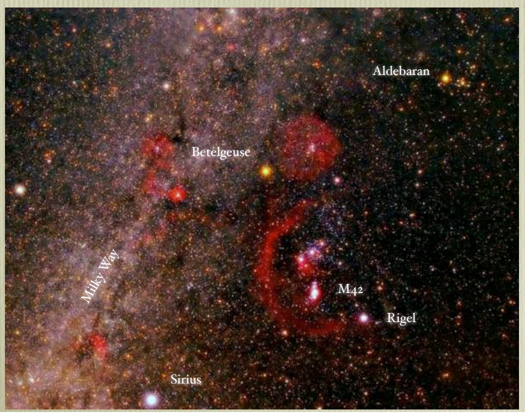
The End of Certainty



Peter Watson

"What I can say is there are many ways to surveil each other now, unfortunately, including microwaves that turn into cameras, etc,"

Kelly-Anne Conway

Two tiny problems

- Microwave pictures aren't very good...

Microwaves are the only household appliance designed to stop ANY radiation escaping

---

Sharon Glotzer has made a number of caree
discoveries, each one the kind "that com
the way you look at the world," she
to say, 'Wow, I need to follow th
Glotzer uses computer simu
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You heard it here first!

https://www.quantamagazine.org

- Jakob stepped back to admire what he had written last: the concise equations of an ideal mass point moving under the influence of elastic forces. How beautiful classical physics is!

Night Thoughts of a Classical Physicist
McCormach

- but note the hubris!
- Jakob stepped back to admire what he had written last: the concise equations of an ideal mass point moving under the influence of elastic forces. How beautiful classical physics is! (Was! He meant before the Quantum Theory)

Mechanics 1600-1700 (Galileo, Newton)

Heat (1750-1890)
Joule, Carnot, Maxwell, Boltzmann

Light (1670-1870)
Newton, Young, Foucault, Maxwell

Electricity (1750-1890)
Franklin, Coulomb, Ampere
Faraday, Maxwell

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

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

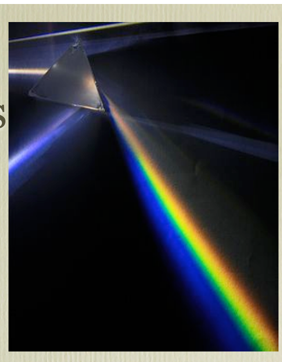
PW

Or Common Sense

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

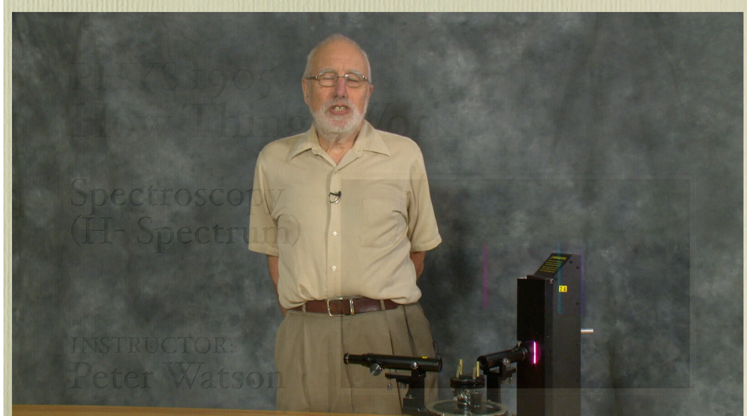
PW

Prism splits light into its constituent colours



- Red (wavelength of 800 nanometres = 0.8 microns)
- Green ~520 nm
- Blue ~400 nm

Hydrogen spectrum



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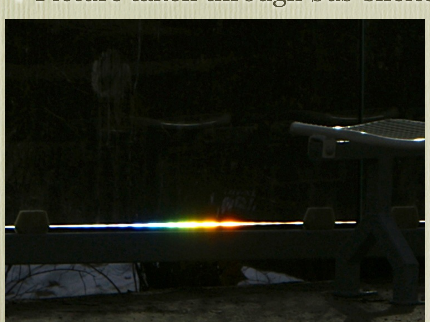
Fraunhofer

- Sunlight split by prism shows dark lines
- Picture taken through bus-shelter glass!



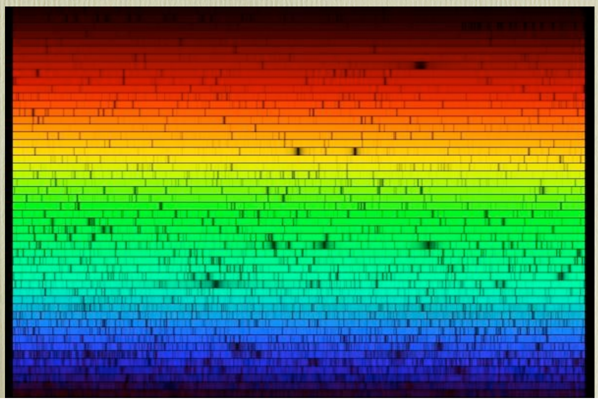
Monika-Landy-Gyebnar

Light from the sun

Etienne Rollin

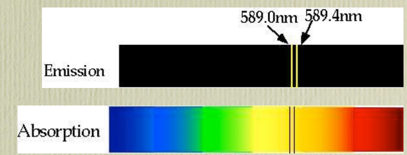
Fraunhofer (1817)

- Found black lines superimposed on sun's spectrum.
- This is the sun's spectrum "folded up"



- Heated gases give characteristic wavelengths, e.g. Sodium

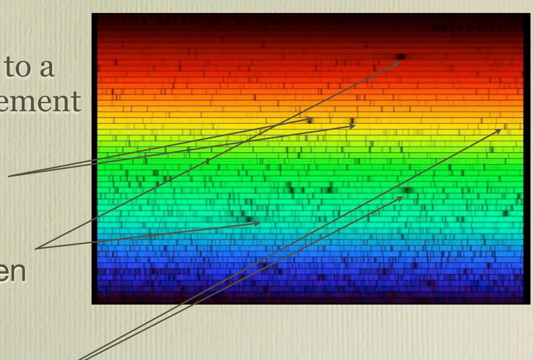
- Can match dark lines in solar spectrum to bright emission lines:



- We can look at the light from the sun
- Each line is corresponds to a particular element

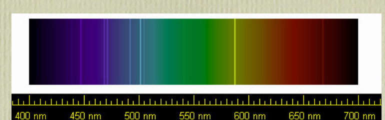
e.g sodium

e.g hydrogen



- But these lines didn't correspond to anything

Until we discovered Helium



- Discovered in sun in 1868, on earth in 1895
- unlike any other element (no compounds)

In what follows, we are in the realm of very small

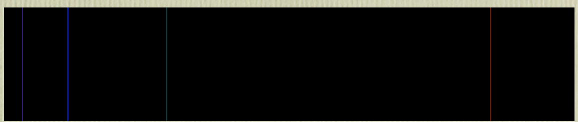
- Size of atoms ~ 0.1 nanometre = 10^{-10} m = 0.0000000001 m
- Size of nucleus~ 5 femptometre = 5×10^{-15}
- Times ~ 1 picosecond = 10^{-12}s

Energy

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

Hydrogen

- Simplest atom



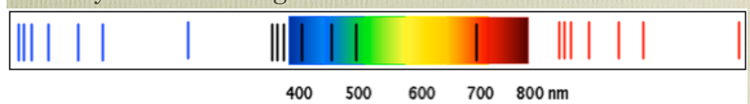
Emission

Absorption

Balmer found a very simple formula for this

$$\frac{1}{\lambda} = R\left(\frac{1}{n^2} - \frac{1}{m^2}\right), m = 3,4,5,6\ldots, m > n$$

- Paschen discovered the spectrum goes to the UV
- Lyman found it goes to the IR



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Problems

1. What gives the formulae?
2. Why do atoms only emit certain wavelengths?
3. How are absorption and emission related?

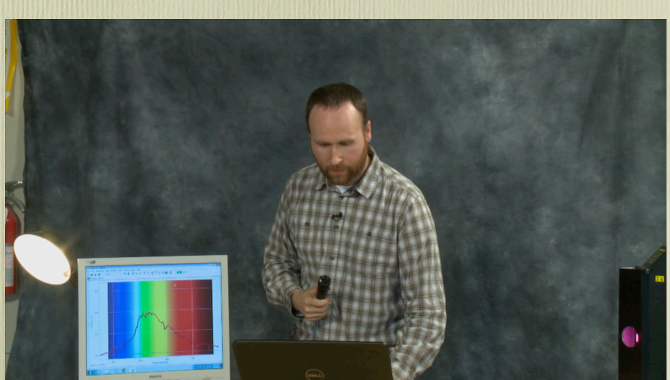
PW

And the most important thing we learn is from barbecues

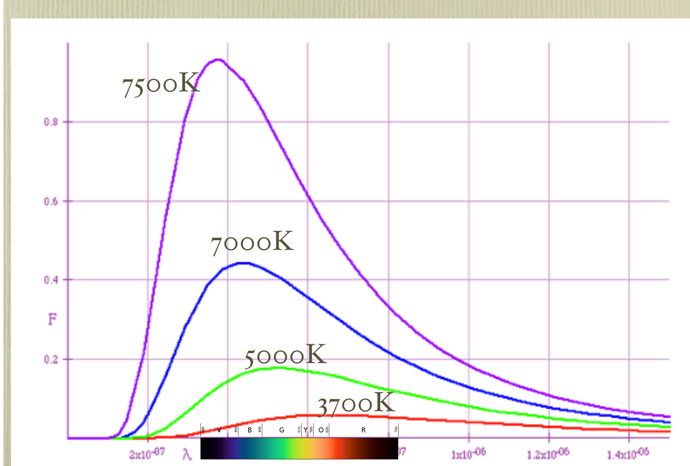
- What's hot and what's not: roughly
- red is 800°C
- orange is 1500°C
- yellow is 2000°C
- blue is 15000°C
- X-rays are 1 million °C

Text

Done a bit more systematically



Etienne Rollin



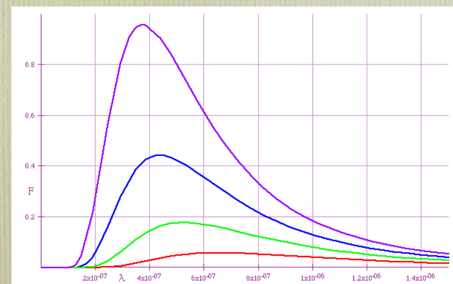
Text

The fundamental laws of barbecues

- Stefan- Boltzmann law
- double the temp, 16 times the energy

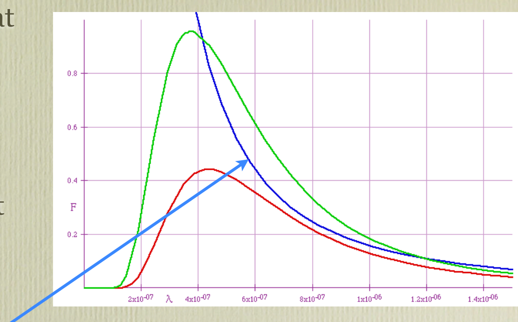
Text

- Wien's law: peak wavelength decreases with temp
- i.e. as we heat up objects, they go
- black ⇒ red ⇒ orange ⇒ yellow ⇒ white



If we take waves at random, don’t expect we would get any particular wavelength

But there are a lot more short waves than long ones

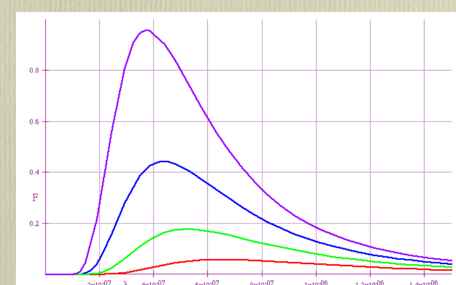


Get completely the wrong curve

Also: how can light have a temperature?

Planck (1900)

- Was trying to understand black body curve



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- Think of box of different atoms:
- velocities of each will be random, but will "average out" to give smooth curve.
- Energy is equally divided between different molecules on the average:
- also average energy increases with temperature.

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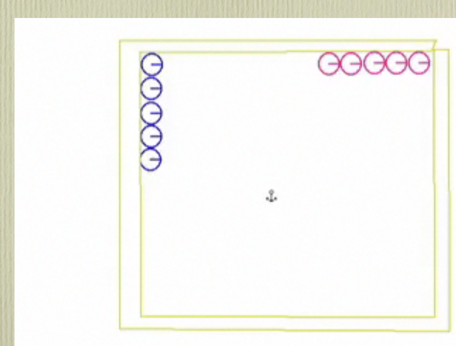
- Collisions redistribute the energy: heavy molecules move slower on average

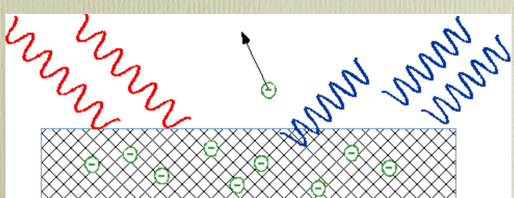


- But suppose light is a particle...
- Planck (1900) suggested that E.M. radiation is emitted in lumps of energy (quanta) which became known as "photons"

- Energy of photon increases with frequency
- $E = hf$
- Photons are also particles with a difference:
- Always travel at c (speed of light) and can easily be created and destroyed.
- At room temperature average photon has E ~1/40 eV (same as average energy of gas molecule)
- photon of yellow light has energy ~ 2 eV

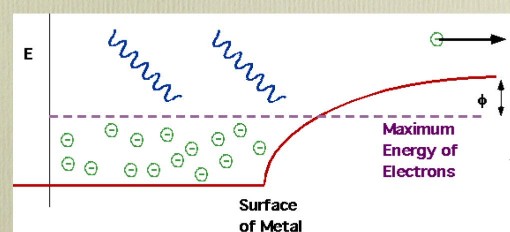
Photo-electric Effect

- Light hitting metal produces (small) electric current
- Electrons are kicked
- Current depends on colour of light & kind of metal
- blue (small λ, large f) gives high energy electrons
- red (large λ, small f) may not give any



Einstein and the Photo-electric Effect

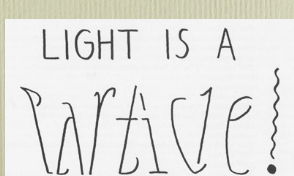
- Photons must carry energy (obviously light has energy: that's how you get a sun tan!)
- Einstein (1903): light is absorbed in quanta (photons)
- most energetic electrons in metal need extra boost to escape:



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 **interacts** as particle



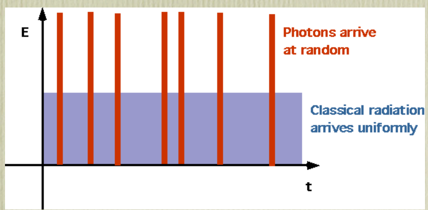
Douglas R. Hofstadter

What is light?

Particle? Newton, Descartes
Kerner: Look at the edge if the shadow. It is straight like the edge of the wall that makes it. This means light is ..little bullets. Bullets go straight.
Hapgood (Tom Stoppard)

Wave? Young, Huyghens
Kerner: When you shine a light through two little gaps, side by side, you don't get particle patterns like for bullets, you get wave patterns like for water. The two beams of light mix together
Hapgood (Tom Stoppard)

- So we have to take photons seriously!
- Electrons are ejected as soon as light strikes (no need for energy to accumulate), since photons arrive randomly



- Photons "average out" to give same total energy

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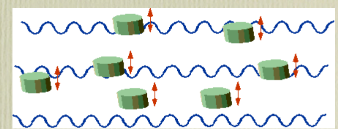
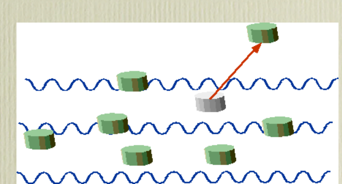
- The first of many paradoxes:
- How could we detect water-waves if we couldn't see water?
- "Classical" corks bob up and down



- "Quantum" corks are either stationary or ejected.



Why are we not aware of discrete arrival of photons?

- Energy of "orange" photon ~ 2eV

- A 60W bulb produces $2x10^{19}$ photons each second , so gap in time ~ 10^{-20} s
- Our eyes take 1/50 s to respond

PW

Problems:

1. How can light be both a wave (spread-out) and a particle (concentrated) at the same time?

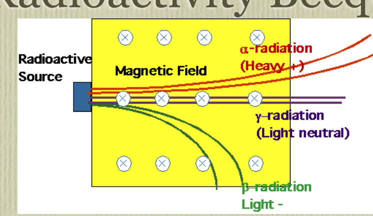
PW

X-rays

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

- Note that the shorter the wavelength, the more like a particle, so X-rays are usually treated only as particles.

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) γ-rays ~ neutral, light

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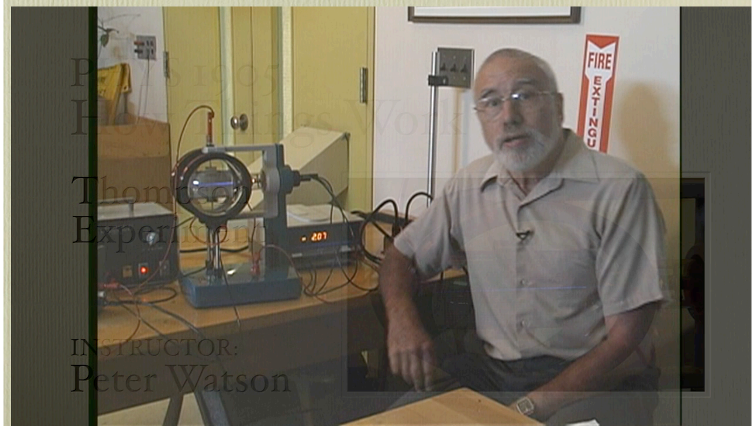
Discovery of Electron
The Thomson Experiment

PW

Thomson and the electron



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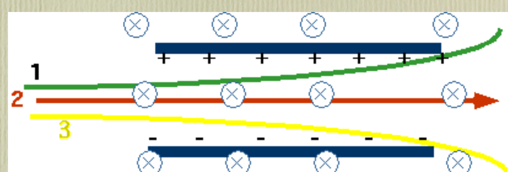
Discovery of Electron

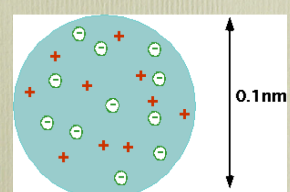


- J. J. Thomson (1899) measured properties of "cathode rays" with "velocity separator":
- suggested made of negatively charged particles called electrons
- electrical and magnetic fields both accelerate particles
- by balancing them can measure charge/mass

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.



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- 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

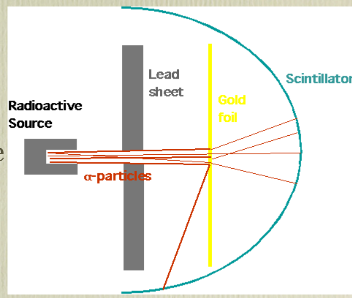
Problems:

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?

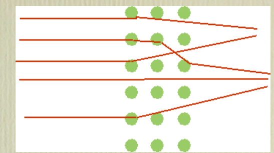
PW

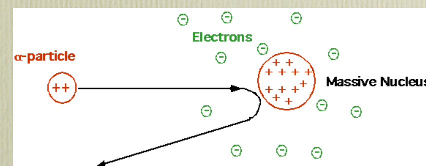
The Nucleus (Rutherford 1909)

- 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

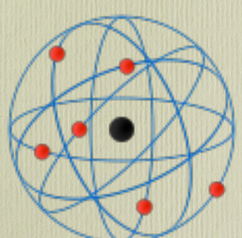


- Expected to see most of them deflected by a small angle
- Discover some deflected by more than 90°
- How could this happen?
- must hit something very small and very heavy

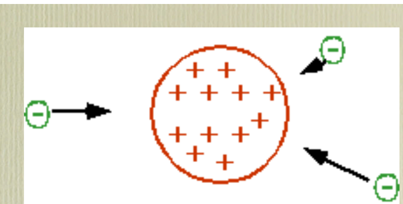




- Gives us something like our "child's model" of atom
- Electrons move round tiny heavy nucleus

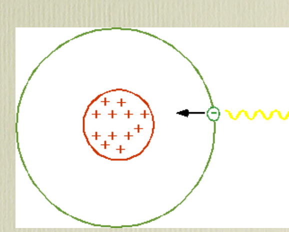


- Why don't the electrons fall into nucleus?



Maybe electrons are in orbit

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



Questions

1. Why don't the electrons fall into nucleus?
2. Why are all atoms the same?
3. What's this nucleus thing anyway?

Back to hydrogen

λ = 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

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.....

PW

- What is wave-length of electron?
- if v = 1000 ms^{-1}, ➠ λ = 500 nm (like yellow light!)

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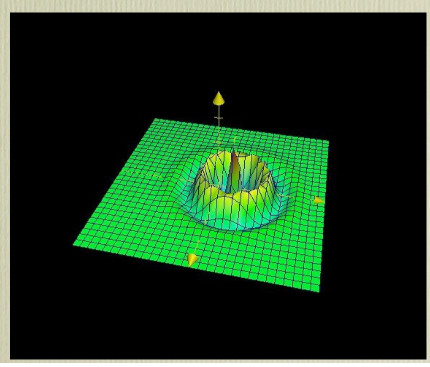
- Wave - particle duality:
- All fundamental (i.e small!) particles also act like waves (what is an electron?...)
- waves act like particles.
- or a wavicle!



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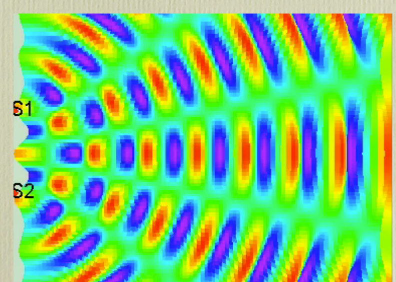
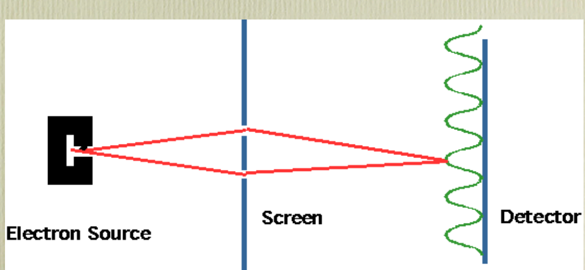
Is it true?

- A simpler experiment is now possible: the electron analog of the ripple tank!



Wikisource

- Very low energy electrons pass through slits
- hit detector (e.g. photo plate) and give 2-slit interference pattern, just like light



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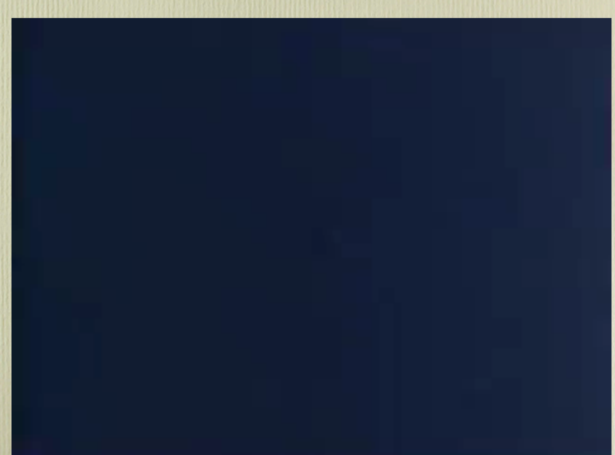
You can even watch how it builds up, one electron at a time

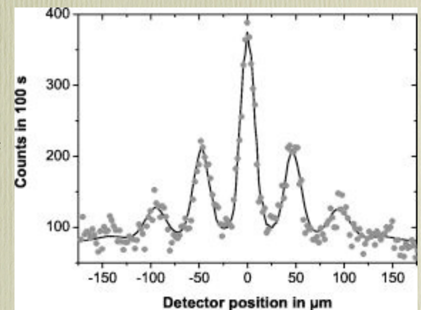


- A dramatic recent example uses a buckyball C_{60}
- Apparatus uses a diffraction grating: velocity v = 117 ms^{-1}

But

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

How can something be bigger than its wave?



Nairz, Arndt, and Zeilinger

Two tiny problems

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

PW

Model for H. atom must explain

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

PW

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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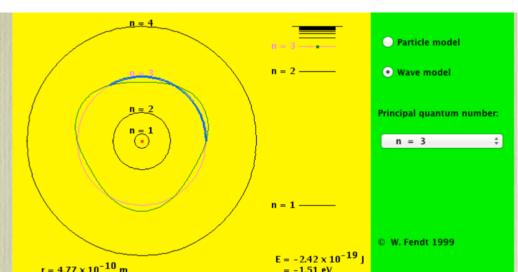
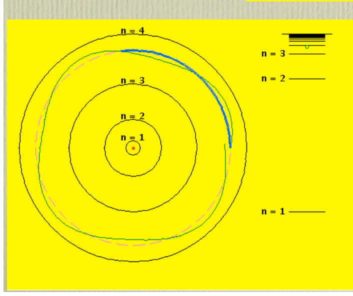
- Allowed n=3 level





Forbidden n ~ 3.5 level

Walter Fendt

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

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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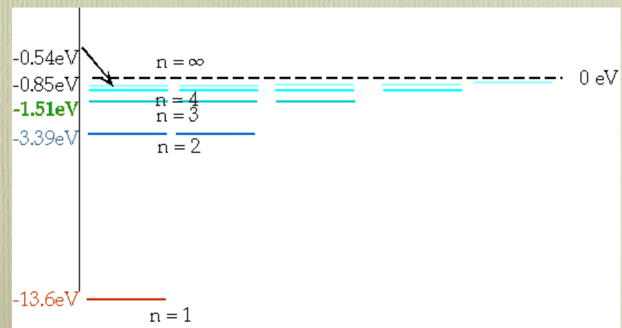
More importantly

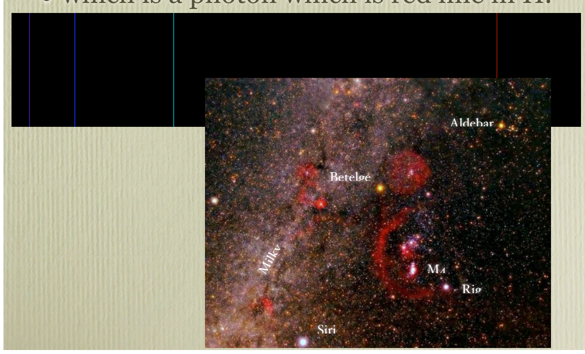
- These levels have energies $E_n = -\frac{13.6}{n^2} eV$



PW

So does this explain the spectra?

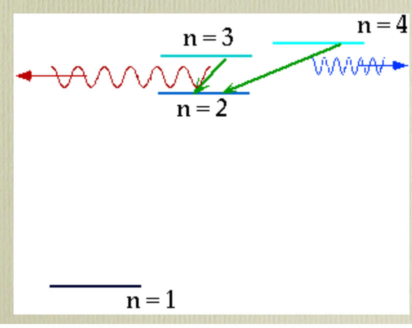
- electron jumps from one to the other, kicks off photon
- e.g. n = 3 ➠ n = 2 gives E_γ=≈ 1.89eV
- which is a photon which is red line in H.



Emission

PW

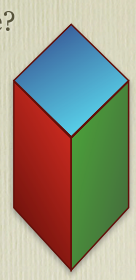
- e.g. n = 3 ➠ n = 2 gives photon which is red line in H.
- e.g. n = 4 ➠ n = 2 gives photon which is blue-green line in H.



PW

Are these ideas of energy levels so crazy?

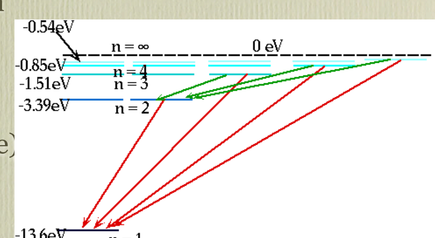
- Think of a block of wood:
- How many energy levels does it have?
- What are its transitions?



PW

We get all the lines in the spectrum

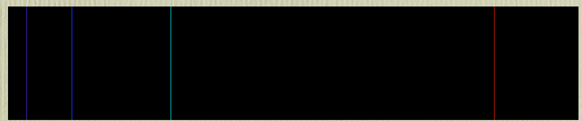
- we get all the lines in the spectrum
- n = 1 Lyman (UV)
- n = 2 Balmer (Visible)
- n = 3 Paschen (IR)



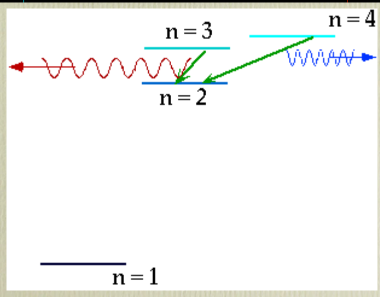
PW

Emission and absorption

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



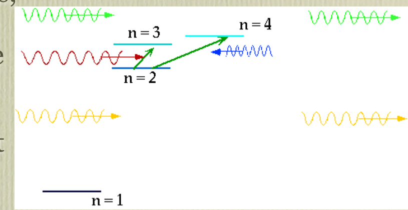
Emission

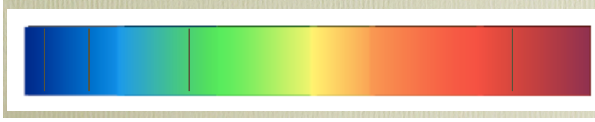


PW

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.

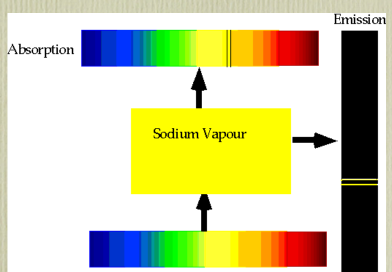




Absorption

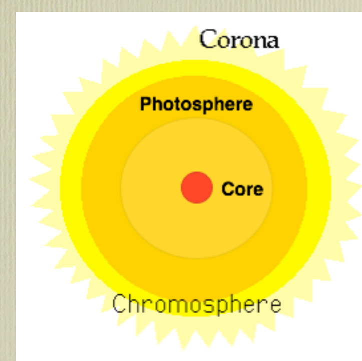
PW

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



PW

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



PW

Other atoms

- are complicated!
- many electrons, so many energy levels
- Nucleus (e.g. oxygen) has Z (8) protons so
- Deepest energy level has
- $E \sim (Z-1)^2\ 13.6$ eV

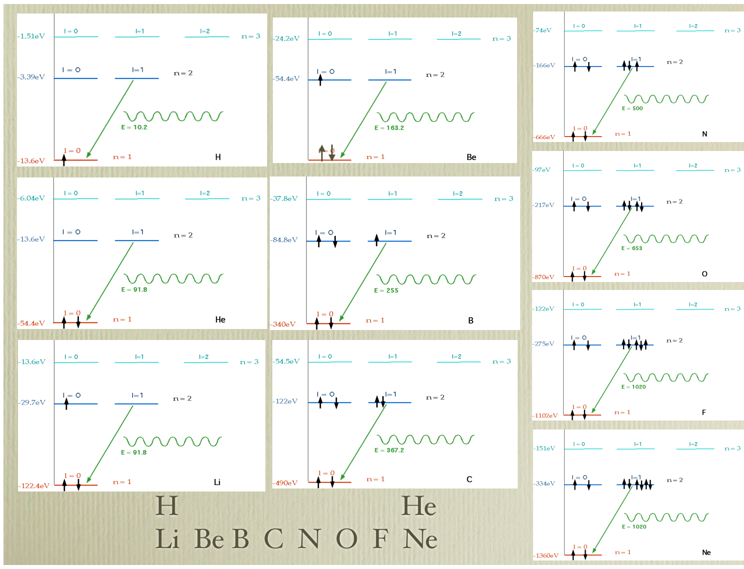
PW

Need one extra rule

Pauli showed particles with same properties (e.g. two electrons) cannot be in same state. i.e. for each level, we can put in 2 electrons

Allows us to understand periodic table: must have number of electrons = Z = charge on nucleus, and fill lowest energy levels first.

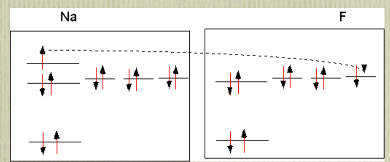
PW



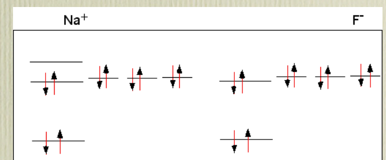
H He
Li Be B C N O F Ne

Not only do we understand Mendeleev, we understand chemistry!

- e. g. sodium-chloride (or sodium floride)

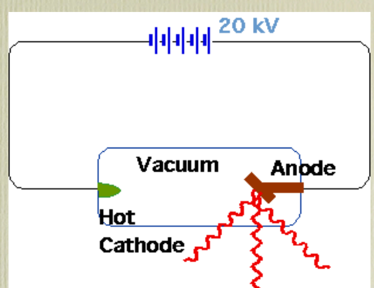


Kate McGarrigle



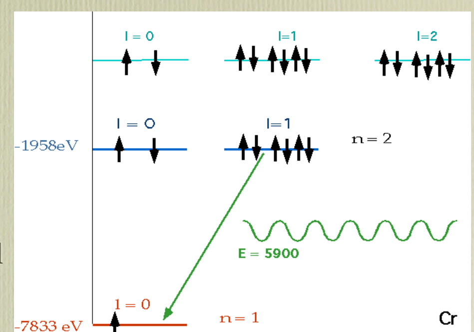
X-rays

- Electron accelerated



PW

- 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)

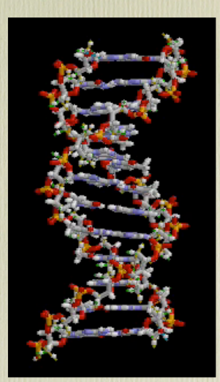


SO X-rays are just very energetic photons

PW

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

- 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

So haven't we learned a lot!

- With the simple assumption that waves have particle-like properties and particles have wave-like properties, we understand **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)

- 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.....

- No known theory can be distorted so as to provide even an approximate explanation [of wave-particle duality]. There must be some fact of which we are entirely ignorant and whose discovery may revolutionize our views of the relations between waves and ether and matter. For the present we have to work on both theories. On Mondays, Wednesdays, and Fridays we use the wave theory; on Tuesdays, Thursdays, and Saturdays we think in streams of flying energy quanta or corpuscles.

— Sir William Bragg

Two tiny problems

1. Which slit did the electron go through??

1. Which slit did the buckyball go through??

2. What waves??