Lecture 6

Quantum physics

A first encounter

Plan of the Lecture

First encounter with phenomena described by quantum physics

1 Success & outlandish claims

2-3 Mach-Zehnder interferometer

4-5 Double-slit interferometer

6 What kind of randomness?

SUCCESS & OUTLANDISH CLAIMS

Quick history of quantum physics

- Phenomena that defy classical physics
  - Spectral lines of emission and absorption (e.g. Balmer)
  - Black-body radiation
  - Photoelectric effect
- Partial models (“old quantum theory”)
  - Planck 1900: blackbody radiation
  - Einstein 1905: photoelectric effect
  - Bohr 1913: model for hydrogen atom
- Unified theory: 1926
  - Schrodinger; Heisenberg, Born; Dirac

Some predictions of quantum physics

Atoms

Photoelectric effect
Lasers

Light

One atom

Nucleus
- Radioactivity
- Nuclear power
- Sub-nuclear particles

Electrons
- Spectral lines

High energy physics
(a.k.a. particle physics)

More atoms

Molecules

Solids

Chemistry

Condensed matter physics
- Conductors, semiconductors etc.
- Magnetism

And much more!

The price to pay

“But then, why don’t we learn it in high school?”

~~“Because th[illegible]s very abstract”~~
~~“Because it’[illegible]oo [illegible]hematical”~~

Because it relies on intrinsic randomness $\Rightarrow$
you can’t make an image of “what happens”.

(and because of this, yes, it is taking some decades to come up with an approach that presents the facts without relying on too many technicalities)

Quantum Buzzwords

- Unpredictability
  - You can’t predict the outcome of each measurement, only its probability
- Uncertainty [better: indetermination]
  - Not all physical properties can have definite values at the same time
- Delocalization
  - A “particle” can explore different regions of space, like a wave
- Entanglement
  - Two or more degrees of freedom may have only common properties, not individual ones

Plan of the sequel

- Hopefully, by the end of Lecture 7, you shall know more about those notions.
- For the time being, it’s *very legitimate* to be skeptical
  - Are these notions only artifacts of the theory?
  - How can I make sure that they correspond to “something” in nature?
- By the way: “quantum” = discreteness is not very fundamental
  - Sure, historically people first notices “discretization of energy”
  - But there is nothing too dramatic in discreteness: coin ☺

Suggested Readings

Books: I just suggest mine (which, by the way, have some obvious similarity with these lectures):

- V.S. Quantum physics, a first encounter (Oxford UP): only text
- V.S., Chua Lynn, Liu Shi Yang, Six quantum pieces (for those who want to learn the basic maths)

Here are the links to the two MOOCs on quantum physics:

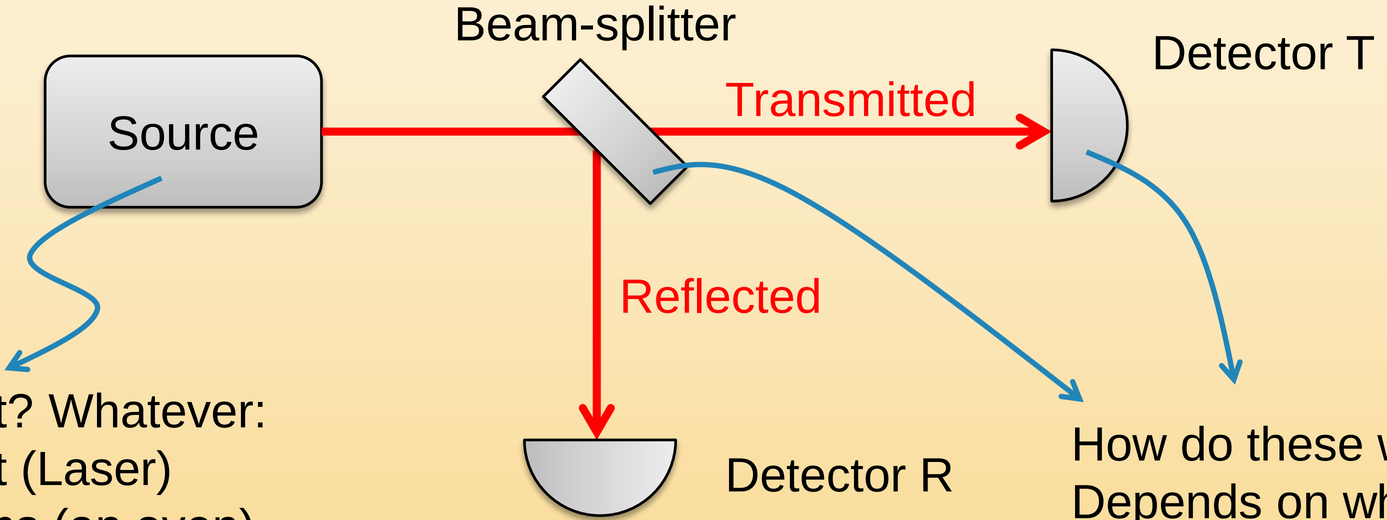
- https://www.coursera.org/course/eqp
- https://www.edx.org/course/uc-berkeley/cs-191x/quantum-mechanics-and-quantum/1033

Wikipedia pages:

- http://en.wikipedia.org/wiki/Quantum_mechanics
- http://en.wikipedia.org/wiki/History_of_quantum_mechanics

BEAM SPLITTING

Experiment #1: setup

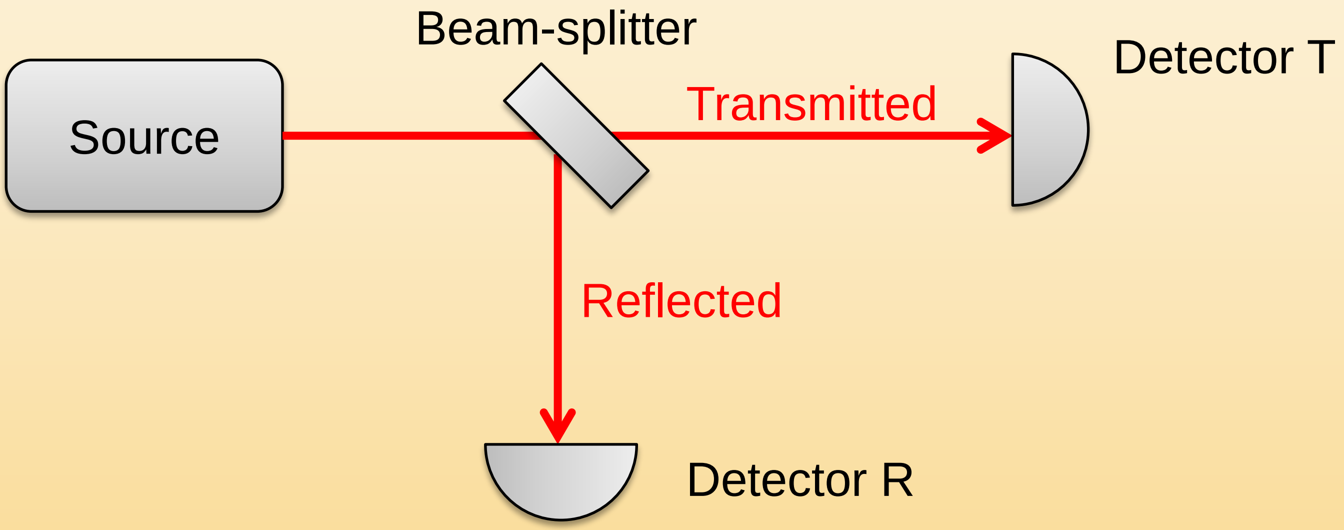


Of what? Whatever:

- Light (Laser)
- Atoms (an oven)
- Neutrons (reactor)
- …

How do these work? Depends on what the beam is made of

Experiment #1: observation



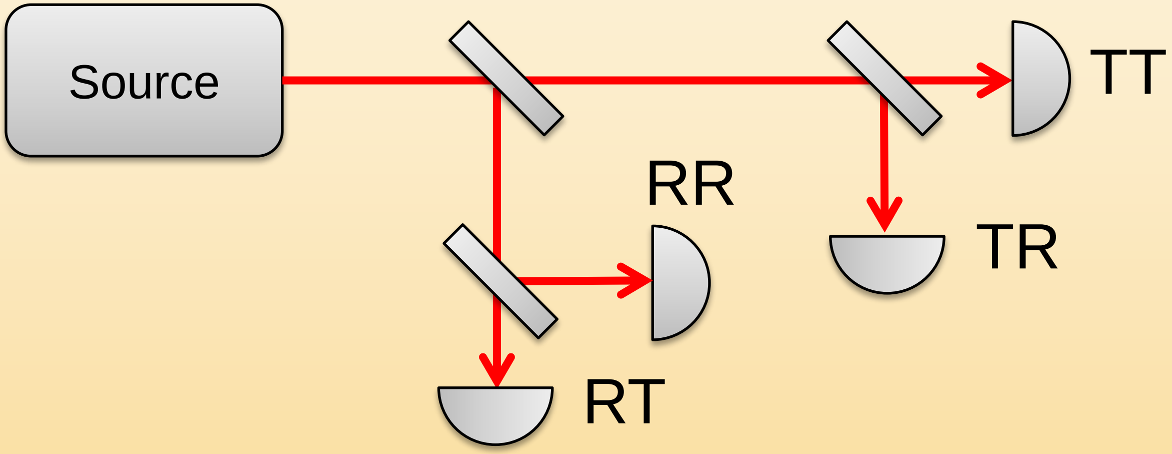
- The detectors register "clicks"
- When one detector fires, the other never fires

  $\Rightarrow$ Indivisible "particles"

Statistics:

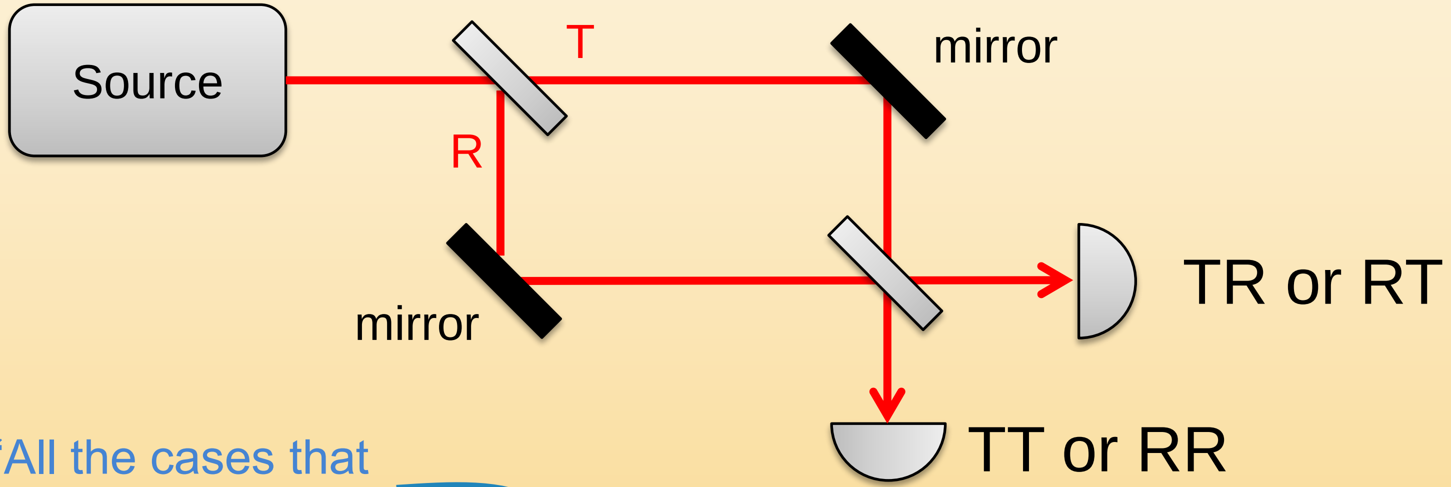
$$P(T) = P(R) = \frac{1}{2}$$

Experiment #2: observation



$$P(TT) = P(TR) = P(RT) = P(RR) = \frac{1}{4}$$

Experiment #3: prediction

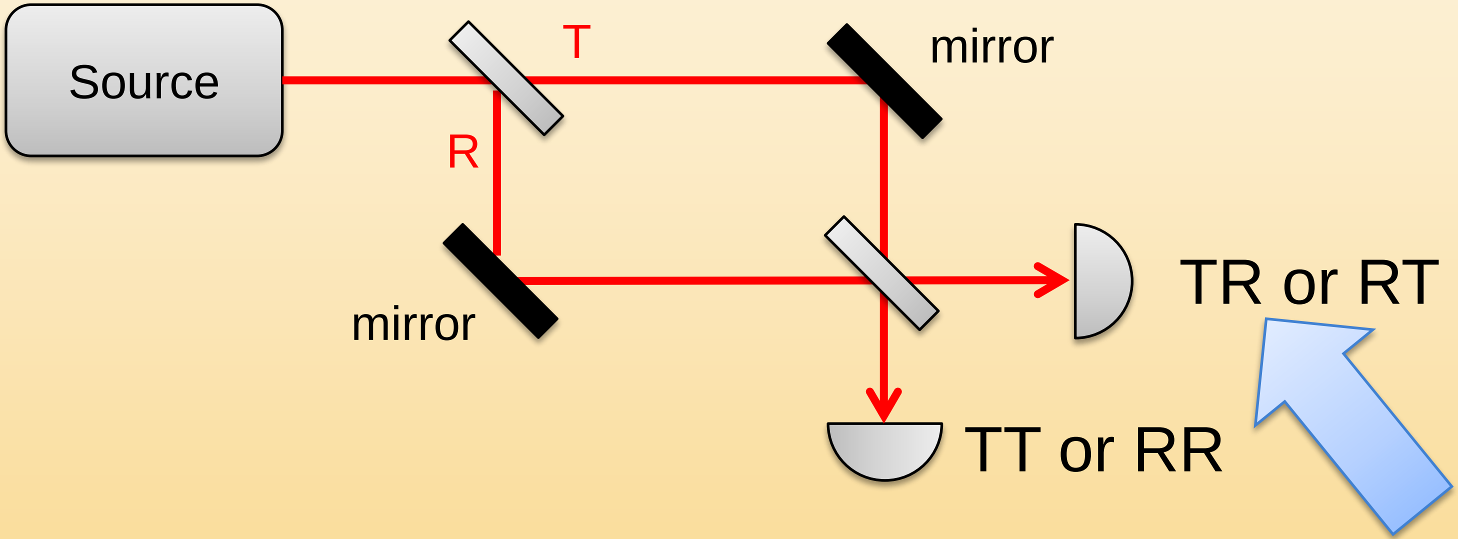


"All the cases that were TT in Exp #2"

$$P(TT\ or\ RR) = P(TT) + \cancel{P(RR)} = \frac{1}{2}$$

This is NOT what is observed!

Experiment #3: observation

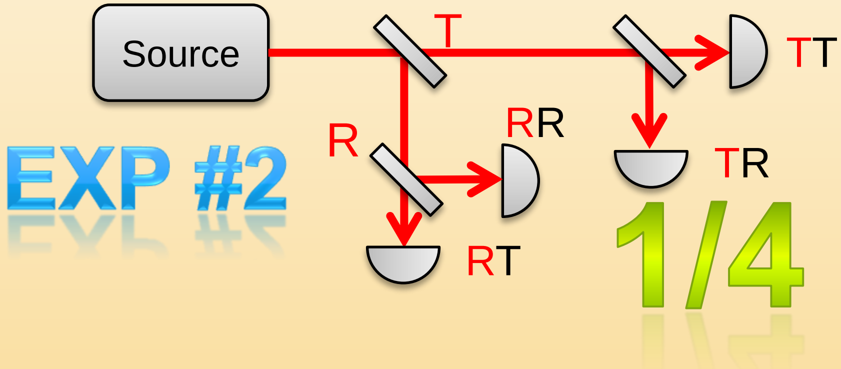


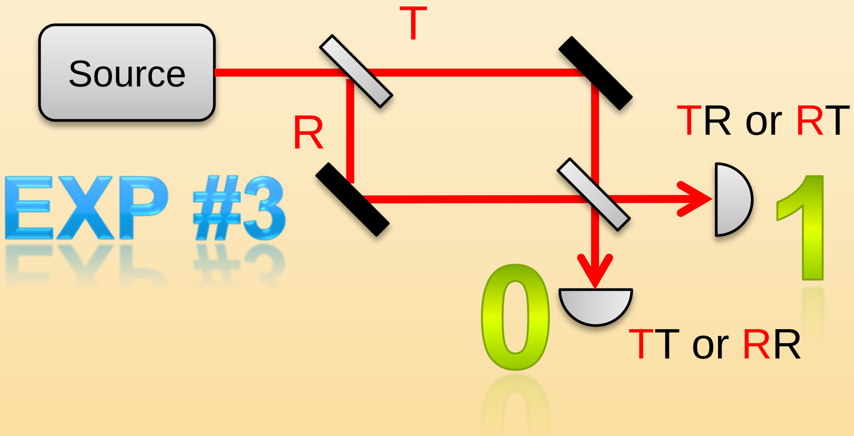
$$P(TT\ or\ RR) = 0$$
$$P(TR\ or\ RT) = 1$$

Only this detector clicks
[All the “particles” are detected here]

Is this sheer madness?

Or is there a physical difference between the two configurations?





There is a difference: **(in)distinguishability**

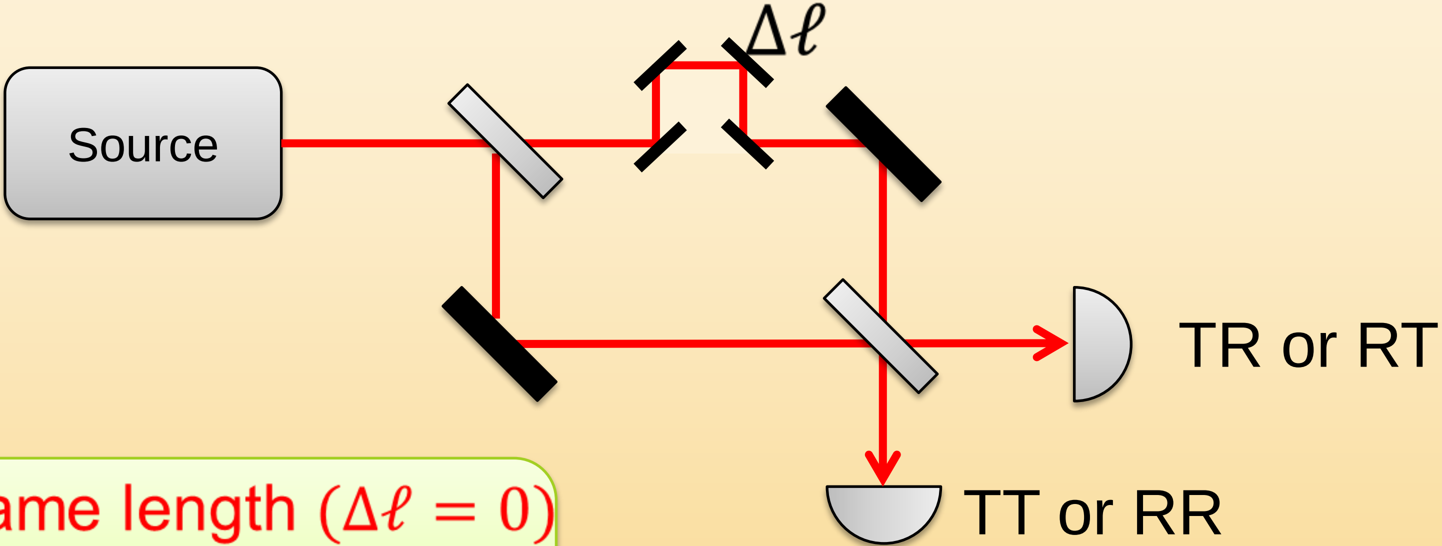
- In Exp #2, each detection corresponds to a unique path.
- In Exp #3, the detection does not allow to know **which path** the "particle" has taken, whether T or R

But can this possible matter for a "particle"?

INTERFERENCE

Mach-Zehnder interferometer

Experiment #3: modification



Paths of same length ($\Delta\ell = 0$)

$$P(TT\ or\ RR) = 0$$

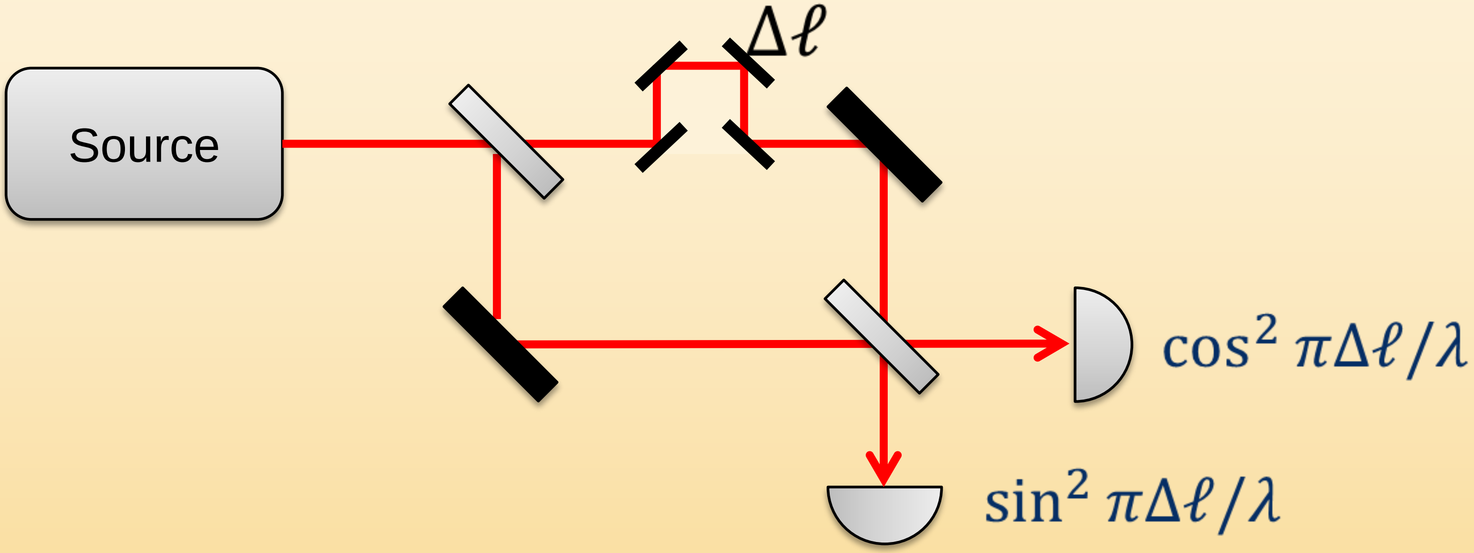
$$P(TR\ or\ RT) = 1$$

$\Delta\ell$

$$P(TT\ or\ RR) = \sin^2 \pi\Delta\ell/\lambda$$

$$P(TR\ or\ RT) = \cos^2 \pi\Delta\ell/\lambda$$

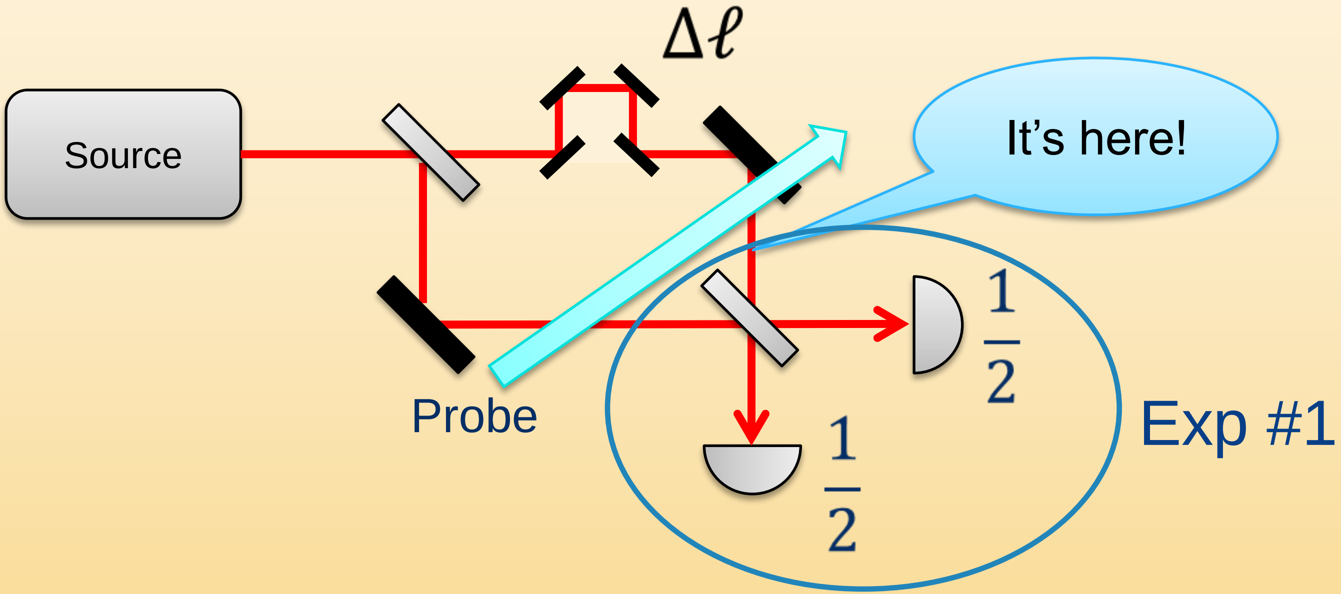
Mach-Zehnder interferometer



- The statistics depend on the **difference** between the paths
- From the clicks: the source is sending one “particle” at a time
- For $\Delta\ell = \lambda/2$, all “particles” have changed: now $P(TT\ or\ RR) = 1$

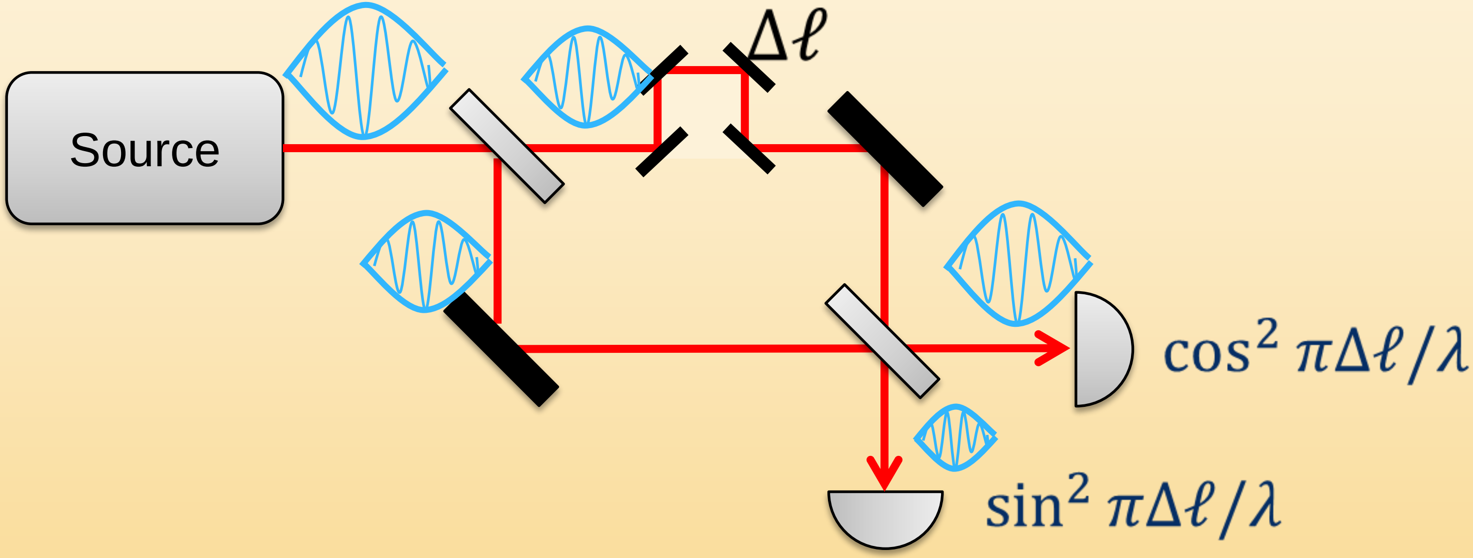
Delocalization: each “particle” must have “explored” both paths

Try to learn which path



Indistinguishability really matters
("measurement modifies the properties")

Waves?



Interference is well known for waves: are we actually dealing with waves?
Not really: single clicks!

Quantum objects

- Interference is ubiquitous in quantum physics
- The Mach-Zehnder interferometer with single "particles" has been implemented with:
  - Neutrons (Rauch's experiments, 1975)
  - Light (Orsay group, 1982)
  - Single atoms, electrons,…

Usually though of as a wave, it can also exhibit "particle" behavior ("photons")

Suggested Readings

Wikipedia pages:

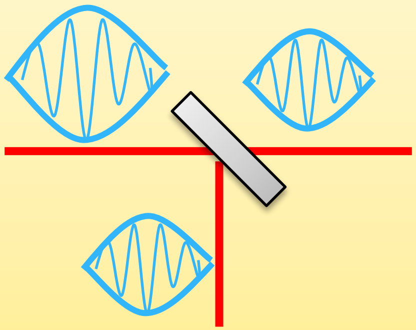
- http://en.wikipedia.org/wiki/Mach-Zehnder

MORE INTERFERENCE

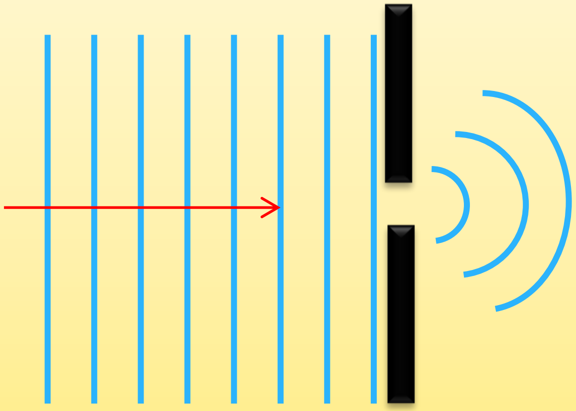
The double-slit setup

Another way of splitting waves

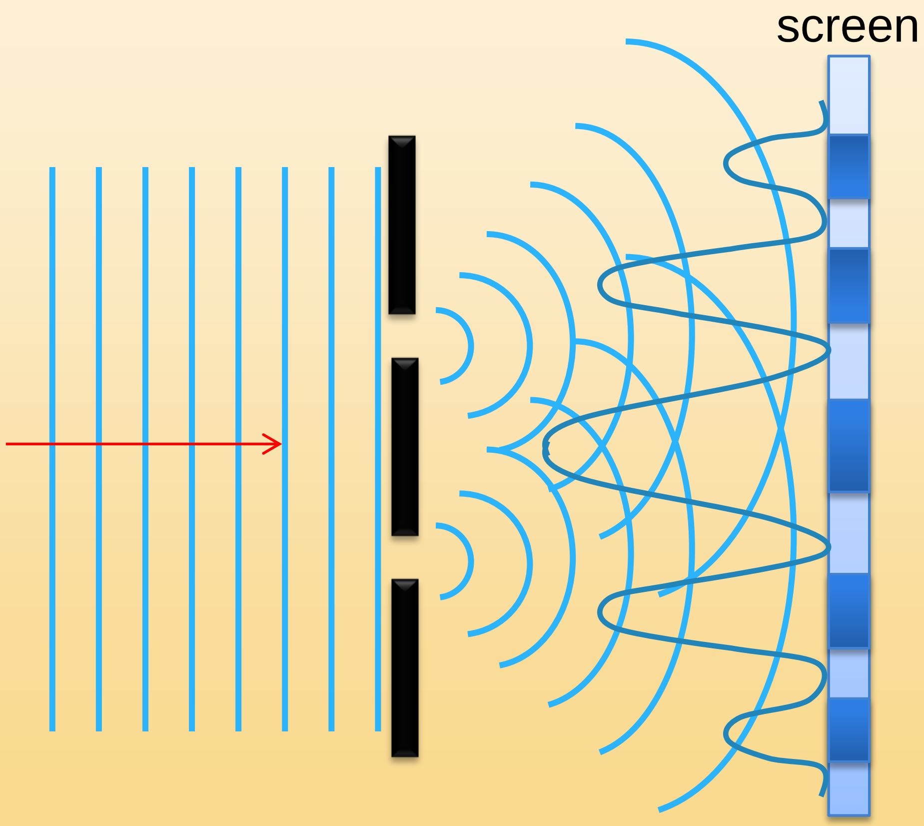
Amplitude splitting



Wavefront splitting



Young's double-slit interferometer



- Reported by Thomas Young in 1803 for **light**
- One of the strongest pieces of evidence that light is a wave
- Attacked for not supporting Newton's view that light is corpuscular.

Matter waves

- Young’s double-slit interference has been repeatedly observed with “matter waves” (i.e. “particles”)
  - Electrons
  - Atoms
- Record of mass (Arndt group, Vienna, since 2001):
  - Far field: C_{60}, C_{70}
  - Near field (Talbot-Lau): several complex molecules
    - $C_{44}H_{30}N_4$, $C_{48}H_{24}F_{51}P$…
    - To go beyond: technical difficulties (sources, speed…)

Suggested Readings

Wikipedia pages:

- http://en.wikipedia.org/wiki/Young%27s_interference_experiment

For experiments of interference with particles, one can start from the list in: http://en.wikipedia.org/wiki/Matter_waves
Curiously, “neutron interferometry” is missing from that entry, and the Wikipedia entry on it is not very informative: rather, look for those words in Google to find links to and images of Rauch’s experiments.

“UNCERTAINTY”

The very famous

Heisenberg's uncertainty relation

$$\Delta x \, \Delta p \geq \hbar/2$$

"uncertainty"
in position

"uncertainty" in
momentum

Planck's
constant

- Since $\hbar \neq 0$, both "uncertainties" must be larger than zero
- The smaller the "uncertainty" on position, the larger that on "momentum"
- But: what kind of "uncertainty" is this?

Confusions

Wrong

- “We cannot measure x and p *at the same time*”
  - Try to show that you can ski and ride a bike at the same time…
- It refers to the *imprecision* of our measurement devices or procedures
  - Like “uncertainty” in reading, error bars etc.

Right

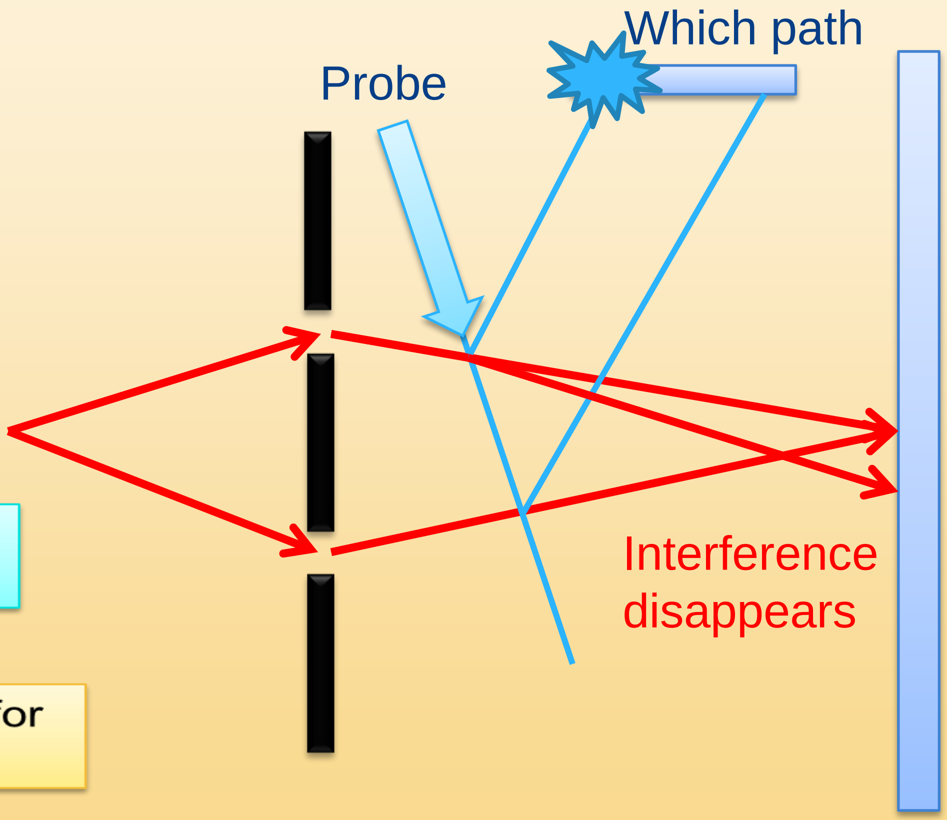
- No “particle” can have a too well-defined x and a too well-defined p at any given time
- It’s about intrinsic randomness ☺

Heisenberg's microscope

- Heisenberg derived the uncertainty relations from the quantum formalism
- In a subsequent semi-popular book, he tried to give an illustration…

Measurement = kick δp
$\Rightarrow$ leads to displacement δx

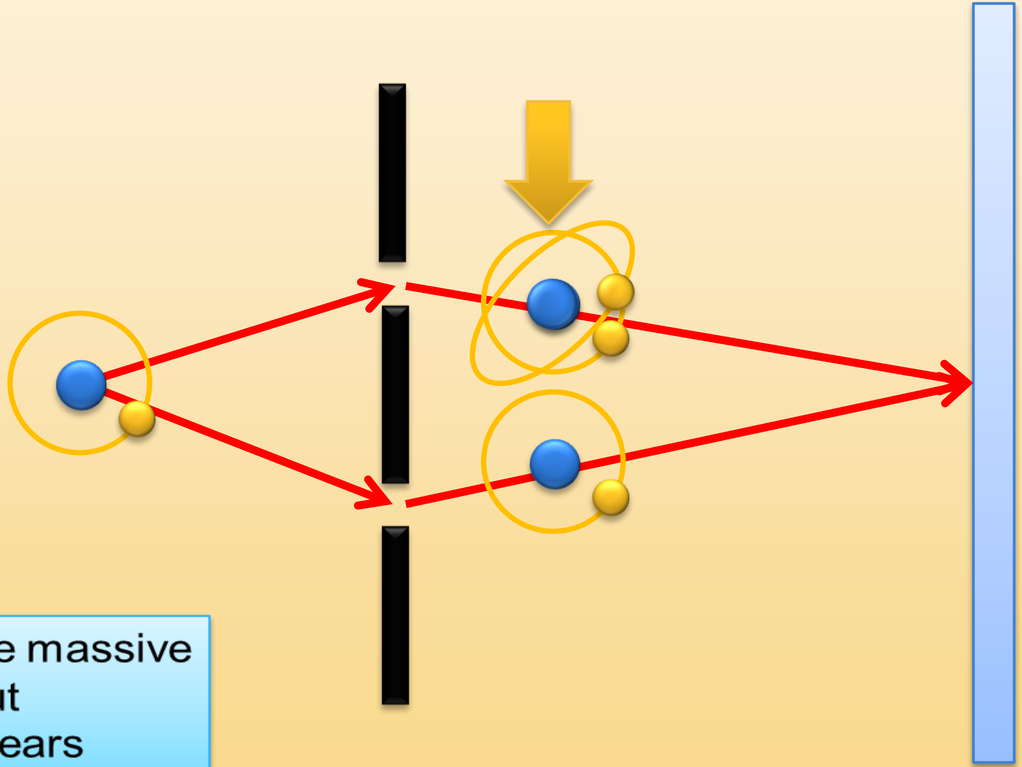
Back-of-the-envelop calculation for photon and electron: $\delta p \delta x \approx \hbar$



Correct, but wrong

- Correct: if you learn "which path", the interference disappears.
- Correct: Heisenberg's microscope is a possible way of knowing the path
- Wrong: this fact has nothing to do with $\Delta x \Delta p \geq \hbar/2$

Nucleus much more massive $\Rightarrow$ no δp , no δx; but interference disappears



"Uncertainty" = indetermination

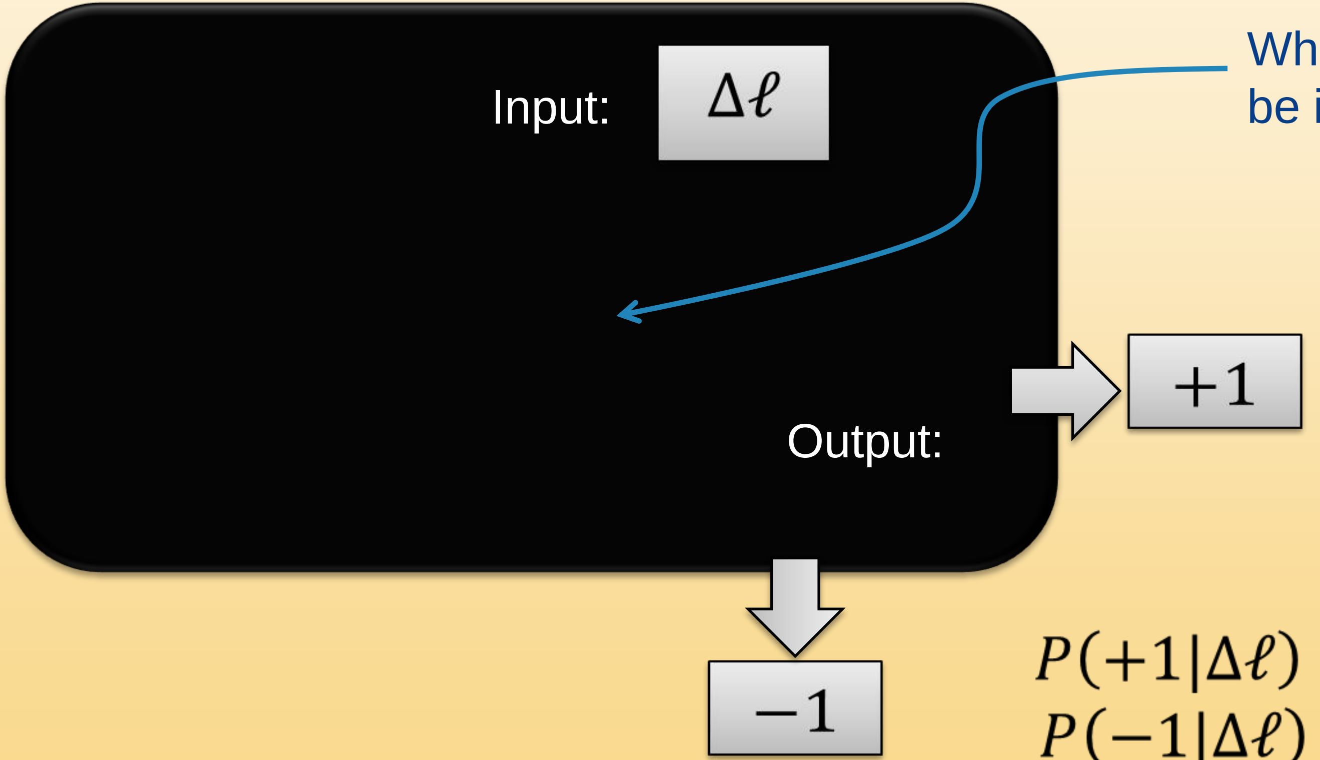
- The "uncertainty relations" do not refer to "measurement", but to "properties"
  - Particles don't have well-defined position and momentum even without anyone trying to measure them
- In this sense, they capture the intrinsic randomness: x and p are just not well defined "out there".
- Don't worry if you have to struggle to become familiar with quantum physics: even Heisenberg had to!

INTRINSIC RANDOMNESS?

Back to randomness

- We have seen typical quantum phenomena
  - Interference
  - Delocalization
- We have mentioned probabilities and even "uncertainty" ("indetermination")
- But is it really random? Can't we find a deterministic explanation for those observations?
  - Without of course going all the way to the theater of conspiracy.

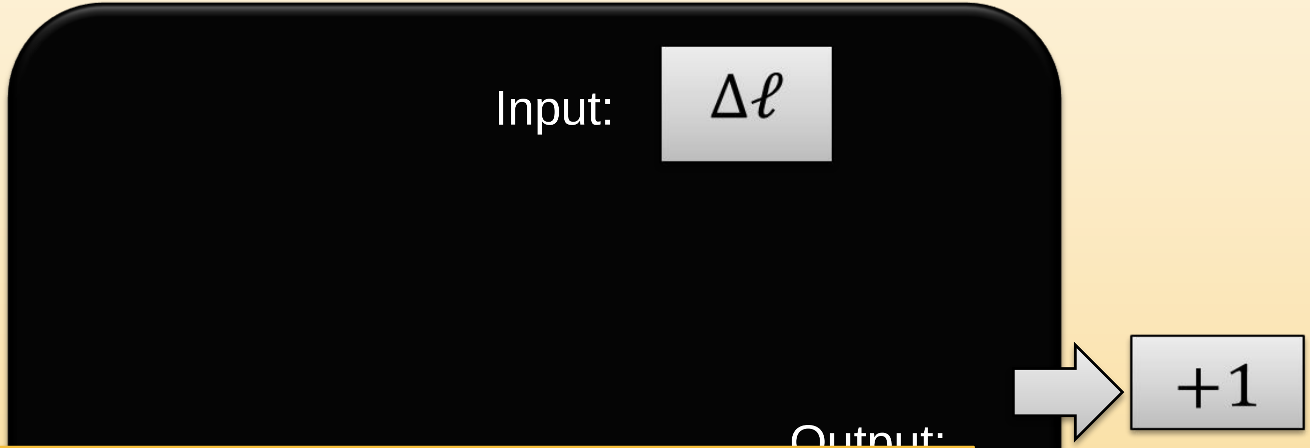
Try to convince a skeptic: black box



What can there be inside?

$$P(+1|\Delta\ell) = \cos^2 \pi\Delta\ell/\lambda$$
$$P(-1|\Delta\ell) = \sin^2 \pi\Delta\ell/\lambda$$

Simulation



- The mere observation of such statistics does not allow to conclude that it's quantum…
- … nor that it's intrinsically random: it's certainly not random for Alice.

$$P(+1|\Delta\ell) = \cos^2 \pi\Delta\ell/\lambda$$
$$P(-1|\Delta\ell) = \sin^2 \pi\Delta\ell/\lambda$$

Bohmian determinism

What if the box is not that black? How to explain delocalization?

- Louis De Broglie, David Bohm: both a particle and a wave
  - The wave creates a complex landscape in which the particle moves.
  - The interferences are due to the landscape, the individual clicks to the particle
- The wave carries no energy, is unobservable
  - Adversaries: postulates the existence of something *unobservable in principle* to save determinism
  - Supporters: better than claiming intrinsic lack of predictability

In the next episode…

- So far, the claims of “intrinsic randomness” seem based on shaky ground (or at most, to be a matter up for endless discussion)
- Next week: evidence of intrinsic randomness.
  - It takes two particles to convince a skeptic
  - A situation where no fair simulation is possible, and where Bohm’s wave shows all its craziness.

Suggested Readings

Wikipedia pages:

- http://en.wikipedia.org/wiki/Bohm_interpretation

Summary of Lecture 6

First encounter with phenomena described by quantum physics

- Single-particle interference
  - Mach-Zehnder setup
  - Double slit setup
- Notions
  - Indistinguishability
  - Delocalization
  - Unpredictability? See next lecture