Quanta and Waves

Rob Plunkett

Fermilab Saturday Morning Physics

Quantum Mechanics

Why Quantum Mechanics?

What was wrong with good old Newton?

Physics of the very small – not designed for it.

Will survey the situation that led to the quantum revolution

What’s all this about particles and waves?

Is Quantum Mechanics “spooky”?

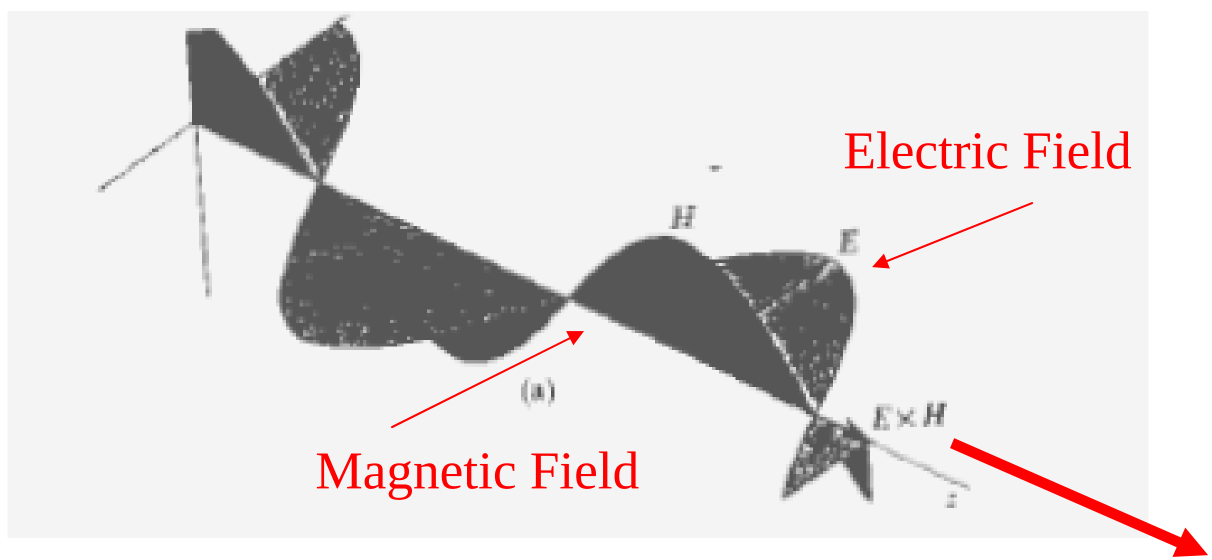
Physics in 1900

Classical mechanics understood – F = ma
Thermodynamics = OK
Atomic theory (from chemistry) – accepted by most.

Complete (they thought) understanding of Electricity.

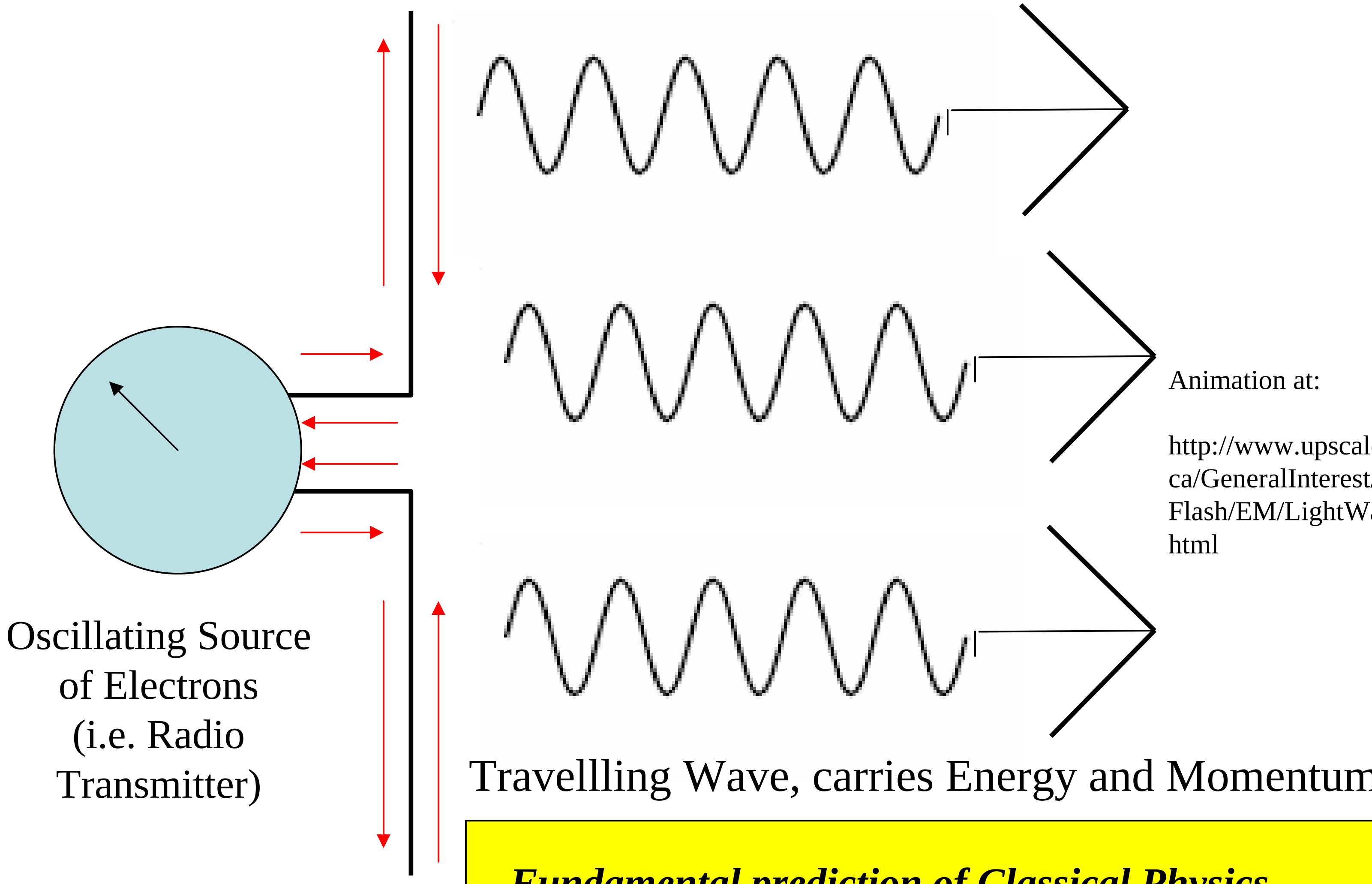
Electromagnetic Waves discovered.

Identified with light! Great triumph of 1800’s.



Credit: Lorraine and Corson

Accelerating Charges make EM waves

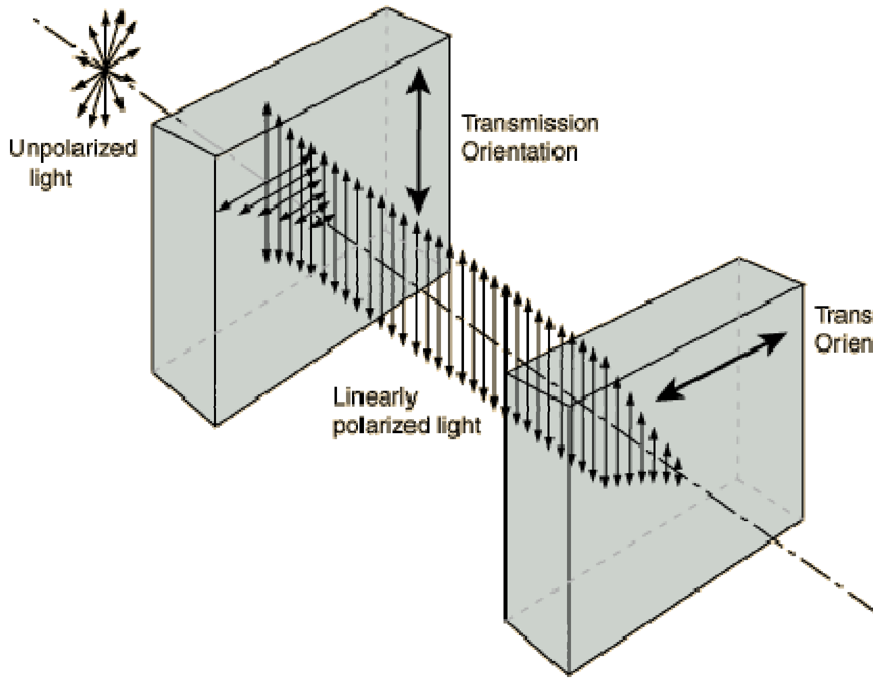


Animation at:

http://www.upscale.utoronto.ca/GeneralInterest/Harrison/Flash/EM/LightWave/Wave.html

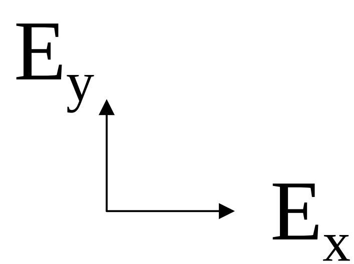
Fundamental prediction of Classical Physics
Power radiated goes as (Current*Frequency)**2

Just a reminder -EM Waves are Polarized



Crossed Polarizers
Nothing comes out

Interpreted as direction of oscillating ***Electric Field*** *in the wave.*

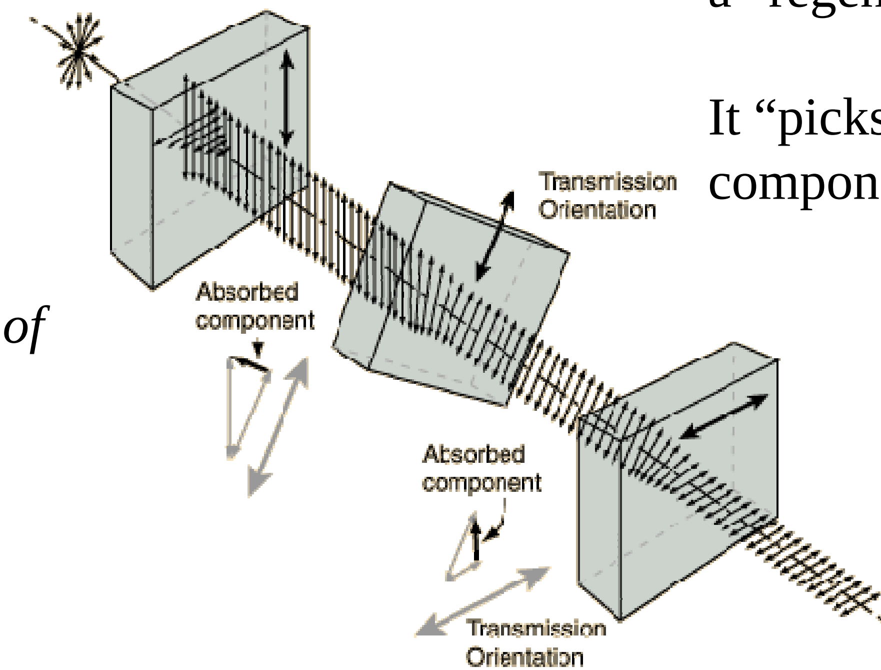


Credit: Hyperphysics

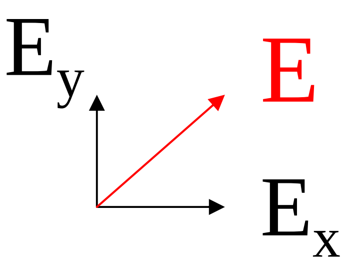
A third polarizer plays with the vector nature of the wave

Middle Polarizer acts as a “regenerator”

It “picks out” a component



Interpreted as resolution of Electric Field into vector components.



Question that was at the interface of EM and Atomic theory ➔ Does this description still work at scales of very small atoms, and very weak waves?

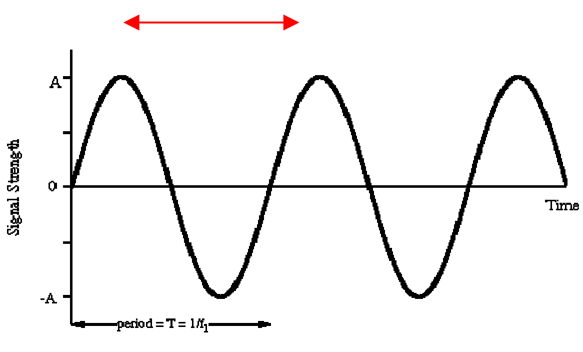
Credit: Hyperphysics

Wave Nature of light was known well before EM waves were known to be its source.

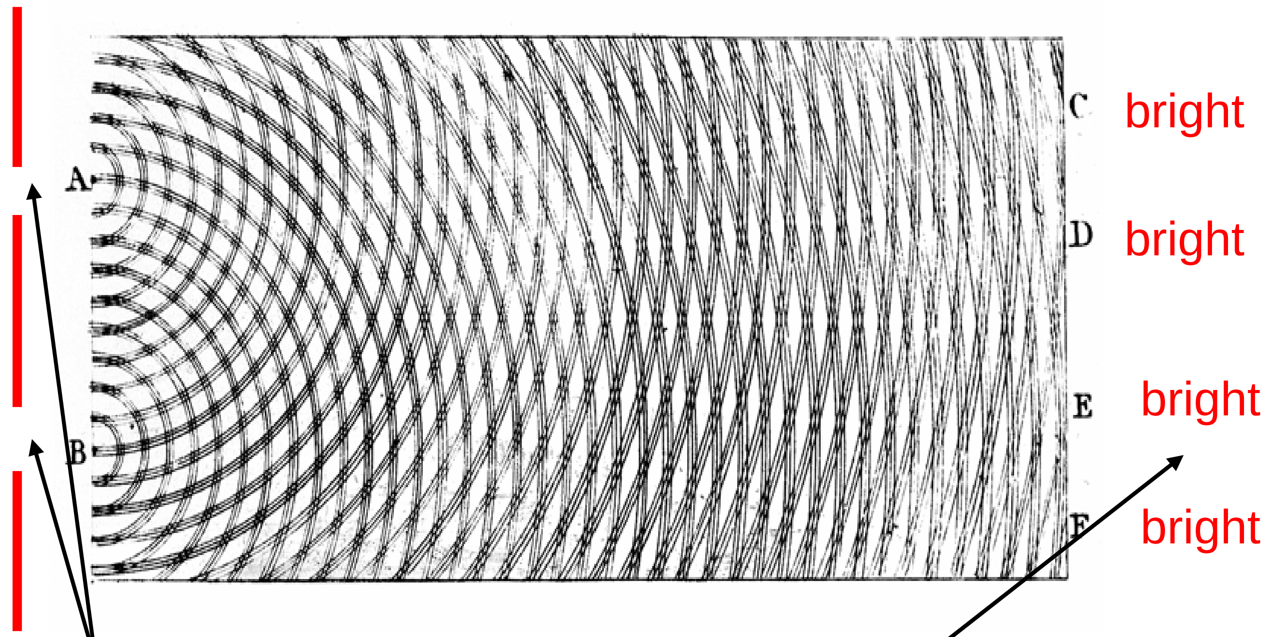
The classic demonstration is TWO-SLIT INTERFERENCE

Young's presentation to Royal Society, 1803

λ = wavelength



(a) Sine Wave



Incoming light wave

Wavelets generated at the two holes

Characteristic spread-out pattern of light and dark

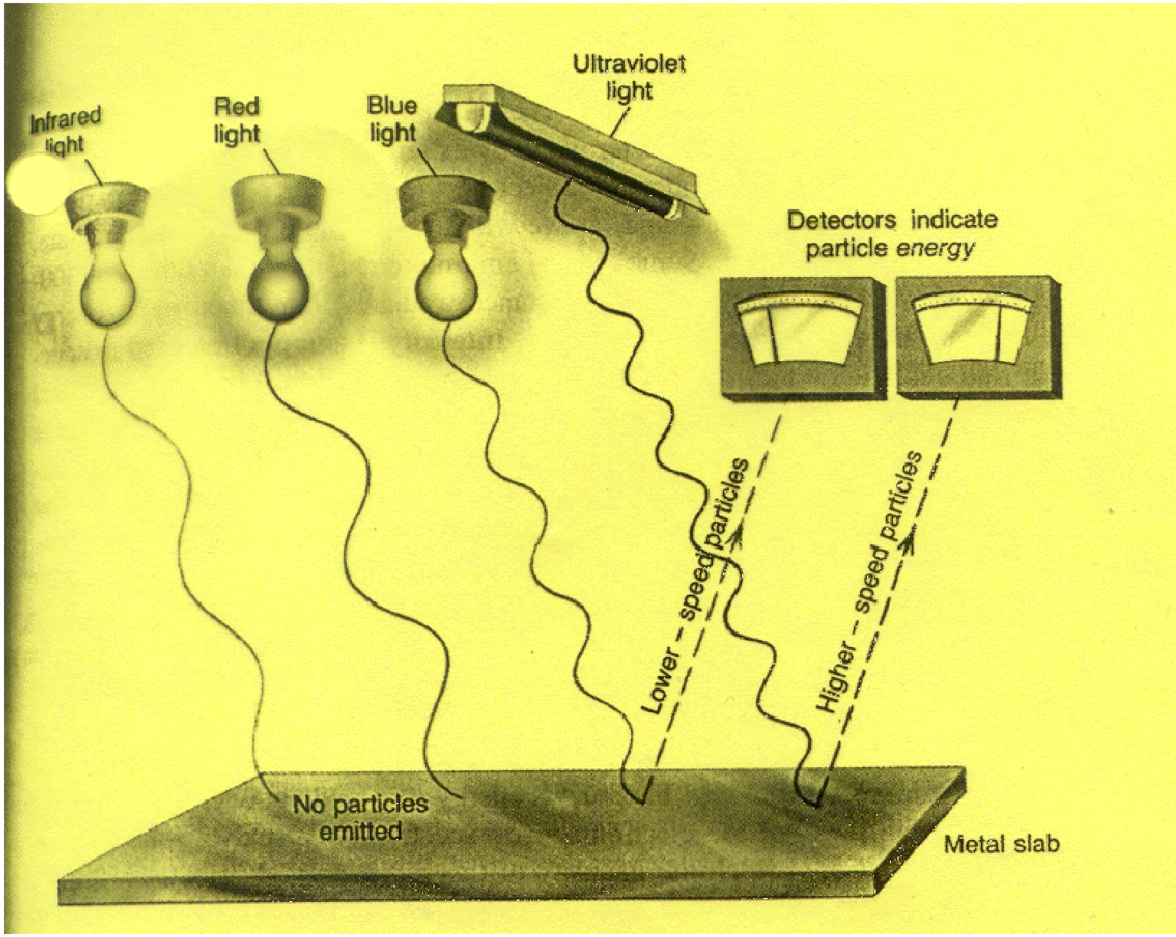
An early test of the new atomic regime – photoelectric effect (or *something is wrong*)

Light on metals produces outgoing electrons
(Electron discovered in 1897)

When the experiment was done, the behaviour was all wrong for an EM wave!

Should be time lag as energy builds up.
<u>NOT SEEN</u>

Depends on color.
<u>TOTALLY UNEXPECTED</u>



Credit: Queens Univ., Ont.

Crucial New Interpretation- Einstein 1905

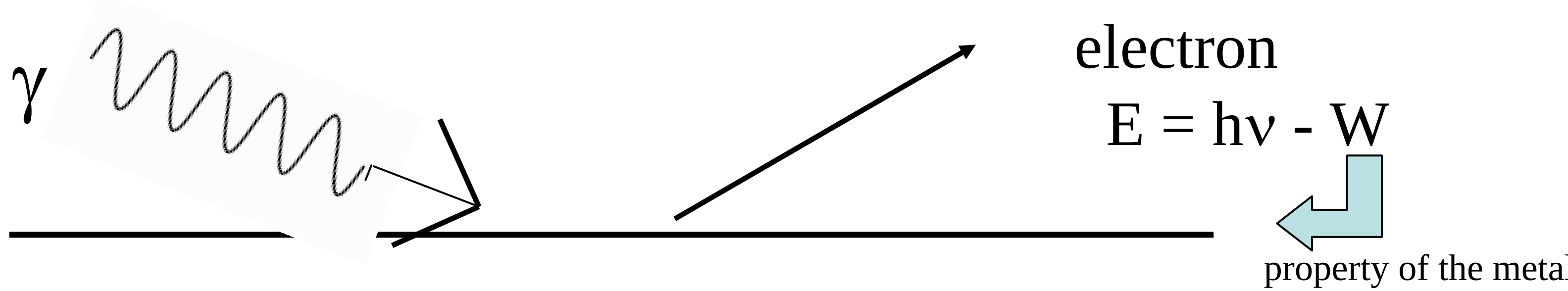
Light comes in particle-like packets (huh?) “PHOTONS”

Each packet is absorbed individually.

The energy of the packets depends on the frequency of the EM wave as

$$E = h\nu$$ (h is a tiny constant, Planck’s constant; ν is the wave frequency)

This appears to make no sense at all.
It explains all the facts. It won the Nobel prize and changed the world



Real World Application – Photomultiplier Tube

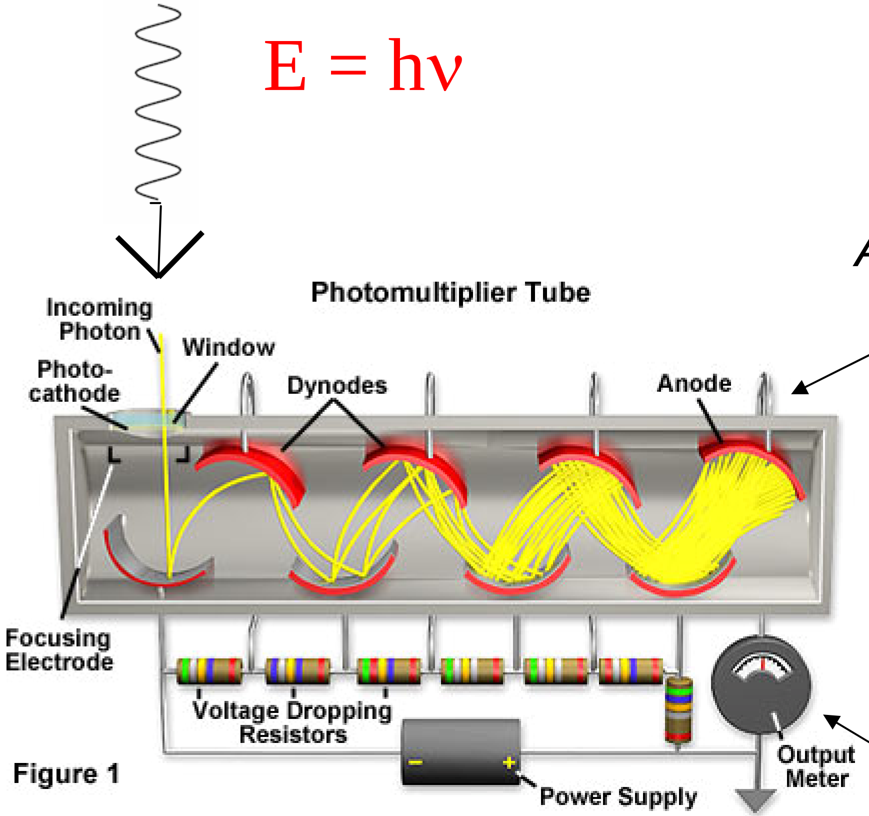
Part of almost every particle physics experiment

In sensitive applications, can detect individual photons

$E = h\nu$

Avalanche of electrons

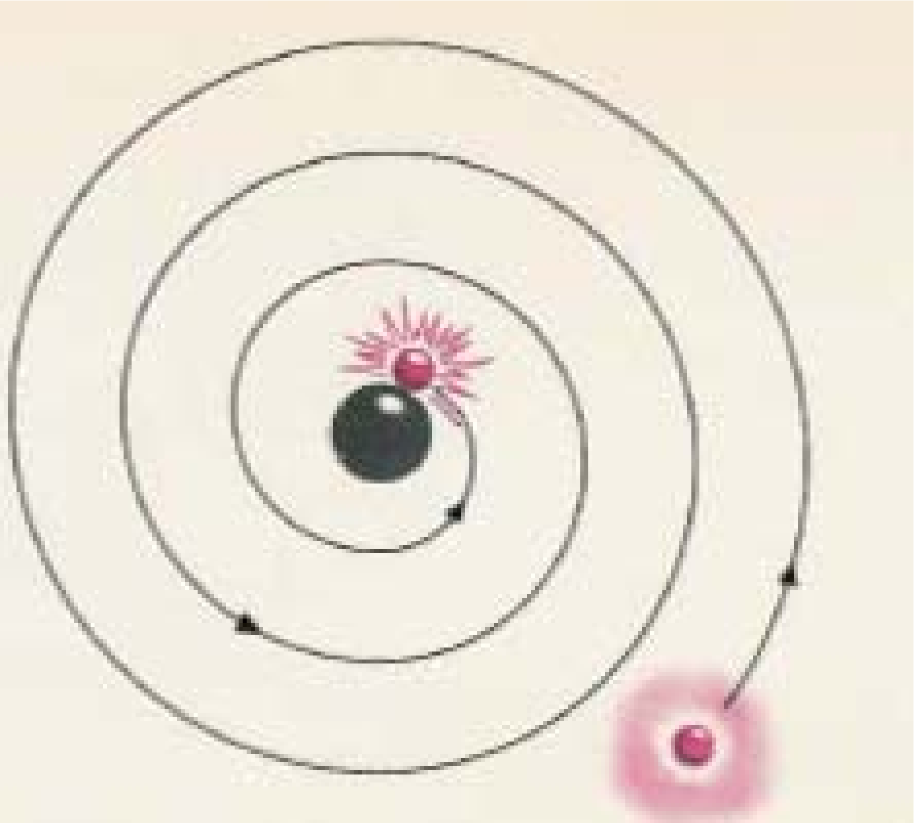
Fun fact – first application was sound movies



Measure output current

Credit: Norsk Teknisk Universitet

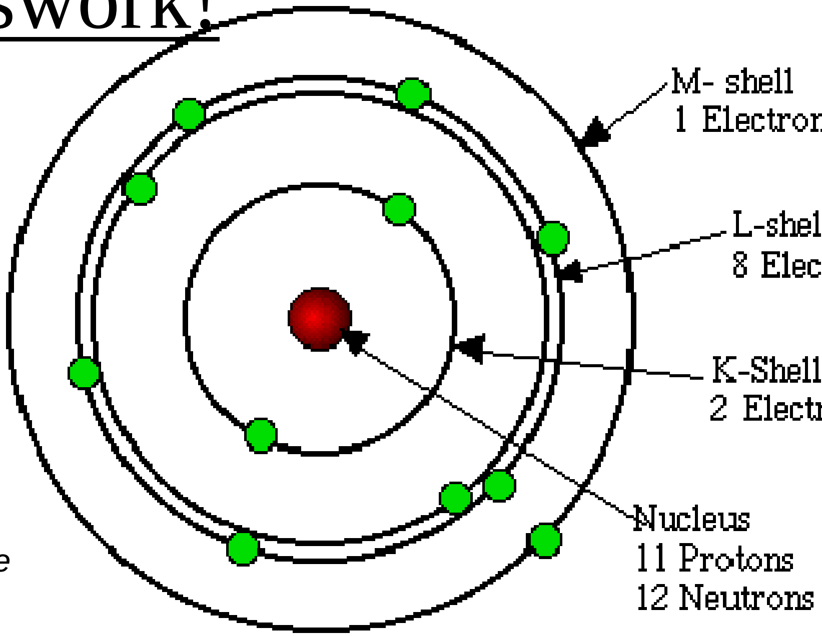
Like our radio station, electrons in atoms should radiate



Nucleus of atom discovered in 1911 (Rutherford)
Big trouble for physics. No matter should exist at all.

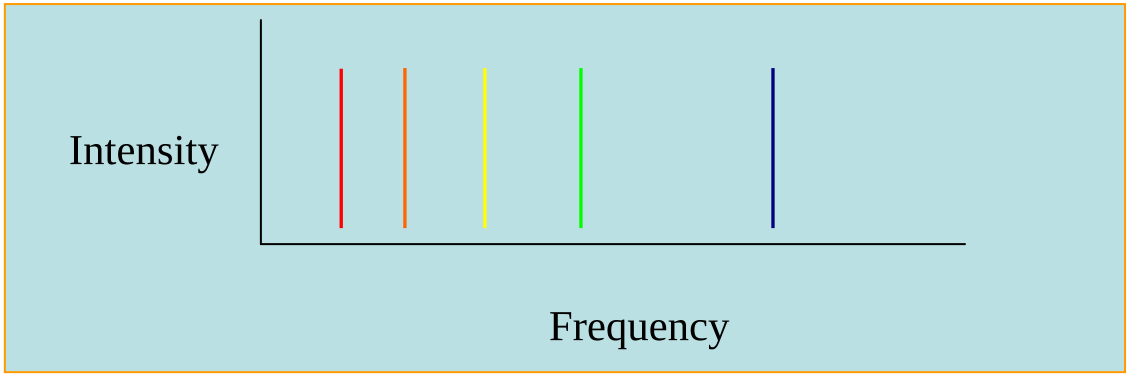
Credit: Fuchs, Physics for the Modern Mind

Quantum Theory applied to the atom as soon as nucleus discovered (Niels Bohr) – inspired guesswork!



The Bohr Picture of the Sodium (Na 11) Atom

Credit: NC State



Atomic Spectra

$E = h\nu$

Orbits stable – unless it makes a "quantum jump"

RADII are set by

$R = nh/2\pi p$

(n is a number 1,2,3,...)

(p is the momentum)

No continuous radiation!

Animation at: http://www.upscale.utoronto.ca/PVB/Harrison/BohrModel/Flash/BohrModel.html

Louis de Broglie (1923) – Particles as Waves

Reasoning by analogy from the photoelectric effect, ask the question:

If photons have a two-fold nature, why not apply the same principle to electrons?

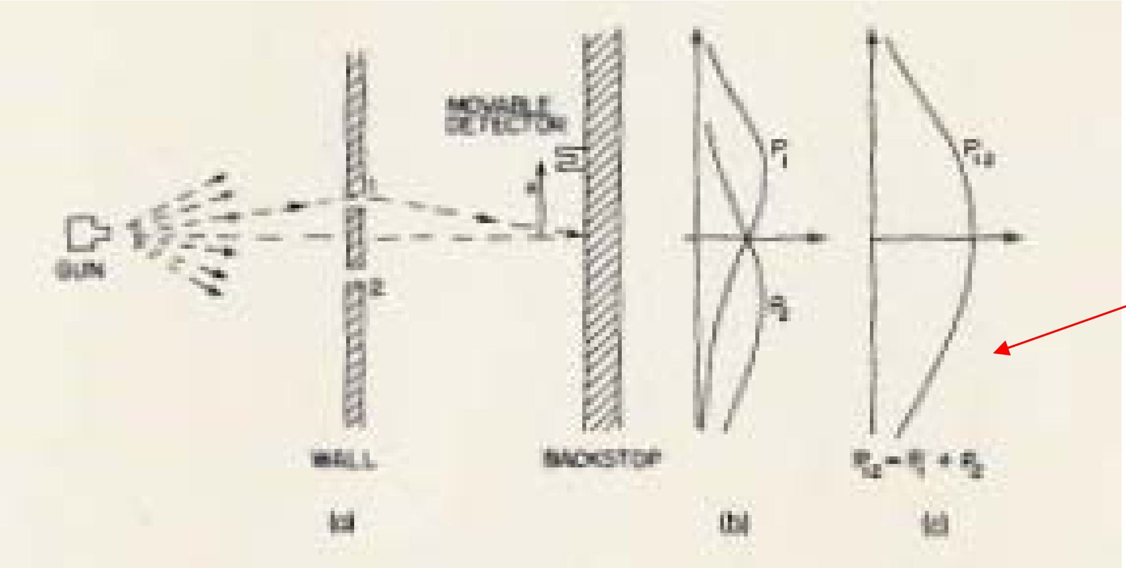
Assumption (to be tested by experiment):

photon $E = h\nu$ ➔ electron $P = h/\lambda$ (λ is the wavelength)

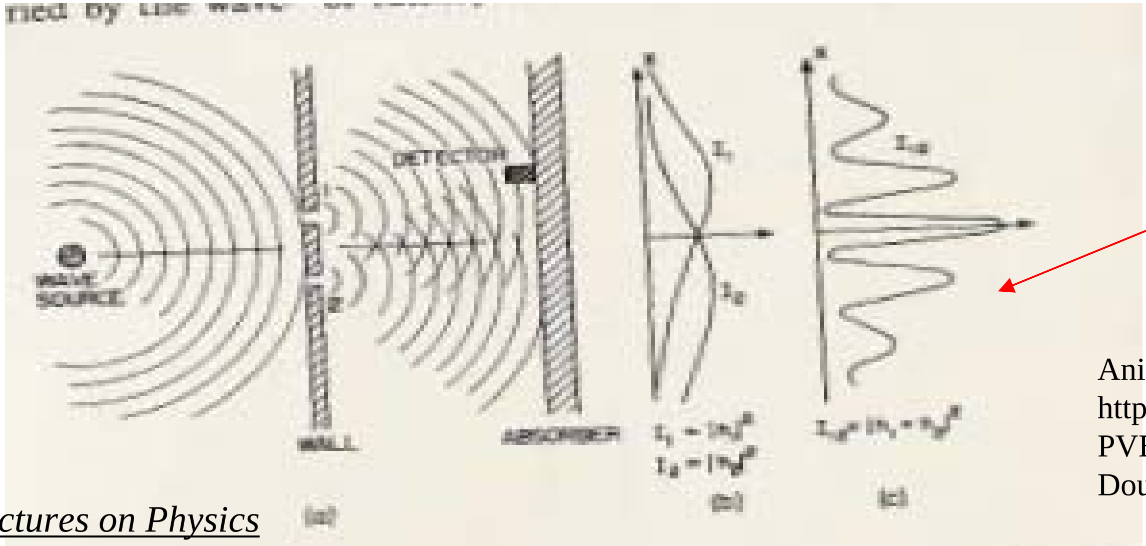
What predictions can we make based on this conjecture?

Credit: Frankfurt Univ.

Two-slit experiment differs for waves and particles



For Particles

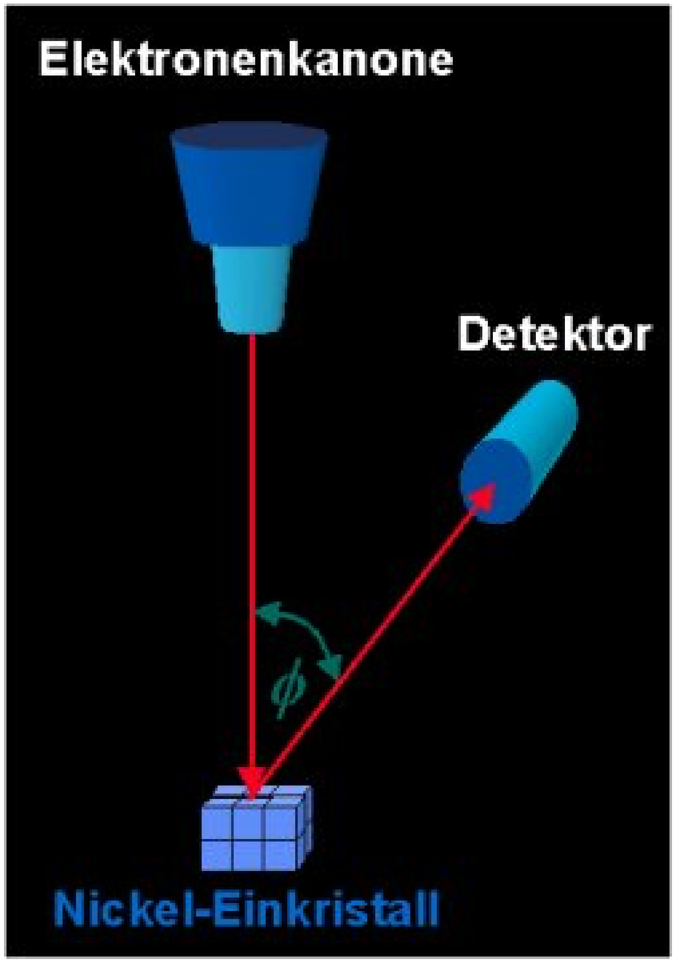


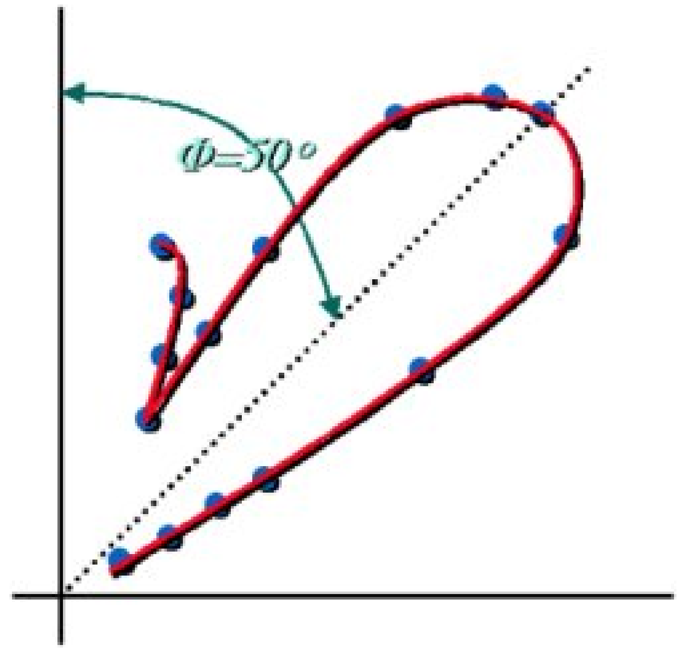
For waves

Animation at:
http://www.upscale.utoronto.ca/PVB/Harrison/DoubleSlit/Flash/DoubleSlit.html

Credit: Feynman, Lectures on Physics

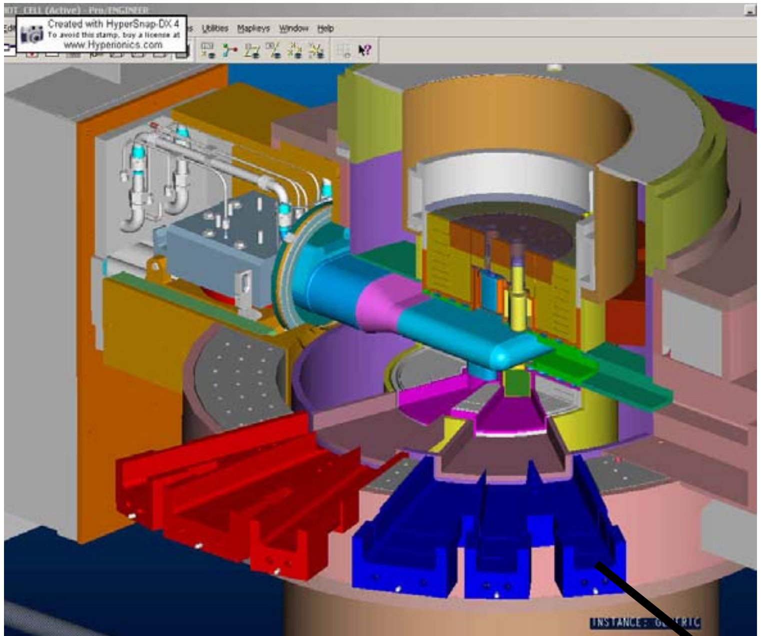
Experimental Verification – Davisson and Germer, 1928





Typical Diffraction Pattern – but with electrons!
Research done at Bell Labs (phone company)

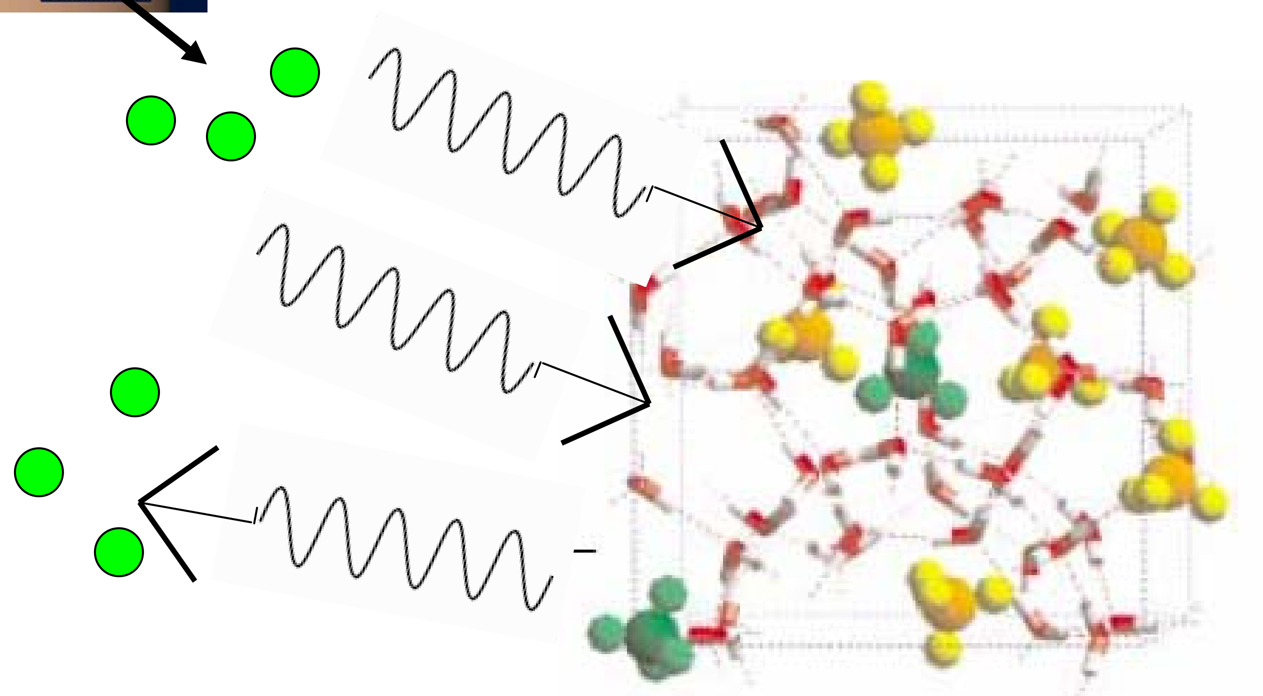
Credit: Univ. Padeborn, Germany



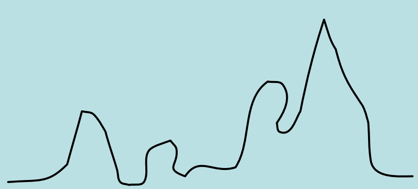
Real Life – big money

Methane Hydrates – found at bottom of sea

Possible fuel source or carbon dioxide "bank"



Neutrons scattering as waves determine structure by diffraction images

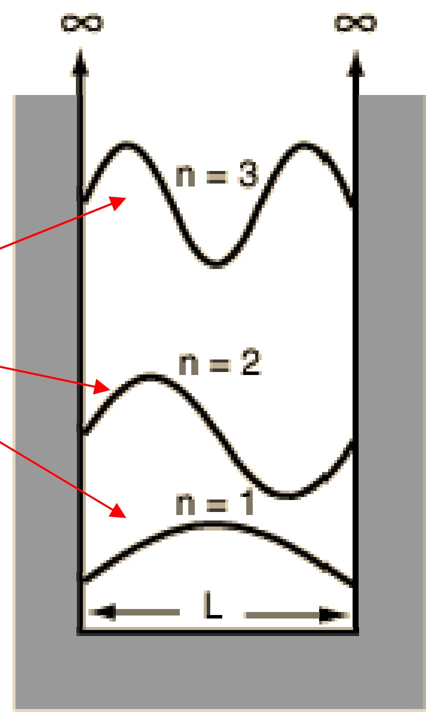


Credits: SNS, ILL

Confined DeBroglie Waves can form standing wave patterns

Deep potential energy well

Increasing Energy =
higher frequency



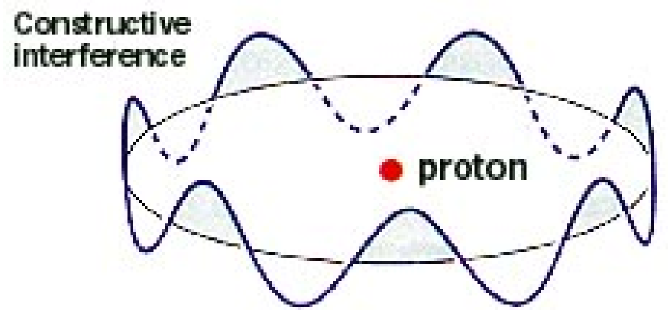
Just like musical notes
in a flute or trombone

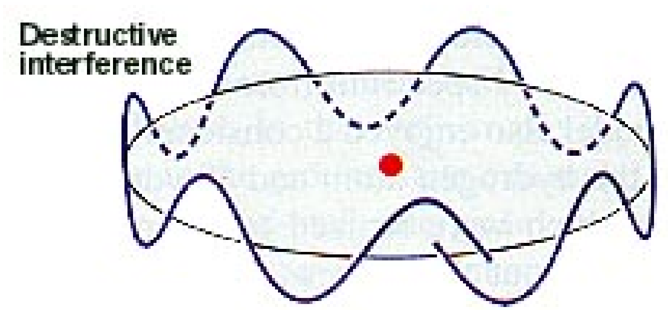
Higher frequencies
mean higher energy
from the Quantum
Principle:

$E = h\nu$

"Particle in a box"
Very similar to Bohr levels in atoms

Credit: Hyperphysics





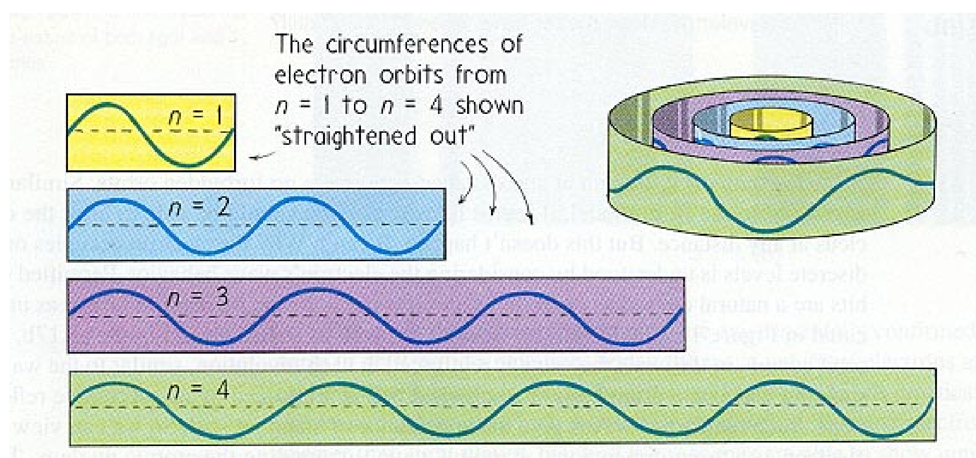
When wrapped in a circle, the DeBroglie waves naturally close on themselves.

If we put $\lambda = hp$, into Bohr's radii $R = nh/2\pi p$

$$2\pi R = n\,\lambda$$

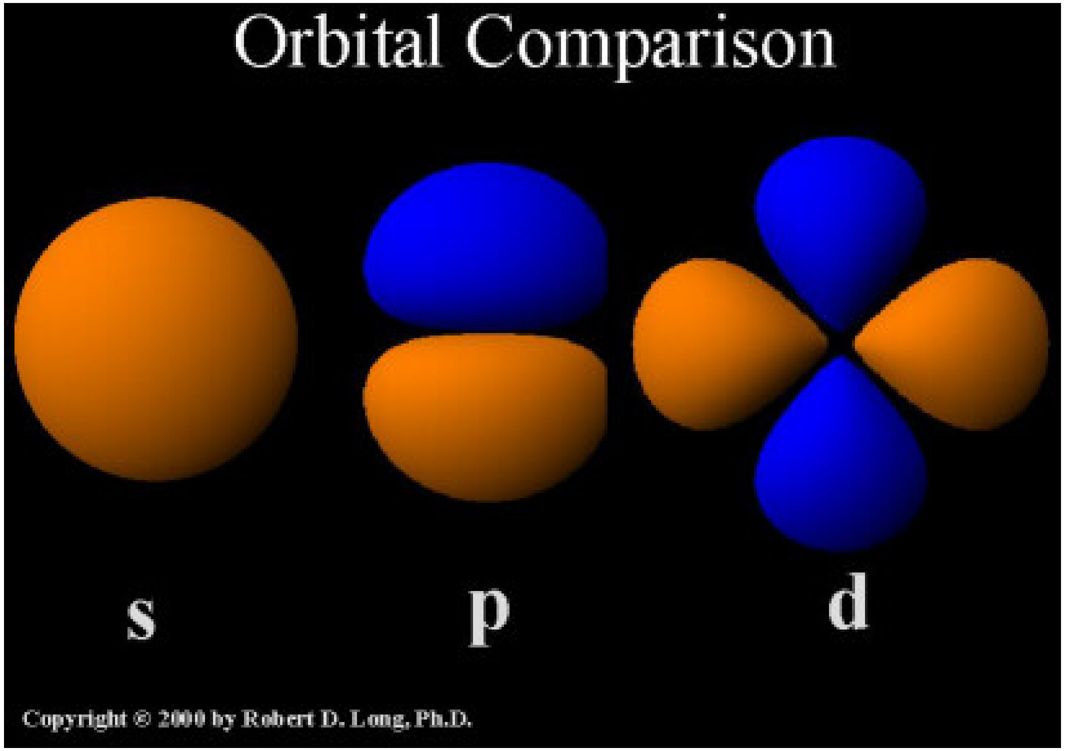
Integral number of wavelengths

The Bohr orbits ARE the closed waves!



Credit: J. Alward, Univ. of Pacific

More Complicated 3-d calculation gives atomic orbitals, familiar to you from Chemistry



These are "probability density" plots – they show where you are likely to find the electron (a particle).

The wave nature has smeared out our knowledge of the position.

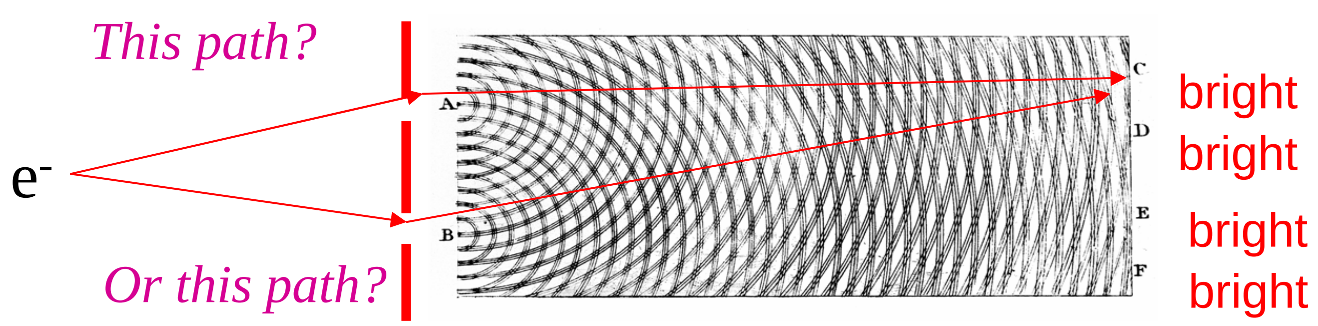
Two-slit experiment as a probability

For electrons, when we do the two slit experiment, the wave nature appears.

HOWEVER – each electron gets there as a LUMP

We say that we don't know what path it took!

The wave nature has sampled both paths.



Animation at: http://www.upscale.utoronto.ca/PVB/Harrison/DoubleSlit/Flash/Histogram.html

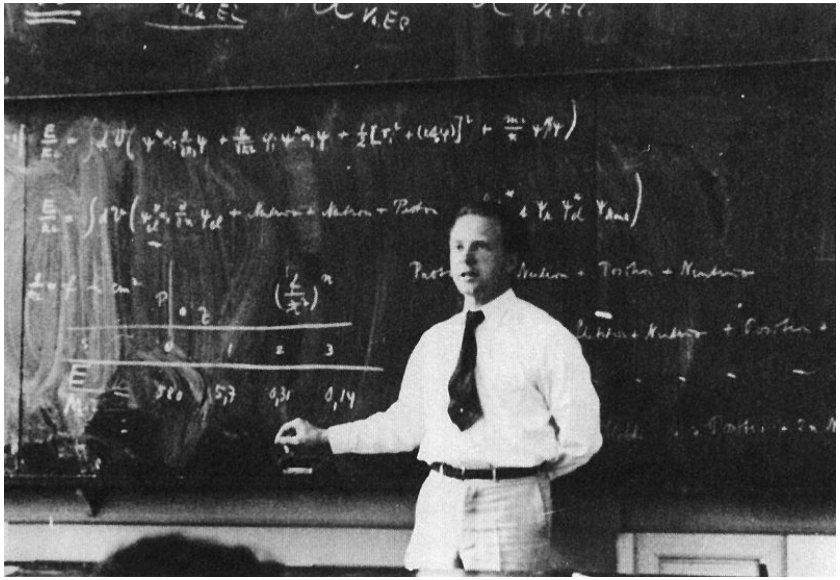
Copenhagen Interpretation and Uncertainty Principle

Wave or Particle – which is it?

Interpretation – both – and neither!

Electrons and atoms follow wave dynamics...

But they appear in experiments as particles.



Werner Heisenberg lecturing

Each of these classical concepts is inadequate by itself – need both.

One consequence of wave nature is uncertainty principle.

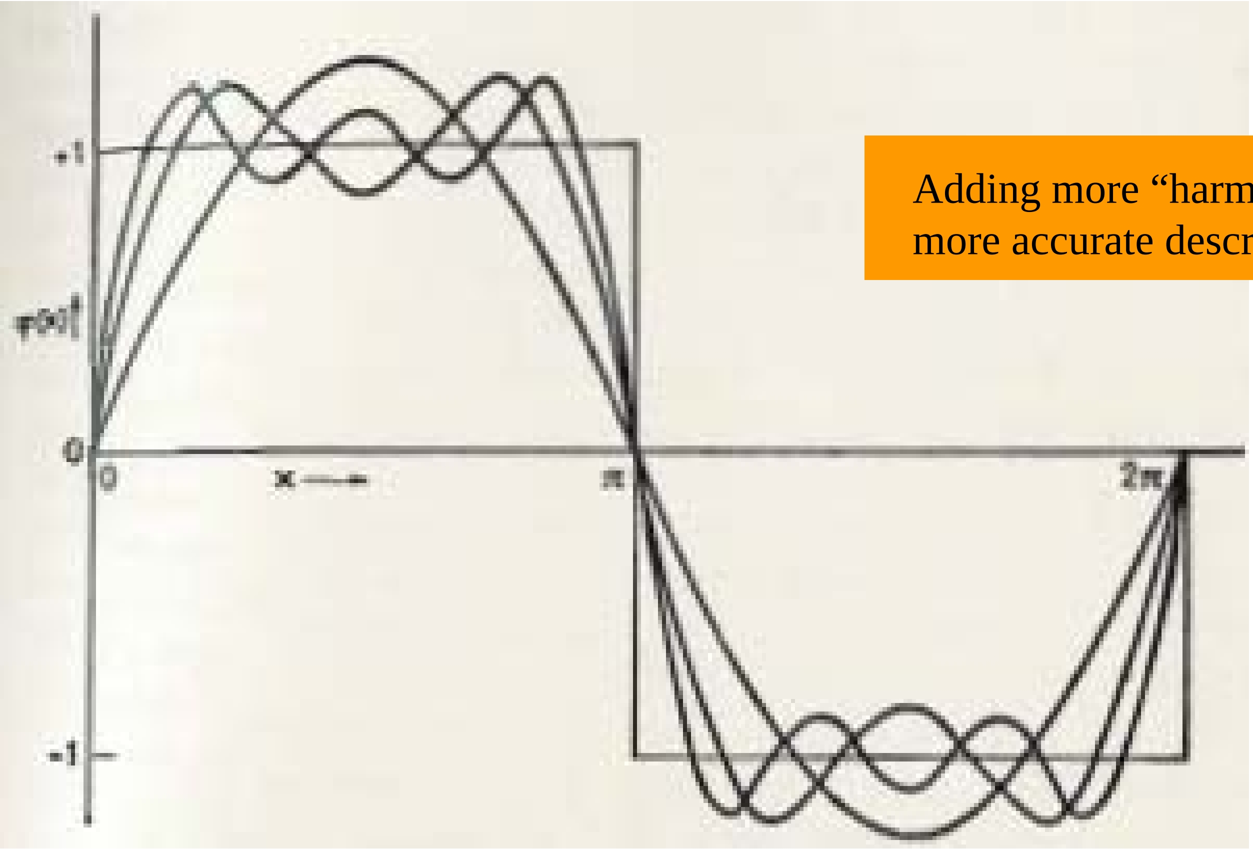
In old mechanics a particle has definite momentum p and position x.

Wave nature washes this out

Shorthand for this - the inequality $\Delta p \Delta x > h/2$

Credit: Frankfurt Univ.

A complicated wave is made up of many components

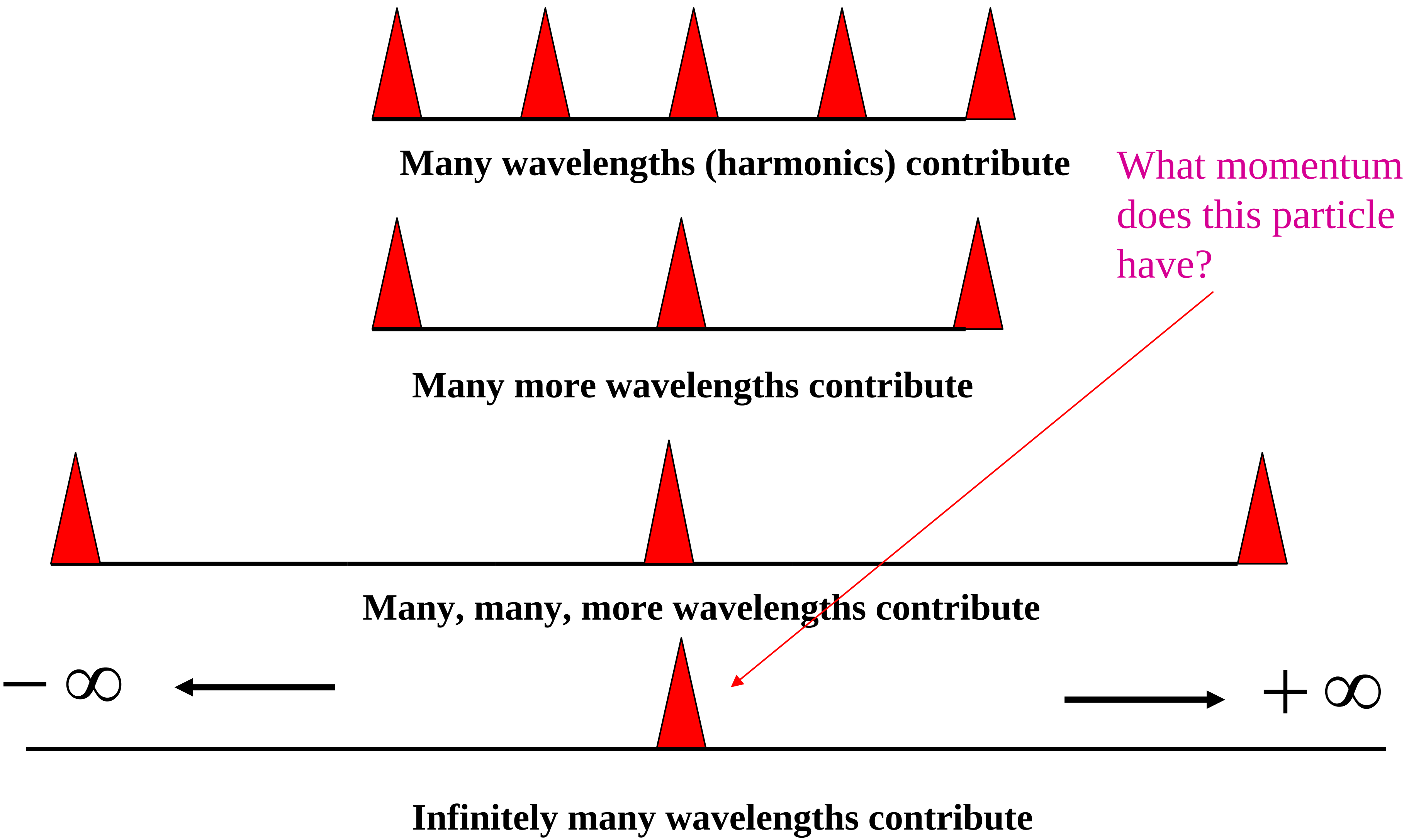


Adding more “harmonics” makes a more accurate description

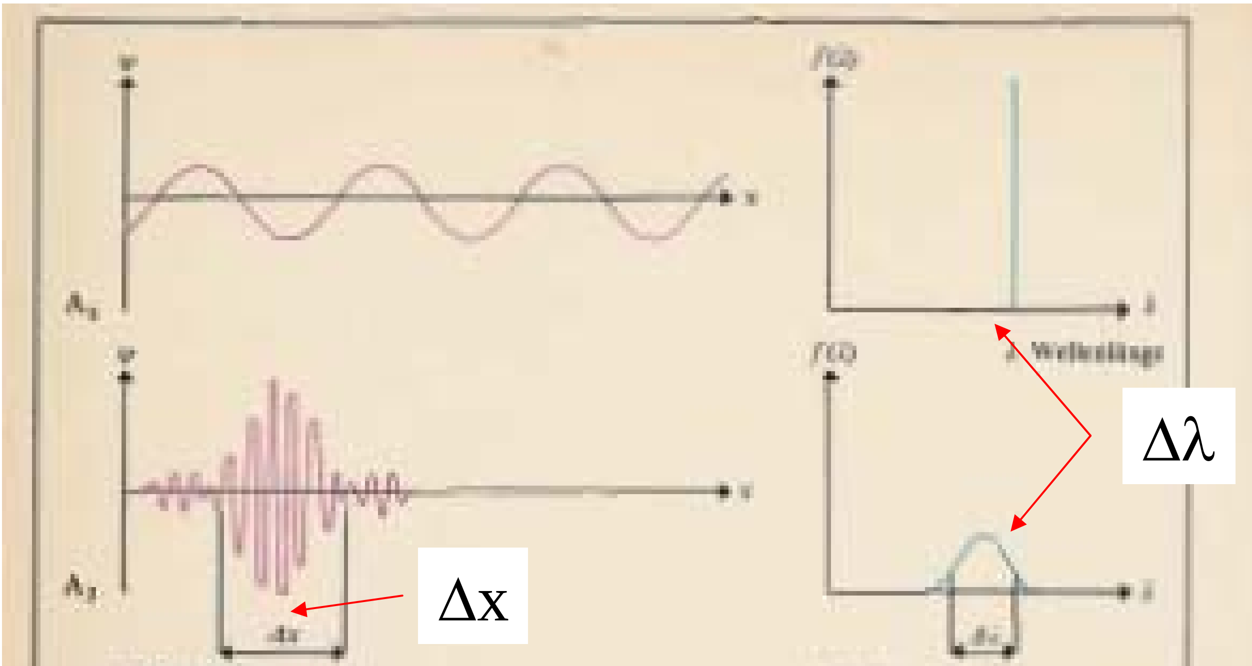
If we want a wave to describe a particle at one spot – will need to be especially complicated

Credit: Pauling and Wilson

Uncertainty Principle – to know a wave-like disturbance's position exactly means loss of meaning of a specific wavelength.



Uncertainty Principle – the wave nature is complementary to the particle nature.



The localized wave has a spread in wavelengths

$$\Delta p \, \Delta x \sim h$$

Δx decreases → $\Delta\lambda$ increases → Δp increases ($p = h/\lambda$)

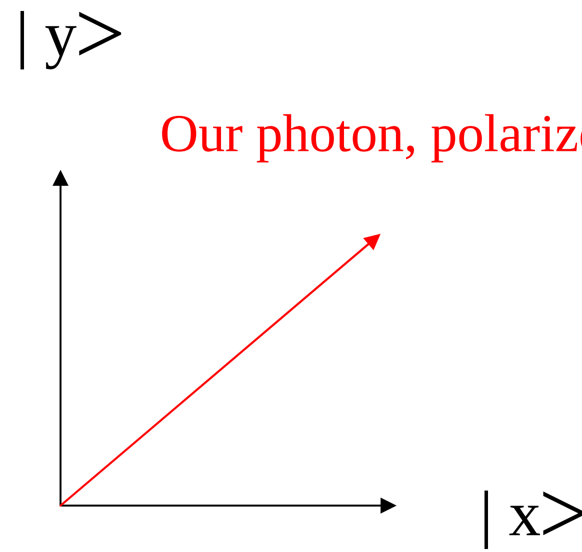
Credit: Atlas zur Atomphysik

Back to light polarization – with our new interpretation

Note: the radio station had about 10^{11} photons at 25 miles. Now we look ONE BY ONE.

There are two "base-components" which we call x- and y- polarization

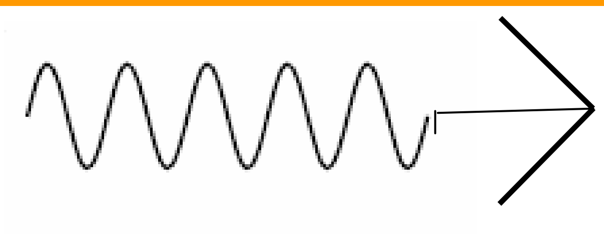
Our photon, polarized at 45°



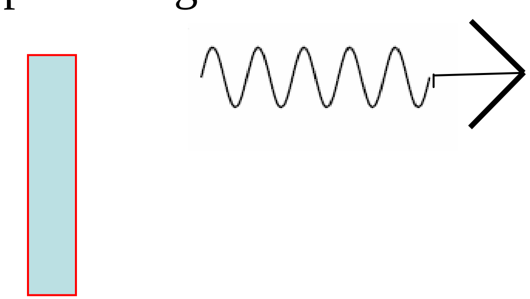
Shorthand is |x> and |y>
(this is called a QM STATE)

A photon can be described as a *combination state*

Photon = a |x> + b |y>



y polarizing filter

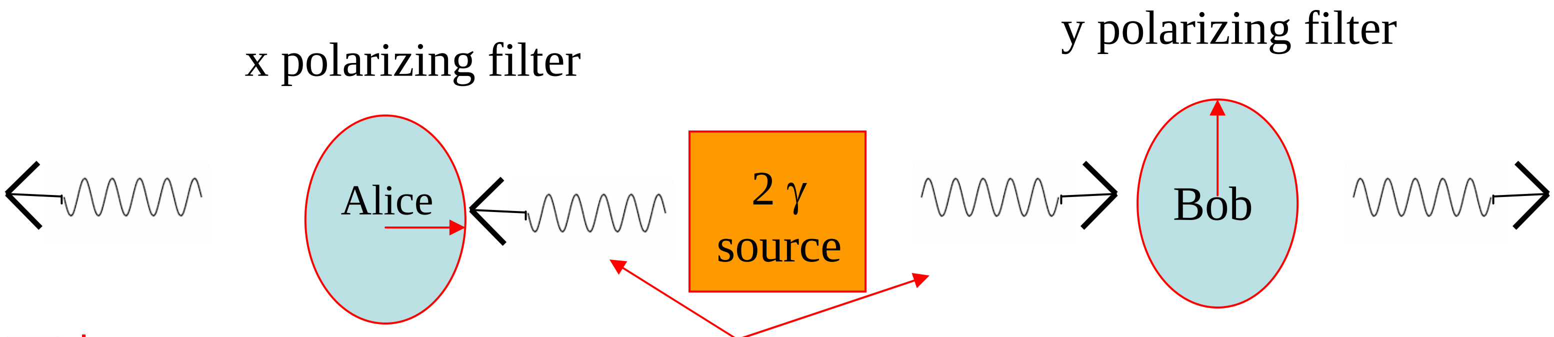


50% |y>

50% |x>
(absorbed)

Introduction to EPR (Einstein-Podolsky-Rosen) and Quantum Correlation

Assume a source which sends out 2-γ states, without overall polarization (such sources exist)



IF $|x\rangle_A$

State $2\gamma = |x\rangle_A|y\rangle_B + |y\rangle_A|x\rangle_B$

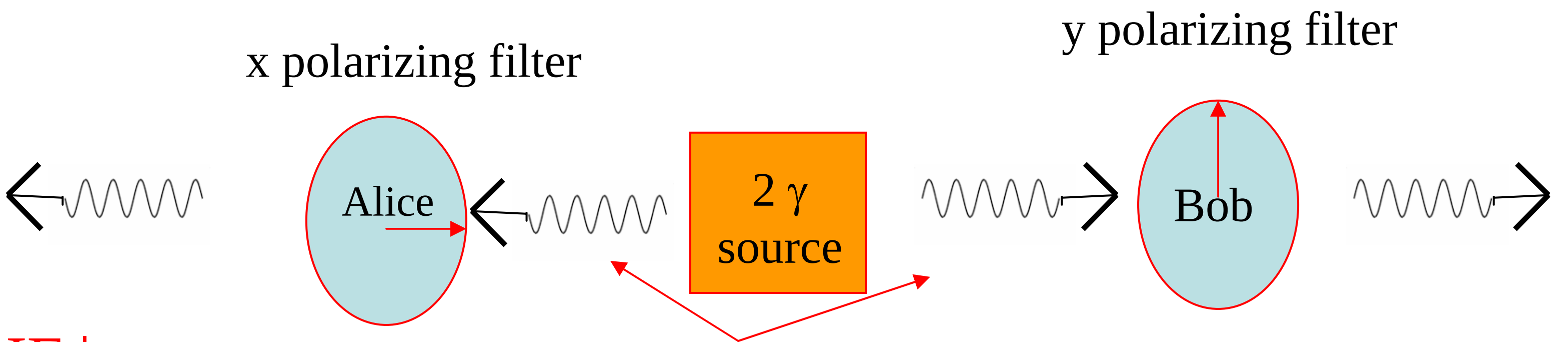
THEN $|y\rangle_B$

We say the states are "entangled"

Measurement of A to be $|x\rangle$ means Bob will see $|y\rangle$; he then knows what Alice has seen immediately.

This seemed (and seems) SURPRISING.

In Quantum Mechanics DIFFERENT BASE components can be used EQUIVALENTLY

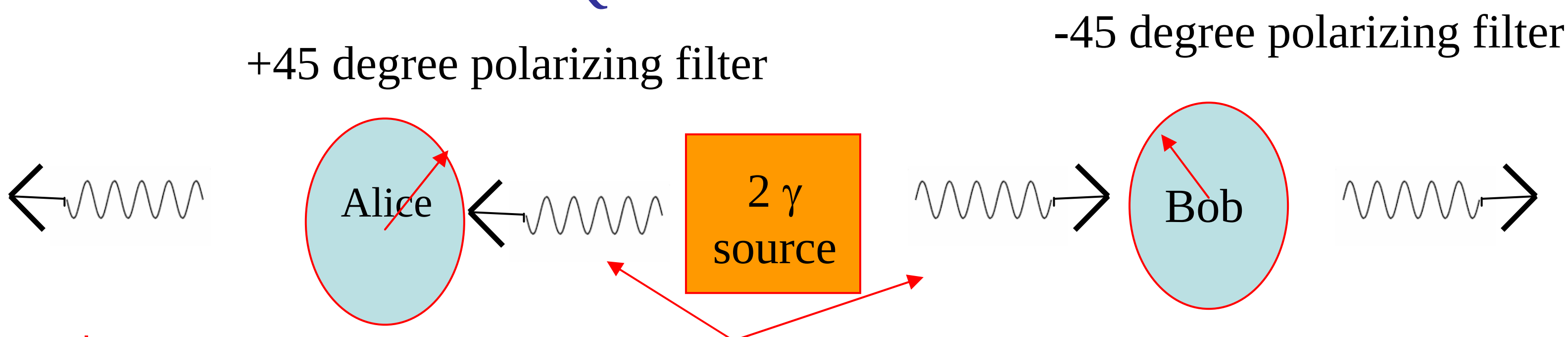


IF $|x>_A$

State $2\gamma = |x>_A|y>_B + |y>_A|x>_B$

THEN $|y>_B$

IS EQUIVALENT TO

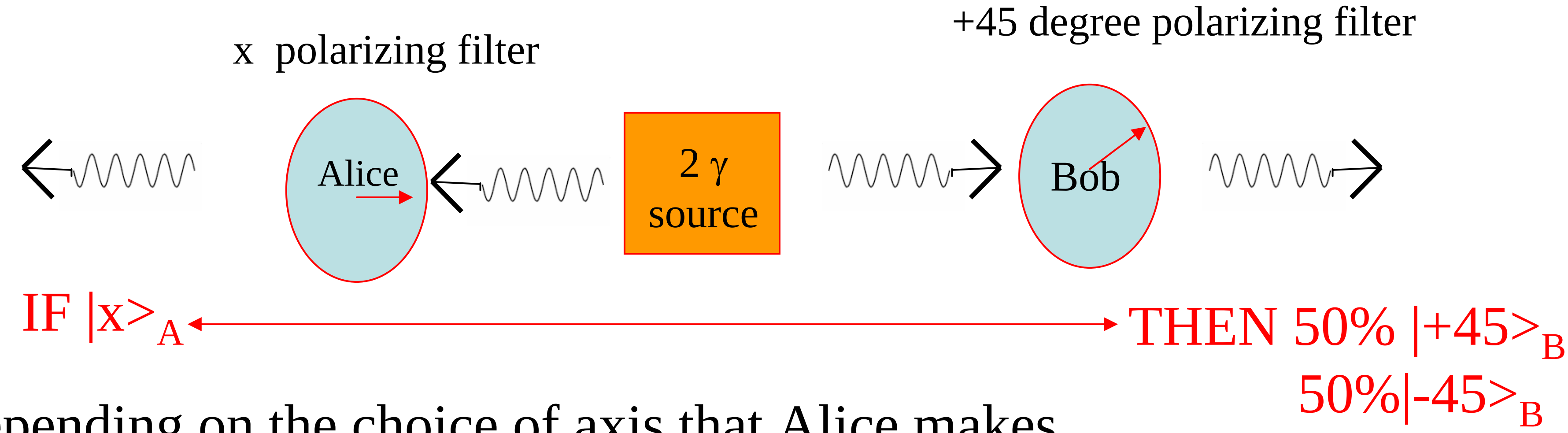


IF $|+45>_A$

State $2\gamma = |+45>_A|-45>_B + |+45>_A|-45>_B$

THEN $|-45>_B$

“Spooky” behaviour if Alice and Bob use differing base components



Depending on the choice of axis that Alice makes

- Bob will see a defined result
- Bob will see a statistical result
- This drove Einstein nuts. It’s a fundamental uncertainty!

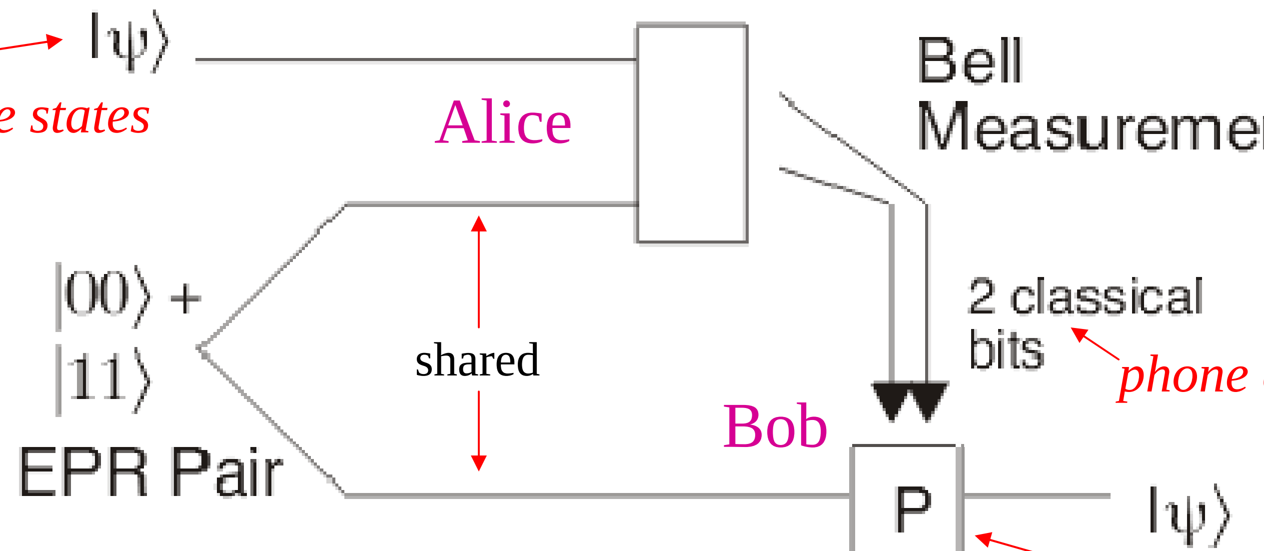
Quantum mechanics defines a very specific set of correlations.

- No “local hidden variable theories”

Looks like faster-than-light information at first glance – but it isn’t.

Real World Application – Quantum Teleportation.

A combination of base states
like a|x> + b|y>



phone call

polarizers and stuff

How to transport a quantum state?

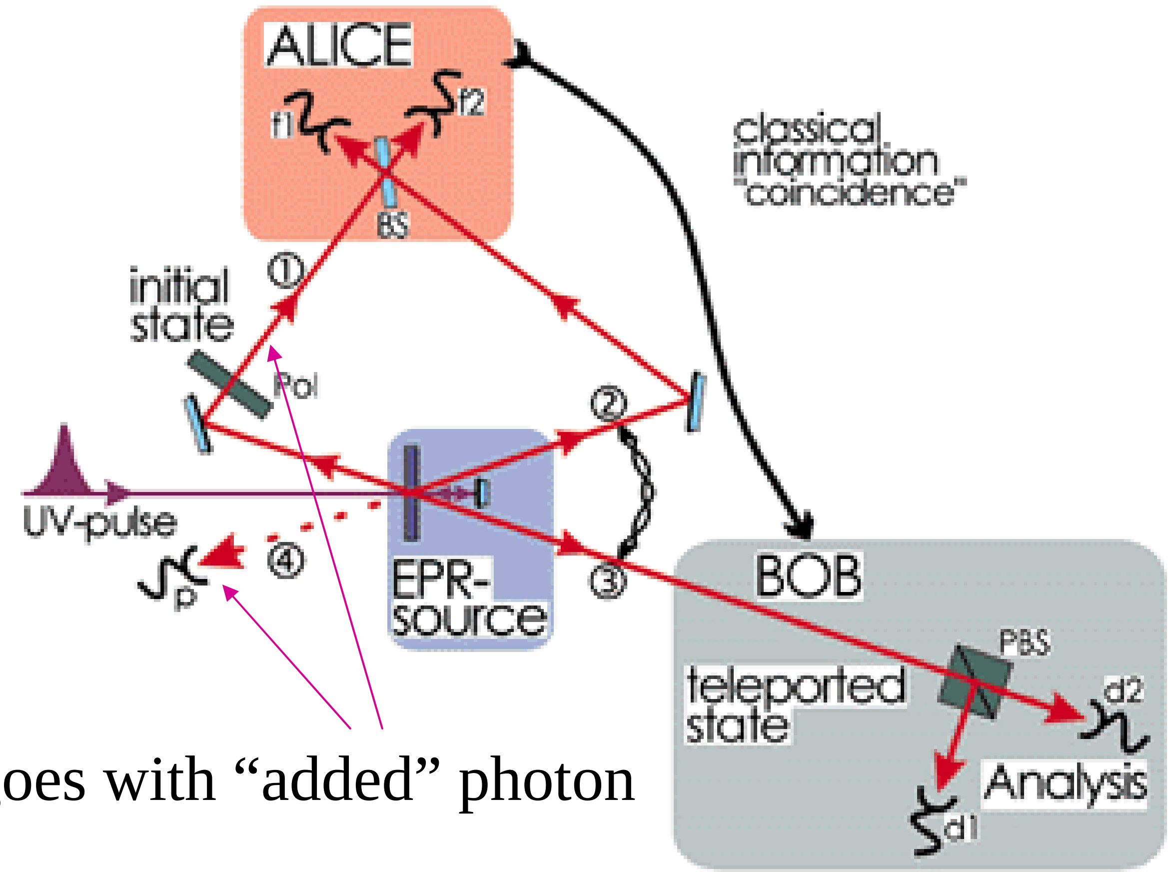
Can't be copied ➔ "No cloning theorem"

Using a third particle and a telephone, can give instructions to allow the state to be recreated.

Destroys original state! Just like real teleportation!

Credit: D.Gottesman, Perimeter Institute, Ont.

Not a fantasy – but real experiments



Trigger goes with "added" photon

Cutting edge of research!

Transported over ~10 km of optical fiber

Credit: Univ. of Innsbruck

Quantum Mechanics - Conclusions

- The great philosophical debates of the 1930's have become today's realities
- First great, and still greatest triumph was periodic table – goes all the way back to Bohr.
- Also explains "stickiness" of atoms (chemistry) and all semiconductors (i.e. computer chips)
- Other apps include all medical imaging.
- Still to come – quantum cryptography, computing
- Also the small matter of particle physics!

*Do you think that it is **not** a "paradox", but that it is still very peculiar? On that we can all agree. It is what makes physics fascinating. – R.P. Feynman, Lectures on Physics*