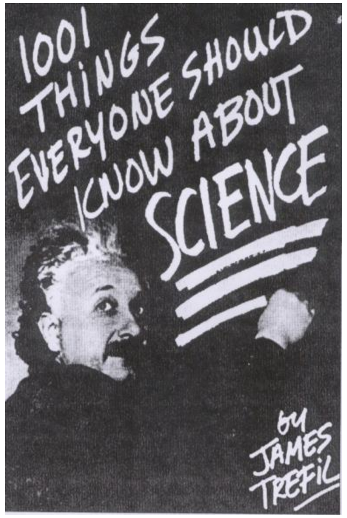
Consider Left and Right Slits !

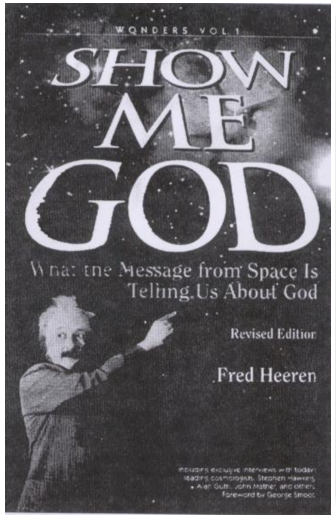
Lecture 10

2 Slits: Thomas Young's Experiment

previous take home (s) !

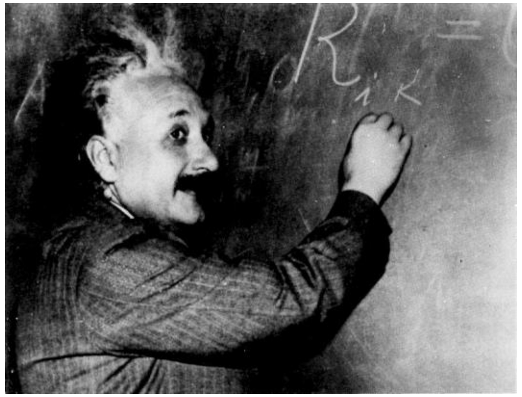
$$E = mc^2$$





$$R_{ij} - \frac{1}{2} g_{ij} R = \kappa T_{ij}$$

$$R_{ij} = 0 \, ?$$



… after people read the paper, a lot of people understood the theory of relativity in some way or other, certainly more than twelve.

On the other hand, I think I can safely say that no one understands quantum mechanics!

$$\boxed{QP - PQ = \frac{ih}{2\pi} = i\hbar}$$

R. Feynman

The Character of Physical Law

$$\sqrt{-1} = i$$

Complex Number

“copy cat “

Recall the Quadratic Equation $ax^2 + bx + c = 0$

From Secondary School : The Solution is $x = \dfrac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

Example : Solve $x^2 - 2x + 5 = 0$

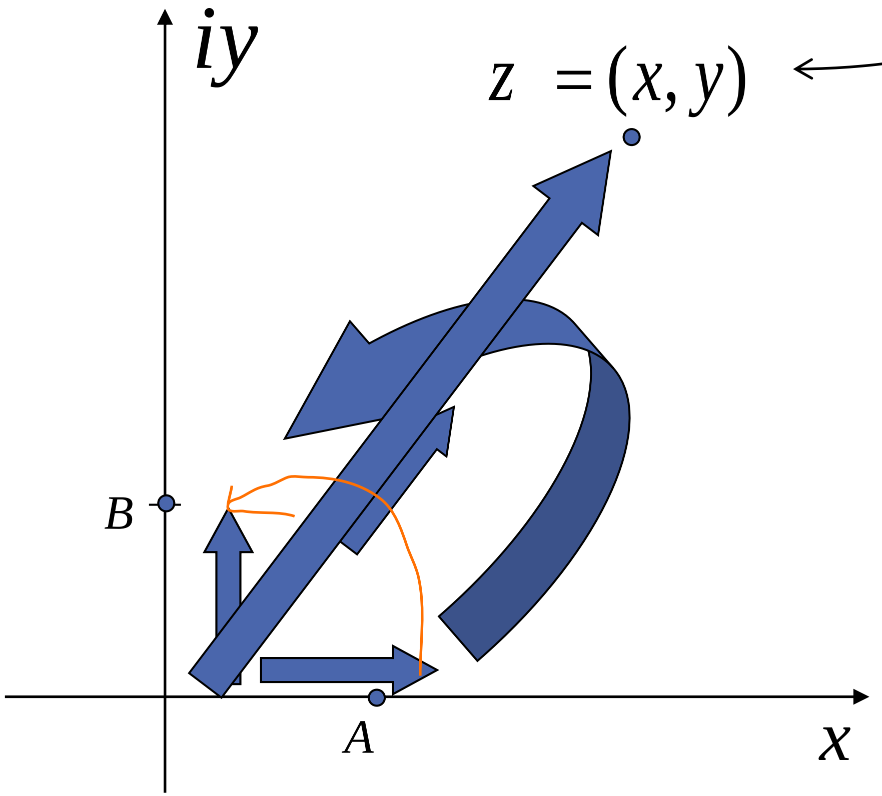
$$x = \frac{2 \pm \sqrt{-16}}{2}$$

$$= \frac{2 \pm \sqrt{-1}\sqrt{16}}{2}$$

$$= 1 + 2i \quad or \quad 1 - 2i \qquad\qquad i = j = \sqrt{-1}$$

How do we visualize a complex number ?

Complex Diagram (Picture)



$$z = x + iy$$

$$z_A = 1 + i0$$

$$iz_A = i(1 + i0)$$

$$= i \quad \text{Or } 0 + 1i$$

$$iz_A = z_B$$

Note $i = \sqrt{-1}$ What can one learn from this exercise ? … Rotation

Consider Left and Right Slits !

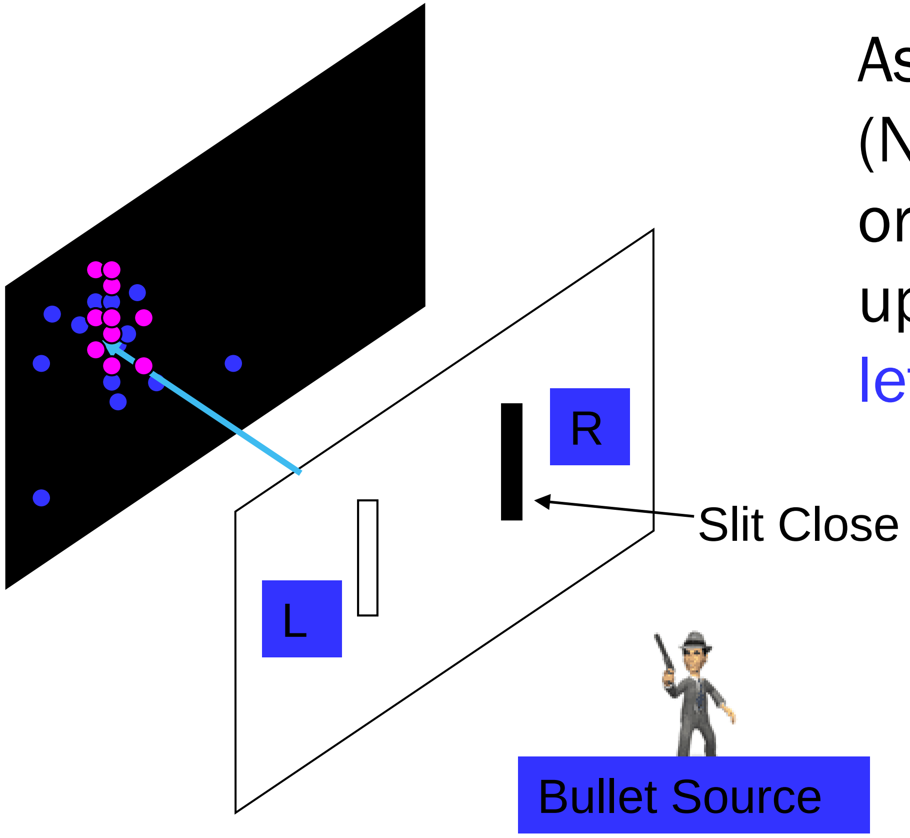
Lecture 10

2 Slits: Thomas Young's Experiment

2 slits experiment

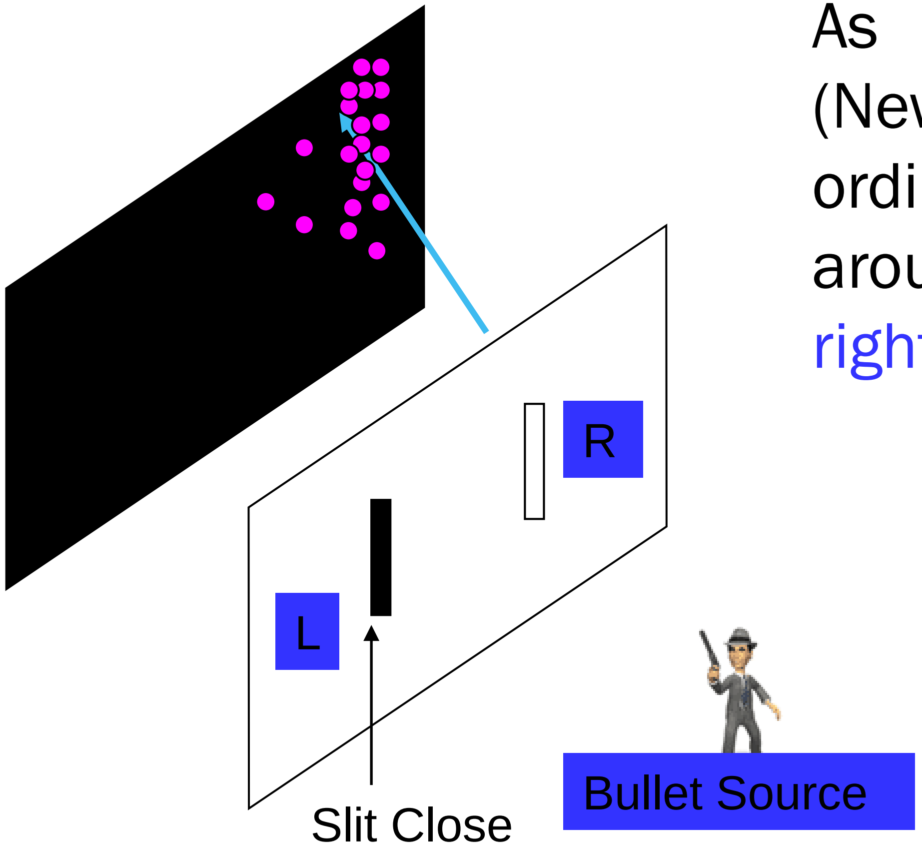
Real Physical Bullets “particle like”

2 slits experiment (Bullets)



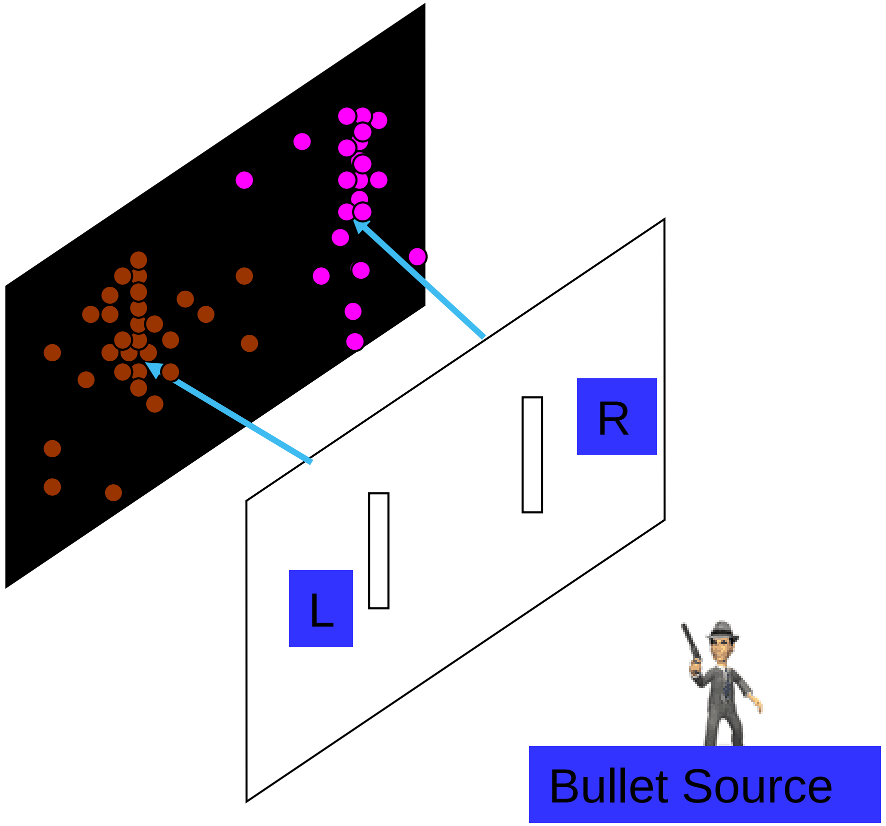
As we expect … from classical (Newtonian) physics … bullets are ordinary lumps (particles) … pile up around one place … in this case left side of the screen.

2 slits experiment (Bullets)



As we expect … from classical (Newtonian) physics … bullets are ordinary lumps (particles) … pile up around one place … in this case right side of the screen.

2 slits experiment (Bullets)

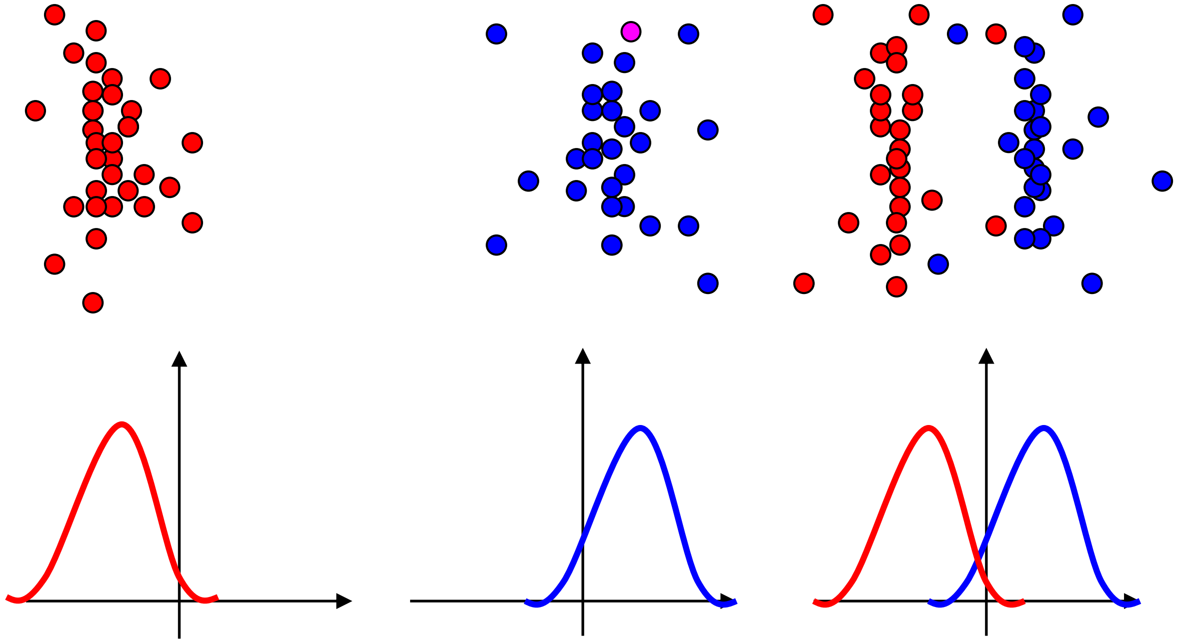


Note :

Both Slits are open.

The bullets pile up at 2 places.

Summary for Bullets (from a real gun)



As expected from classical physics … everyday experience.

Note: Bullets are real "lumpy" objects or "particle" like.

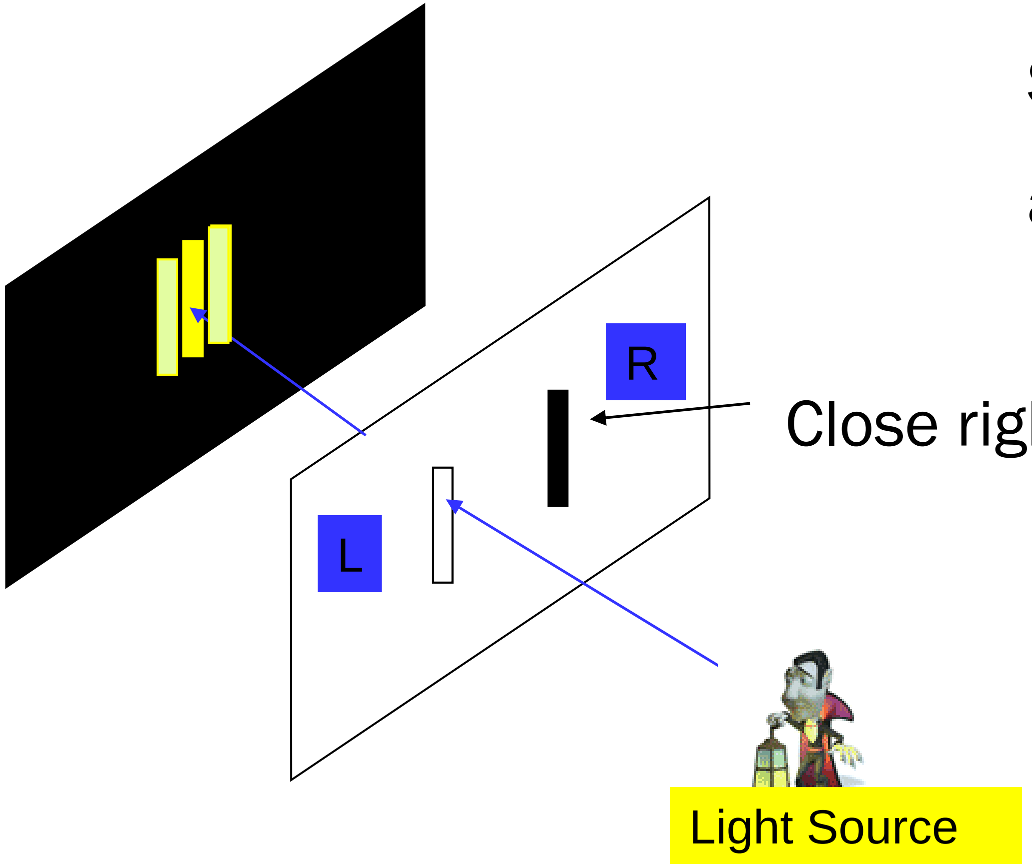
2 slits experiment

Light Waves “wave like”

Redo-2 Slits Experiment (Light as wave)

Single Slit Diffraction…

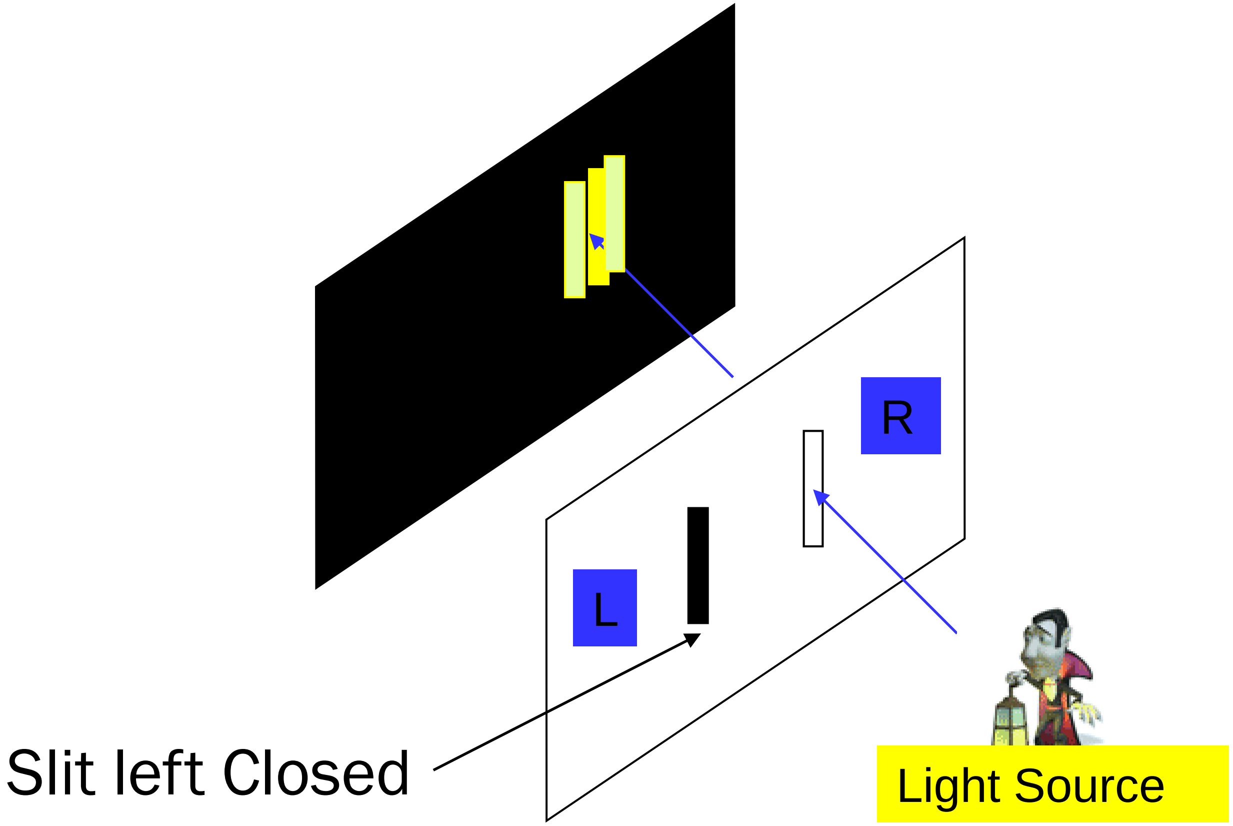
as we expect from wave theory.



Close right slit

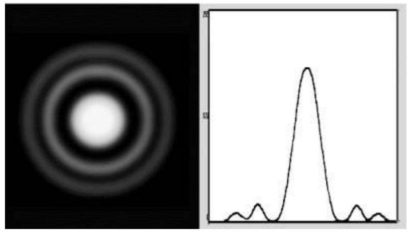
video

2 Slits Experiment (Light as wave)

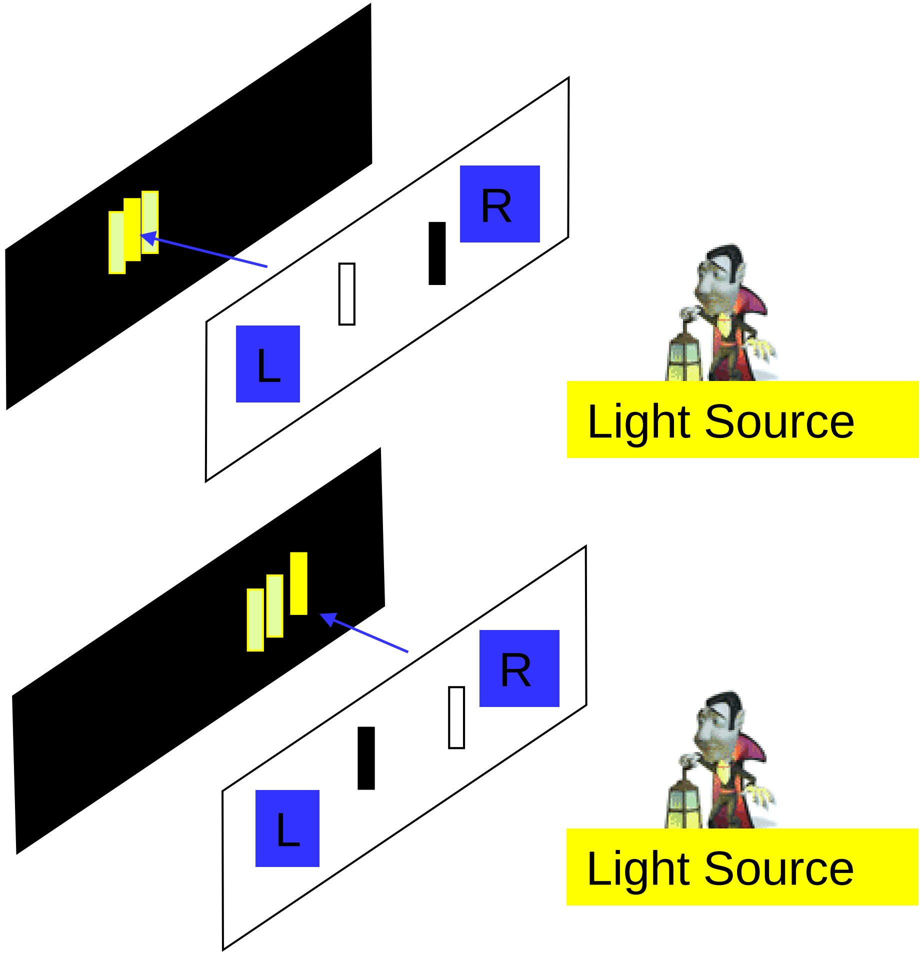


Single Slit Diffraction …

as we expect from wave theory.



Summary for Waves (one slit closed)



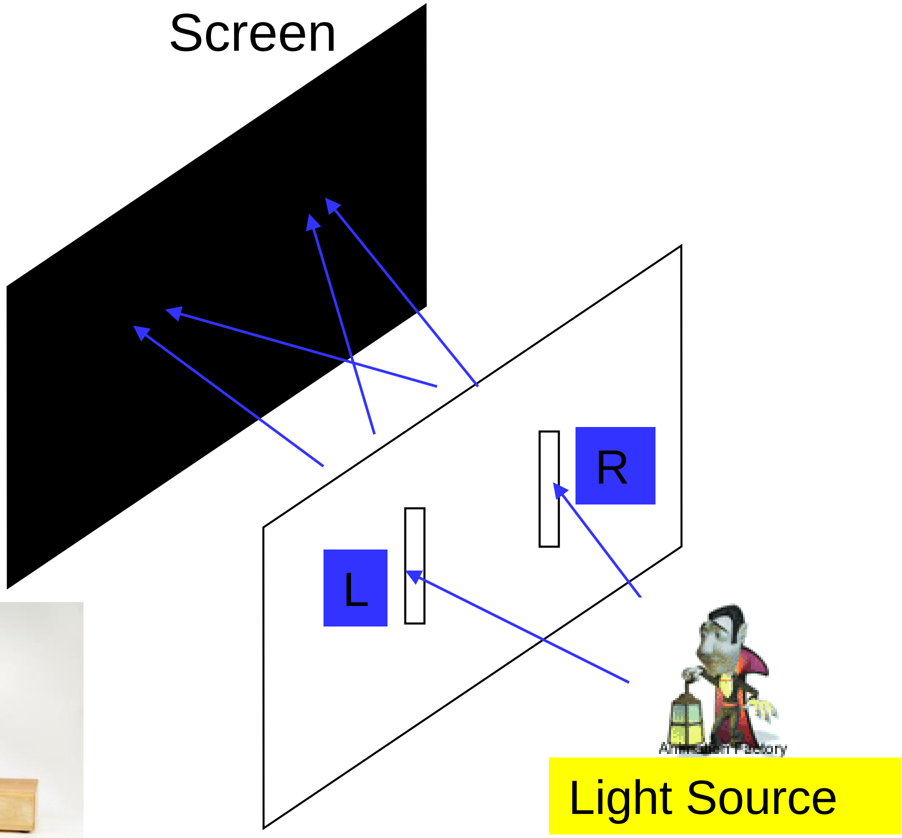
2 Slits Experiment (with Light waves)

Sometimes called Single Slit Diffraction.

In this case it piles up on one side just like the case of the bullet .

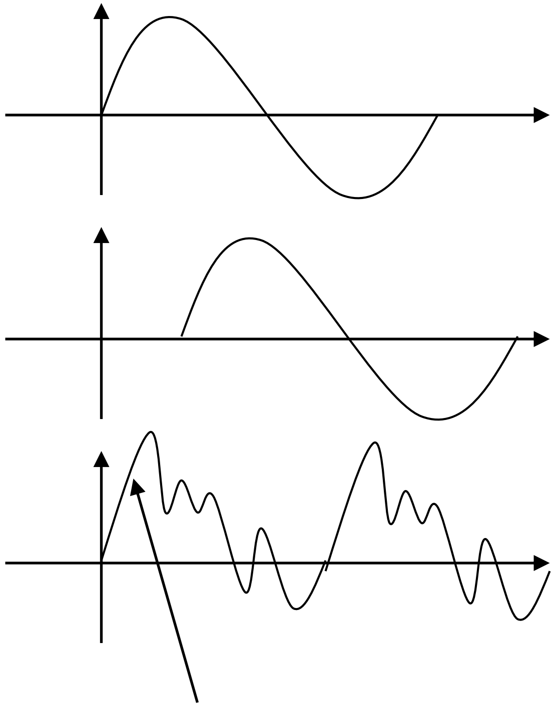
One can also use water waves.

Redo 2 Slits Experiment (2 slits Open)



Recall Tuning fork demo in school.

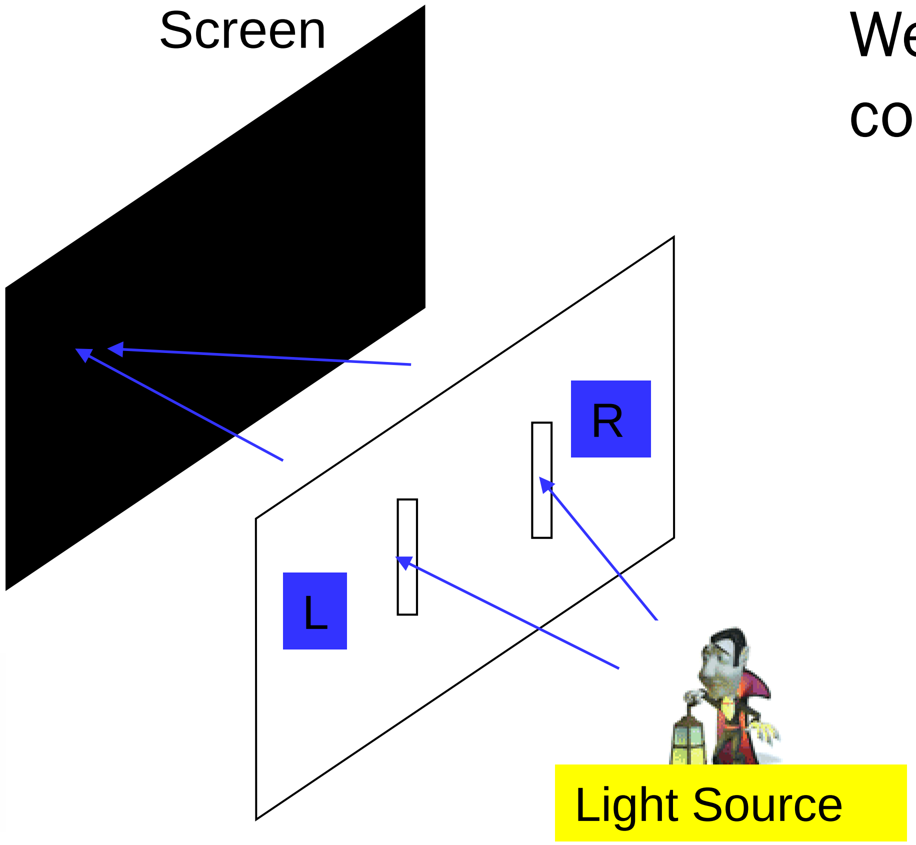
Interference of 2 out of phase waves.

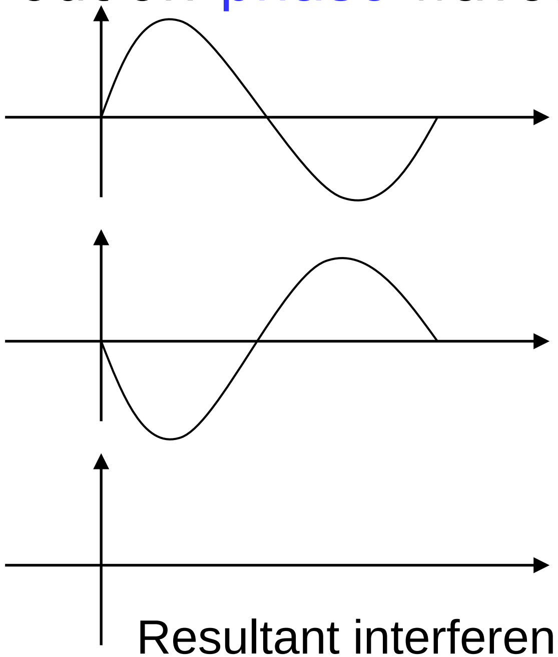


Resultant interference wave (beats)

2 Slits Experiment (2 slits Open)

We expect interference of 2 completely out off phase waves.



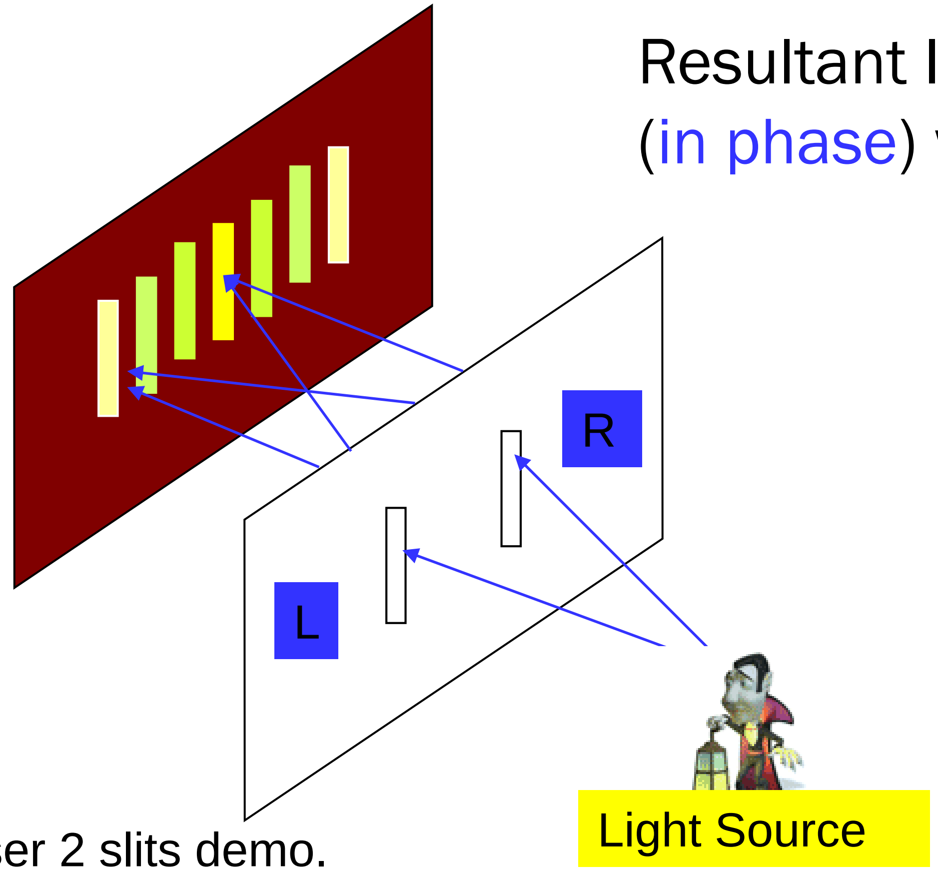


Resultant interference wave

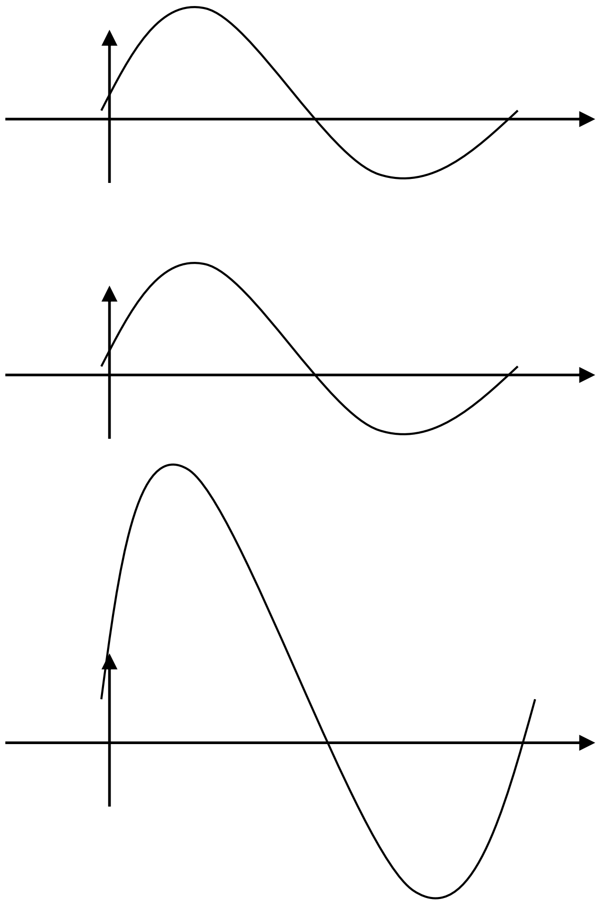
Recall cup demo

Monochromatic light (one wavelength or one colour)

2 Slits Experiment (2 slits Open)



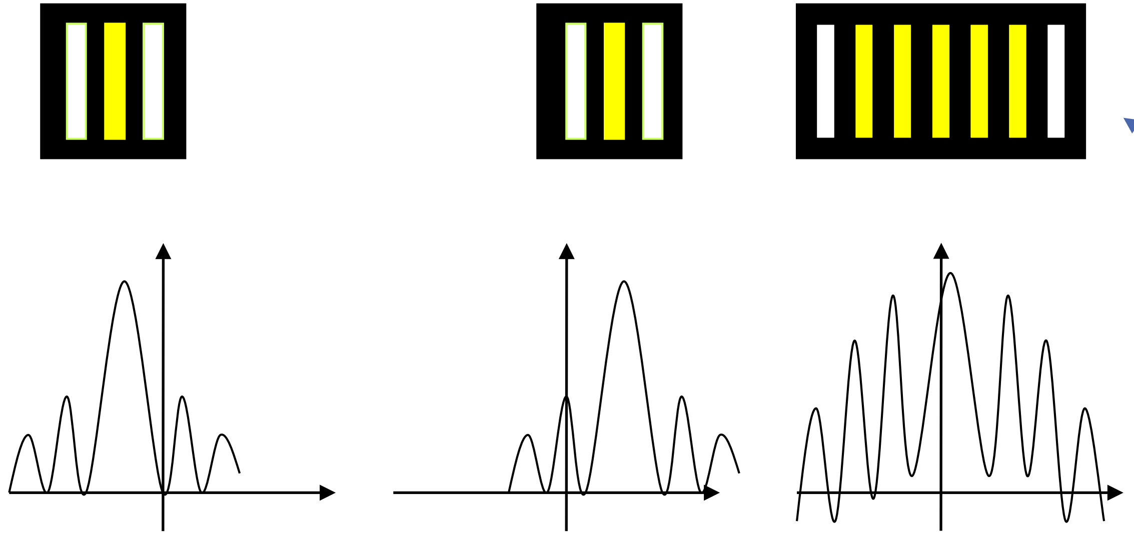
Resultant Interference (in phase) wave



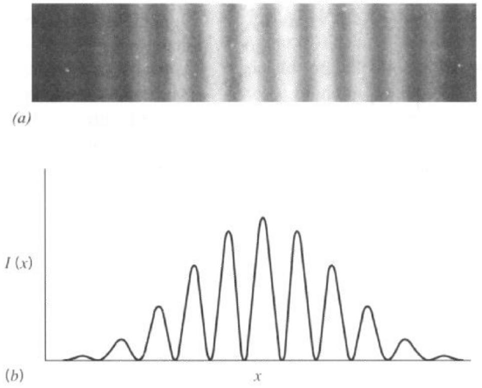
Recall Laser 2 slits demo.

Constructive and Destructive Interference

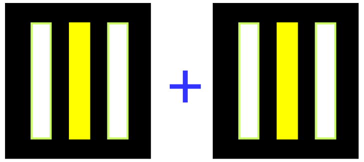
Summary for Waves (from Light)



The results above are consistent with wave theory of light … every star you see through a telescope is not a dot but a small circle surrounded by little dark and bright concentric circles (diffraction patterns) … so there is no perfect telescope.

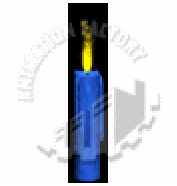


But It is not



But we did not get this pattern !

1909 Experiment !

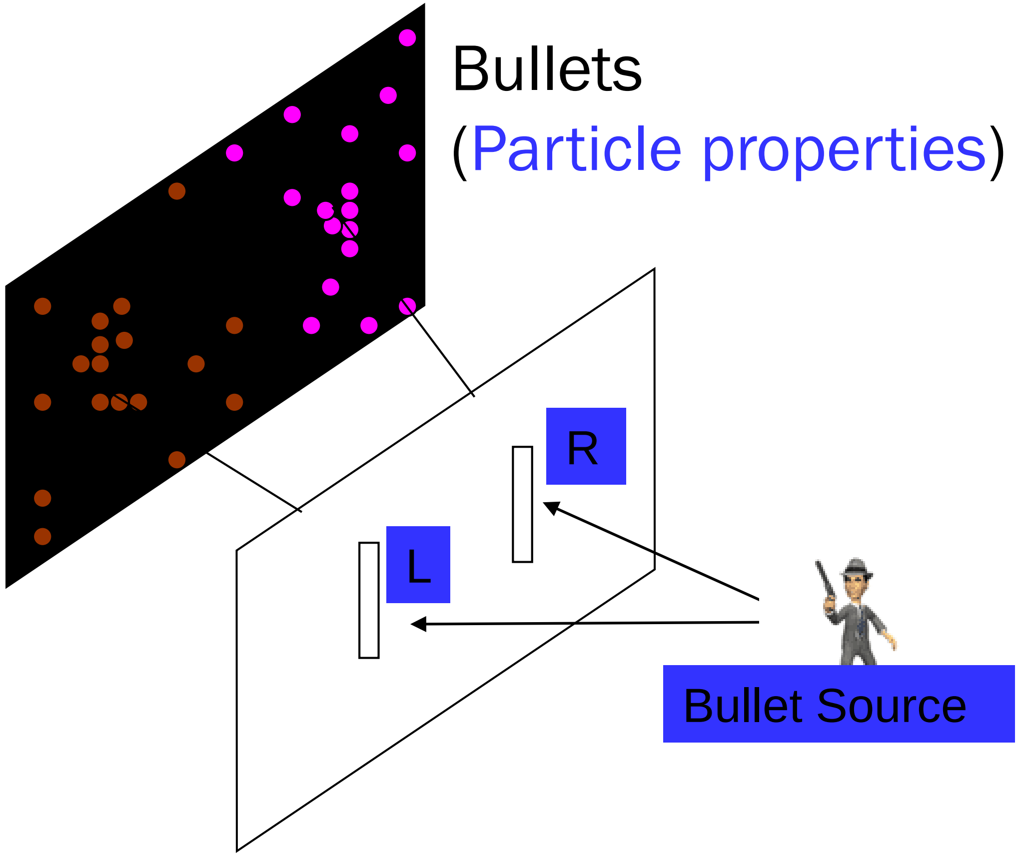


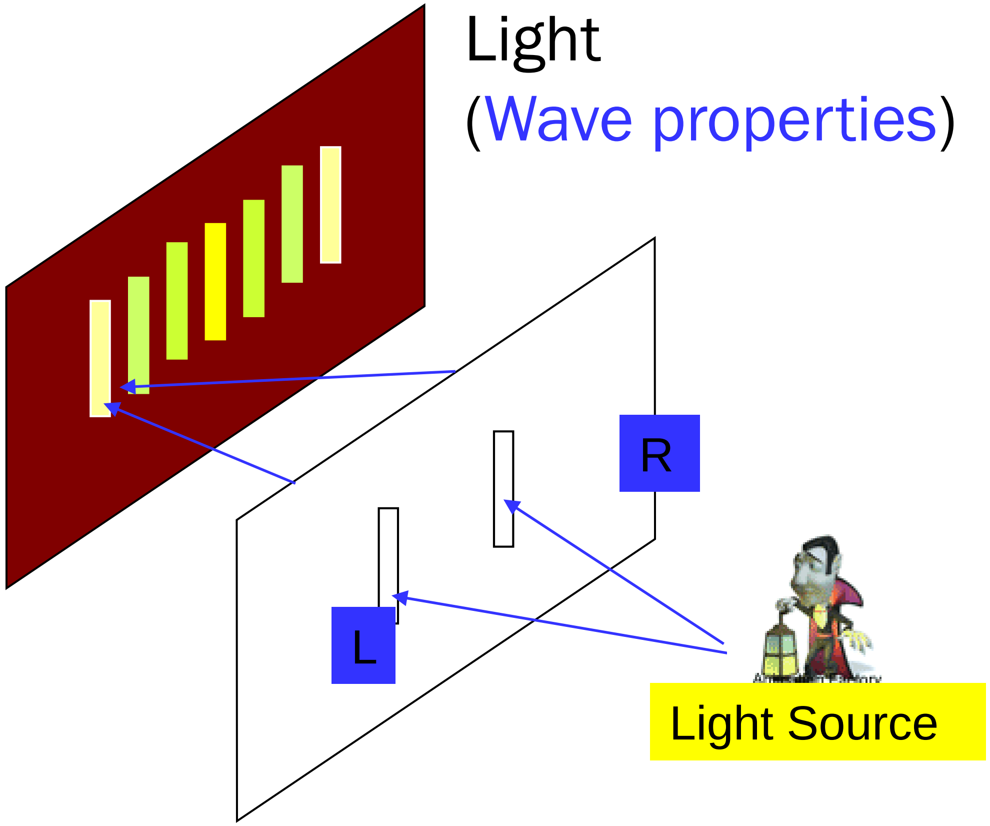
Motivated by J.J. Thomson's doubt that interference can be observed for extremely weak light.

One million photons of yellow light per sec. per square inch … one photon every 2 sec striking a photographic grain of size 10 microns.

G.I. Taylor successfully photographed the diffraction pattern of a needle, at a luminosity equivalent to a candle burning at a distance of slightly less than a mile. The exposure time was 3 months, during which time he went on a yacht trip. Proc. Camb. Phil. Soc. 15 (1909) 114

Summarize A bit more !



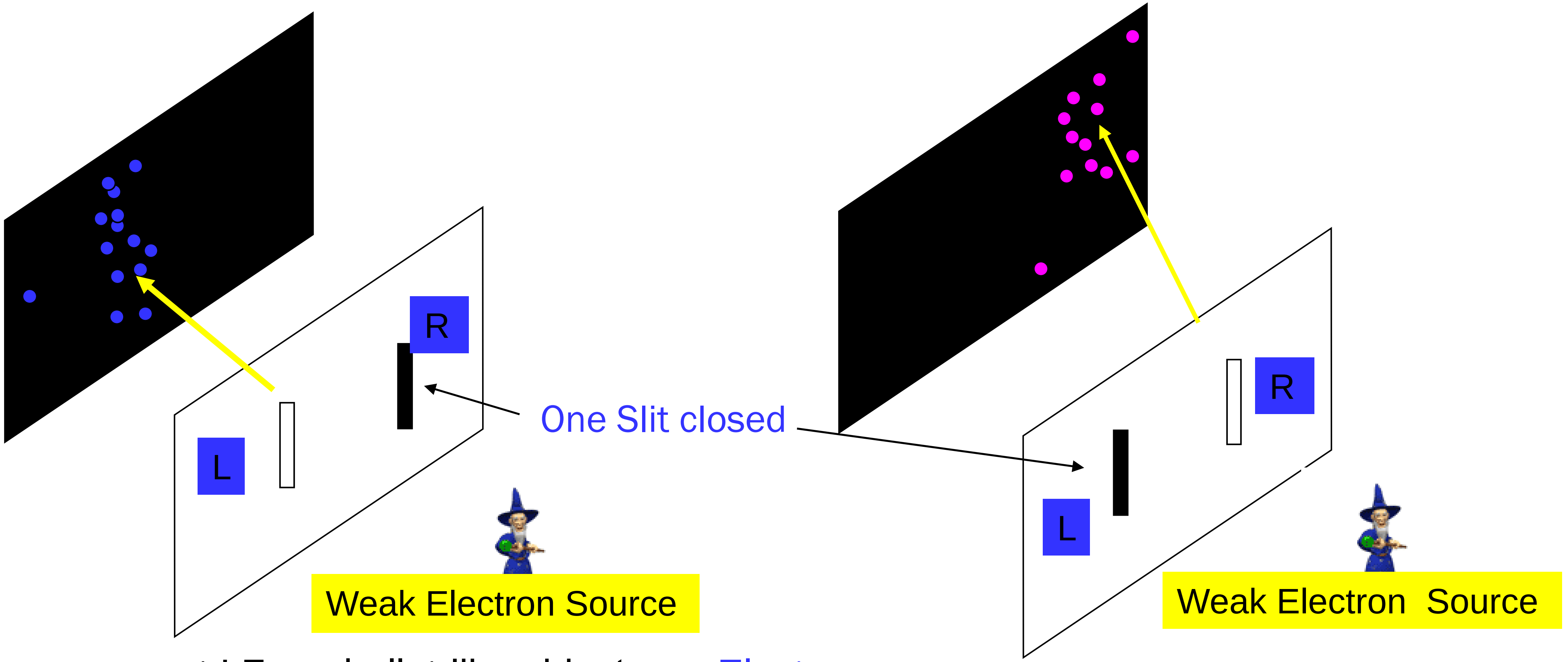


So far everything is still “understandable” & not (very) mysterious at all.

2 slits experiment

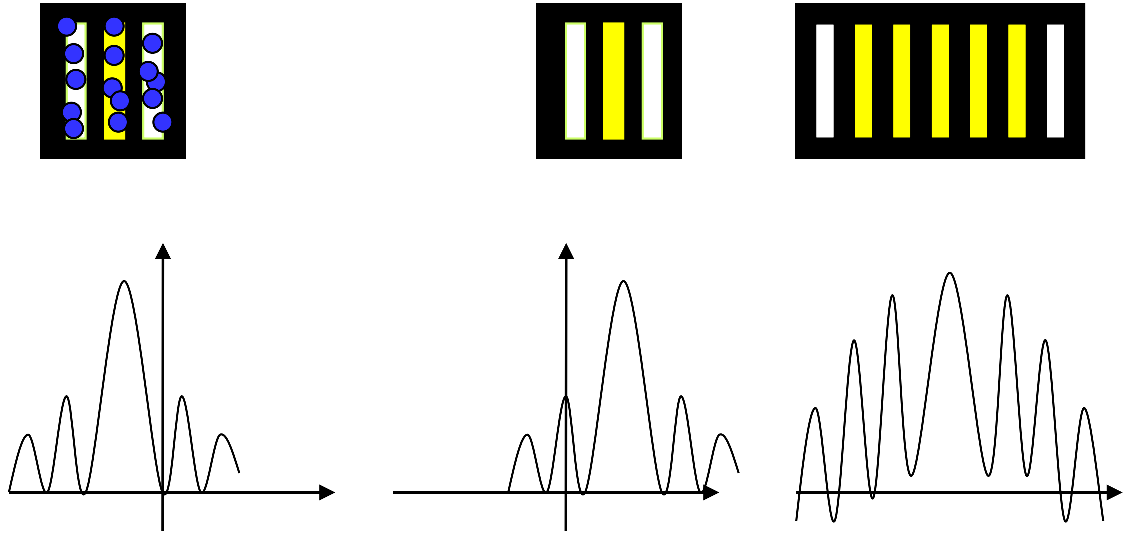
Electron Bullets “lumpy and particle like”

Redo 2 Slits Experiment (Weak Electron Source)

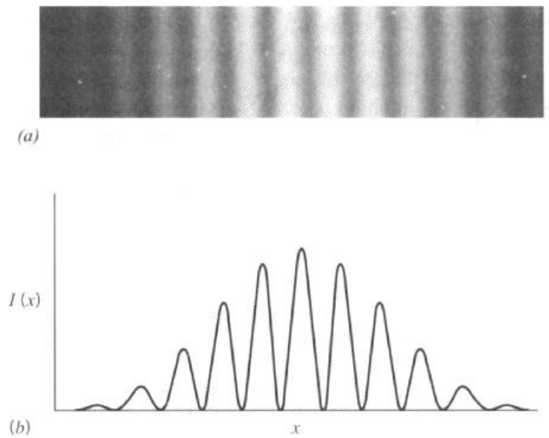


As we expect ! From bullet-like objects, … Electrons expect the particle like electrons to not have wave like properties when both slits are open

What would you expect from Electrons ?



Amazing !



Left Open

Right Open

Left and Right Open

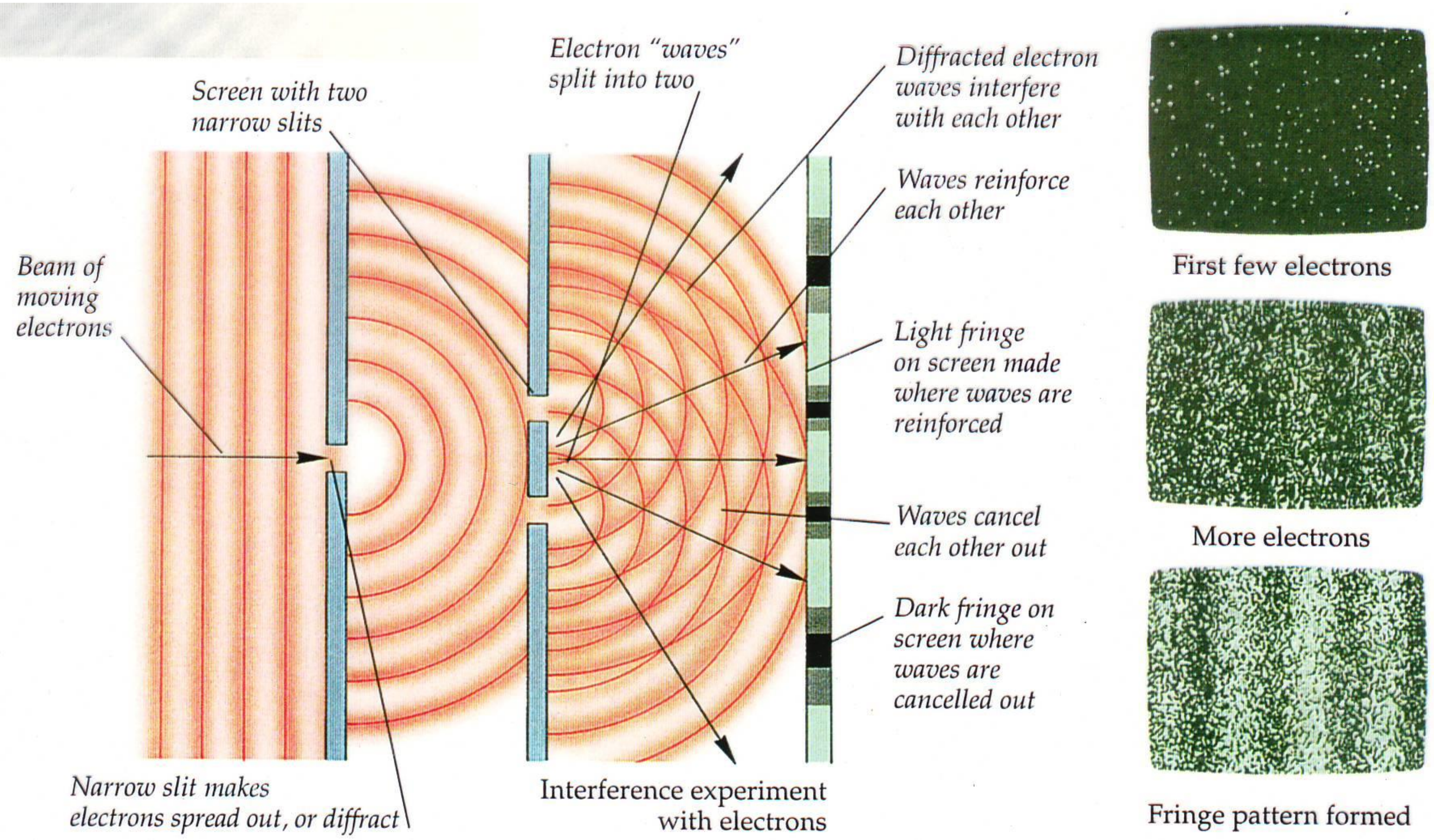
Hey hey ! Isn't an electron a particle ? Should we not expect patterns like that of bullets?
Does it mean the same electron goes through both the slits ?
Does the electron secretly breaks up and go through both the slits
and eventually recombine once it gets through the slits ?

A Nicer Picture for Electrons Patterns

We find that the electron behaves like a particle when only one slit is open and behaves like a wave when both the slits are open.

Socratic Question : How does **"it"** know when to behave as a particle and when to behave as a wave ?

There are places Electrons will not go ??



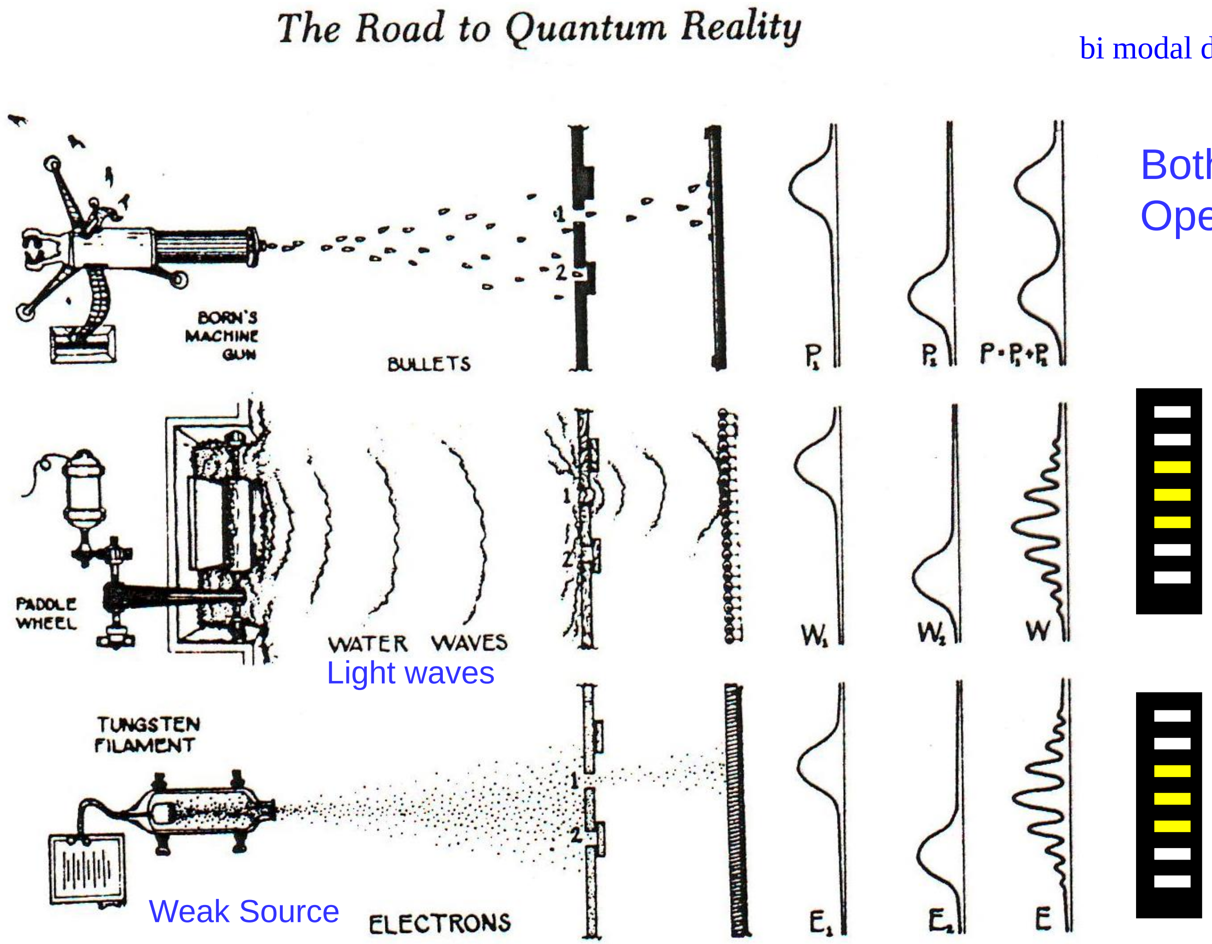
Sometimes Wave sometimes Particle

bi modal diagram

Particles
Bullets

Waves

Micro
Particles

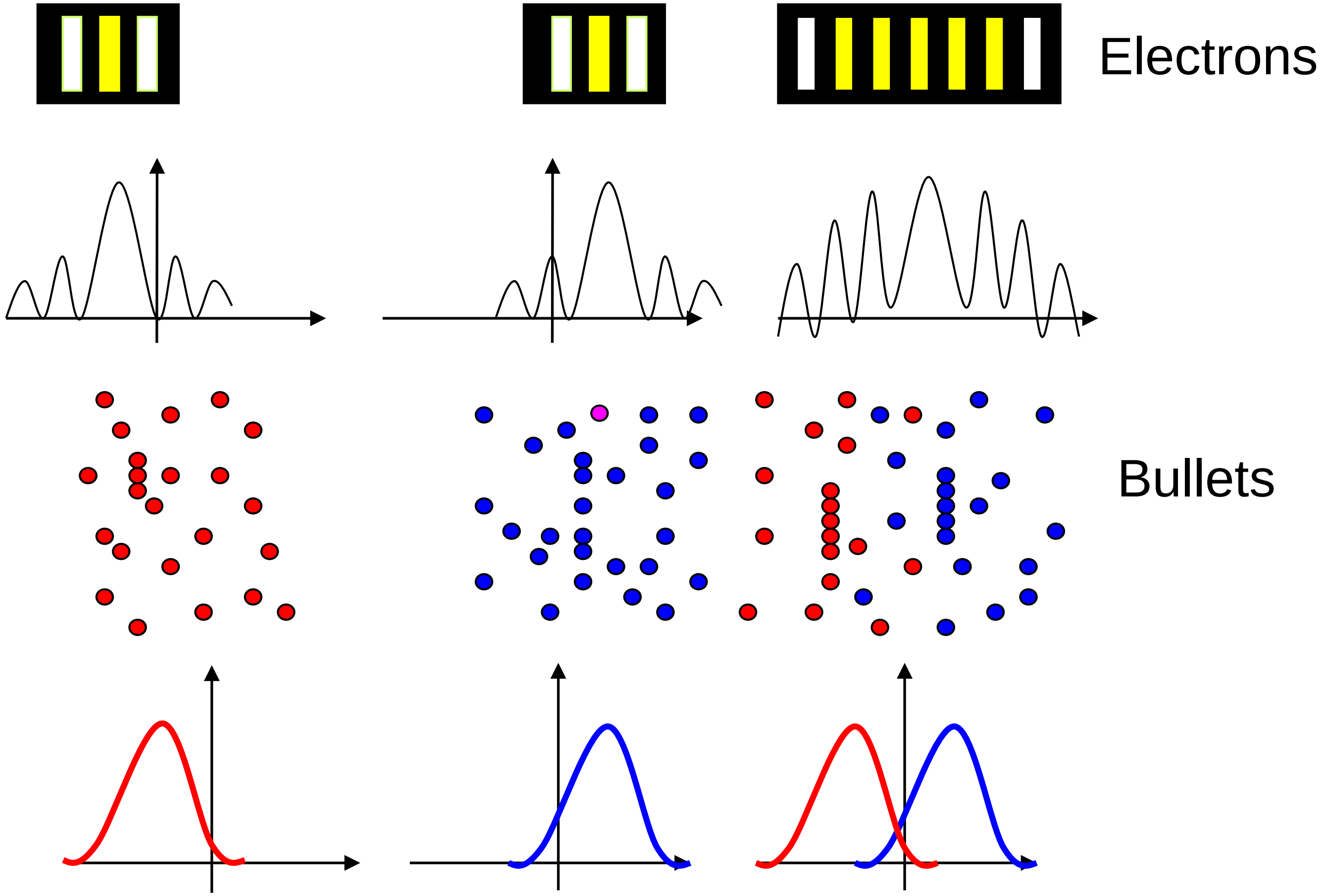


As expected

As expected !

Unexpected !
Amazing !

Compare your expectations ?

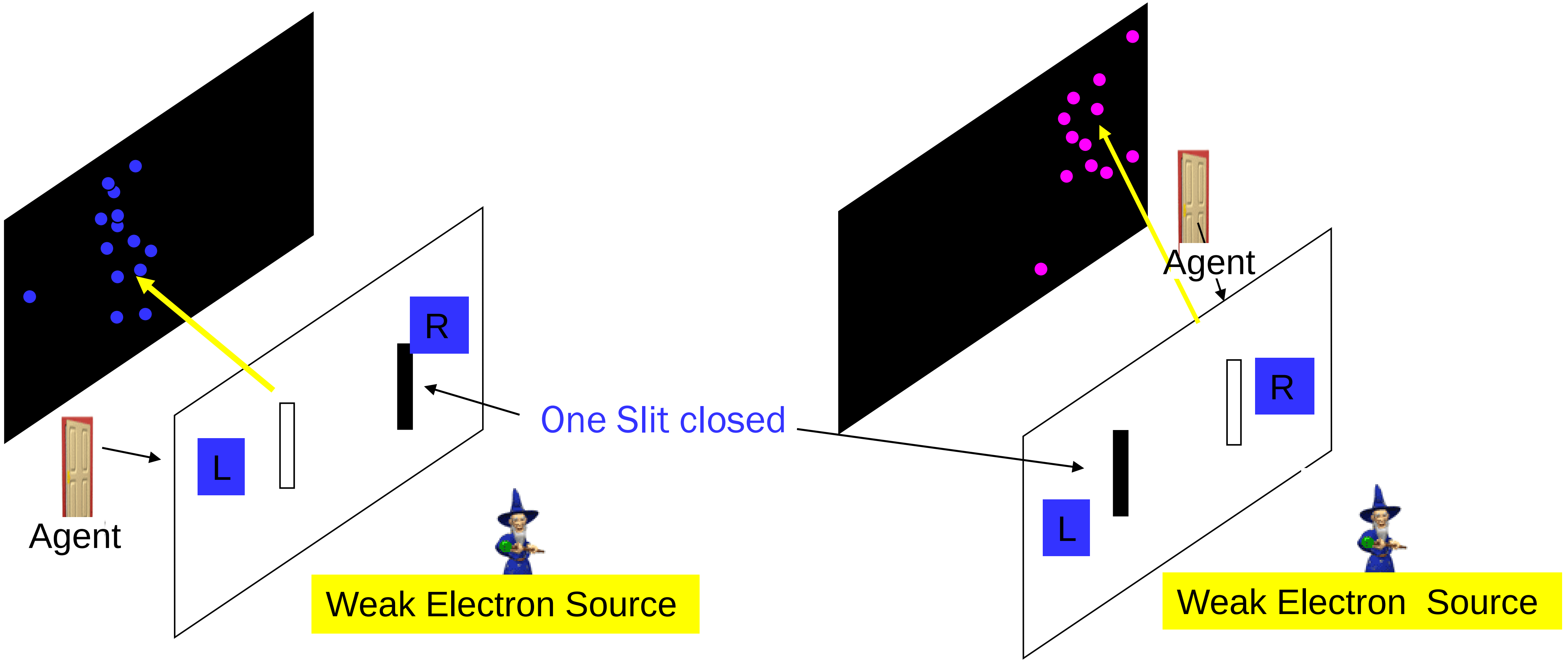


Well, you may argue that the electron also possesses wave properties due to Einstein, de Broglie and Compton … last lecture 9.

2 slits experiment
To deepen the mystery …

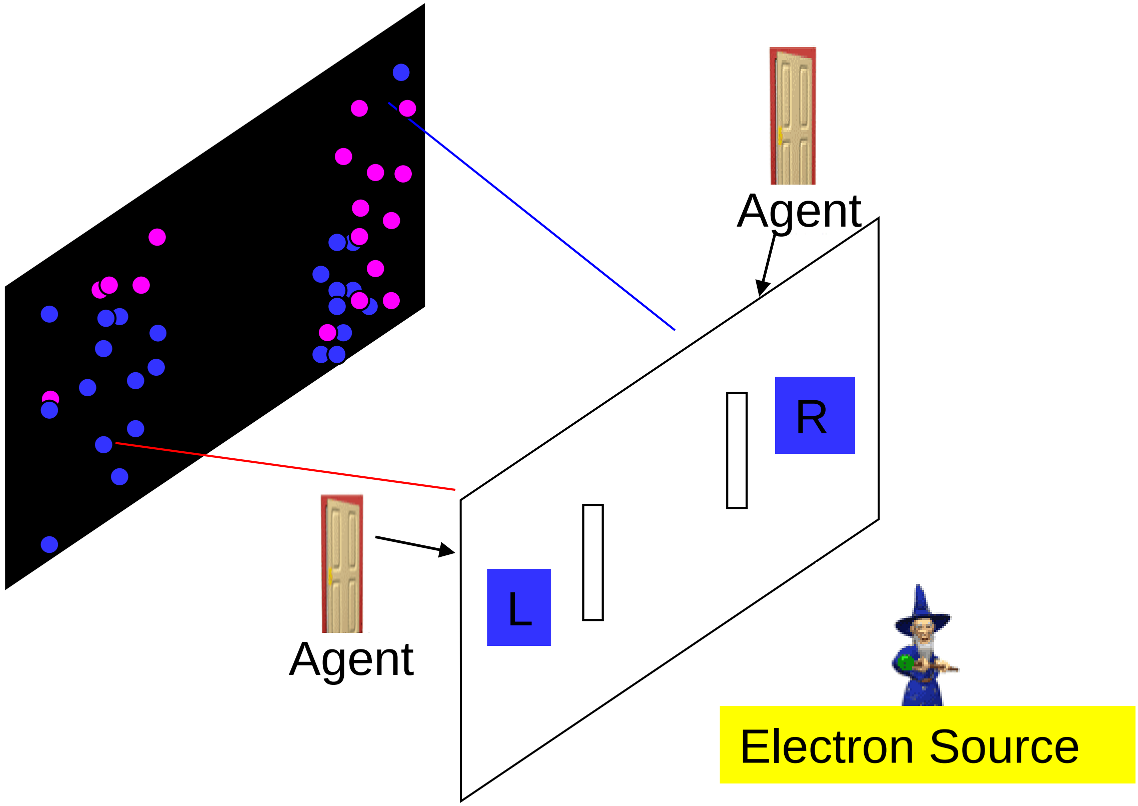
Electron Bullets “lumpy particle like and with observers”

Redo 2 Slits Experiment (Electrons with Agents)



As we expect ! From bullet like objects, electrons

2 Slits Open (Electrons with Agents)



Do we expect this ? From bullet like objects, electrons

When both slits are opened,
Oh No !
We did not get Interference Pattern.
This is surely Amazing !

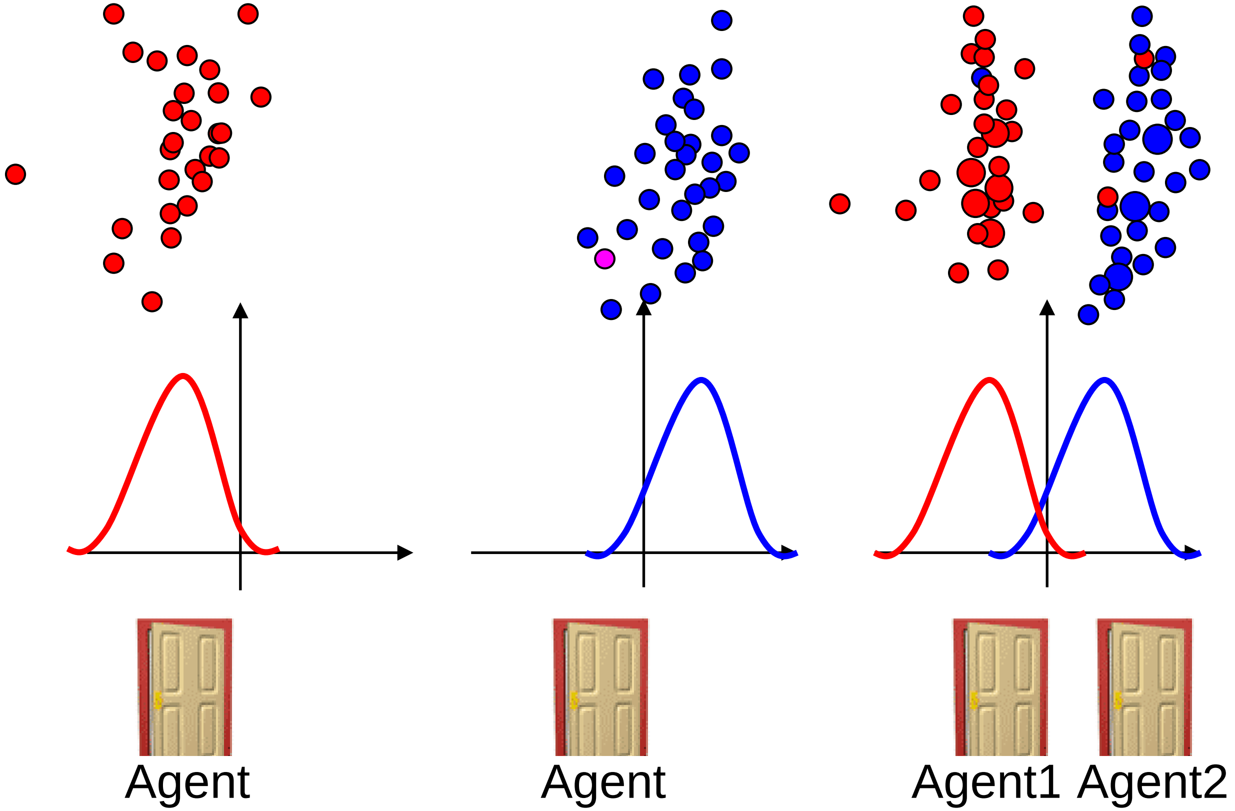
Why ?

Because when both slits are opened, we should get back the interference pattern since Electrons are waves !

... but did not.

when being observed they will now become particle like

Summary: (Electrons with Agents)



Oh No !

We got something different .... pattern like real bullets !

In short, when the agents are looking, electrons behave like particles just like bullets. Absolutely stunning !

A Strange Result indeed !

This is a very strange result, since it seems to indicate that the observation plays a decisive role in the event and that reality varies, depending upon whether we observed it or not.

W. Heisenberg

We cannot make the mystery go away by explaining how it works.

Historically, the electron was thought to behave like a particle and then it was found that in many respect it behaved like a wave. So it really behaves like neither.

Now we have given up. We say: it is like neither.

R. Feynman

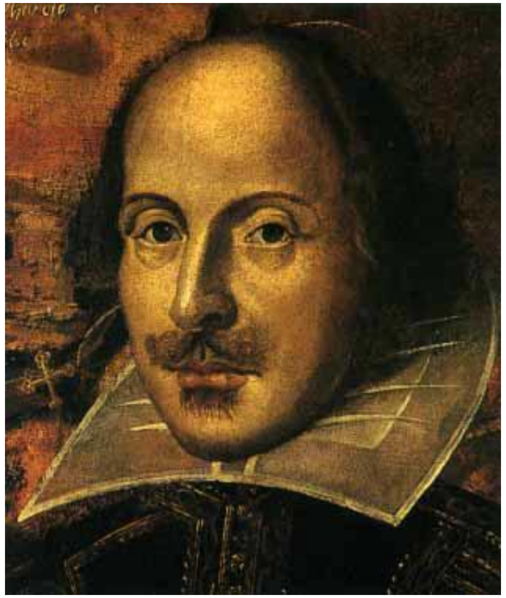
William Shakespeare, *Hamlet*

Horatio :

O day and night, but this is wondrous strange !

Hamlet :

And therefore as a stranger give it welcome.
There are more things in heaven and earth, Horatio,
Than are dream of in your philosophy.



Act 1, scene 5,
lines 166-167

Lecture 10

Consider Left and Right Slits !

2 Slits: Thomas Young's Experiment

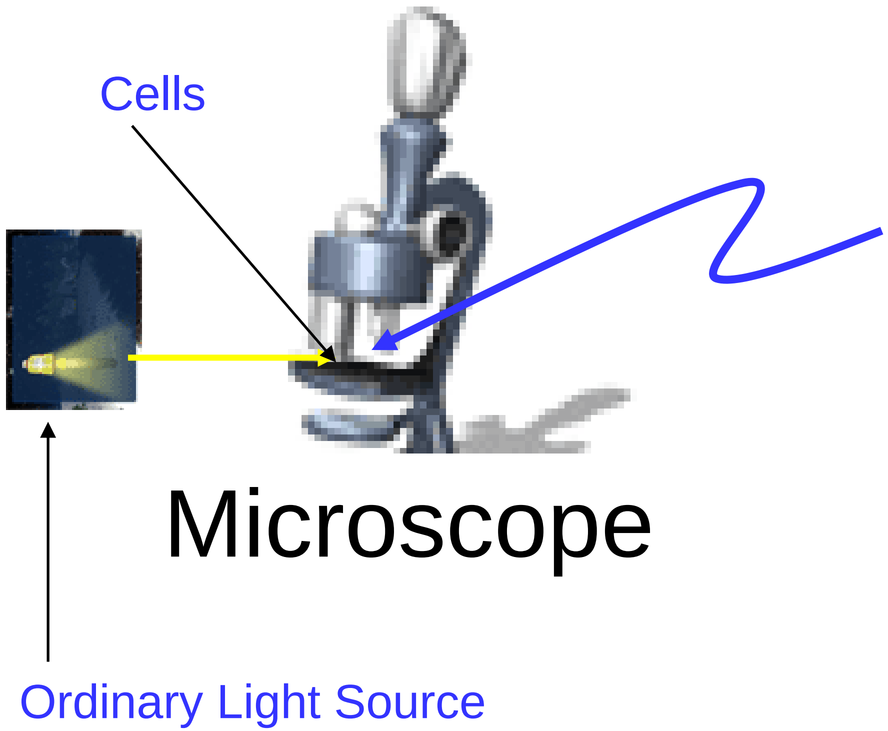
http://www.youtube.com/watch?v=aAgcqgDc-YM

Another experiment

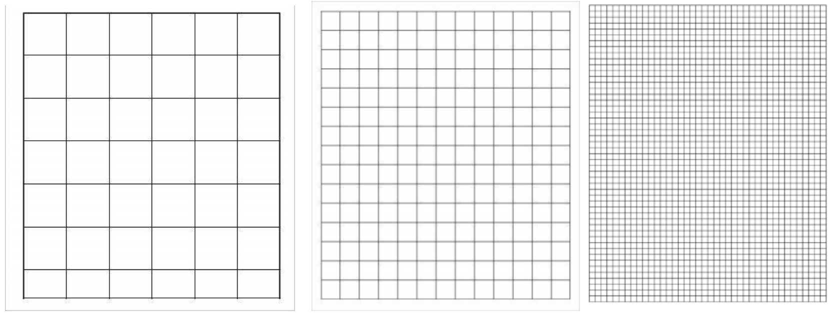
“**Seeing** very very very very very very very very small micro objects”

… our eyes cannot “resolve” them

Standard Optical Microscope:
The Heisenberg Uncertainty Principle



1 : Make grid divisions more fine, Δx

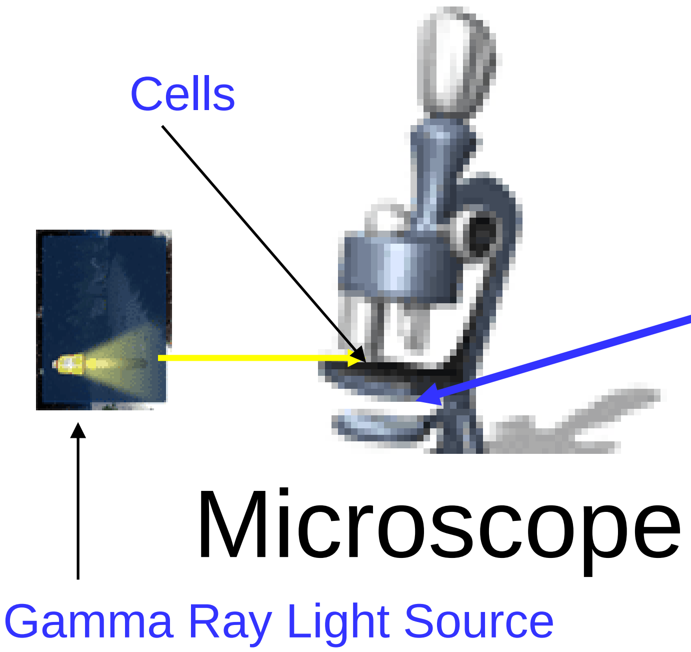


2 : Or Classically $\Delta x \sim \lambda$ ~ order of

Classically there is a limit to optical resolution due to the wavelength of light (radiation) used. … Nothing mysterious here still !

3 : But there will come a time where there will be an Unavoidable Fuzziness … in Δx

Gamma Rays-Microscope :
The Heisenberg Uncertainty Principle



What is this Unavoidable Fuzziness ... in Δx ?

$$\Delta x \sim \frac{\hbar}{\Delta p}$$

Re-arrange

$$\Delta x \Delta p \sim \hbar$$

Equivalent to

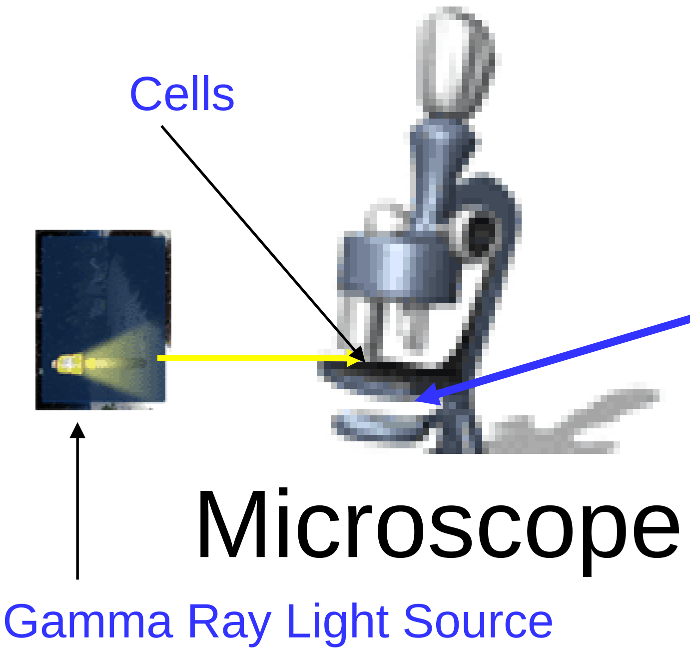
$$xP - Px \sim h$$

$$QP - PQ = \frac{ih}{2\pi}$$

New Idea: Cannot measure x (position) and p (momentum) Simultaneously !

There seems to be a limit to knowledge ...also to how much you can know !

Gamma Rays-Microscope : Energy & Time
The Heisenberg Uncertainty Principle



What is this Unavoidable Fuzziness ...
in ΔE ?

$$\Delta E \sim \frac{\hbar}{\Delta t}$$

Re-arrange

$$\Delta E \Delta t \sim \hbar$$

Another Version ..... ??????? **Why** ???????

New Idea: Cannot measure x (position) and p (momentum) Simultaneously !

There seems to be a limit to knowledge ...also to how much you can know !

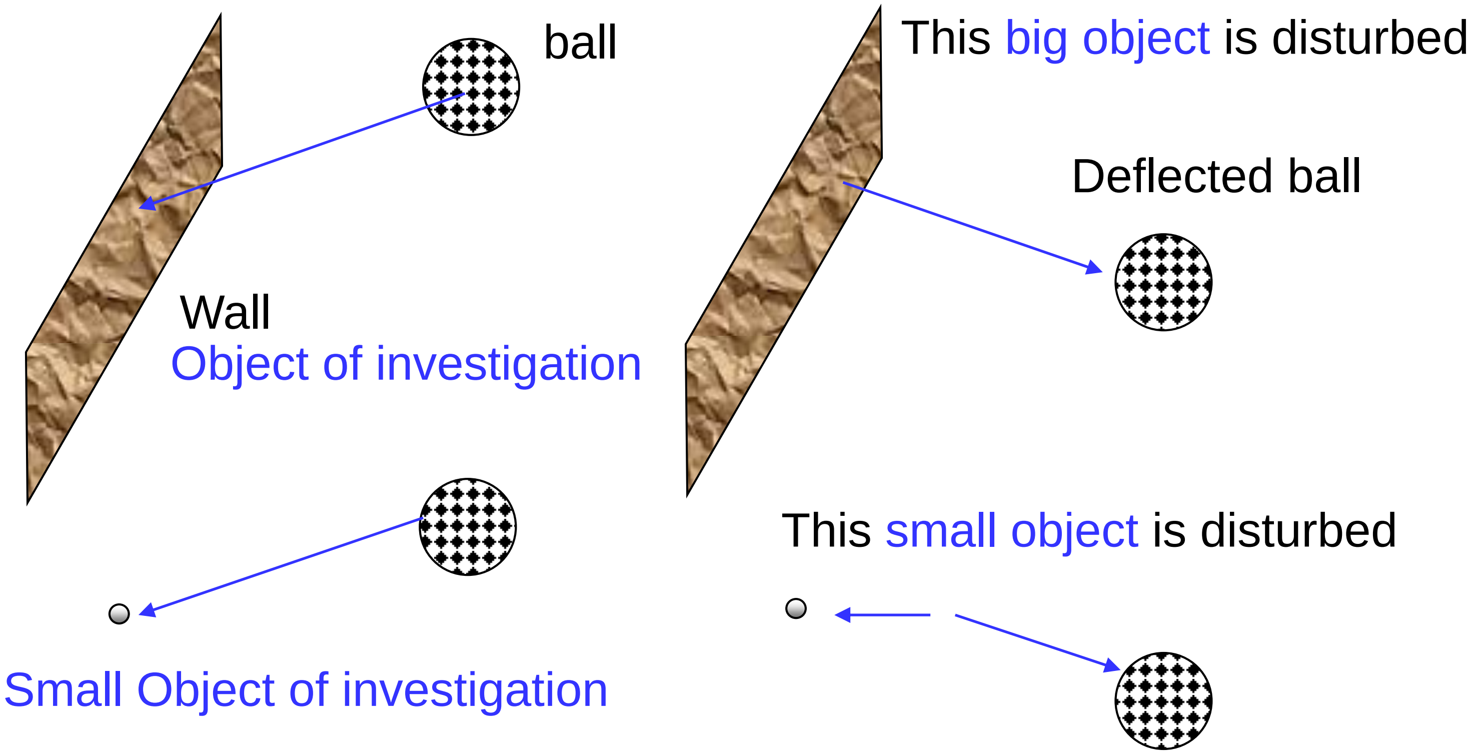
Say it another way !

"seeing very very very very very small micro objects"

… our eyes cannot "resolve" them

Scattering of Objects (Classical)!

How can we see the wall (bigger) ... by scattering an ordinary ball (smaller) ?

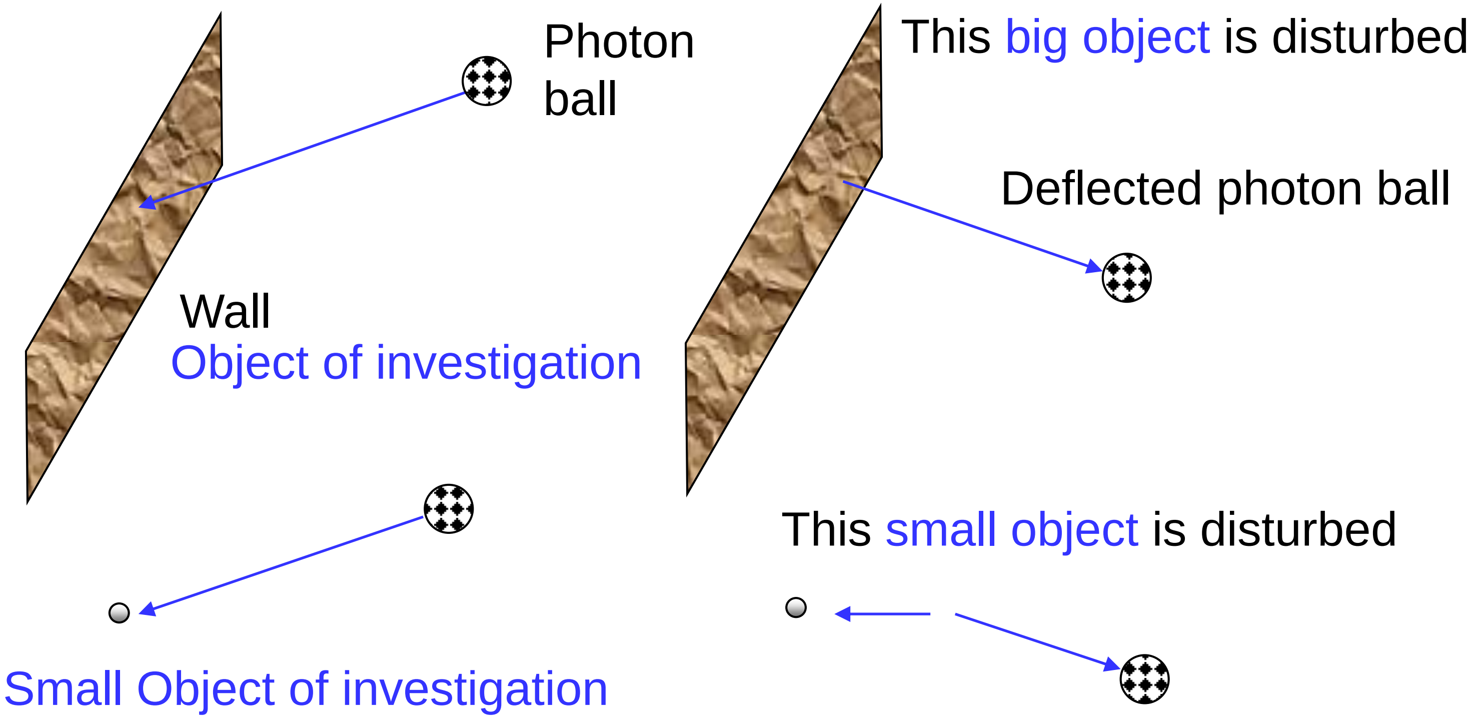


Note
You can see the trajectory

Again you can see the trajectories ... Ball may not bounce back

Scattering of objects !

How can we see the wall (big) ... by scattering a photon ball ?

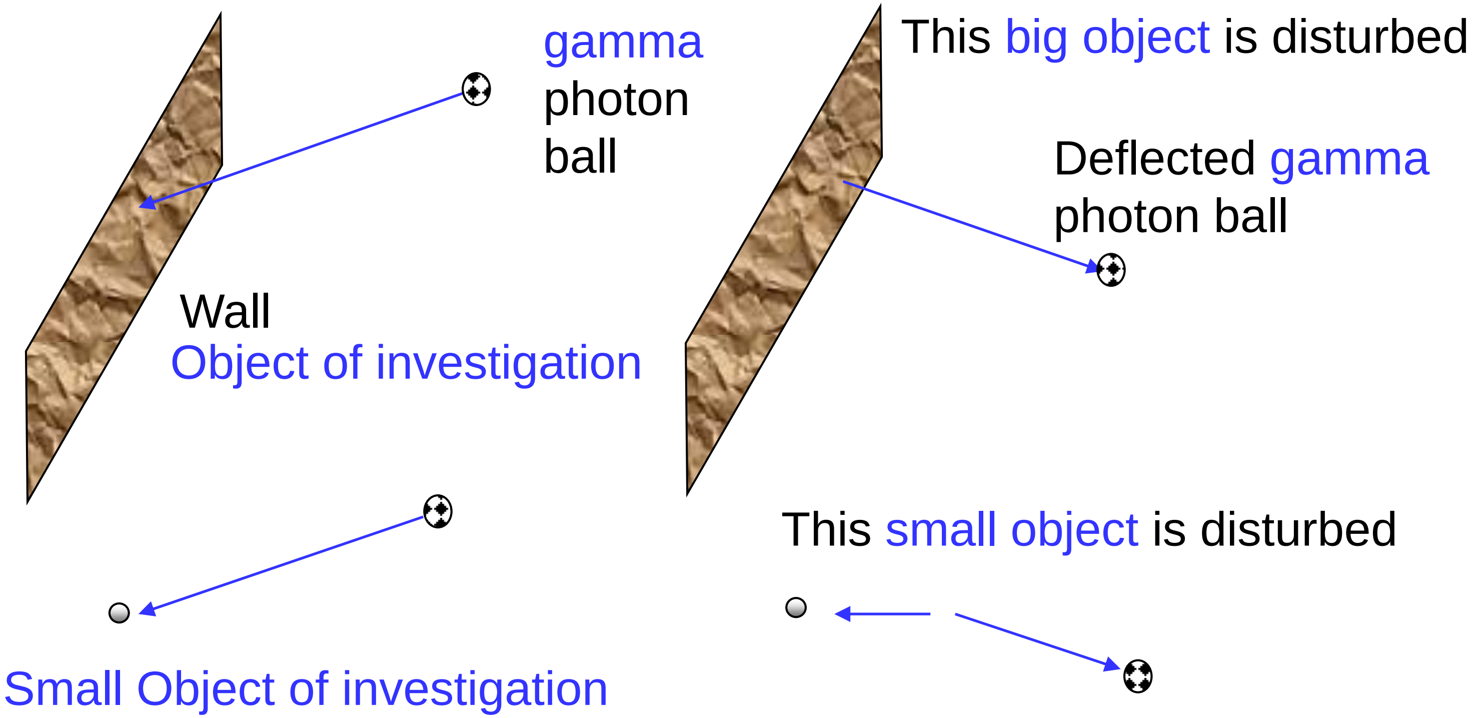


Can you can “see” the trajectory ?
(deflected laser demo and handphone camera)

Again you can see the trajectories ... Photon ball may not bounce back

How to see even smaller objects ?

How can we see the wall (big) ... by scattering a gamma photon ball ?



Can you can “see” the trajectory ?

Use a small micro Ball (electron or gamma photon) may bounce back ... at a price ...

$$p = \frac{h}{\lambda}$$

So there is a problem with measurement !

Another version of

$$QP - PQ = \frac{ih}{2\pi} = i\hbar$$

$$XP - PX = \frac{ih}{2\pi} = i\hbar$$

$$\Delta x \Delta p \approx \hbar$$

Another version of ??

$$QP - PQ = \frac{ih}{2\pi} = i\hbar$$

$$Et - tE = ?$$

$$\Delta x \Delta p \approx \hbar$$

… after people read the paper, a lot of people understood the theory of relativity in some way or other, certainly more than <u>twelve</u>.

On the other hand, I think I can safely say that no one understands quantum mechanics !

$$\boxed{QP - PQ = \frac{ih}{2\pi} = i\hbar}$$

R. Feynman

The Character of Physical Law

$$\sqrt{-1} = i$$

Heisenberg

Nature of Uncertainty

In the case of measuring the microscopic objects like electrons, even a single photon bouncing off an electron can appreciably alter the position of the electron and in *an unpredictable way.*

The significance of the uncertainty principle in that even in the best of conditions, the lower limit of uncertainty is *h* bar. i.e. if we wish to know the momentum of an electron with great accuracy (delta ***p***) the corresponding uncertainty in position, (delta ***x***) will be large or vice versa.

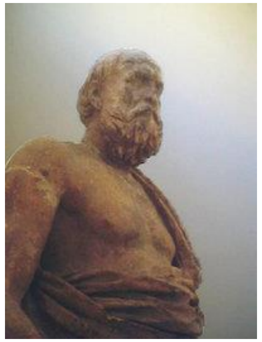
$$\Delta x \Delta p \sim \hbar \leftarrow \boxed{p = \frac{h}{\lambda}}$$

$$\Delta E \Delta t \approx \hbar \leftarrow E = hf = \frac{h}{T}$$

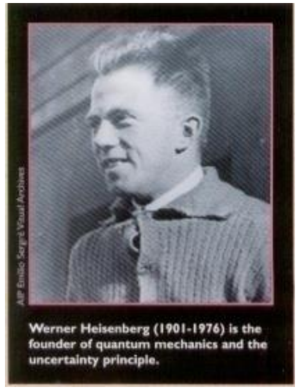
We cannot measure a particle energy with complete precision in an infinitesimally short span of time. It just means that we are more uncertain of the time during which the particle of investigation has that energy.

Reductionistic thinking

We can easily forgive a child who is afraid of the dark; the real tragedy of life is when men are afraid of the light.



Plato 427-347 BC



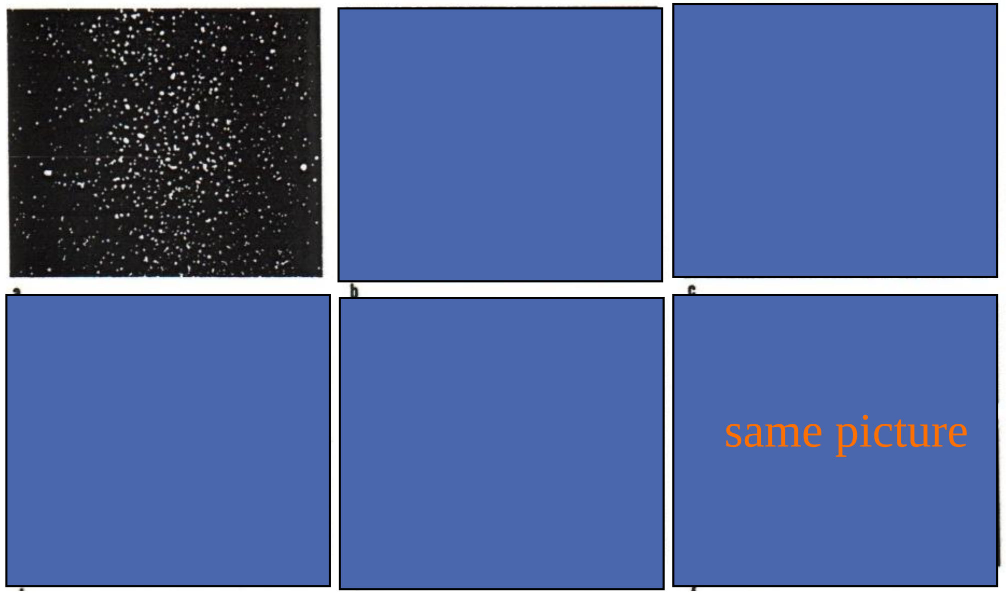
... that one can never understand the Universe until the smallest components of matter are known. Heisenberg was influenced by this tenet of Plato all his life.

By getting to smaller and smaller units, we do not come to fundamental or indivisible units. But we do *come to a point* where further division has no meaning.

W. Heisenberg

Quantum Randomness

When a photograph is taken with very feeble (weak source … photon by photon) light, one can find that the image is build up by individual photons that arrive *independently* and are seemingly "*random*" in their distribution.



$$E = mc^2$$

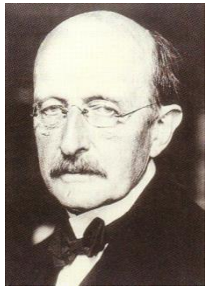
rewrite

$$E = pc$$

$$E = hf$$

simple wave equation

$$v = f\lambda$$



$$p = \frac{h}{\lambda}$$

conflict?
GR tells us that light will follow space-time curvature
-but here, electrons will randomly hit, but after awhile, it will still form the same picture

Quantum Randomness

How did the photon know where to go on the Film or Digital Camera ? …. having travelled 2.2 millions light years

M31 Andromeda galaxy

$$p = \frac{h}{\lambda}$$

same picture

Bohr’s Complementarity Theory

Quantum phenomena exhibit complementary properties … appearing either as particles or as waves … depending on the type of experiment conducted … both are necessary for the comprehension of light.

Bohr use the Yin-Yang emblem to symbolize the principle of complementarity.

Formulated an explicit expression of the wholeness inherent in this dualism.

Break down of Cartesian Philosophy ! why ?

More Knowledge !

… off making many books there is no end much study is the weariness of the flesh.

King Solomon

Ecclesiastes 12:12

“Why” said the Dodo, the best way to explain it is to do it.”

Lewis Carroll

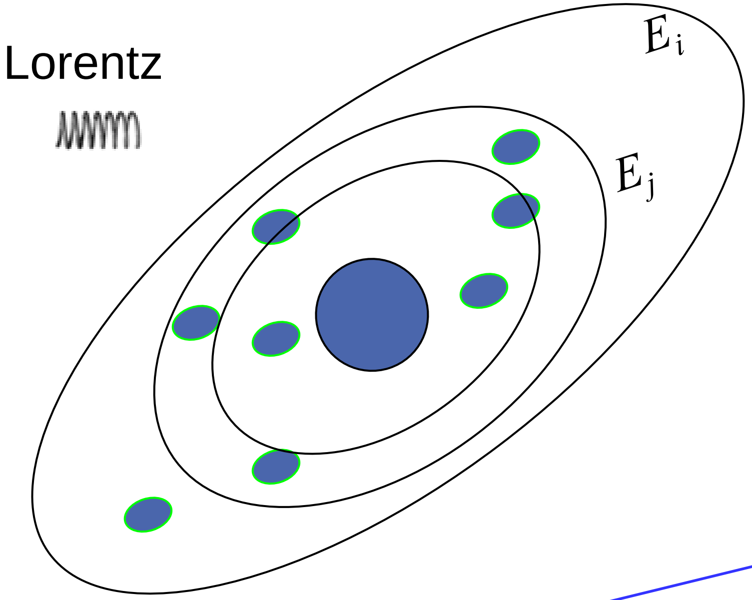
Alice’s Adventures in Wonderland

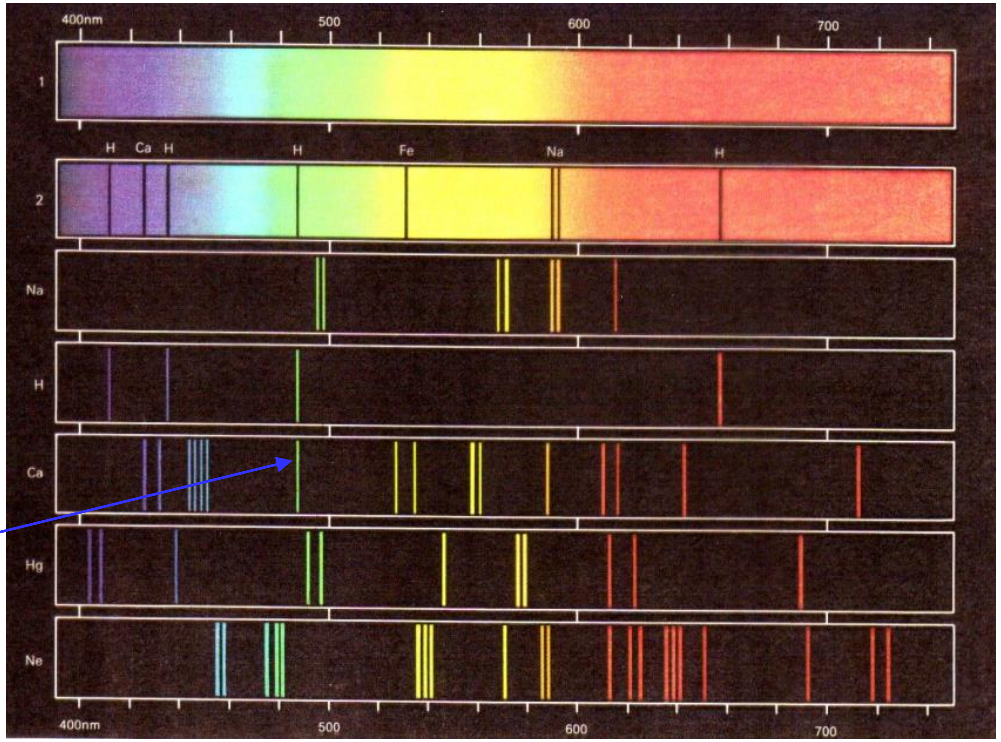
How did Heisenberg discover it ?

$$XP - PX = \frac{ih}{2\pi} = i\hbar$$

$$\Delta x \Delta p \approx \hbar$$

So how did Heisenberg do it ?





$$\begin{array}{ccccc}
 & T_1 & T_2 & T_3 & \dots \\
T_1 & 0 & f(12) & f(13) & \dots \\
T_2 & f(21) & 0 & f(23) & \dots \\
T_3 & f(31) & f(32) & 0 & \dots \\
\dots & \dots & \dots & \dots & \dots
\end{array}$$

$$QP - PQ = \frac{ih}{2\pi} = i\hbar$$

$$\Delta x \Delta p \approx \hbar$$

Heisenberg's Approach

He had the idea that one should try to construct a theory in terms of quantities which were provided by experiment, rather than to build it up on the basis of a model which involved many quantities which could not be observed.

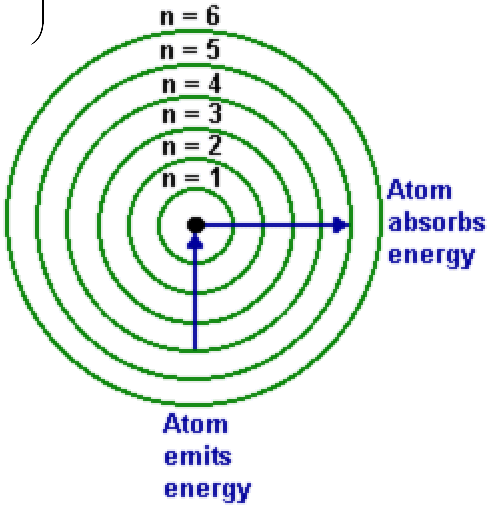
He set out to construct matrices for physical observables such as energy, momentum, position, frequency and velocity. Thus there would be an energy matrix, a position matrix and so on.

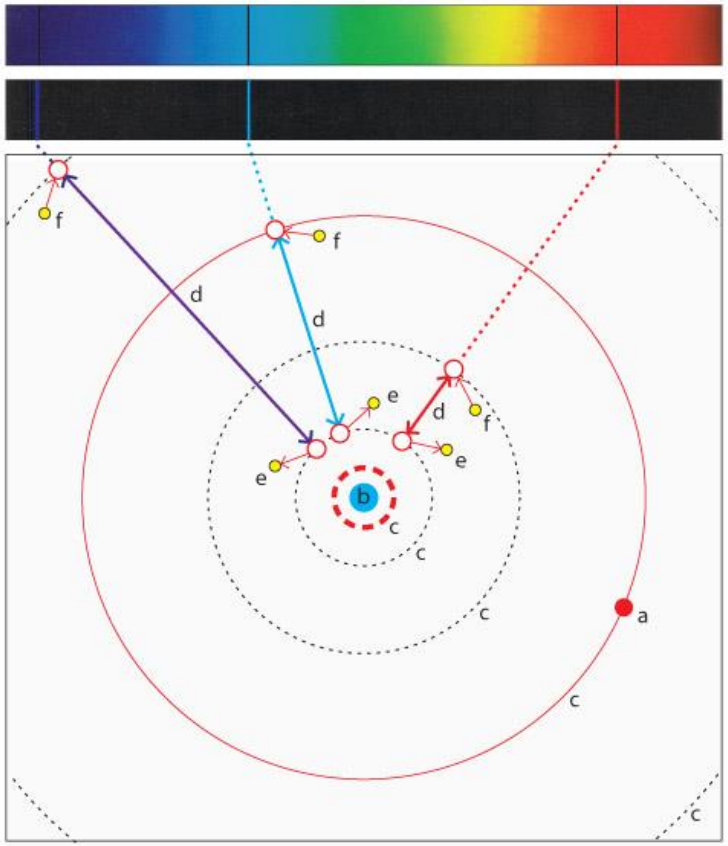
The Development of Quantum Mechanics
Alex Montwill & Ann Beslin (2008)

A “Matrix” for everything !

Matrix of light frequencies

$$\begin{array}{cccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ \end{array}$$
$$\begin{pmatrix} & & & & & & & \\ & & & & & & & \\ & & & f(6,4) & & & & \\ & & & & & & & \\ & & & & & & & \end{pmatrix}$$





First three Balmer series absorption lines for hydrogen

First three Balmer series emission lines for hydrogen

Bohr’s model of the hydrogen atom showed how its single electron (a) achieved stablility around the positively charged nucleus (b). The electron could move only in permitted orbits (c) where it did not emit or absorb energy. 5 orbits are shown; the innermost acts as a “quantum fence” to keep the electron out of the nucleus. The electron could jump from one permitted orbit to another (d). When the electron jumps from a higher to lower orbit, it emits energy quanta (e) that make the colored light of the Balmer series spectral lines. When it jumps from a lower to a higher orbit, it absorbs energy quanta (f), making dark lines in the solar spectrum. 3 possible emission-absorption jumps are shown.

… after people read the paper, a lot of people understood the theory of relativity in some way or other, certainly more than twelve.

On the other hand, I think I can safely say that no one understands quantum mechanics !

$$QP - PQ = \frac{ih}{2\pi} = i\hbar$$

R. Feynman

The Character of Physical Law

$$\sqrt{-1} = i$$

Heisenberg

Born

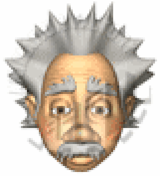
This is the Reality !

We cannot make the mystery go away by explaining how it works.

All that can be done is to tell you "how" it works; that is the way with Quantum Physics.

R. Feynman

There is no quantum world. There is only an abstract quantum mechanical description. It is wrong to think that the task of Physics is to find out how Nature is. Physics concerns what we can say about Nature.



N. Bohr

"There are things that are so serious that you can only joke about them."

W. Heisenberg

Is there a Real world out there?

What we observe is not nature itself, but nature exposed to our method of questioning."

Heisenberg

Perhaps this is what we mean … by "understanding" nature at its most fundamental level !