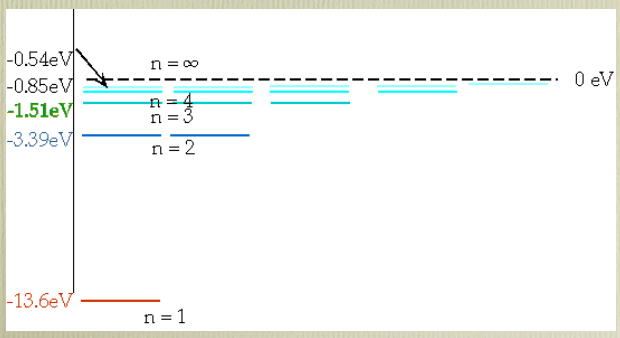
More importantly

- These levels have energies

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



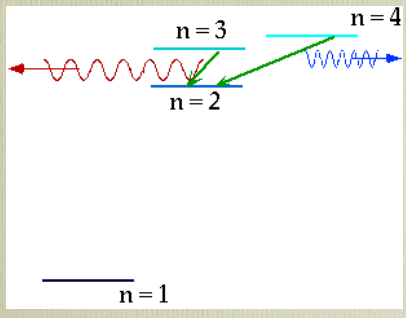
PW

So how does this explain the spectra?

- Since these are the only allowed levels, energy can only be emitted when electron jumps from one to the other
- e.g. n = 3 ➠ n = 2 gives
- E_3-E_2=(-1.51) - (-3.39) ≈ 1.89eV
- what wavelength light does this correspond to?
- photon which is red line in H.

PW

- e.g. n = 3 ➠ n = 2 gives photon which is red line in H.
- e.g. n = 4 ➠ n = 2 gives photon which is blue-green line in H.



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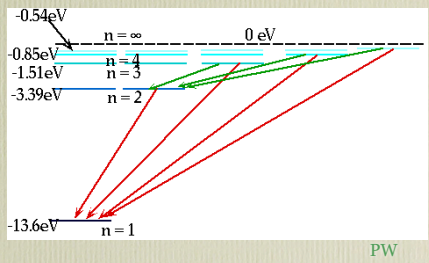
We get all the lines in the spectrum

- we get all the lines in the spectrum

$$\frac{1}{\lambda} = \frac{13.6}{hc}\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

- n = 1 Lyman (UV)
- n = 2 Balmer (Visible)
- n = 3 Paschen (IR)



PW

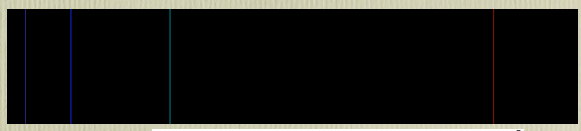
Are these ideas of energy levels so crazy?

- Think of a block of wood:
- How many energy levels does it have?
- What are its transitions?

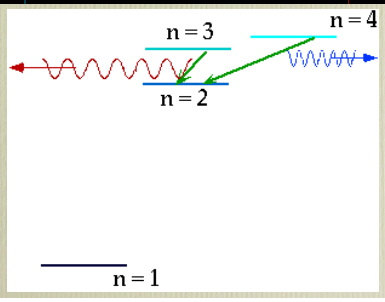
PW

Emission and absorption

- Electron makes transition from one level to lower one, ➡ emission line of definite energy



Emission



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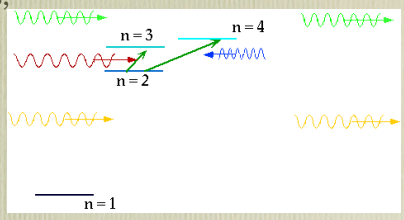
Emission and absorption

- However, if we have photons of all energies, one may have exactly the energy to raise the energy of an electron.
- Note that this will just remove one energy of photon from continuous spectrum.



Absorption

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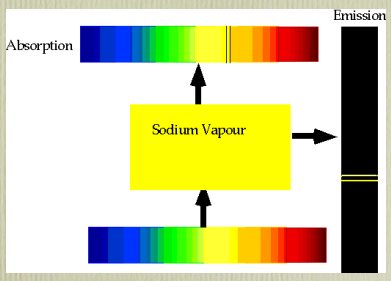
- With care, can see both absorption and emission at the same time.



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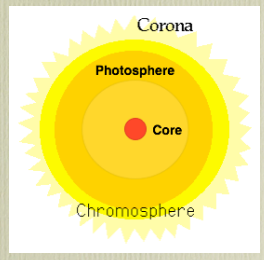
- Why did Fraunhofer see lines in the sun?
- The atoms in the chromosphere (the solar atmosphere) absorb the radiation from the solar "surface".



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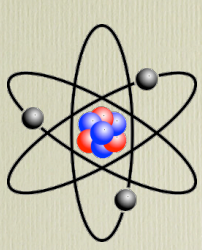
Other atoms

- are complicated!
- many electrons, so many energy levels
- Nucleus (e.g. lithium) has Z (3) protons and Z (3) electrons so
- Deepest energy level has
- $E \sim (Z-1)^2\ 13.6$ eV



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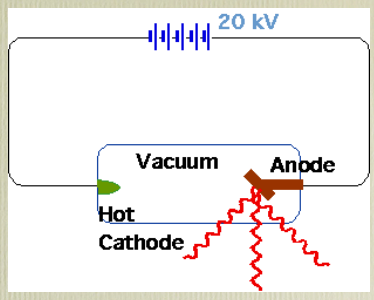
X-rays

- Electron accelerated



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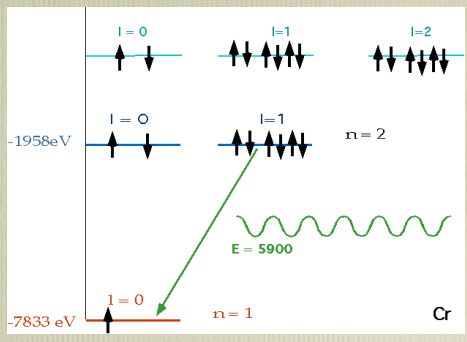
- Electron collides with atom, knocks out electron in lowest energy level,
- leaves vacancy for electron in higher level to fall into
- e.g Chromium: (Z = 24)



SO X-rays are just very energetic photons

PW

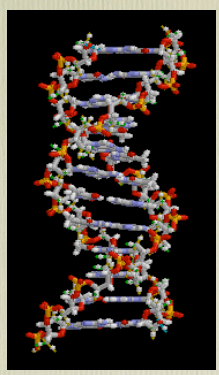
Why are X-rays (and UV) bad for you?

- Typical energy of chemical bond 1 - 10 e.V. cannot be broken by visible light, but can be broken by U-V

PW

Why are X-rays (and UV) bad for you?

- e.g. DNA is two interlocked coils of amino-acids
- X-rays (1000 e.V) break chain
- U-V (~ 10 e.V) causes thiamin to bond to other coil (dimer) so cannot replicate.



PW

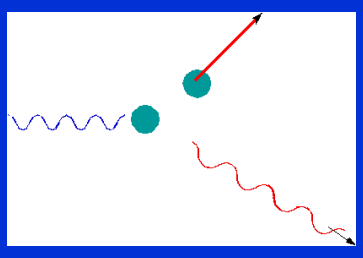
Alexander Patti

1. Why does ElectroMagnetic Radiation with a shorter wavelength have more penetrating power? (Thicker blocks of lead are required to stop it.)

PW

Photons!

1. Short wavelength photons have higher energy, so are likely to penetrate further
2. Wil scatter off electrons without being absorbed



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So haven't we learned a lot!

- So with the (in principle) simple assumption that waves have particle-like properties and particles have wave-like properties, we have understood all of the problems that arose at the turn of the century.

PW

Only part of quantum mechanics: can also understand (e.g.)

- Antimatter (PHYS 5602)
- Solids and liquids: e.g why copper is a good conductor and plastic is a lousy one (PHYS 4508)
- Nuclear forces (why don't they simply fall apart, why uranium is radio-active, but not lead) (PHYS 3606)
- Transistors and hence integrated circuits (PHYS 4508)

PW

- Light in fibres (PHYS 4204)
- Stars: how long will the sun last,and what will happen to it (PHYS 4203
- Superconductors (why some materials conduct electricity perfectly) (PHYS 4508)
- Lasers (PHYS 4208)
- Magnetic Resonance Imaging (MRI) PHYS 5203

Since quantum mechanics works so well, maybe we shouldn't worry about what it actually means.....

PW

Two tiny problems

1. Which slit did the electron go through??

2. What waves??

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