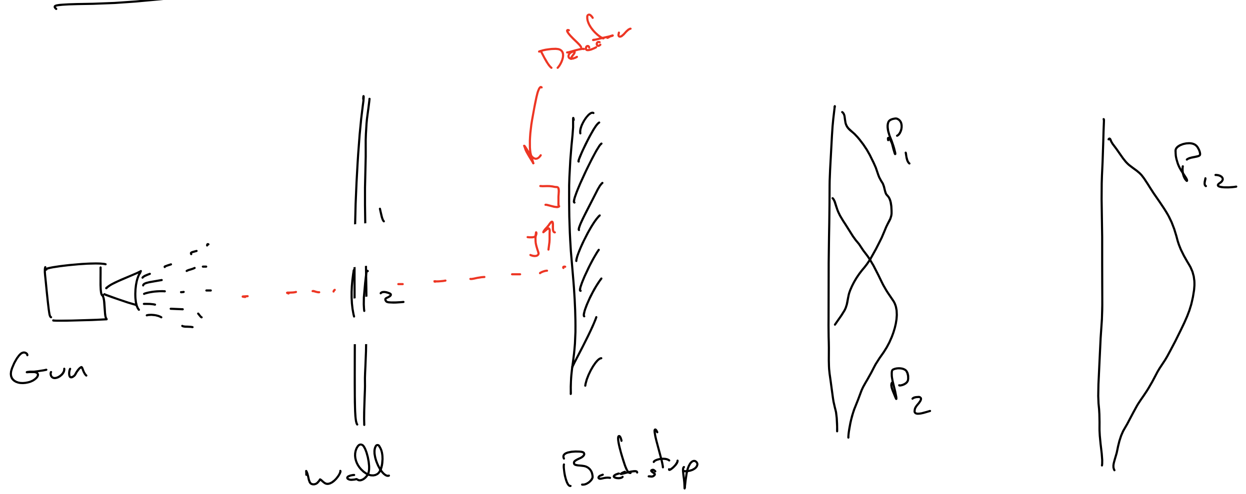
Try to understand what QM is telling us w/ simple experiment. "Double Slit"

Start w/ Classical Particles eg Bullets



-) Bullets come out randomly

-) Most hit wall + stop

-) Some make it thru holes ① + ②

Have a detector to measure # Bullets for certain value of y.

Bullets always arrive (are detected) in lumps

Start by only opening one of the holes

When 2 is closed see P_1

" 1 " P_2

Now, with both holes open see ...

P_{12} is the probability measured when both holes are open.

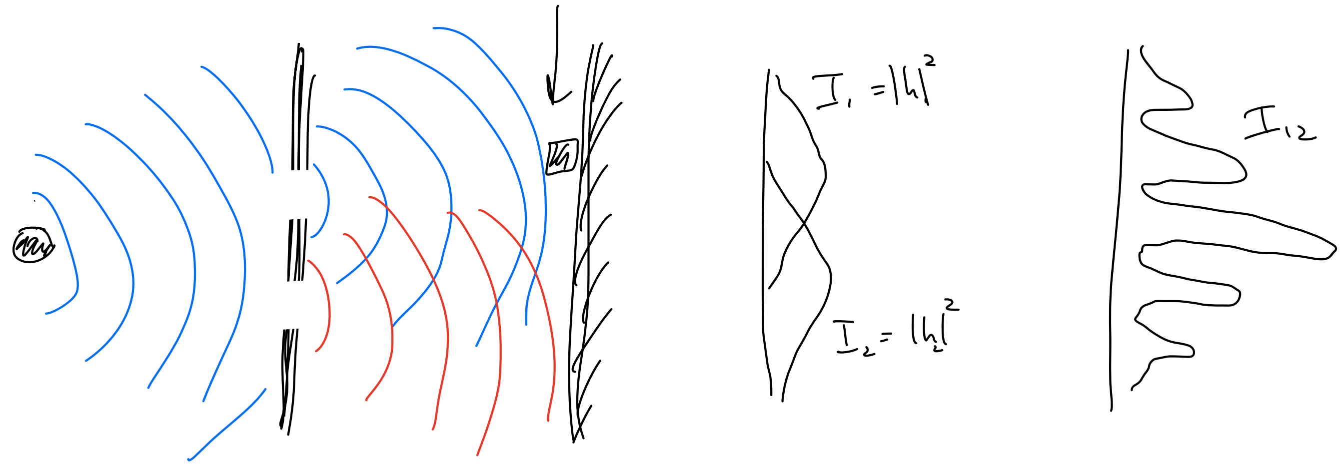
$$P_{12} = P_1 + P_2$$

The bullet either goes through 1 or 2

Probabilities Add. All as expected

Do the same thing w/ waves (water waves)

Measure E in wave



- Energy of wave "Intensity" = $|\text{height}|^2$
- heights / Intensities not quantized (Not lumpy)
- when only one hole is open see I_1 / I_2
- However now, when both holes are open we have interference. $I_{12} \neq I_1 + I_2$

Makes sense, waves coming from both holes At the same time

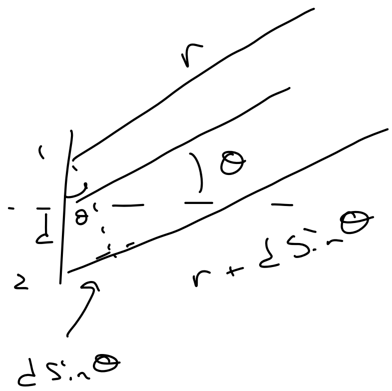
$$I_{12} = |h_1 + h_2|^2 = |h_1|^2 + |h_2|^2 + 2|h_1||h_2|\cos\delta$$

$$= I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\delta$$

δ - is phase difference h_1 + h_2

Find δ

$$h \sim e^{ikr + \omega t}$$



So

$$h_1 \sim e^{ikr + \omega t}$$

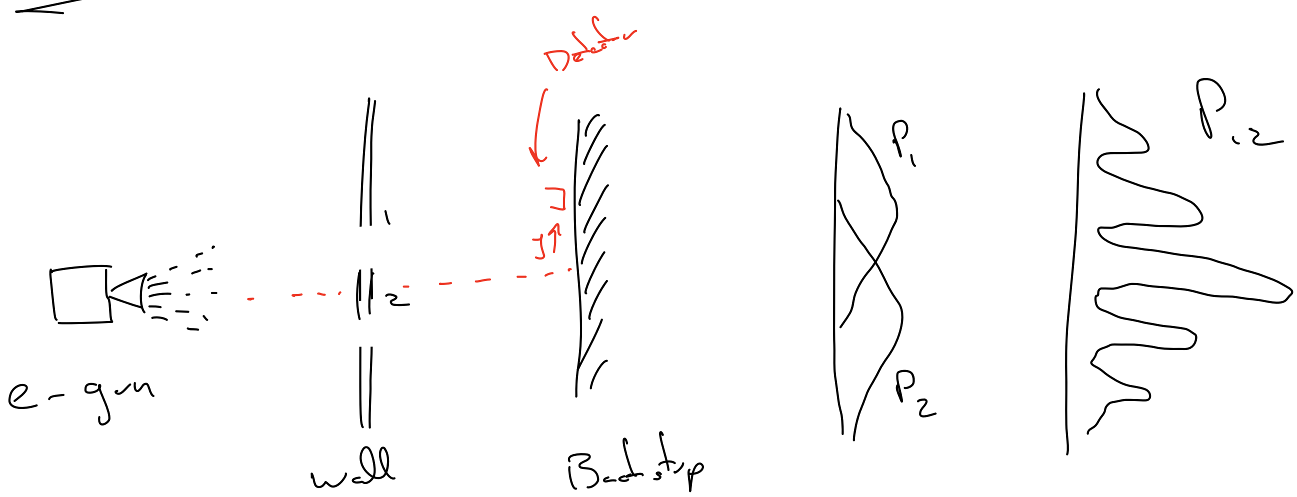
$$h_2 \sim e^{ik(r + d\sin\theta) + \omega t} = e^{ikr + \omega t} e^{ikd\sin\theta}$$

$$\Rightarrow \delta = kd\sin\theta$$

Again all non-controversial...

Now for the controversial part

Same thing w/ Electrons Stress one e at a time!



- Start w/ one hole open at a time.
- Find electrons come in lumps (like Bullets)
  Never "part of" an electron seen.
- See Probabilities P_1 & P_2
- When Both holes are open see
  P_{12} !!!

$$P_{12} \neq P_1 + P_2$$

$\Rightarrow$ Not true that e's either go through ① or ②

Maybe they go through both?

- Cannot split!

- Some points of

<u>destructive interference</u>

- fewer e's when both holes open
- more when 1 hole closed

⇒ Closing one hole, increases e's from other.

<u>Constructive interference</u>

- $P_{12} > 2(P_1 + P_2)$

⇒ Closing one hole, decreases e's from the other.

Hard to explain Both effects by proposing that e's travel in complicated paths though both holes.

<u>Mysterious</u> However the math is <u>simple</u>

$\psi(y) = \psi_{1}(y) + \psi_{2}(y)$ $\quad P_1 = |\psi_1|^2 \quad P_2 = |\psi_2|^2$

$$P_{12} = |\psi_{①} + \psi_{②}|^2 \Rightarrow \text{Math the same as water waves}$$

Conclusion

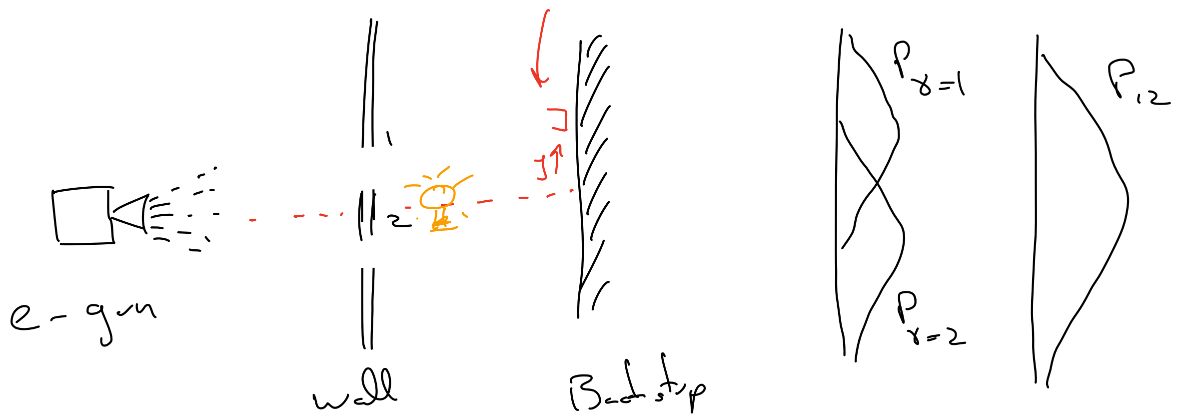
- Electrons arrive in lumps / Are detected as particles
- Arrivals are distributed according to an interference wave!

"Act not like particles or waves, but sometimes like particles, sometimes like waves."

Lets do more experiments

Test claim that particles don't go through ① or ②

Lets add light source to see e^-'s



- We know (Compton effect) that e^-'s scatter light.

- Add γ detectors to detect the scattered light. If coming from 1 $\Rightarrow$ e thru 1
  " " " 2 $\Rightarrow$ " " 2

- What we find, every time we detect an e we see scattered γ from either 1 or 2 !

  Never Both at once!

$\Rightarrow$ e^-s do indeed go through ① or ②!

Before saw $P_{12} \neq P_1 + P_2 \Rightarrow$!(① or ②)

Now see detecting γ's $\Rightarrow$ (① or ②)

- Lets look at P_{12} w/ γ near ①

  See what we get when ② closed P_1

- Same for P_{12} w/ γ near ② $= P_2$

- But All γ's either near ① or ②

  Indeed now $P_{12} = P_1 + P_2$

When we measure which hole the e^-s go thru we destroy the interference!

When we look at them we change the distribution.

- Not too crazy. Compton Scattering changes p_e^{γ} after all.

- Lets try to turn the brightness down. (Light dimmer $\Rightarrow$ less impact on e's)

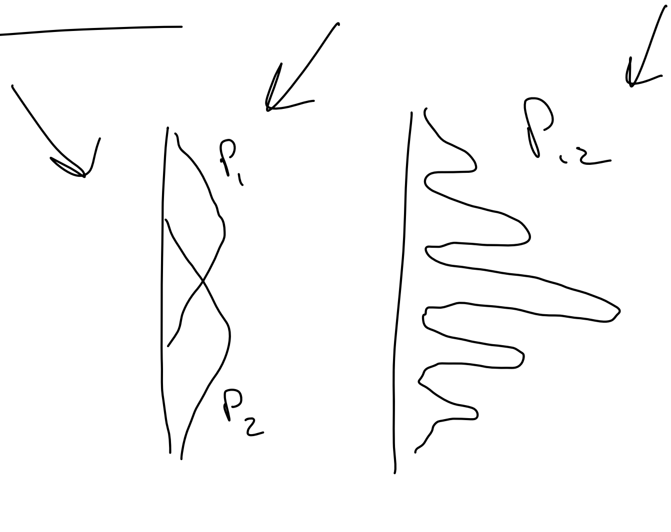
What happens? We know...

light quantized, fewer γ's when dim

Observed flashes of light always same size only now sometimes no γ's for the e to interact with.

<u>Do the experiment</u>

3-categories: <u>See γ at 1</u> / See γ 2 / No γ



Result?

<u>Makes sense</u>

Anything else we can do? Yes

Lower E_γ $\Rightarrow$ Softer collision w/ e

$E \sim \frac{hc}{\lambda}$ Don't lower the intensity!

" " frequency.

Now what happens

Repeat with "redder" + redder light

- At 1st, nothing changes
- Then, eventually $\lambda \sim$ distance ① + ②

  Can no longer tell which hole the e went through.
- Exactly when this effect kicks in !!!

  we start seeing interference effects...!

Impossible to know which hole the e went through w/o destroying interference.

Example of uncertainty principle in action.

So ((1) or (2)) True if can determine which hole the e goes through If observing the e

&

!((1) or (2)) If not observing the e path.

Summary

- Prob $= |\psi|^2$ ψ - Amplitude

- When an event can occur in several alternative ways, Amplitude is sum of the amplitudes for each alternative

$$\psi = \psi_1 + \psi_2$$

- If you measure which alternative is actually taken, the probability is the sum of probabilities (Not Amplitudes!) for each Alternative.

ie: the interference is lost.

How could we explain this?

- **One attitude:** Can only talk about things that you observe. Can't say where something goes when you don't observe it

"positivism"

- **Other Point of View** Realist Explanation

Explanation the point of Science.

- e^-'s go through 1 or 2
- See interference pattern. ⇒ Something going though the other slits to interfere

- Interfering entities behave exactly like e^-'s
  eg: e-charge, mass, same interactions etc.

- Cannot be seen!

"Shadow e^-'s"

"tangible" e^-'s we can see
"Shadow" e^-'s only infer B/c of their interface w/ Tangible e^-'s

For each tangible e^- there are a bunch of shadow e^-s $\longrightarrow$ nearly continuously ∞ #
(we can move the slit & still see interference)

Shadow e^-s would go entirely unnoticed if not for the interference

Not something special to e^-s, this interference seen for every type of particle.

$\Rightarrow$ Reality much bigger thing than seems
most of it is invisible.

- Our universe: Universe of tangible particles
- Many Parallel Universes of partitioned shadow particles.

Not one tangible & one vastly bigger shadow
Rather huge # of parallel universes
each similar to the tangible one.

eg Consider what happens when shadow e's hit the barrier when one of the holes blocked

s-e's are blocked, we know no interference.

What stops them? Can't be for "tangible" atoms

s-e's do not interact w/ t-atoms.

(Can also verify w/ detector.)

↳ s-e's no effect

So, s-e's + t-e's Both blocked by barrier

But Barrier only effected by t-e's

⇒ Must be a shadow barrier at same place as the tangible barrier.

What could they possibly be made of?

<u>s-atoms</u>.

(Can argue from semi-transparent Barriers that s-e's only interact w/ a tiny fraction of s-atoms)

__So__ - Behavior of objects we observe can only be explained if there are unobserved objects present. (and if they have certain properties)

- Single particle interference rules out the possibility that the t-universe is all that exists.

- Interference only observed in special cases where the path of the t-e + s-e separate + reconverge, + interference between any two universes requires an interaction to take place between <u>all particles whose positions are not identical</u> in the two universes.

=> Only have interference when 2 universes are very much alike

Interference seen when universes differ only in the position of one e.

If the e affects other particles as it travels (eg is detected) then the universes become differentiated + lose interference.

"Observation Destroys Interference" is misleading.

<u>Note</u>: The argument for ∞-Universes stems only from the interpretation of the experiment Not from the formal QM description of whats happening.

What is amazing (we will see next time) is this is exactly what is predicted by the formal theory!!!

"Why can't we just say that e's behave <u>as if</u> they were interacting w/ invisible entities?"

Requires a new level of description beyond what was previously the scope of science.