Open book Test 2 Reminder

Test 2: Wednesday Lecture slot again : 10:00 am (one Hour test)

7th April 2021 (12th week)

Instructions : need you to position your "PC or handphone" cameras on yourselves for the Zoom.

MCQ & short Questions : If you have participated in all the (Lecture 9 to where we stop in week 11) Lectures & Tutorials (T3(a little), T4, T5) LumiNUS Forum and read the uploaded Relativity related essays/articles, it should be straightforward. (the pdf readings in LumiNUS should consolidate your learning)

Lecture 9

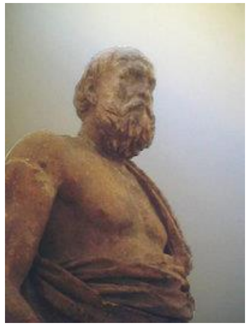
Classical Mechanics
to
Quantum Mechanics

What is Light (historical) ?

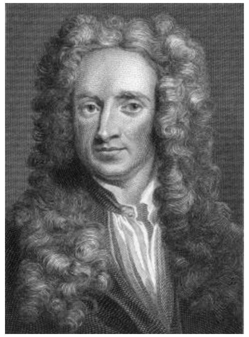
Plato: light consist of streamers emitted by the eye.

Euclid also held this view.

Pythagoras: believed that light emanated from luminous bodies in the form of very fine particles.



I. Newton, 1704: A stream of particles or corpuscles. He also knew light particles have certain wave properties too.



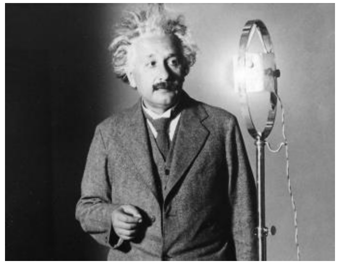
C. Huygens, 1678 : advocated a wave theory of light.

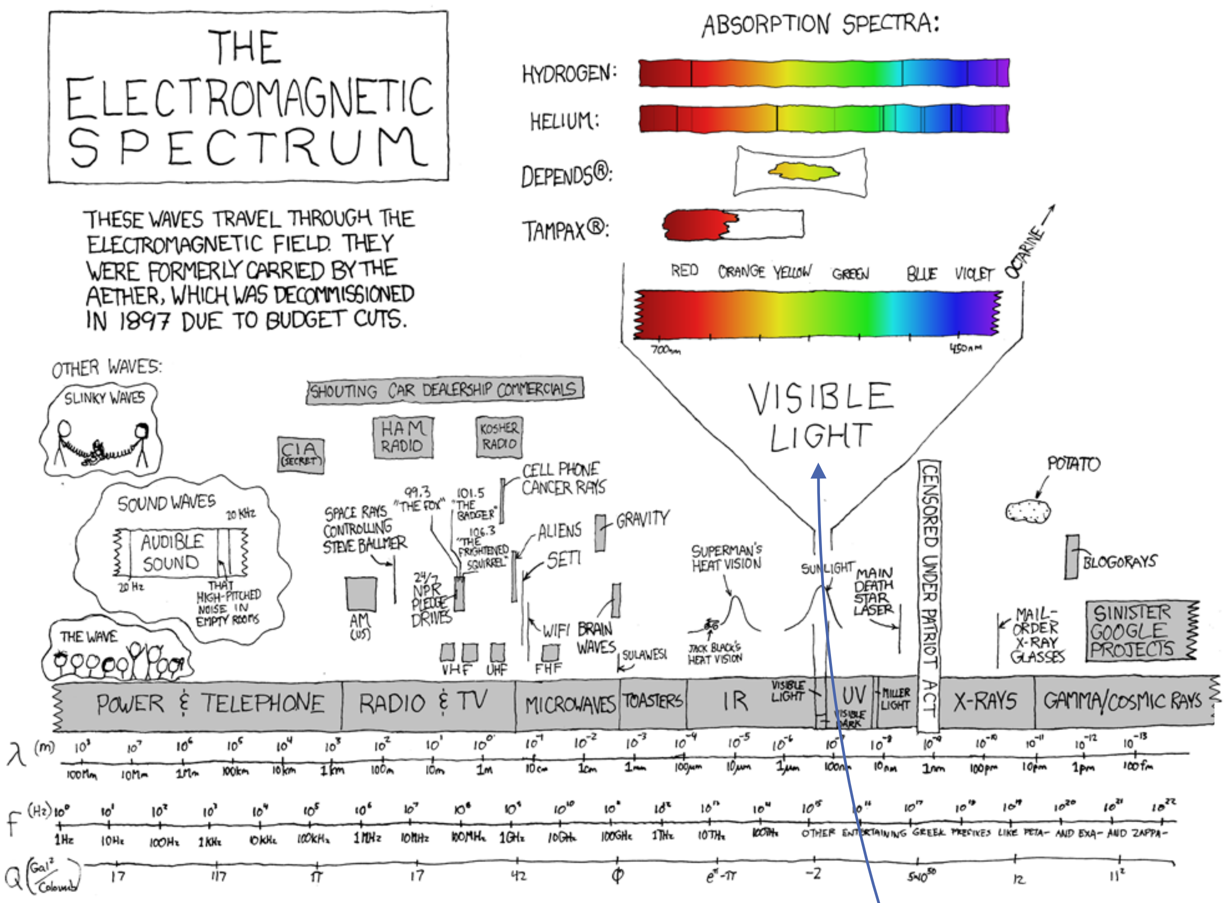
What is Light (historically) ?

T. Young, 1801: did the double slit experiment and finally "proved" (showed) that light is a wave phenomenon.

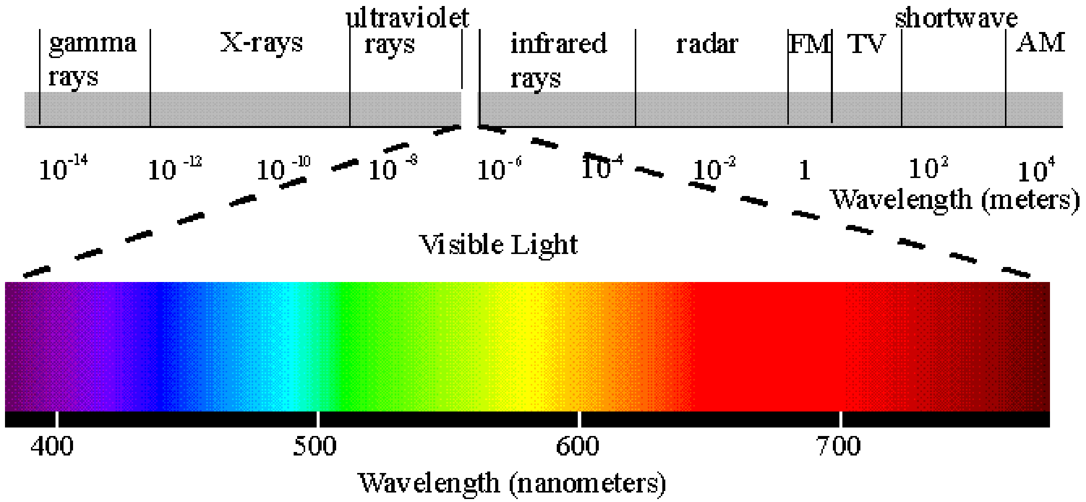
Maxwell, 1862 & Hertz 1891,: light is electromagnetic wave.

A. Einstein, 1905: light interacts with matter not in continuous fashion as envisioned by Maxwell but in tiny packets of energy that we now call photons.



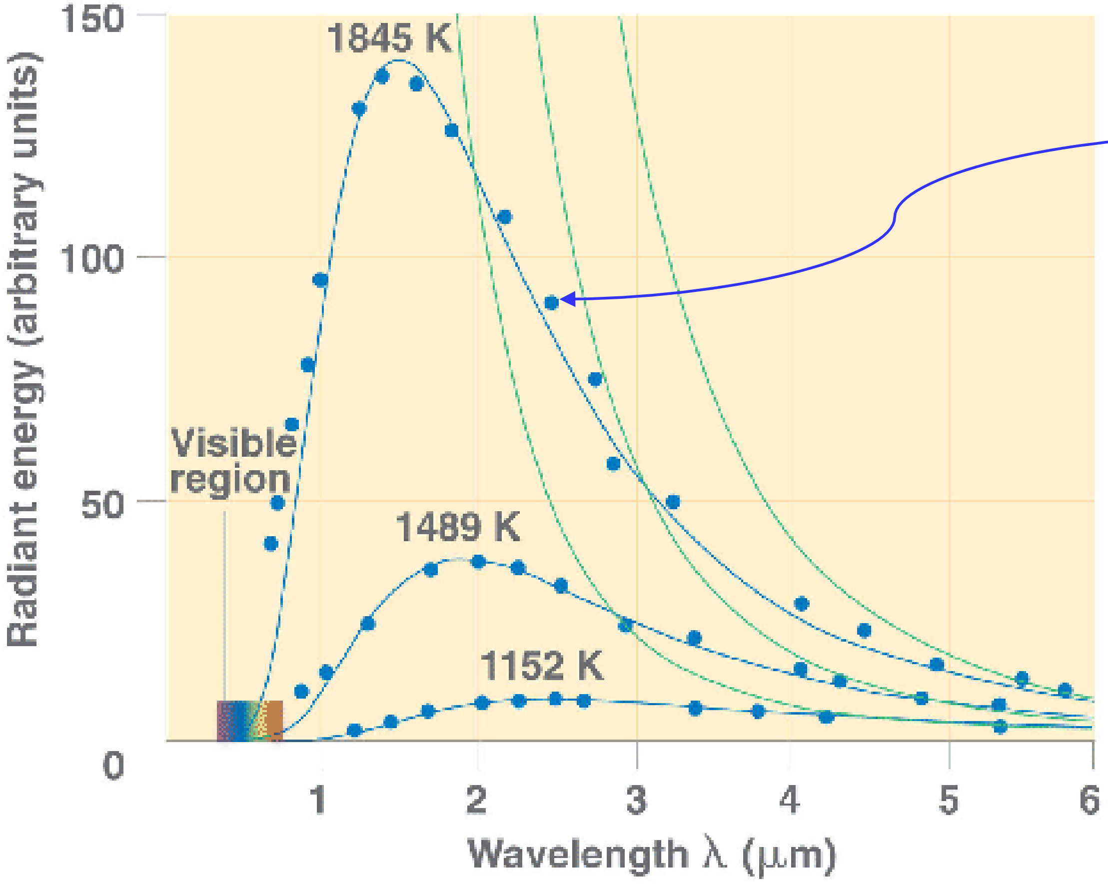

THE ELECTROMAGNETIC SPECTRUM
THESE WAVES TRAVEL THROUGH THE ELECTROMAGNETIC FIELD. THEY WERE FORMERLY CARRIED BY THE AETHER, WHICH WAS DECOMMISSIONED IN 1897 DUE TO BUDGET CUTS.
ABSORPTION SPECTRA:
HYDROGEN:
HELIUM:
DEPENDS®:
TAMPAX®:
RED
ORANGE
YELLOW
GREEN
BLUE
VIOLET
OCTARINE
VISIBLE LIGHT
OTHER WAVES:
SLINKY WAVES
SOUND WAVES
AUDIBLE SOUND
THE WAVE
SHOUTING CAR DEALERSHIP COMMERCIALS
CIA (SECRET)
HAM RADIO
KOSHER RADIO
CELL PHONE CANCER RAYS
SPACE RAYS CONTROLLING STEVE BALLMER
ALIENS
GRAVITY
SETI
SUPERMAN'S HEAT VISION
SUNLIGHT
MAIN DEATH STAR LASER
CENSORED UNDER PATRIOT ACT
POTATO
BLOGORAYS
MAIL-ORDER X-RAY GLASSES
SINISTER GOOGLE PROJECTS
WIFI
BRAIN WAVES
VHF
UHF
FHF
POWER & TELEPHONE
RADIO & TV
MICROWAVES
TOASTERS
IR
UV
X-RAYS
GAMMA/COSMIC RAYS

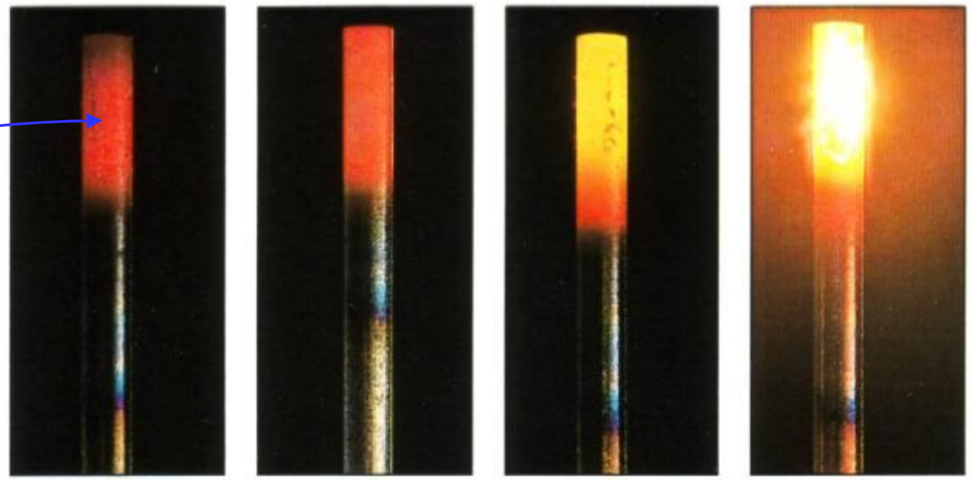
$$v = f\lambda$$


gamma rays
X-rays
ultraviolet rays
infrared rays
radar
FM
TV
shortwave
AM
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
Wavelength (meters)
Visible Light
400
500
600
700
Wavelength (nanometers)

One problem, 1

Surface Temperature of "Blackbodies"





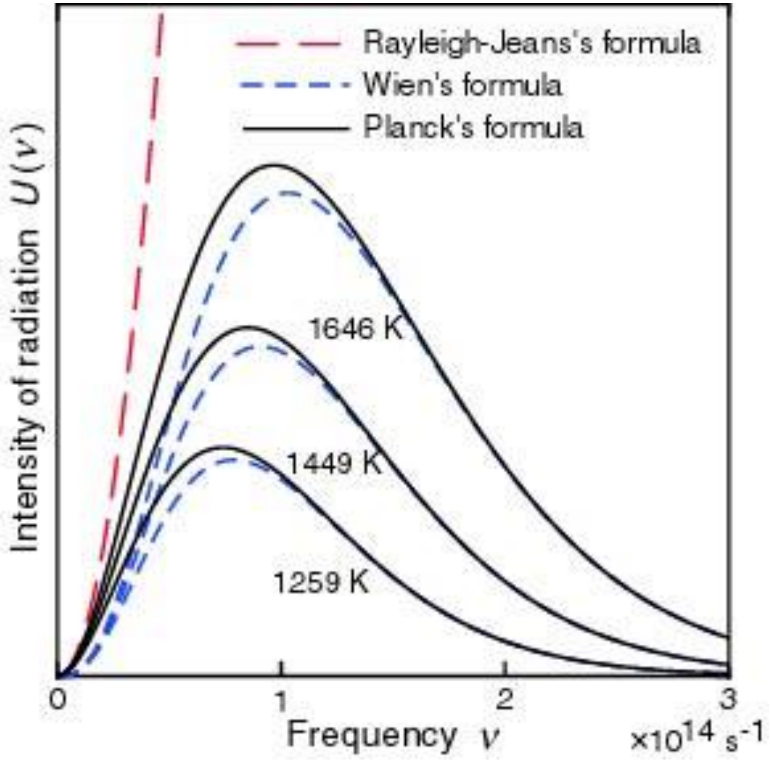
Red light
When the iron bar is heated, it begins to lose its original dark colouring and glow a dull red. The iron atoms emit light as the heat energy makes them vibrate.

Orange light
As the bar continues to be heated, the iron atoms vibrate more quickly. They now emit an even brighter light, which has changed in colour from red to orange.

Yellow light
The metal is now extremely hot and the tip of the iron bar glows a bright yellow in colour. However, the cooler parts of the bar still emit orange and red light.

White light
The bar has now been heated up to its melting point. The heat is so intense that the bar is white hot. If it could survive melting, the bar would shine blue-white.

Rayleigh-Jeans Law

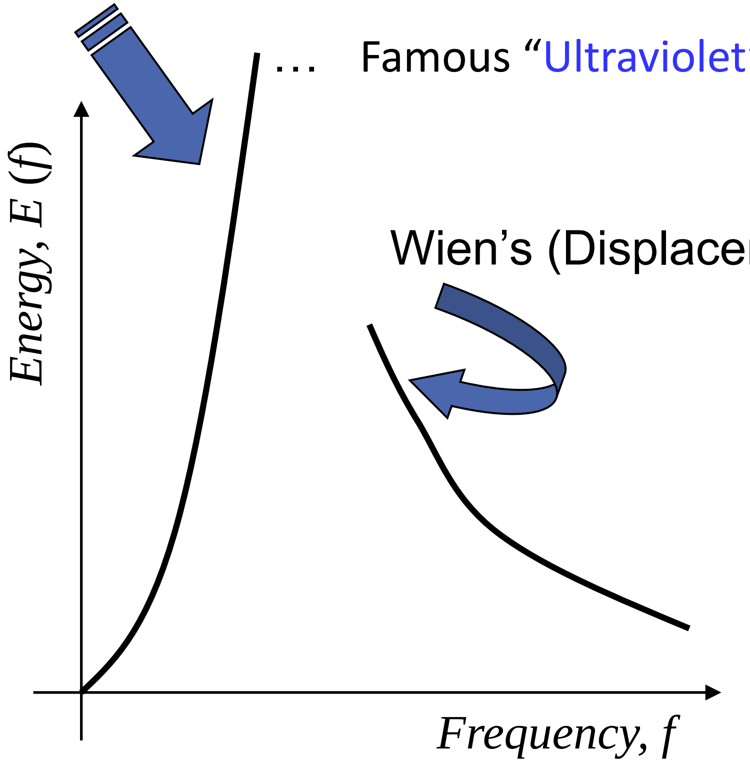


(Some books)

Sir James Jeans is a Famous Astronomer

… Famous "Ultraviolet" Catastrophe

Wien's (Displacement) Law



Wavelength and Frequency are related by $v = f\lambda \Rightarrow c = f\,\lambda$

Why is the Sky blue ?

Rayleigh discovered that light of different frequencies is scattered with different efficiencies.

The amount of scattering is proportional to f^4.

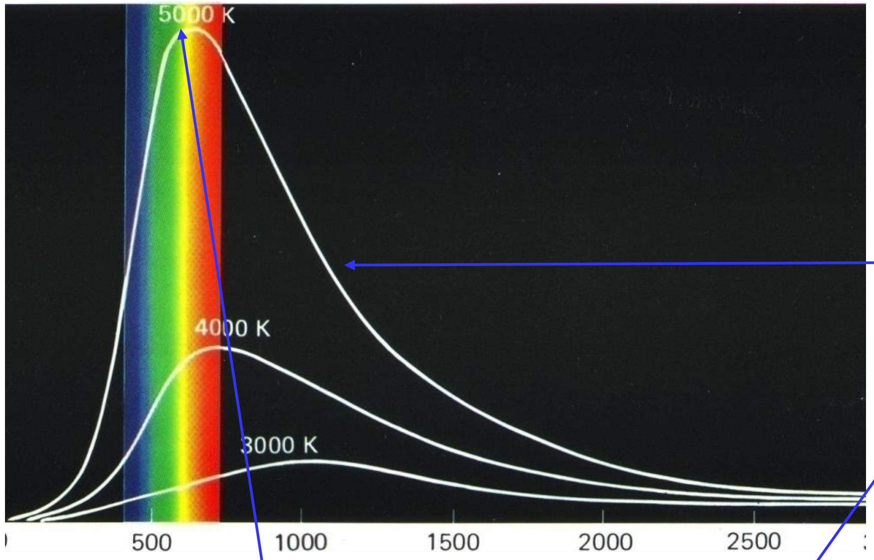
$$c = f\lambda$$

Do you know why red light can travel longer distances without being scattered ?

Why do astronomers use red light while attending to their telescopes at star gazing sessions ?

Why is the sea blue and setting sun orangy-reddish ?

Surface Temperature of Stars : “Blackbodies”

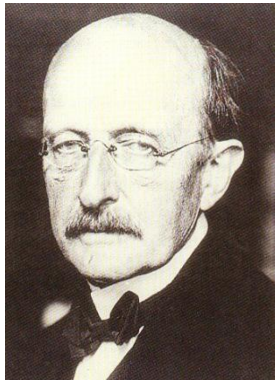


Energy (Intensity)

wavelength, λ

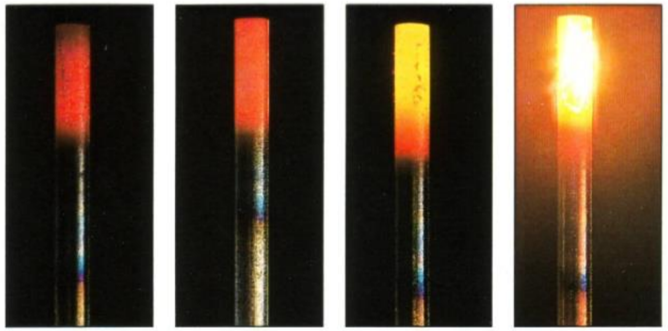
Planck’s Radiation Law for Black Bodies

$$\rho(f,T) = \frac{8\pi f^2}{c^3} \frac{hf}{e^{\frac{hf}{kT}} - 1}$$



Wien’s Law

$$\lambda_m T = 2.90 \times 10^{-3}\, mK$$



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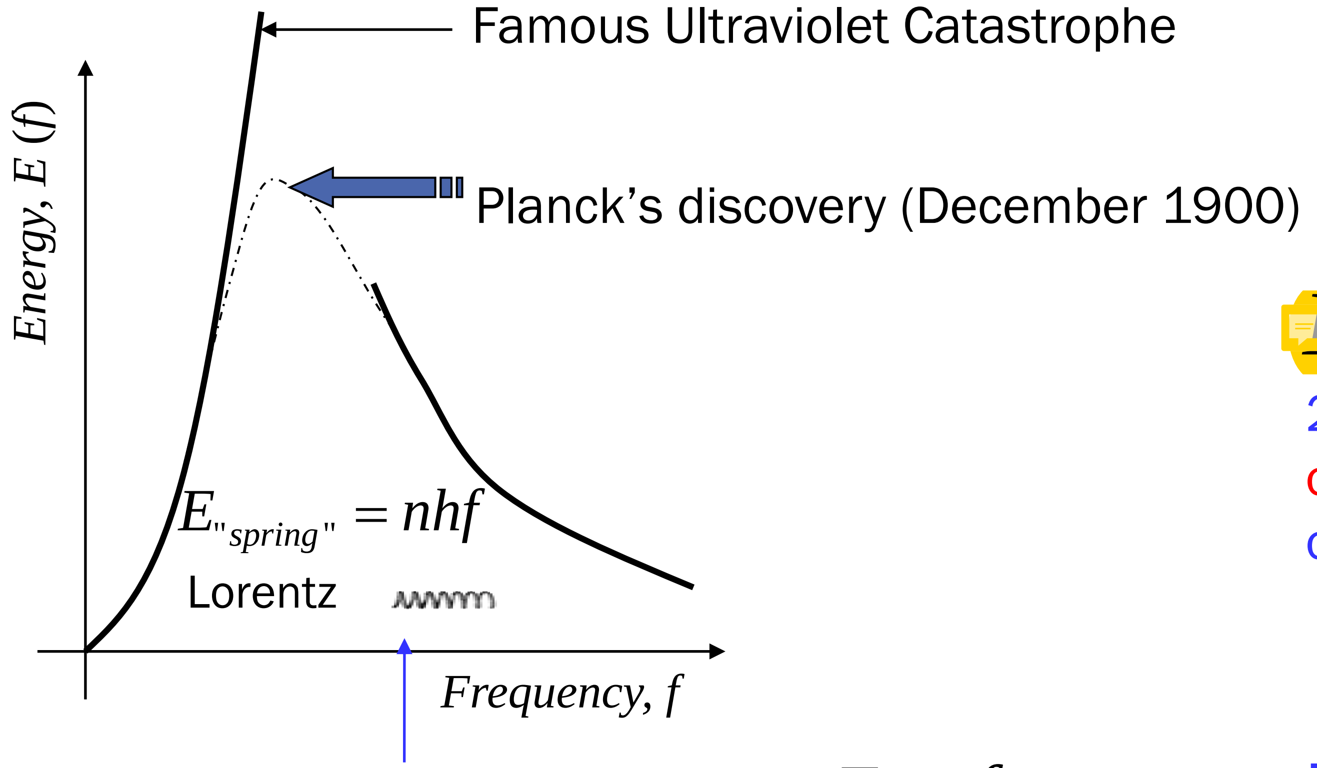
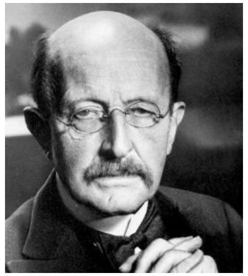
White light *The bar has now been heated up to its melting point. The heat is so intense that the bar is white hot. If it could survive melting, the bar would shine blue-white.*

Blackbody Explained

Christmas Present to the World !



Discovery: 1) Oscillator Energy is $E \propto f$ proportional to Frequency.



$$E = hf \qquad\qquad E = nhf$$

2) But must postulate that an oscillator of frequency can have only the energies

$$n = 0, 1, 2, 3, \ldots$$

Note: Only discrete values ...

Quantization ... quantized ...

Blackbody is a box of discrete "Springs"

In physics we call …
Oscillators

Education

"For everything that's lovely is/But a brief, dreamy, kind delight." - 'Never Give All the Heart', W. B. Yeats

William Butler Yeats

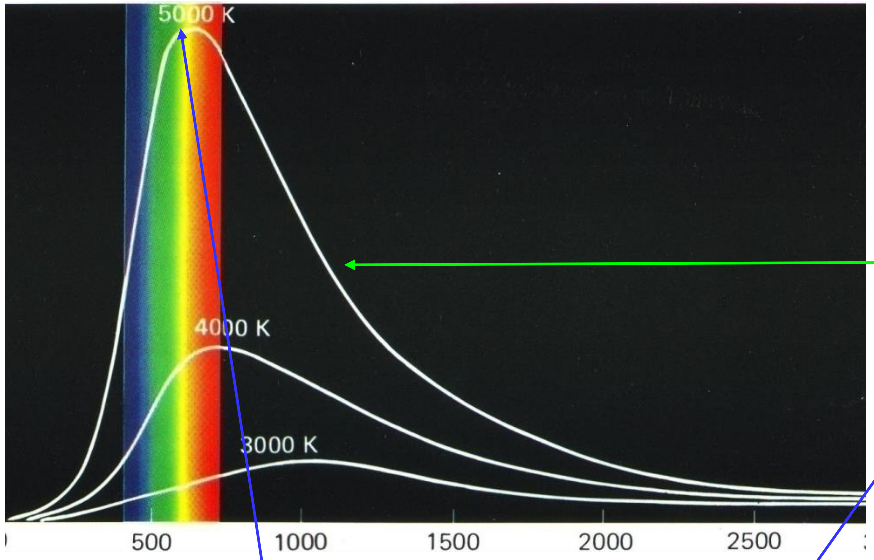
Education is not the filling of a pail, but the lighting of a fire.

William Butler Yeats

20th century poet and writer

Planck assumed that energy in matter is quantized, but that radiant energy is continuous. … later Einstein on the other hand, attributed quantum properties to light itself and viewed radiation (light) as a hail of particles.

Surface Temperature of Stars : “Blackbodies”



Energy (Intensity)

wavelength, λ

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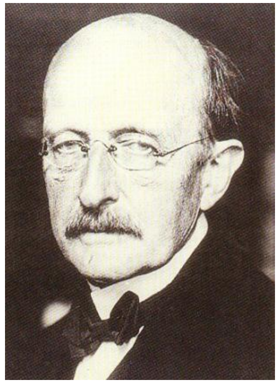

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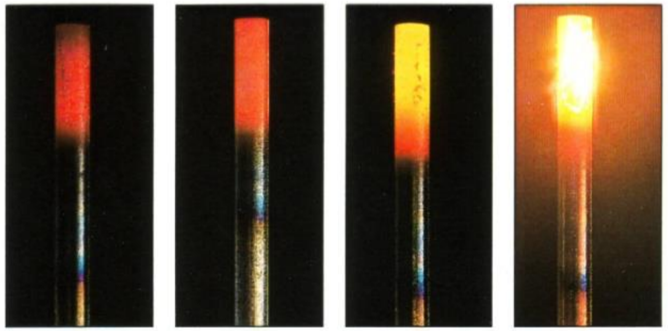

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How did Planck do it ?

Kirchhoff

Kirchhoff conjectured that a blackbody,

$$E_{BR}(f) = J(f,T)$$ Amount of radiation Energy

Where J does not depend on any particular body ... **Universal.**

He challenged Experimentalists / Theorists to determine the form J *that is :*

$$J(f,T) = \frac{c}{8\pi}\rho(f,T)$$

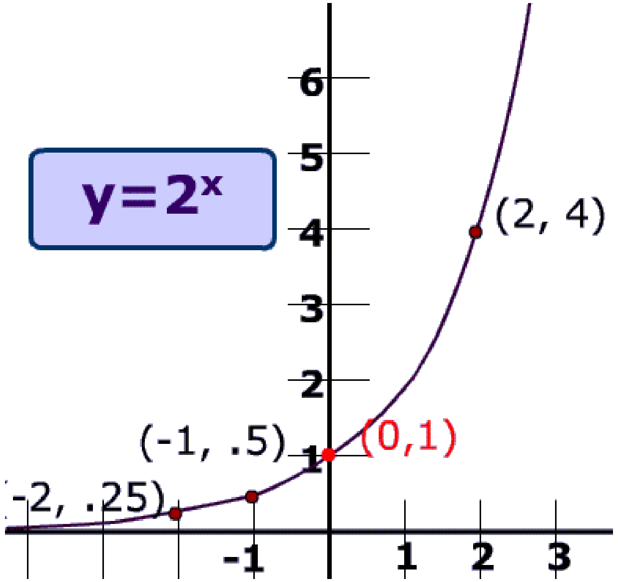
The Game Plan of that time was to come up with good **phenomenological** models for, which would satisfactorily explain blackbody experimental results (data).

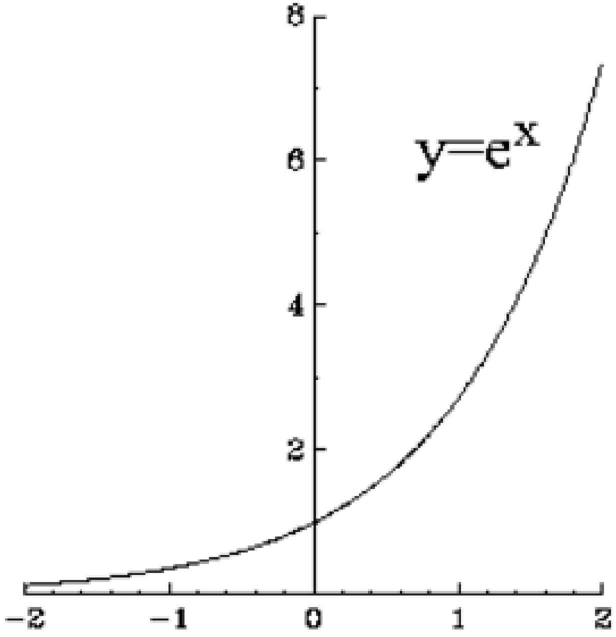
$\rho\ (f,\ T)$: energy per unit volume (energy density) inside the cavity or the radiation energy density. c is the usual speed of light.

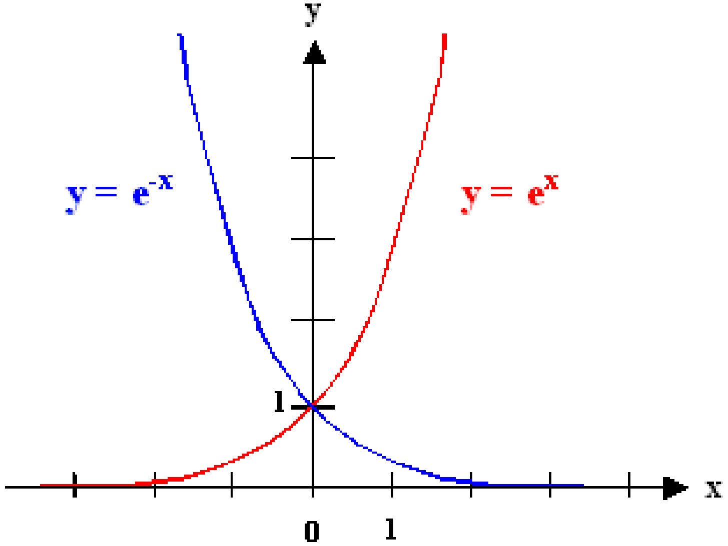
Recall Sec. School Math

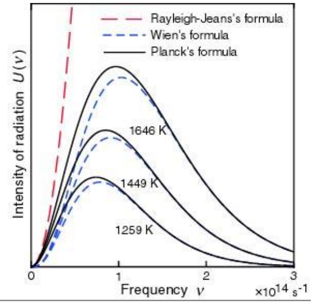
Exponential Functions

$Y = e^x$









How did Planck do it ?

$$\rho(f,T) = C_1 f^3 e^{-\frac{C_0 f}{T}} \quad (Wien's\ Law)$$

Good for high frequency f

$$\rho(f,T) = C_2 f^2 T \quad (Rayleigh's\ Law)$$

Good for low frequency f

called Ultraviolet Catastrophe

$$\rho(f,T) = C_3 f^2 e^{-(\frac{C_4 f}{T})}$$

Put a cut off function … basically putting on a switch.

There was an error ….
Rayleigh-Jeans Law

$$\rho(f,T) = \left(\frac{8\pi h}{c^3}\right) f^3 \frac{1}{e^{\frac{hf}{kT}} - 1}$$

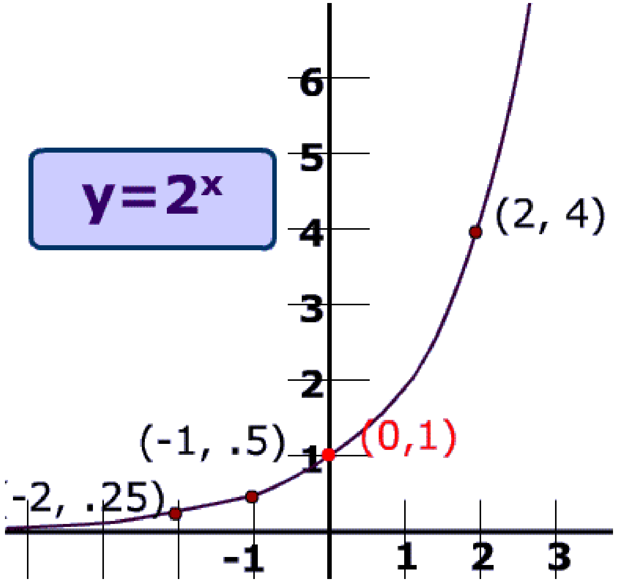
Planck’s Law in full glory

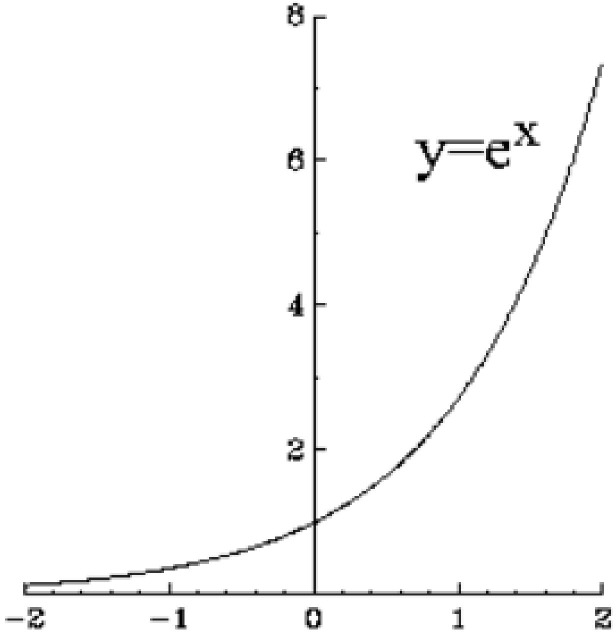
Planck scribbled this formula on a **post card and sent** to his friend Rubens, 1900

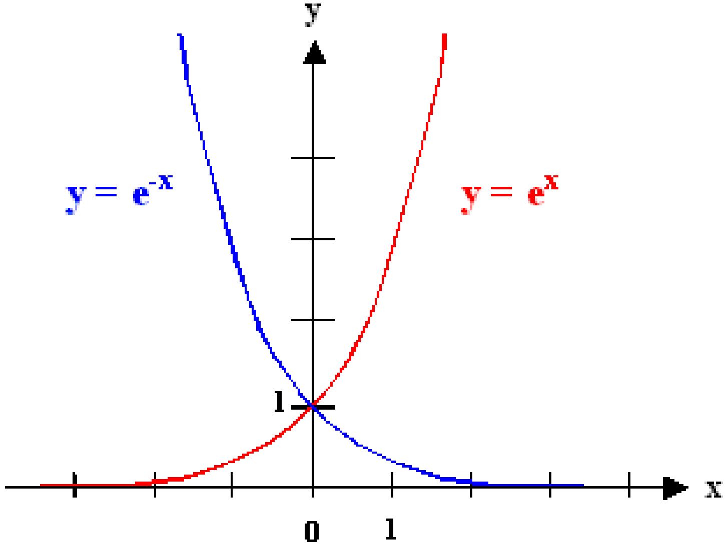
Recall Sec. School Math

Exponential Functions

$Y = e^x$







Energy Density For Pundits

$$\rho(f,T) = \begin{pmatrix} \text{number of} & \text{degrees of} \\ \text{freedom for} & \text{frequency, } f \end{pmatrix} \times \begin{pmatrix} \text{average} & \text{energy per} \\ \text{degree of} & \text{freedom} \end{pmatrix}$$

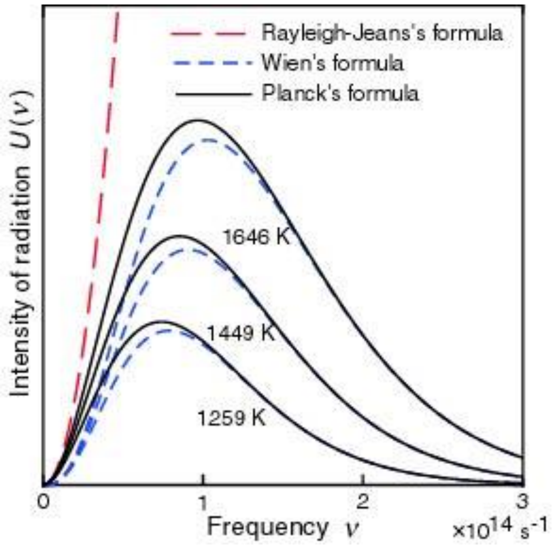
$$\rho(f,T) = \frac{8\pi f^2}{c^3} \times \text{average energy per degree of freedom}$$

Rayleigh (Jean)

$$\bar{E} = \frac{\int_0^\infty E e^{-\frac{E}{kT}} dE}{\int_0^\infty e^{-\frac{E}{kT}} dE} \Rightarrow \bar{E} = kT$$

$$\rho(f,T) = \frac{8\pi f^2}{c^3} \times kT$$

If f is large it blows up
Upon integration one gets infinity



Planck's Genius

$$\boxed{E = nhf}$$

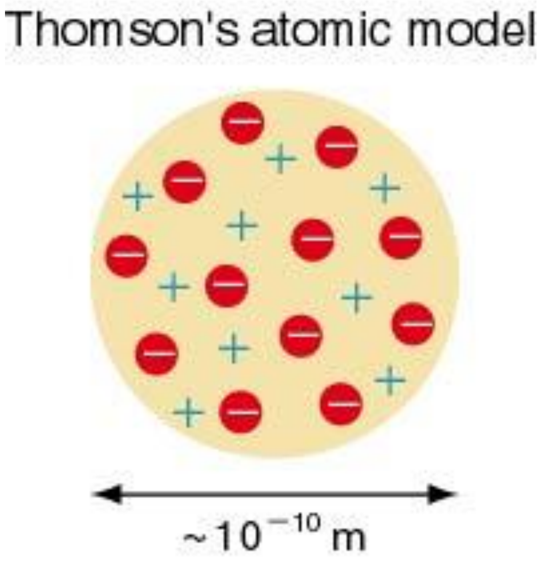
$$\bar{E} = \frac{\sum_{n=0}^\infty E e^{-\frac{E}{kT}}}{\sum_{n=0}^\infty e^{-\frac{E}{kT}}} \Rightarrow \bar{E} = \frac{hf}{e^{\frac{hf}{kT}} - 1}$$

$$\rho(f,T) = \frac{8\pi f^2}{c^3} \times \frac{hf}{e^{\frac{hf}{kT}} - 1}$$

Explain full continuous curve
Replace calculus, Quantization, n
Planck's constant, h

Another problem, 2

J. J. Thomson



Raisin bread model

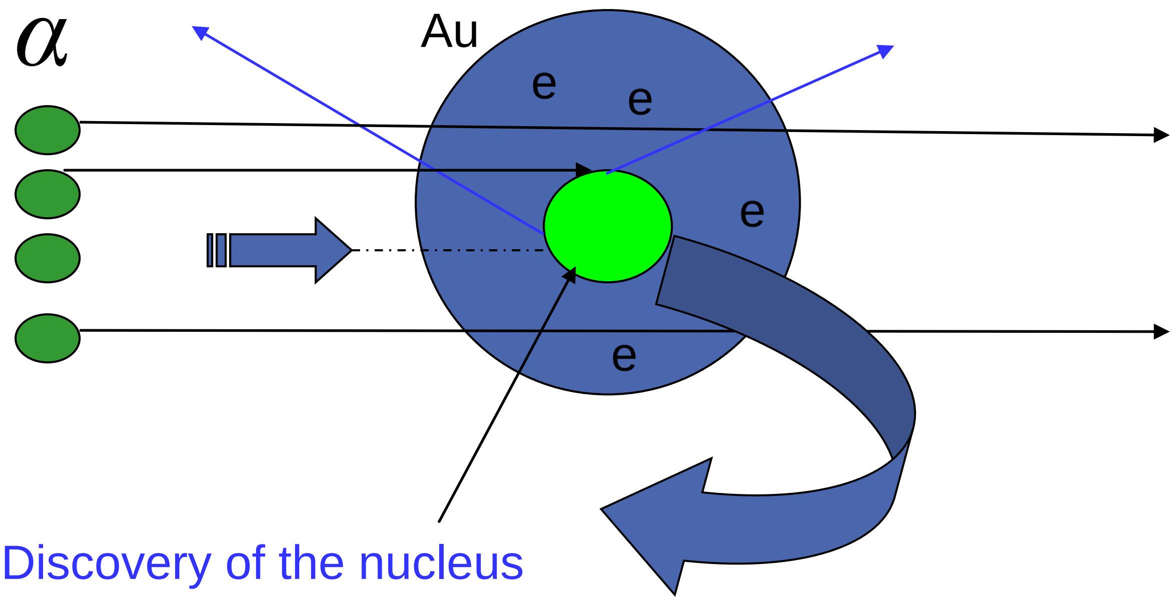
'plum pudding' model

Discovered the electron in 1897

The atom is a spherical object containing N electrons confined in homogeneous jelly-like but relatively massive positive charge distribution whose total charge cancels that of the N electrons.

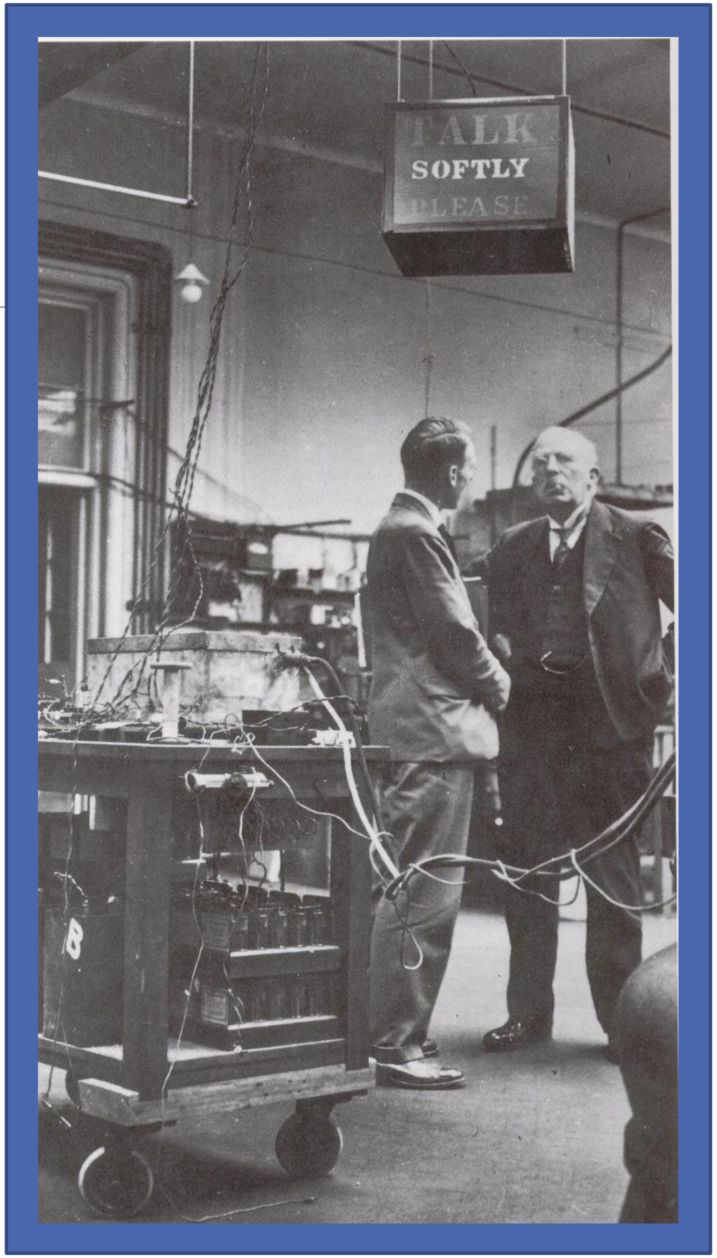
think that there is something in the middle since deflect back
means hit the middle and go back

Rutherford, 1911



Discovery of the nucleus

Also theorize the existence of neutrons.



Succeeded J. J. Thomson

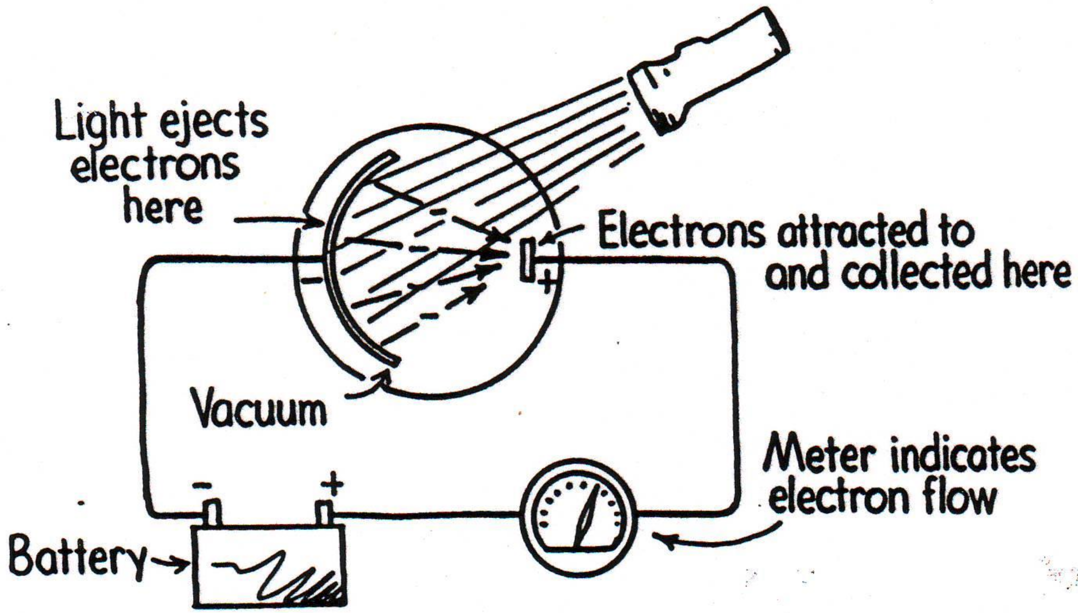
"In science there is only physics; all the rest is stamp collecting."

One more outstanding problem, 3 !

this shows that einstein is not just a theoretical physicist
- likes to do experiments first

Photo Electric Effect

Discovered by Hertz in 1887.



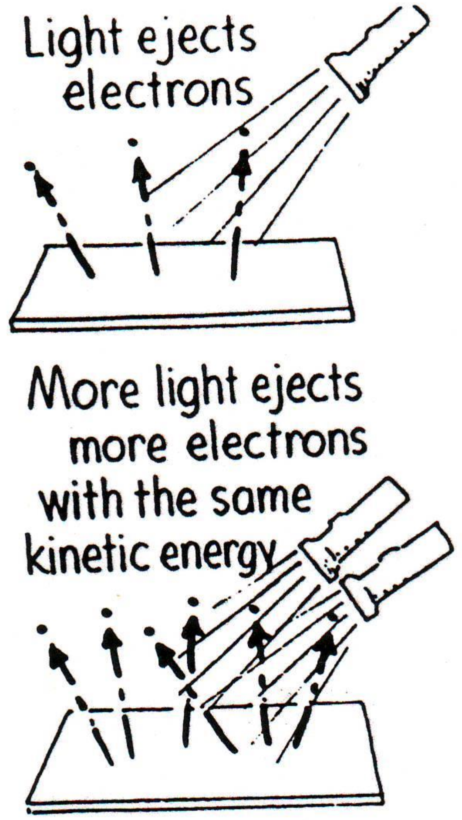
To explain the puzzling phenomenon, Einstein use Planck's idea of Quantization of energy.

Planck's Constant

$$h = 6.6 \times 10^{-34} J.s$$

Einstein's Nobel Prize Experiment, 1922

Photo Electric Effect Facts

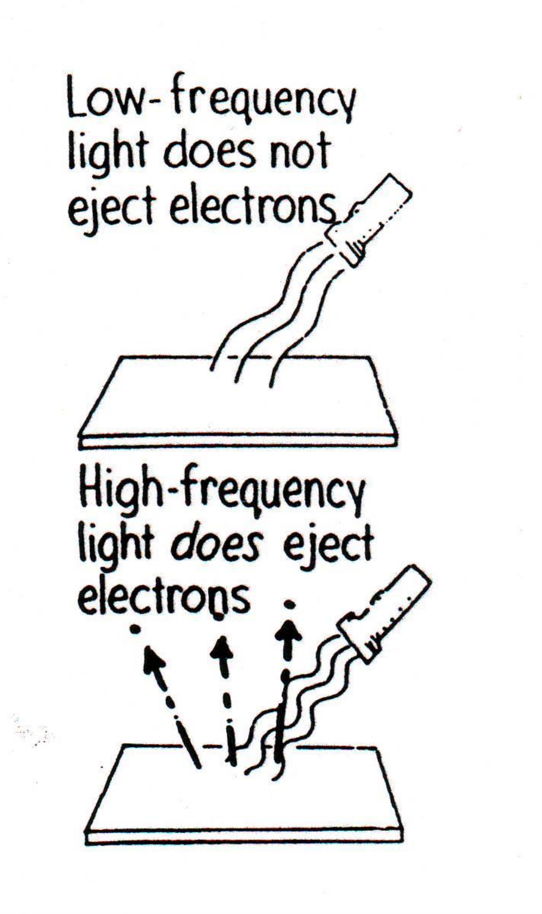


The rate at which electrons were ejected was proportional to the brightness of the light.

The maximum energy of the ejected electrons was not affected by the brightness of the light. However, there were indications that the electrons’ energy did depend on the frequency of light.

The photoelectric effect depends on intensity.

Photo Electric Effect Facts



The time lag between turning on the light and the ejection of the first electron was not affected by the brightness [redacted] of the light.

The effect was easy to observe with violet (bluish) or ultraviolet light but not with red light.

The photoelectric effect depends on frequency

$$E \propto f$$

$$E \propto \frac{1}{\lambda}$$

$v = f\lambda$

$$c = f\lambda$$

Photo Electric Effect. Why ?
Facts that are hard to understand

1) The lack of any appreciable time lag was also difficult to understand.

2) People expected that if the metal plate was illuminated with a very intense light source, then the electron should be kicked out of it with much greater energy.

Puzzling Comments on 1)

If one uses wave description of light,

An electron in dim light (if treated as a wave) should (after some delay) build up enough vibrational energy to eject, while an electron in bright light should be ejected almost immediately.

This did not happen but electrons were also emitted immediately under dim light and strong light.

This means that light might not be a wave, since it will immediately kick out the electron, so means it might be a particle to just kick out

Puzzling Comments on 2)

If one uses wave description of light,

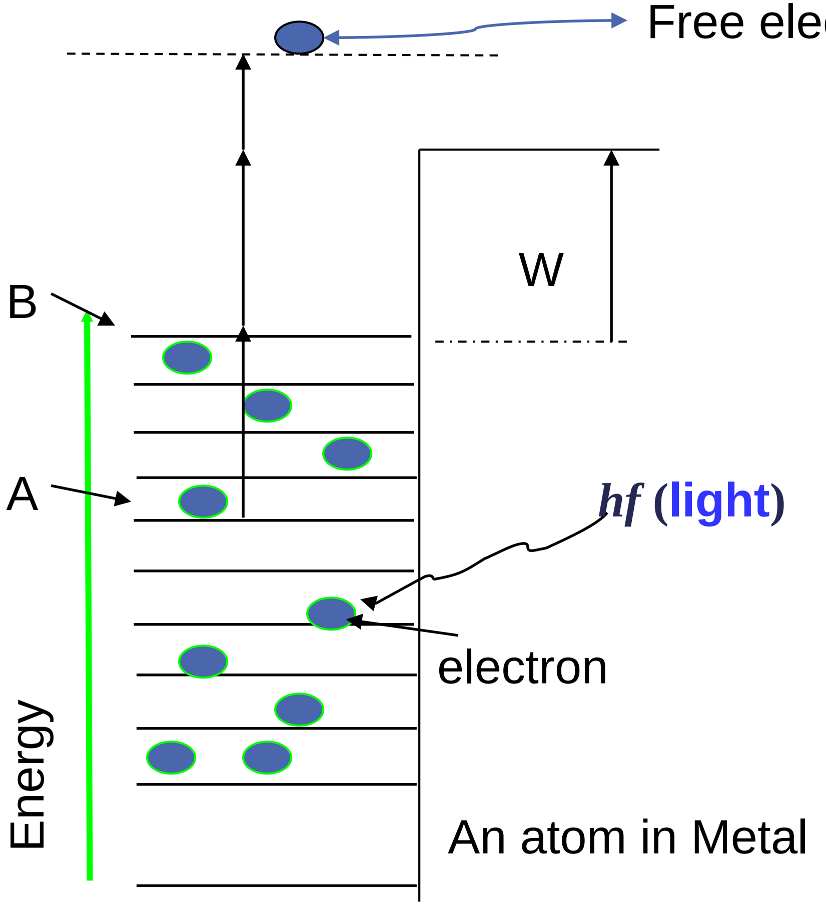
Even if the incident light intensity varied as much as 1000 times, but the emitted electron had the same energy.

More electrons were ejected in brighter light but not at greater energy.

A weak light beam of say ultra violet light, induce a smaller number of ejected electrons but are more energetic,

How did Einstein Solve it ?

1922



$$E_{kin} = hf - E_{A\,to\,B} - W$$

Work Function

(Metal "Tax")

Note : Recall Planck's Recipe

The absorption is an all or nothing process *and* is immediate, so there is no delay as wave energies build up.

hf (light) has a name, called a quantum unit

Summary of Photon Electric Phenomenon

Electrons were emitted when light photons interact with atoms of metal.

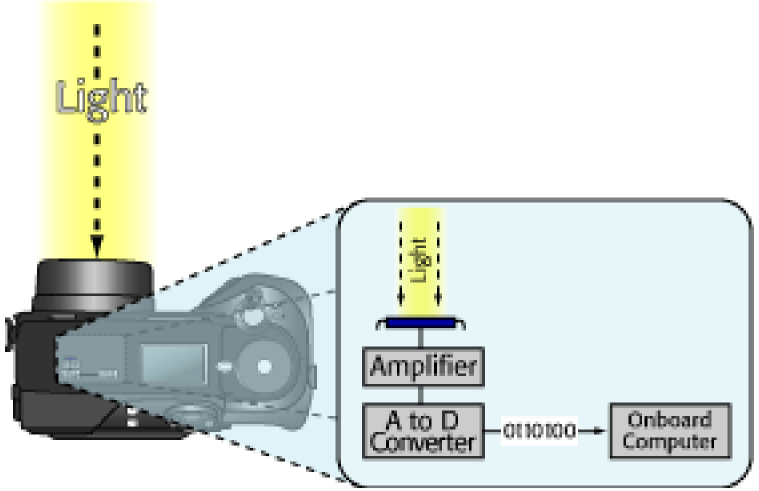
The # number of photons in a light beam controls the brightness (intensity) of the whole light beam, whereas the frequency of the light controls the energy of each individual photon.

The photoelectric effect shows "conclusively" that light (being a wave) has particle properties.

Why should I learn Einstein's photoelectric effect ?

Photo Electric Devices (reading)

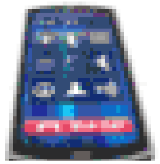
Photo Electric Effect seems so remote from us.



When you take a picture, the image sensor samples the light coming through the lens and converts it into electrical signals. These signals are boosted by an amplifier and sent to an analog-to-digital (A-to-D) converter that changes those signals into digits. An onboard computer processes those digits to produce the final image data, which is stored on a memory card of some type.

An image sensor is able to sample light thanks to a natural phenomenon called the photoelectric effect in which some metals release electrons when exposed to light.

Photo Electric (CCD or CMOS) Reading

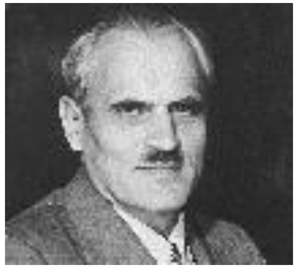


To exploit the photoelectric effect in an image sensor, the surface of the chip is covered with a grid of electrodes called photosites. Each photosite corresponds to a pixel in your final image. Before you shoot a picture, your camera charges the photosites with electrons. Because of the photoelectric effect, when light strikes a particular photosite, the metal in that site releases some of its electrons. Each photosite is bounded by a non-conducting metal, so these released electrons get trapped, effectively piling up inside a little well.

After the exposure, your camera simply has to measure the voltage at each site to determine how many electrons have heaped up there, and thus how much light hit that particular spot. These voltages are amplified and then fed to an A-to-D converter.

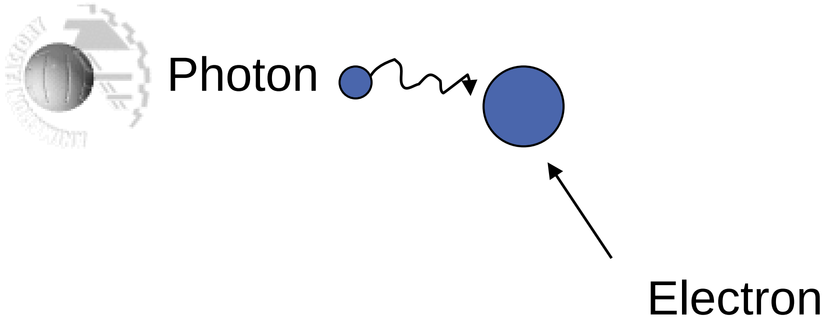
So many quantum Skeptics !

Compton Effect



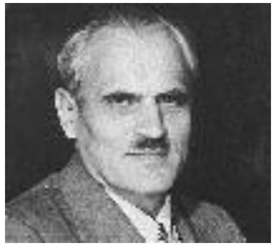
If light did consist of quanta as Einstein said, could one bounce them off each other ? Why not ?

A. Compton: why not then bounce a photon off an electron ?



Many people were still skeptical: Lorentz, Bohr …

Originally called light quantum after it has been accepted, Chemist: G. Lewis called it the photon, 1926 science can always be superceded by new theories, even if the old one win prizes



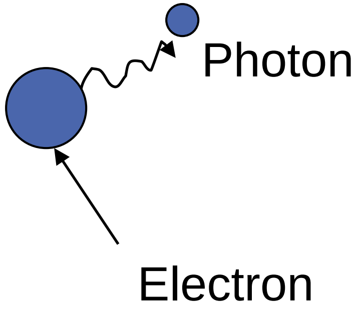
Compton Effect 1923

So what is the result after the scattering of the photon by an electron?

A. Compton: the scattered photon would naturally have a lesser energy than the incident photon.

This would mean a lower frequency photon than before collision.

$$E = hf$$



He "proved" that radiation behaves as if it consisted of discrete energy projectiles, not only in regard to energy transfer but also in regard to momentum transfer.

A. Einstein

A Creative question !

A new quantum convert and admirer

de Broglie

Enchante !

similar to Einstein Field equation
LHS and RHS are different properties

A fan of Einstein's photon hypothesis

Try to get this form !!!!

$$E = mc^2 \Rightarrow E = pc$$

$$E = hf \quad \text{and} \quad \boxed{p = \frac{h}{\lambda}}$$

particle

wave

de Broglie thinks that these should also hold for particles like electrons.

Einstein's Light particles :

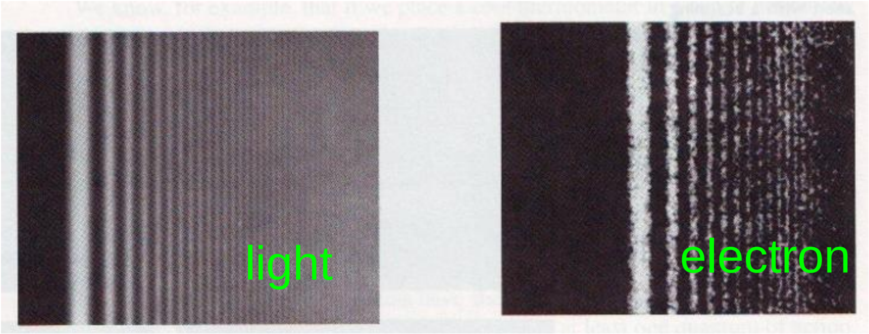
Wave exhibit (behaves as) Particles (properties)

de Broglie's Electron particles :

Particles exhibit (behaves as) Waves (properties)

Hint : $c = f\lambda$

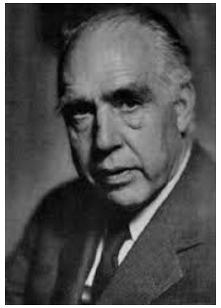
Diffraction patterns



A quick application to make sense

… of these new ideas !

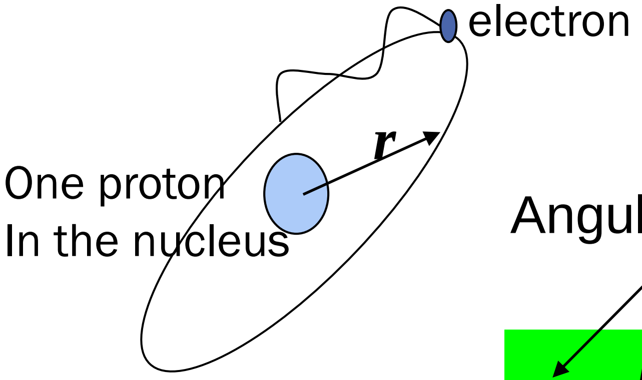
Niels Bohr



If an electron is a wave, say in the hydrogen atom, it would have been reasonable to use the circumference of the circular orbit to be the wavelength.

$$2\pi r = \lambda$$

Recall from Einstein: $E = hf \quad \text{and} \quad p = \dfrac{h}{\lambda}$



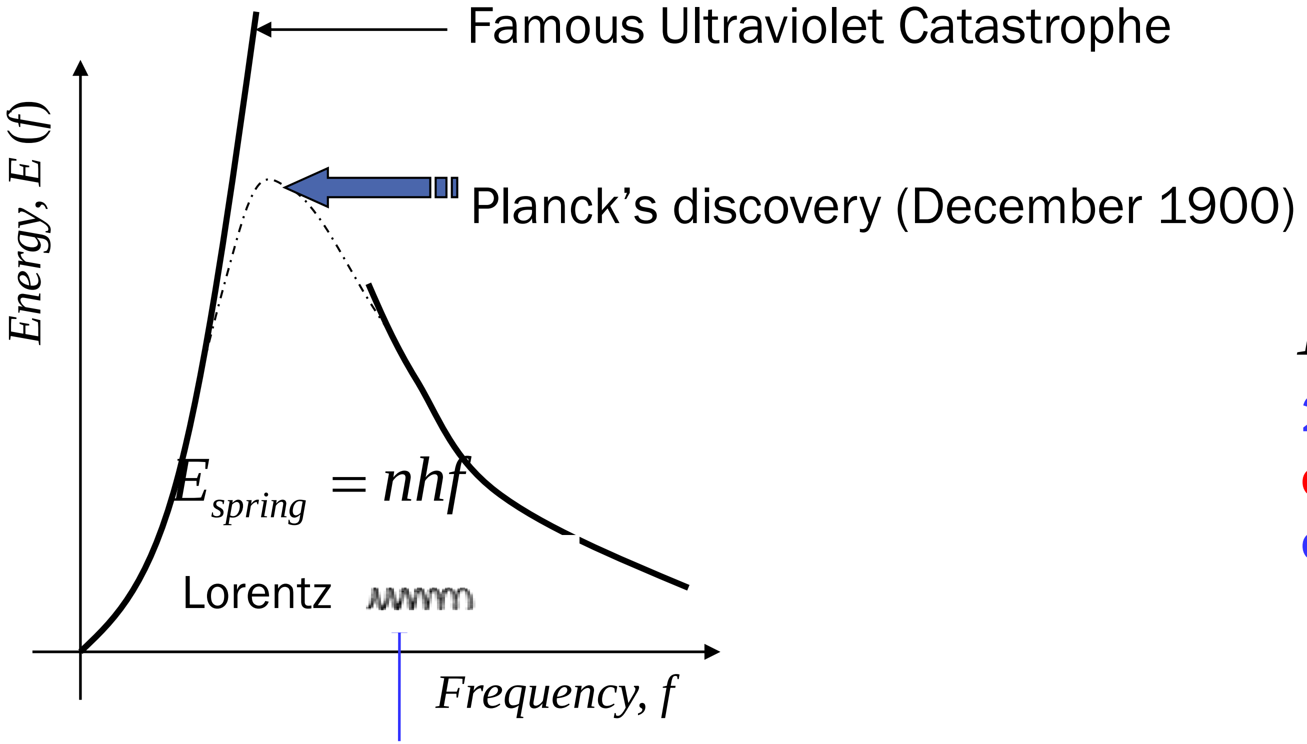
Angular Momentum: $\boldsymbol{L} = \boldsymbol{r}\,\boldsymbol{p}$, $\boldsymbol{p}$ is ordinary momentum

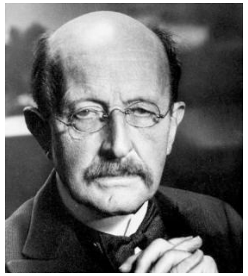
$$L = \frac{h}{2\pi} n$$

One gets the **Bohr Quantization condition**

When does the *n* (integer) come in ?

Blackbody Explained
Christmas Present to the World !





Discovery: 1) Oscillator Energy is $E \propto f$ proportional to Frequency.

$$E = hf \qquad\qquad E = nhf$$

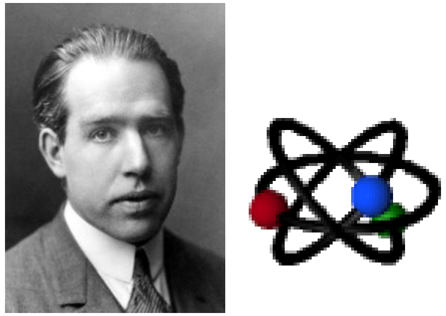
2) But must postulate that an oscillator of frequency can have only the energies

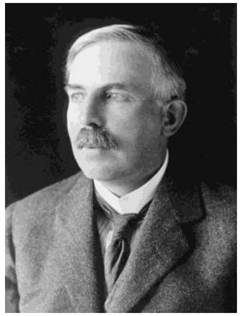
$$n = 0, 1, 2, 3, \ldots$$

Note: Only discrete values …

Quantization … quantized …

Niels Bohr

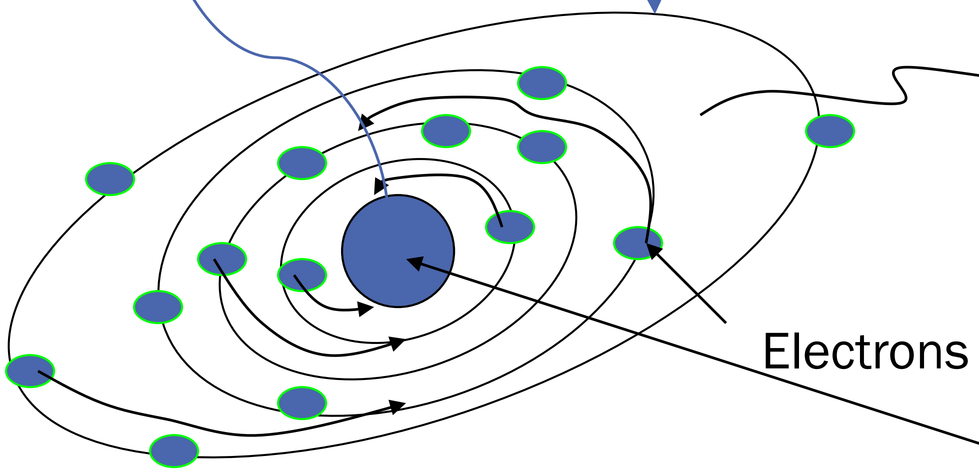




Invented the Mini Solar System Model

Rutherford

Discovered the Nucleus

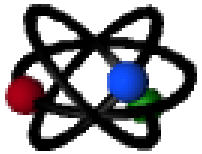


Electrons will spiral into the nucleus and emit radiation, eventually the atom will collapse.

the electron will emit radiation aka light, when it jump from outer shell to inner shell

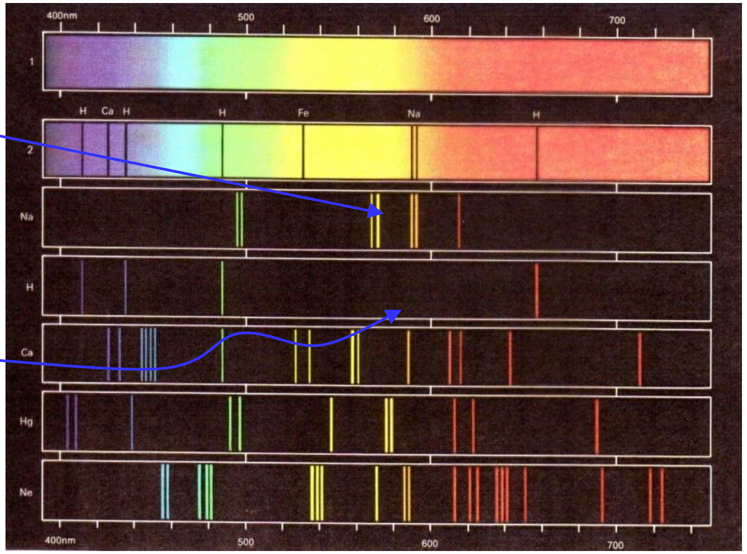
Protons and Neutrons reside in the Nucleus … collectively called Nucleons.

Niels Bohr Atoms

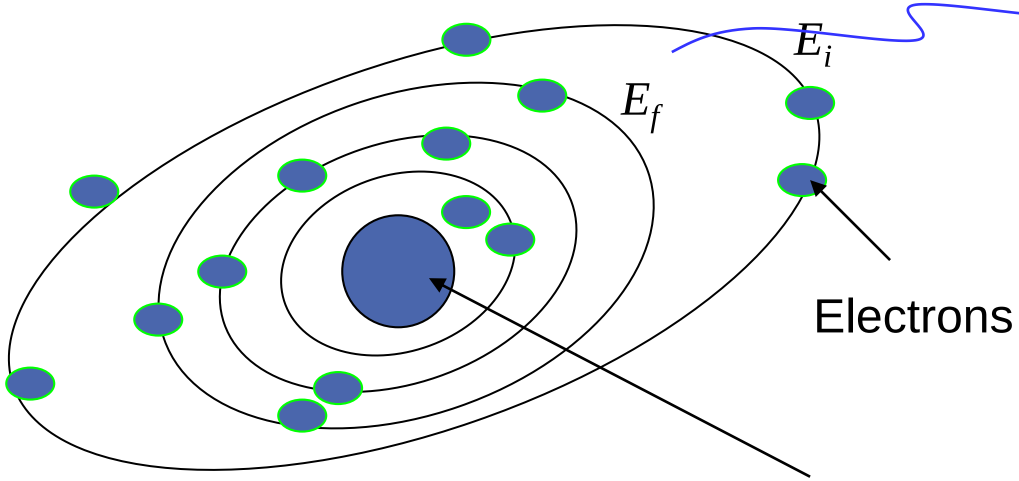


How Bohr's theory explain this ?

Bohr's Suggestion : "**Jumps up & down**" !



Bohr's Mini Solar System Model



$$E_i - E_f = hf = E_g\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

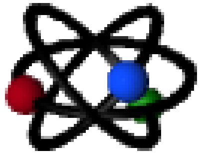
orbit

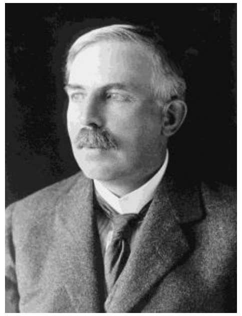
-13.6 eV … ground state energies

Note 1 : Negative value

Note 2: There is a value ? Why ?

Protons and Neutrons resides in the Nucleus … Nucleons





Niels Bohr

Invented the Mini Solar System Model

Rutherford

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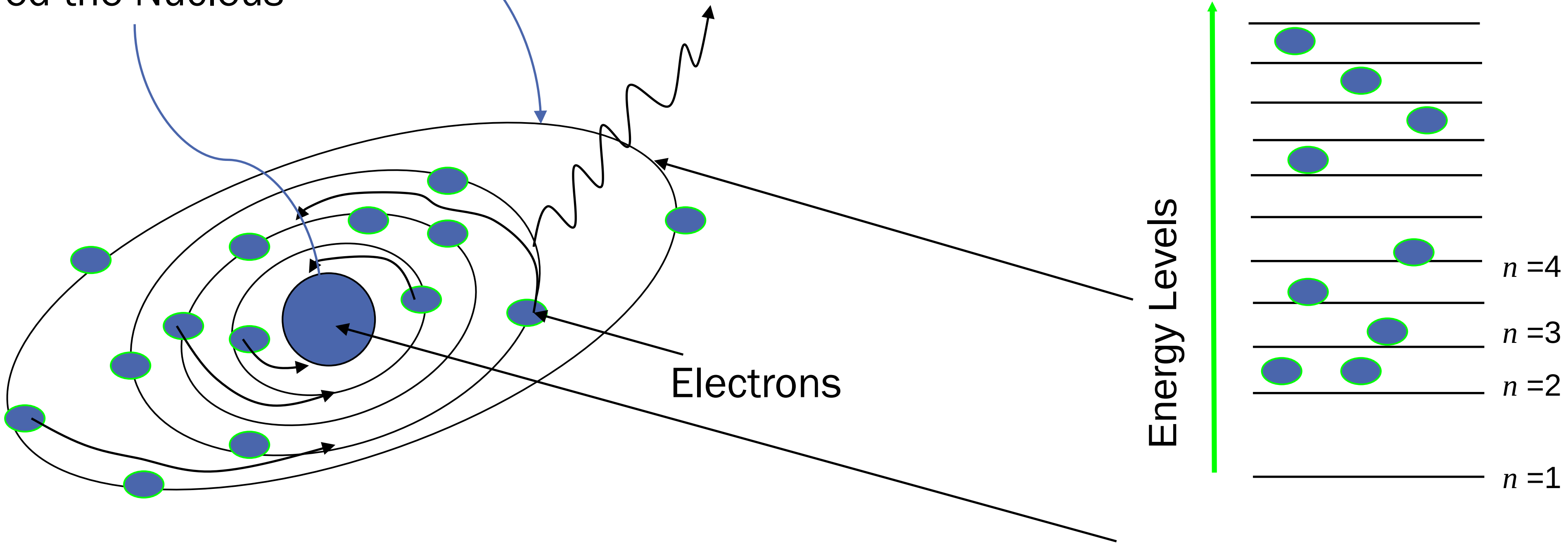
Another cartoon



Protons and Neutrons reside in the Nucleus … collectively called Nucleons.

How did Bohr know the Energy formula?

Who was Balmer ?

Balmer's formula

Balmer noticed that a single number had a relation to every line in the hydrogen spectrum that was in the visible light region. That number was 364.50682 nm. When any integer higher than 2 was squared and then divided by itself squared minus 4, then that number multiplied by 364.50682 (see equation below) gave a wavelength of another line in the hydrogen spectrum. By this formula, he was able to show that certain measurements of lines made in his time by spectroscopy were slightly inaccurate and his formula predicted lines that were later found although had not yet been observed. His number also proved to be the limit of the series. The Balmer equation could be used to find the wavelength of the absorption/emission lines and was originally presented as follows (save for a notation change to give Balmer's constant as *B*):

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

Lamda, λ is the wavelength.
B is a constant with the value of 3.6450682×10^{-7} m or 364.50682 nm. *m* is equal to 2,*n* is an integer such that $n > m$.

$$E_i - E_f = hf = E_g\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

Rydberg (refinement)

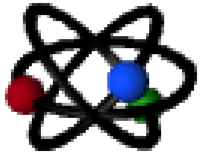
In 1888 the physicist Johannes Rydberg generalized the Balmer equation for all transitions of hydrogen. The equation commonly used to calculate the Balmer series is a specific example of the Rydberg formula and follows as a simple reciprocal mathematical rearrangement of the formula above (conventionally using a notation of *m* for *n* as the single integral constant needed):

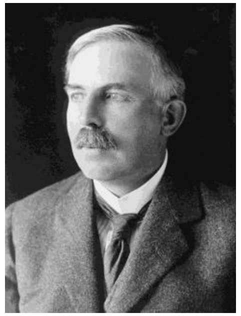
$$\frac{1}{\lambda} = \frac{4}{B}\left(\frac{1}{2^2} - \frac{1}{n^2}\right) = R_{\mathrm{H}}\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \quad \text{for } n = 3, 4, 5, \ldots$$

where λ is the wavelength of the absorbed/emitted light and R_H is the Rydberg constant for hydrogen. The Rydberg constant is seen to be equal to 4/*B* in Balmer's formula, and this value, for an infinitely heavy nucleus, is $4/(3.6450682 * 10^{-7}$ = 10,973,731.57 meter-

http://en.wikipedia.org/wiki/Balmer_series

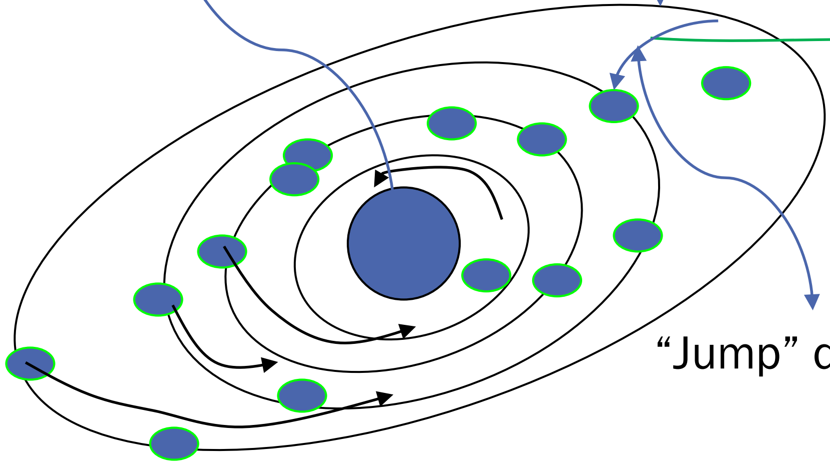
Niels Bohr



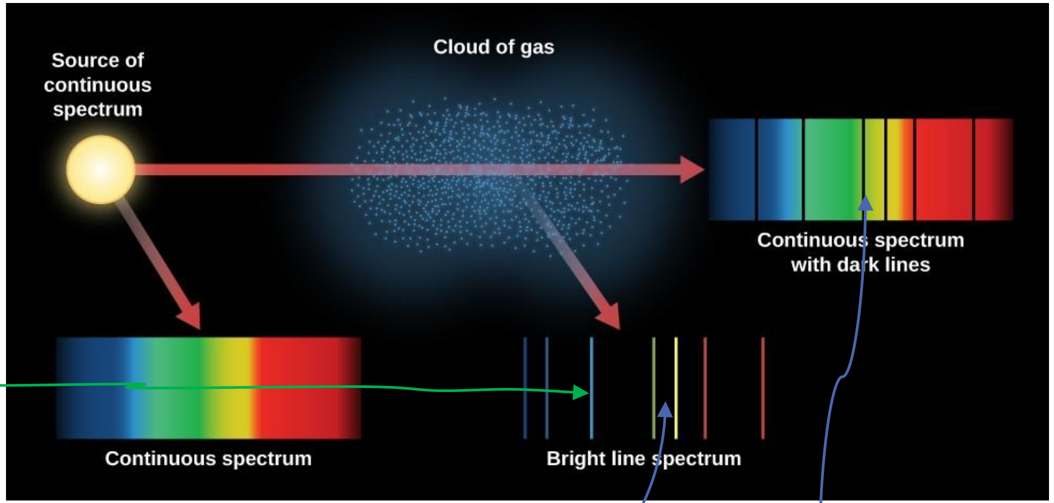


Rutherford

Discovered the Nucleus



“Jump” down



Rainbow Spectra

Absorption Spectra

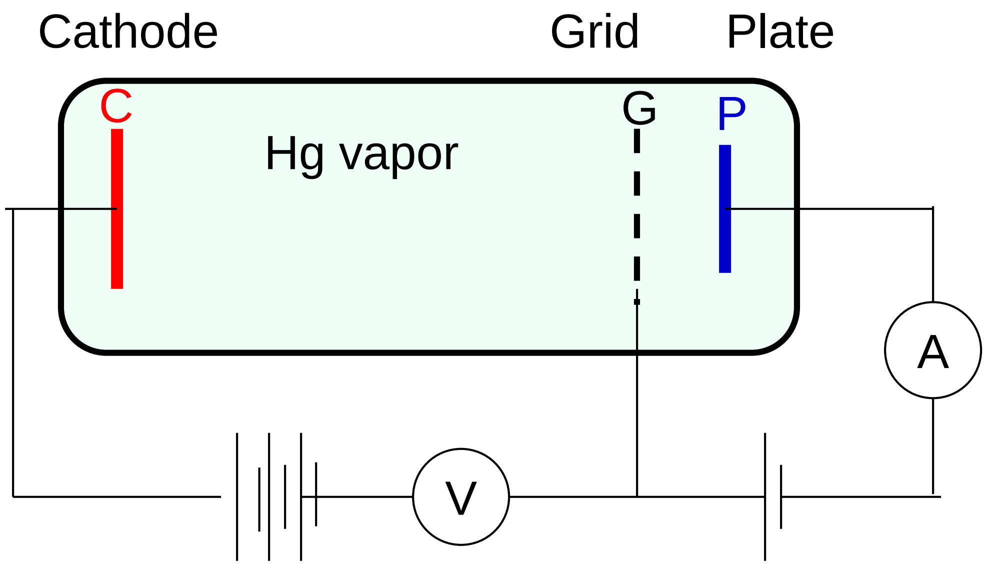
Emission Spectra

Protons and Neutrons reside in the Nucleus … collectively called Nucleons.

Any Experimental Evidence for energy levels ?

Franck-Hertz Experiment, 1925 Nobel

The first experiment to provide support for the discrete energy levels was performed by James Frank and Gustav Hertz (nephew of Heinrich Hertz) in 1914. The setup is similar to the one below.



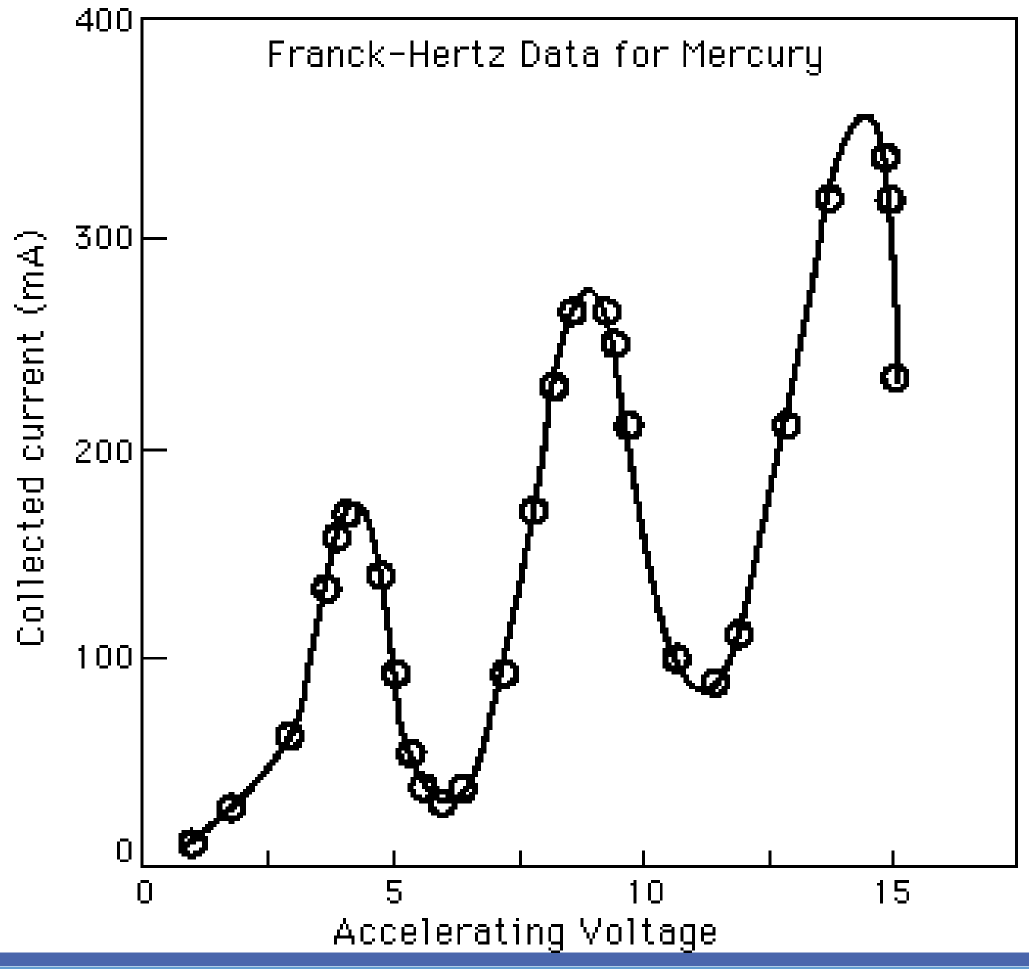
The cathode C is heated (not shown) and emitted electrons are accelerated toward grid G. They gained KE = eV. Some passed through the grid and collected by plate P, showing up as current I. Plate P is at slightly lower potential than G.

The tube is filled with mercury vapor. Electrons collided with Hg atoms. If the collision is elastic, the current I is not affected by the vapor as the electrons lose very little KE ($m_{atom} >> m_{electrons}$.)

Franck-Hertz Experiment

When V < 4.9 V, I increases with increasing V as expected, as the collisions are elastic and the electrons have enough KE to overcome the slight reversed bias between G and P.

When V = 4.9 V, current drops drastically as the electrons suffered inelastic collisions and transferred most of its KE to the atoms (raising them to their first excited state) and the remaining KE is not enough for the electrons to P.



Franck-Hertz Experiment

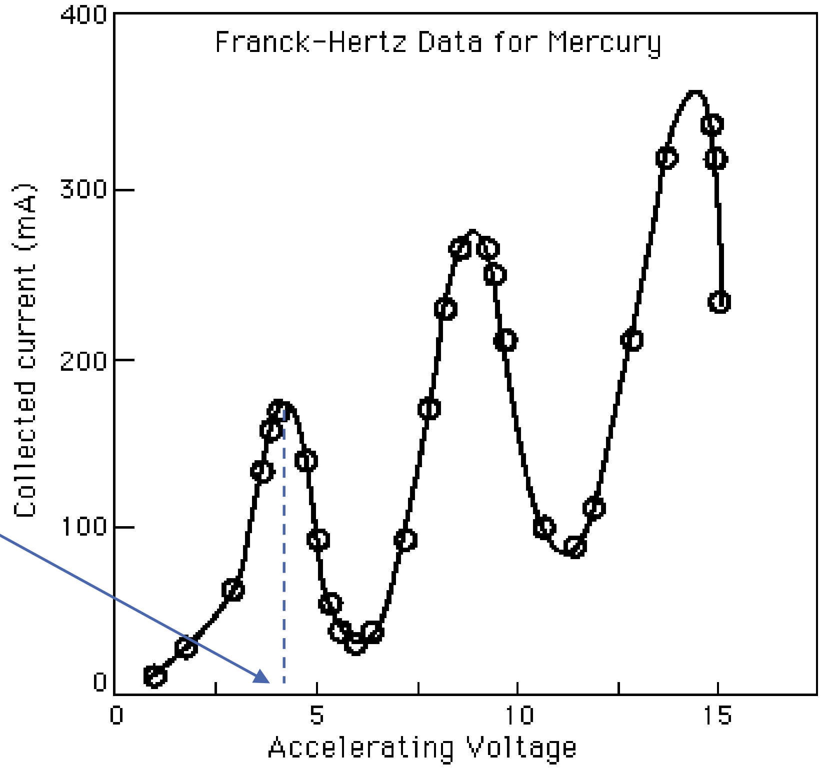
Frank and Hertz also noted that at this voltage the 253.6 nm spectral line of mercury appeared in the emission spectrum. This corresponds to photons of energy:

$$E = \frac{hc}{253.6 \times 10^{-9}} = 7.838 \times 10^{-19}\ \mathrm{J}$$

$$= 4.89\ \mathrm{eV}$$

which was emitted when the atoms drop from the first excited state back to their ground state.

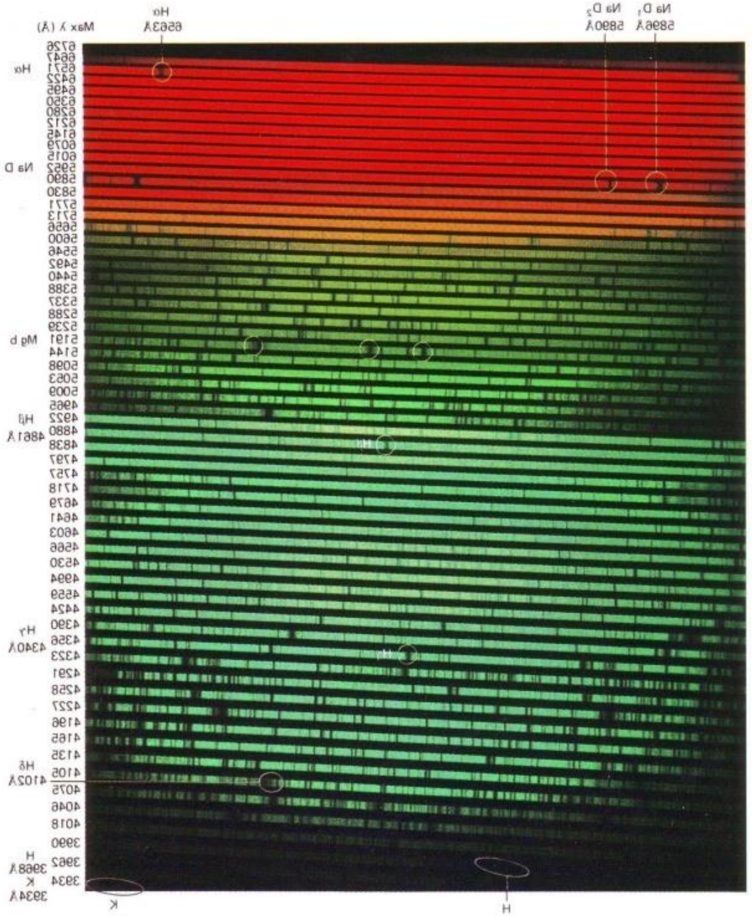
The behavior was repeated at multiples of 4.9 V, indicating the electrons exciting two or more atoms to their first excited states.



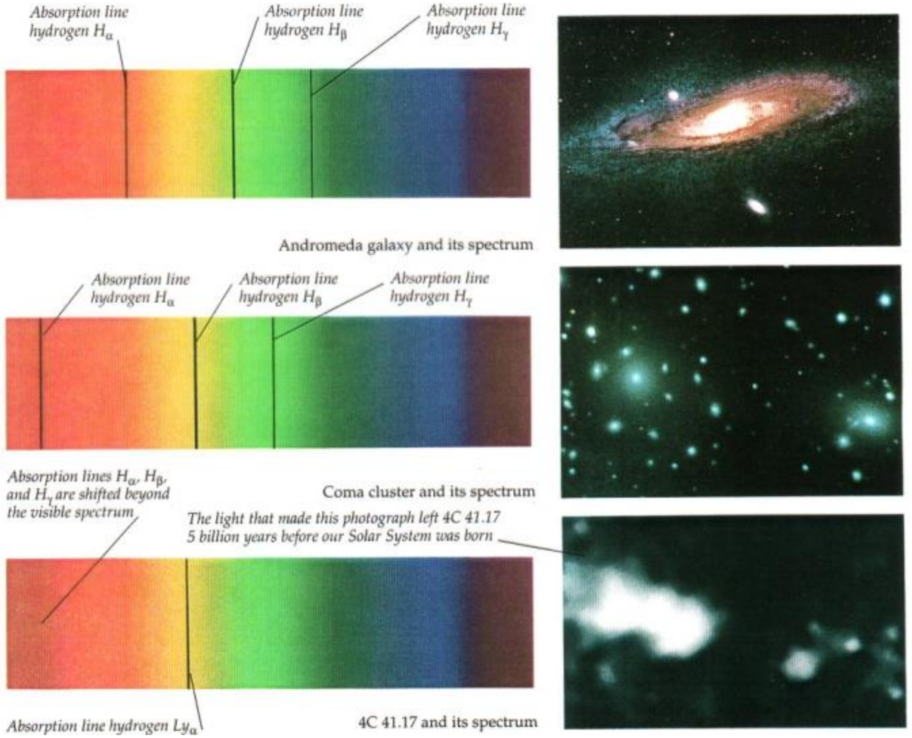
Astronomy flourishes after the discovering the theory for the Hydrogen atom

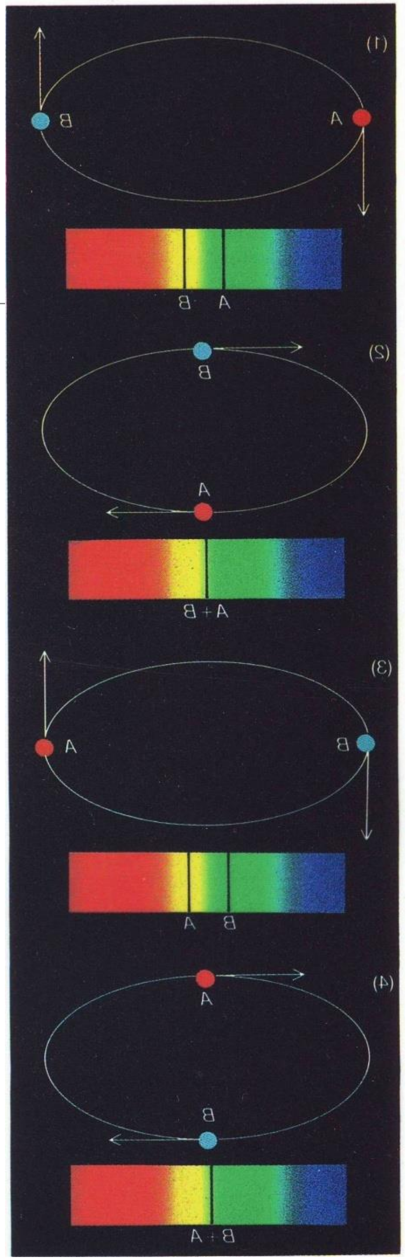
http://en.wikipedia.org/wiki/Balmer_series

Stellar Absorption Spectra

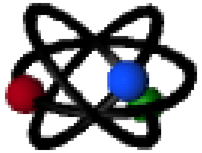


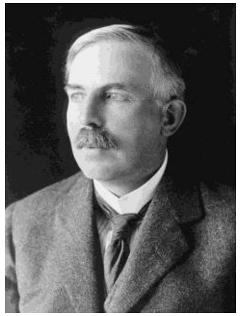
What good are the Spectra from outer space ?





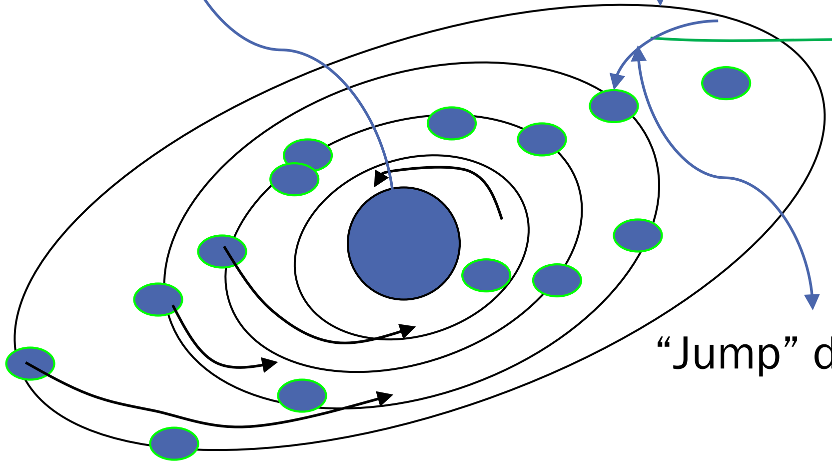
Niels Bohr



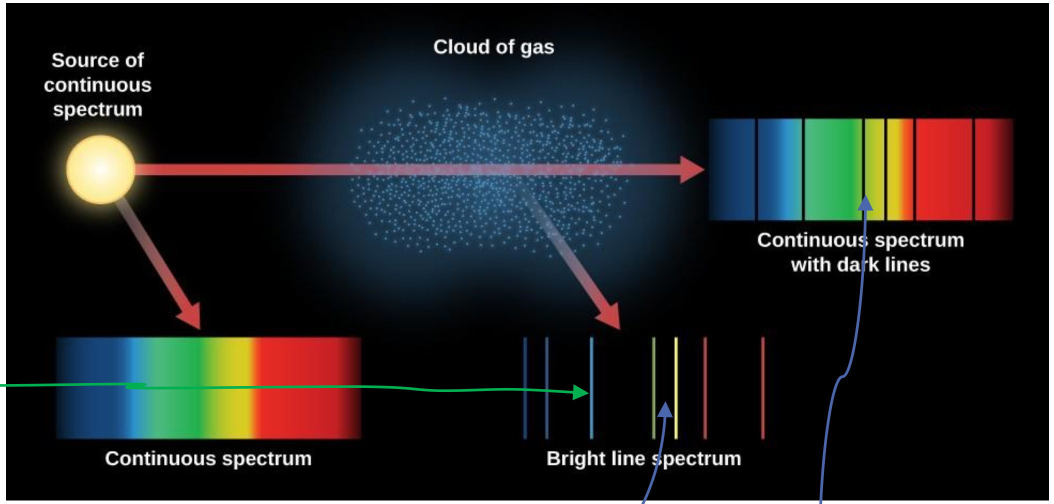


Rutherford

Discovered the Nucleus



“Jump” down



Rainbow Spectra

Absorption Spectra

Emission Spectra

Protons and Neutrons reside in the Nucleus … collectively called Nucleons.

Problems with Bohr's Atom

Education is not the filling of a pail, but the lighting of a fire.

William Butler Yeats 20th century poet

What are electron "jumps" ? Like *ad hoc* manner

Electrons moved in stationary orbits, they are not obliged to radiate

How, when and why does an electron make a transition ?

Seems to apply to only Hydrogen but not any higher elements.

Nobody knew and Niels Bohr was very much worried despite the great success of his Atomic (mini solar system) Model

Epistemic Problem 1

Why does the electron stay in the excited energy level for an unspecified period before it descends to a lower energy level ?

What is the physical mechanism that makes it wait ?

Classical Physics

A round stone sits on the side of a hill, popped by another stone, and the second is then removed, the round stone will roll down hill, immediately. It is because of the action of the force of gravity that is there all the time.

In comparison, the electron in the excited state of an atom does not drop to the lower energy level because of the electric force of the nucleus on it.

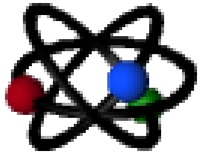
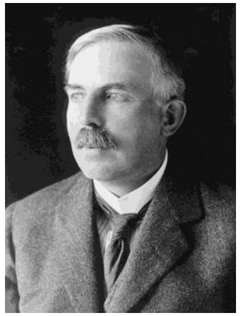
Epistemic Problem 2

When an electron in an excited energy level E_n level drops to a lower energy level E_m, to conserve energy a photon is created with the same energy as the loss of energy of the electron (and its host atom).

The problem is this : after the electron drops from the energy level E_n but before it arrives at the energy level E_m it will have lost energy, but there is yet no photon to take this loss.

Hence the law of conservation of energy does not hold true at these interim times of transition between states. It is only true when the electron is in one definite state or another.

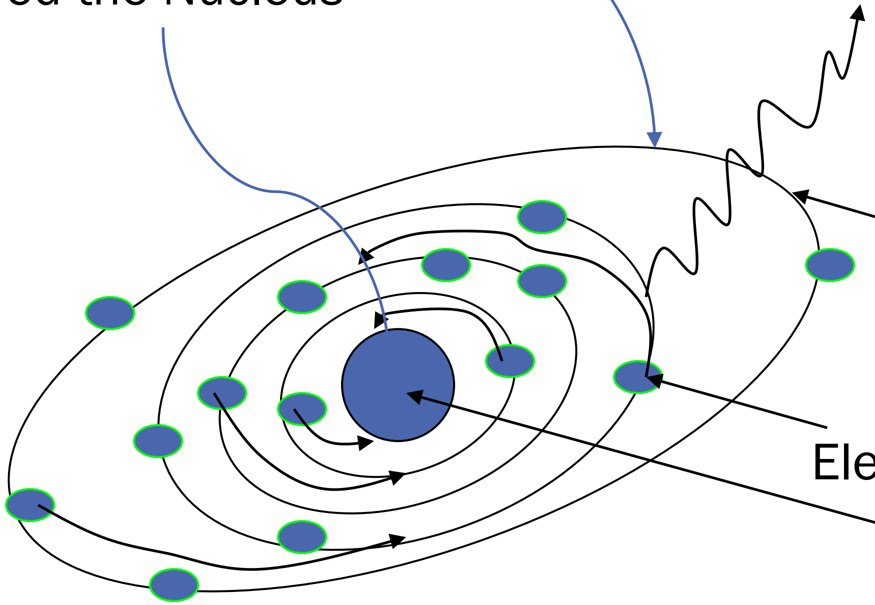
Niels Bohr

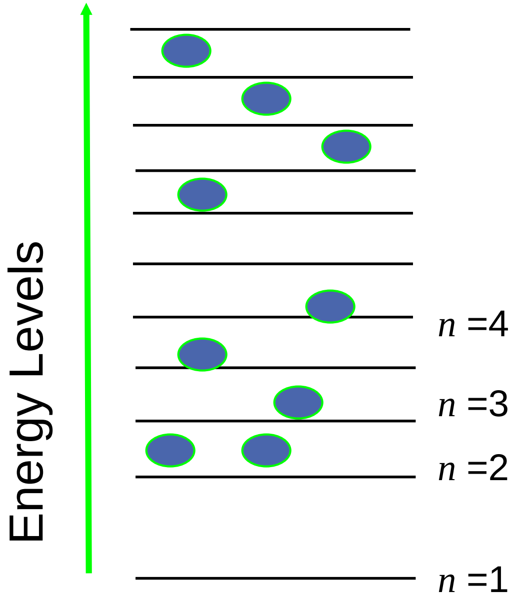
Rutherford

Invented the Mini Solar System Model

Discovered the Nucleus



Another picture



Protons and Neutrons reside in the Nucleus … collectively called Nucleons.

Epistemic Problem 3

What is the physical mechanism that causes the creation of a photon, when the electron arrives at the lower energy level ?

Homework for the weekend.

a) Think about the 3 problems !
b) How should we picture the "Atom" ?