INTERFERENCE EXPERIMENTS.

CLASSICAL VERSUS QUANTUM BEHAVIOR.

We review basic experiments that illustrate the quantum behavior and compare to classical one. Today amount of math and formalism is minimal.

The experiments will be discussed again when we apply the principle of Quantum Physics (after next week). They illustrate two core concepts; the "superposition principle" and "the measurement postulate".

1) Double slit experiments.

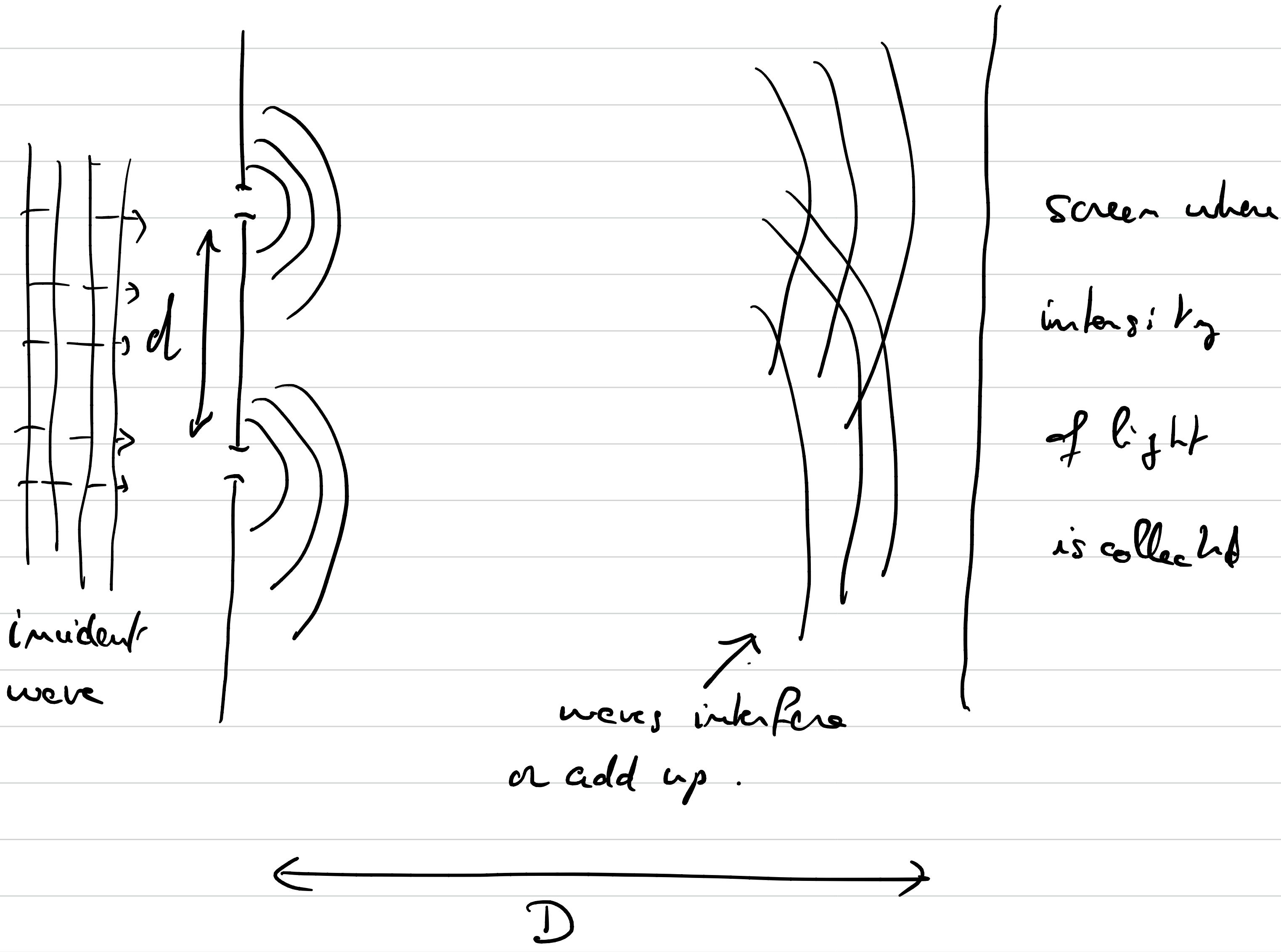
2) Mach-Zehnder interferometer.

3) ...

1) Double slit experiment.

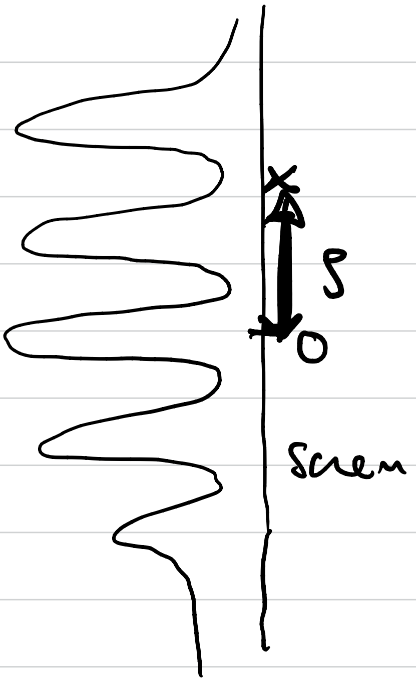
Waves

Young in 1803 performed the following experiment with light. This experiment demonstrated the wave like behaviour of light (not known to be an electromagnetic wave at the time...)



$d \ll D$.

One observes interference fringes on the screen with alternating regions of high and low light intensity.



A good approximation to the intensity is

$$I(\rho) = \frac{4A^2}{D^2}\left[\cos \frac{\pi}{\lambda}\frac{d}{D}\rho\right]^2$$

A = intensity incoming wave
λ = wave length of light
ρ = distance on screen from O

From observed period of $I(\rho)$ Young deduced λ.

For visible light he concluded that $\lambda \simeq 700 - 800$ [nm]

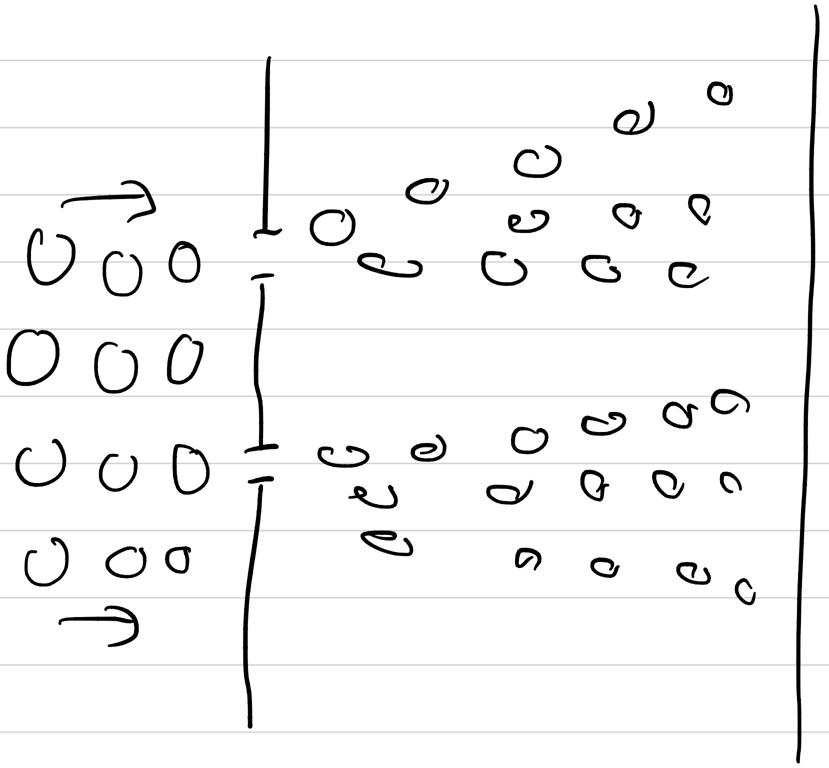
[nm] = nanometer = 10^{-9} meter.

Back in 1800's smallest size ever measured!

Classical particles/balls.

Why does this experiment suggest light is a wave?

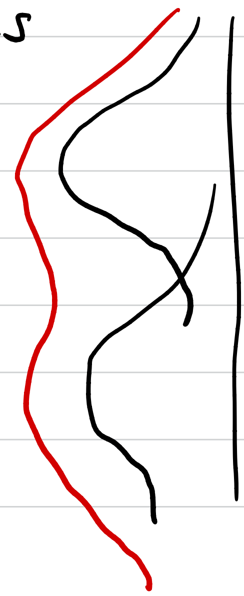
Lets try it with balls (ping pong balls or cannon balls...)



some balls fall here

some balls fall here.

Each ball passes through slit 1 or slit 2 (and not both). The density profile collected on the screen is

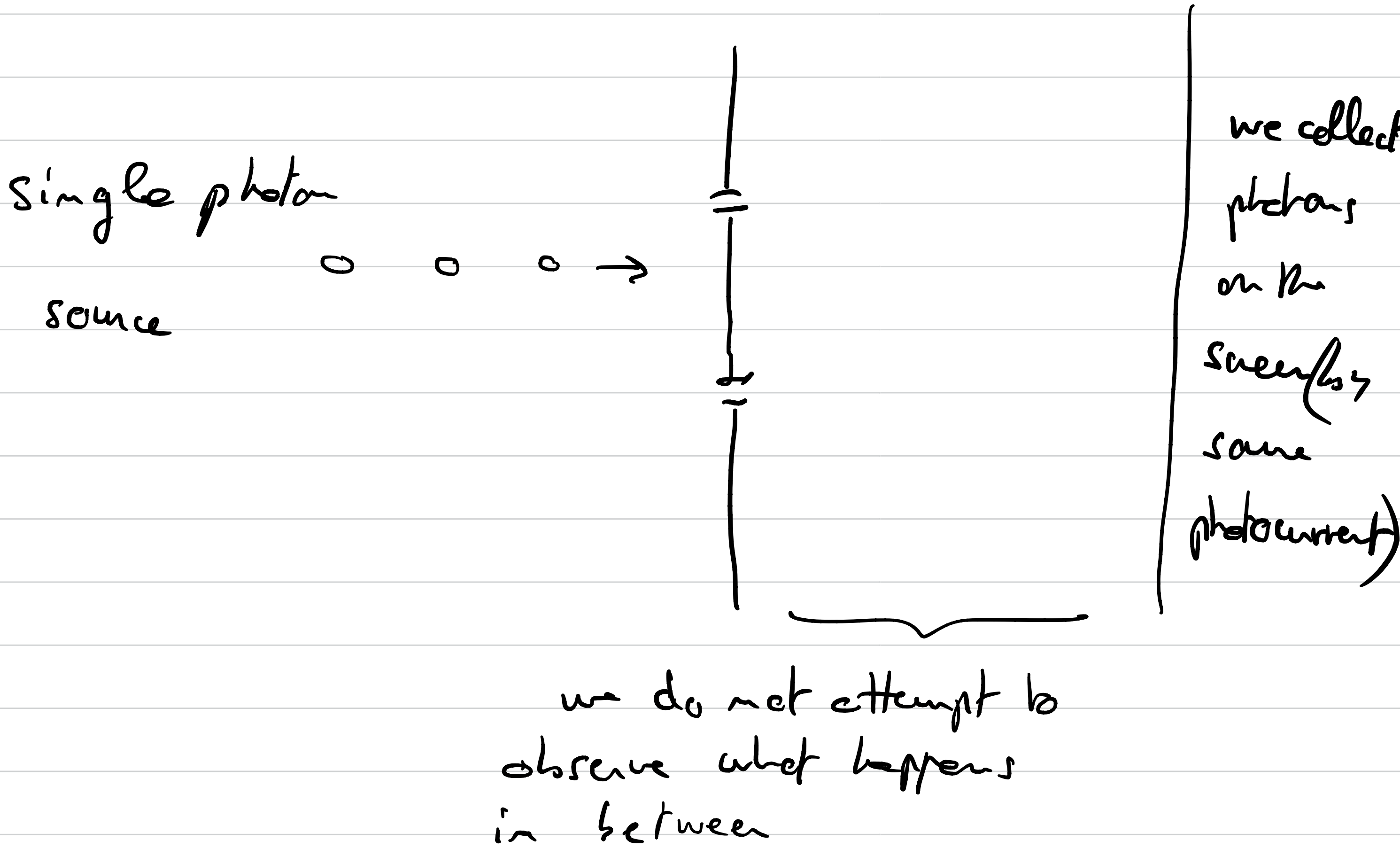


$N(y)$ = sum of two bell shaped curves.
Very different from interference pattern with waves.

Modern Young experiment with photons, electrons, C60 molecules. Quantum behavior.

Nowadays we are able to repeat Young's experiment with individual photons, electrons, C_{60} molecules. These are all "objects" with a quantum behavior.

[**Note**: photoelectric effect in 1900's induced Einstein to postulate that light also has a particle like behavior. The elementary particle associated to light is called the "photon". Think of it as a little grain of luminous energy.]

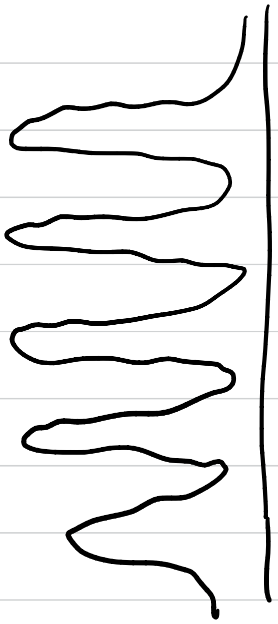


* At first we observe that photons fall on the screen at <u>discrete</u> and <u>random</u> locations,

* After some time when sufficiently many photons have fallen on the screen we observe a

histograms (of the random locations).

The shape of the histograms is the same as the interference fringes (observed for waves).



$$\text{Probability (detect photon at } \rho) \propto \left[\cos\left(\frac{\pi}{\lambda}\frac{d}{D}\rho\right)\right]^2$$

proportional to

This is an astonishing experimental observation! Do photons behave like waves or particles? Provisional answer: like both / it depends on the way we observe them.

We will next time enunciate the measurement principle:

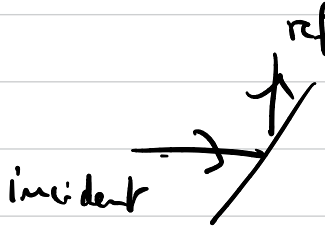
|| Prob to find photon at location ρ is equal to intensity predicted by wave theory

Remark 1: Historically this quantum double-slit experiment with single photon sources (or electrons, C60, ...) could not be done until 50's or 60's. So it was an important thought experiment in the development of quantum physics. In fact other interference experiments where carried on (e.g diffraction of electrons in crystals etc..) but are more complicated to describe here. Davisson and Germer ~ 1927.

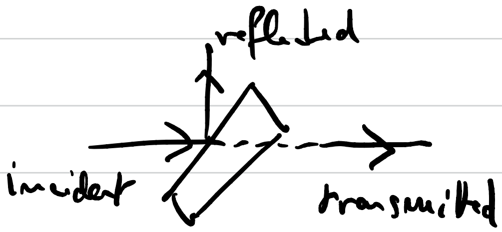
Remark 2: For the derivation of the intensity curve within wave theory see Appendix at end of notes.

2) Mach-Zehnder interferometer.

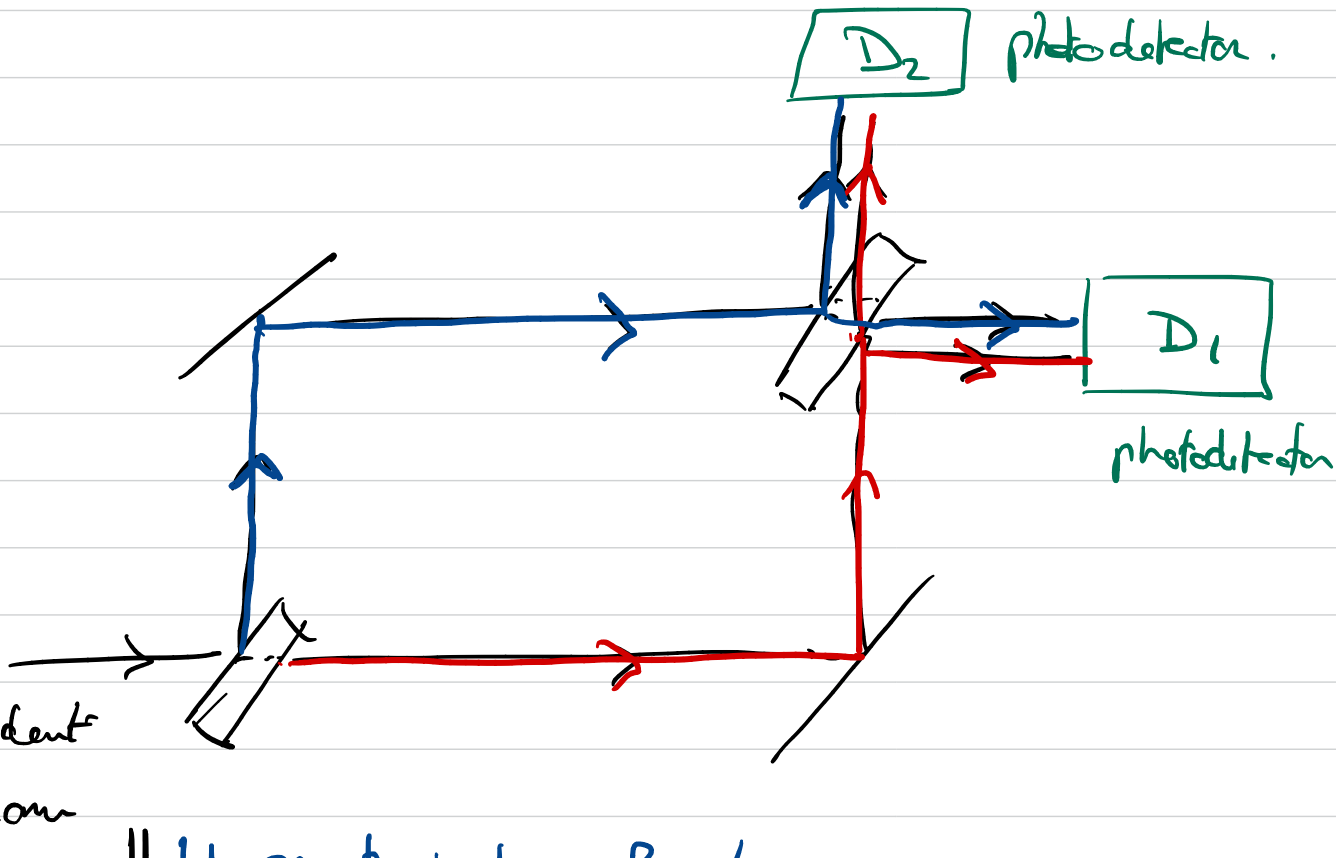
We take mirrors and beam splitters and again explore the behavior of light beams.



(perfectly reflecting mirror.)



(semi-transparent mirror.)



Upper trajectory of a beam

Lower trajectory of a beam.

Experiment with waves.

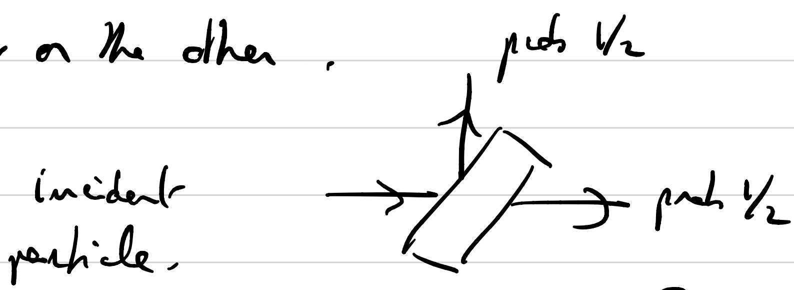
- Turns out all intensity is found in D_2.
- No intensity in D_1.

Interference effects cancel the wave before D_1 and build it up at D_2.

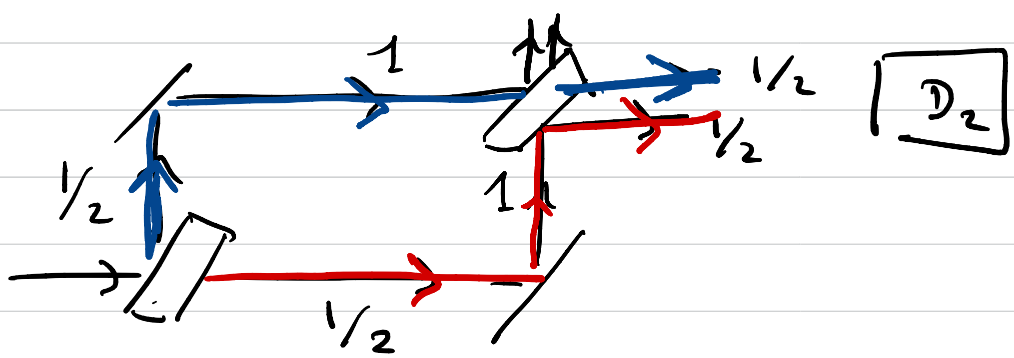
This is analogous to Young's fringes.

Experiment with "classical particles" billiard balls:

Imagine each beam splitter has prob 1/2 to deflect particle one way or the other.



What is the probability to detect particle in D_2?



- prob to follow lower path and fall in D_2:

$$\frac{1}{2} \cdot 1 \cdot \frac{1}{2} = \frac{1}{4}$$

- prob to follow upper path and fall in D_2:

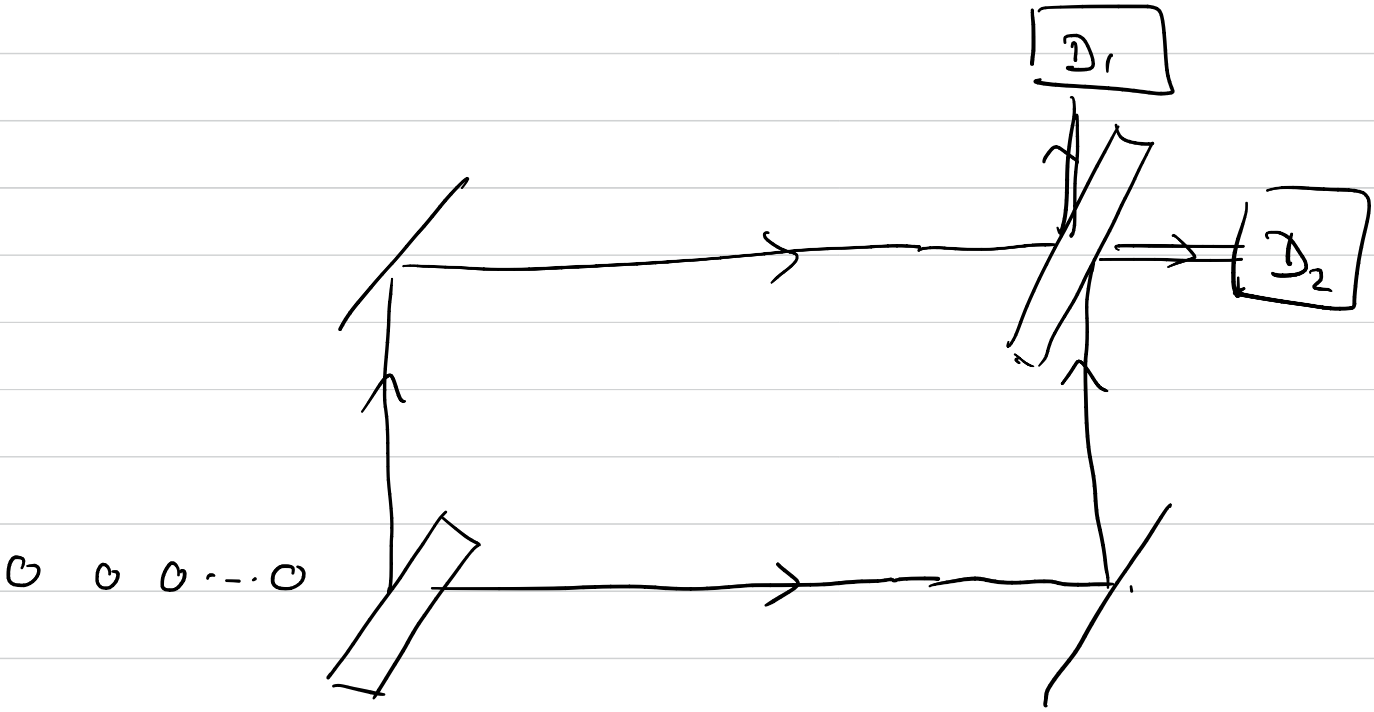
$$\frac{1}{2} \cdot 1 \cdot \frac{1}{2} = \frac{1}{4} .$$

$$\boxed{\text{Prob (detect in } D_2) = \frac{1}{4} + \frac{1}{4} = \frac{1}{2} .}$$

Similarly $\boxed{\text{Prob (detect in } D_1) = \frac{1}{4} + \frac{1}{4} = \frac{1}{2}}$

This is the classical particle behavior similar to double slit with ping-pong balls.

Experiment with individual photon source:



- A photon source sends photons one by one in the interferometer.
- We do not attempt to observe what happens before photodetector clics (e.g. we do not try to find out "path" of photon)
- We register clics of D_1 or D_2 and collect statistics
- We observe that

Prob (detection) = Intensity predicted by wave theory

e.g. Prob(detection in D_2) = 1 , Prob(detect in D_1) = 0 .