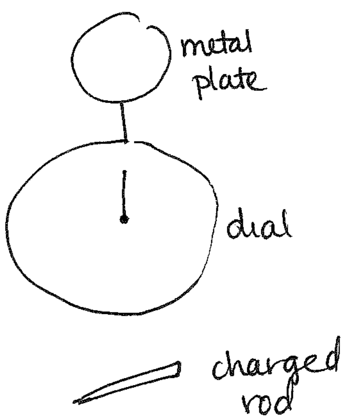
experiments

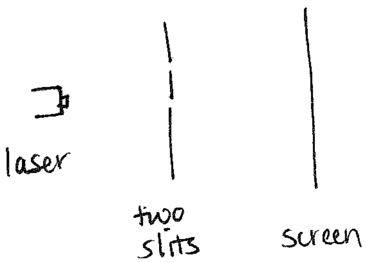
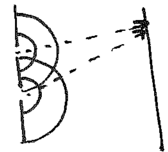
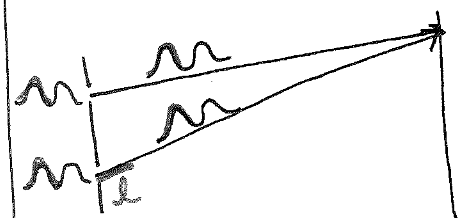
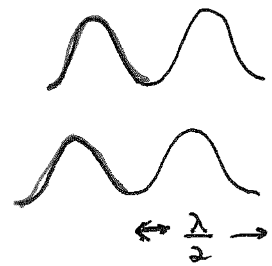
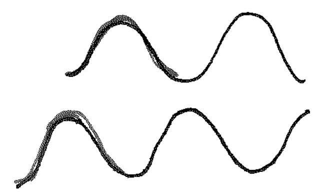
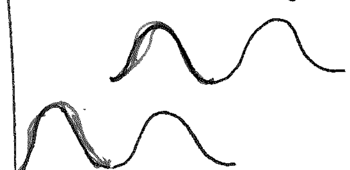
1. setup
2. predictions
3. what do we see?
4. how can we explain it?
5 conclusions

experiment	conclusion
photo electric effect	light : photons / particles matter : particles / electrons
laser diffraction	light : waves
electron diffraction	matter : waves

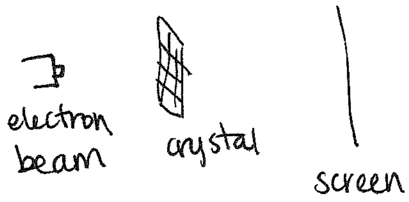
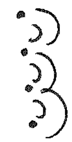
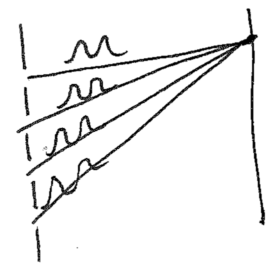
Photoelectric Effect

setup	predictions	what do we see?	how do we explain?
	shine two kinds of light on plate: white light (low energy) UV light (high energy)	<u>white light:</u> nothing	• light transfers energy to plate • do not have to wait for enough energy to be delivered, + white light does nothing ⟹ energy is transferred in discrete packets
	<u>white light:</u>	<u>UV light</u> needle moves back to left	⟹ energy per packet is related to frequency
• add electrons, dial moves to right • dial measures charge	<u>UV light</u>	high energy light removes electrons from plate	⟹ "particle" of light = photon $E \propto f$ ⟹ single photon ejects single electron
		low energy light does nothing effect happens immediately	think about: what if E_{ph} is greater than energy needed to release e^-?

Laser Diffraction

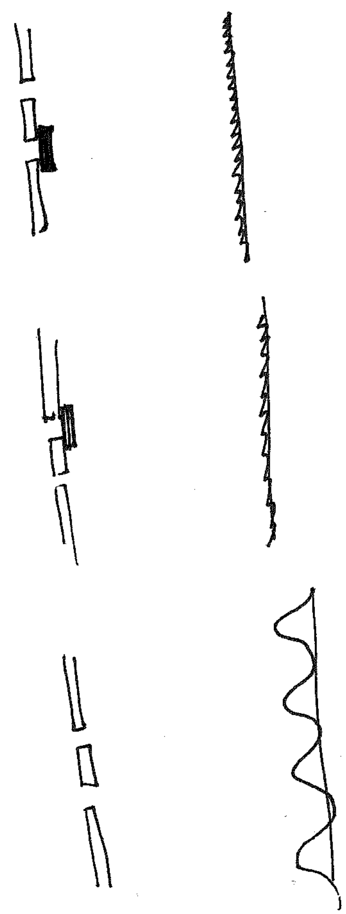
setup	predictions	find?	explain
		fringes - bright + dark spots	 overlapping waves create interference
		spacing btw slits determines spacing between fringes	 amount of separation determined by extra path length
• laser = coherent source (all waves in phase)			think about: · calculate ℓ · what happens if slits are wider?
• measure intensity (brightness of light) on screen			 separated by $\frac{\lambda}{2}$: destructive
			 separated by λ : constructive
			

Electron Diffraction

setup	predictions	find?	explain
 crystal (front view)  · regularly spaced atoms · acts like series of slits screen: lights up when hit by electron		bright spots + dark spots (constructive + destructive interference) pattern tells us something about structure of crystal	 overlapping waves create interference ⟹ <u>electron</u> waves!  bright spot = constructive interference not convinced?  same double slit experiment but w/ electrons same interference pattern If we cover either of slits, we lose interference 

Electron Diffraction

instead of laser beam,
use electron beam:



Electron Diffraction

what is an electron?

→ a charged particle

evidence for particle behavior?

→ photo effect

what happens if we ~~shine~~ shoot a particle at a slit?

one of two things:

- passes through slit
- bounces off of wall

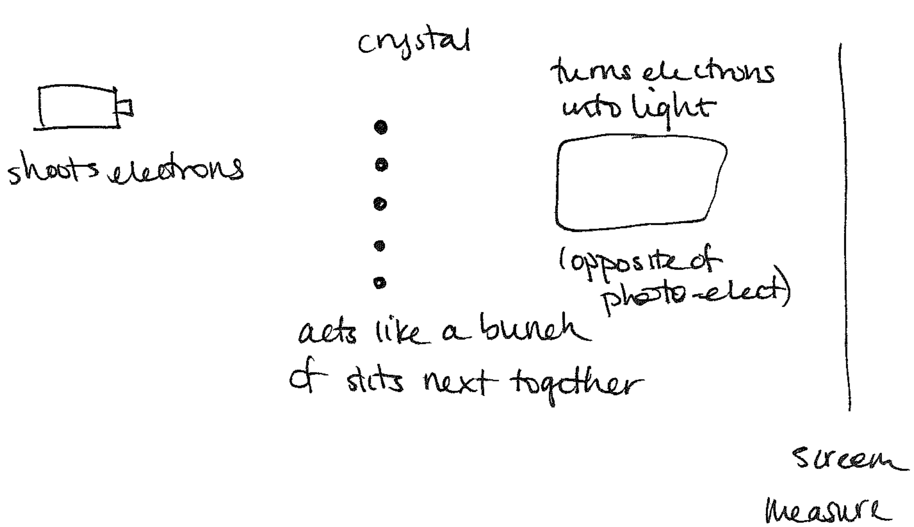
predictions: random bright spots

see: specific pattern of light (electrons)

conclusion: electrons can behave like waves! that interfere w/ each other

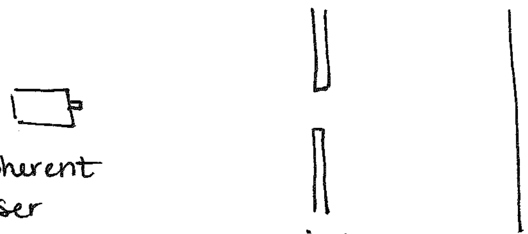
(see 2D pattern b/c crystal is series of 2D slits

setup



Diffraction w/ Laser Light

setup:

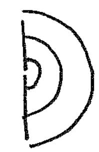


coherent laser (all waves are in phase)

single slit

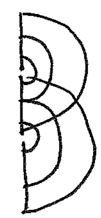
measure on screen (what are we going to measure?)

1. small slit
   observe: single peak

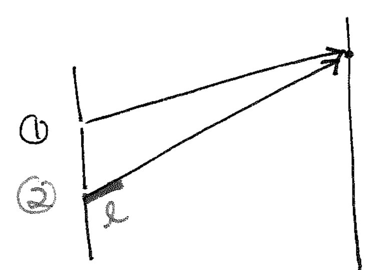


~~2. large slit~~
~~observe: many peaks (fringes)~~
~~why?~~

2. two small slits
   observe: fringes
   why?



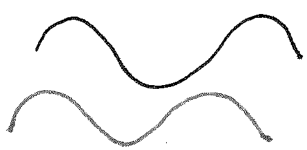
two waves interfere w/ each other



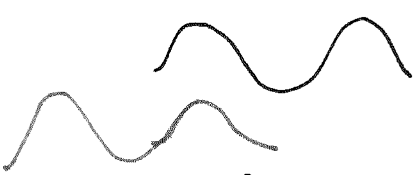
wave ② has to travel a longer distance

~~conclusions~~

if wave ② is enough behind, it will line up again:



off by part of a wavelength.

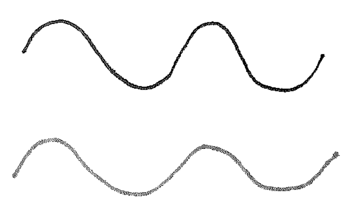


off by a full wavelength

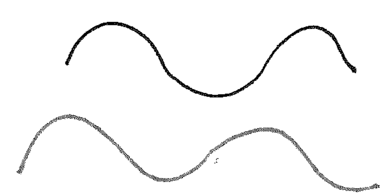
- what determines how far behind wave ② is?
  → the extra distance

when the extra distance is the right length, the two waves add up

same distance:



different distances:



ahead

behind

calculate maxima:

off by a full wavelength

$\ell = \lambda$

more general - could be off by any integer multiple:

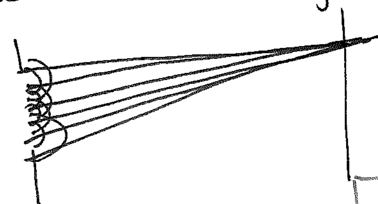
$\ell = m\lambda \quad m = 1, 2, 3 \ldots$

how do we find ℓ? (trig)

> for you to try:
> calculate ℓ

3. single large slit:

acts like many small slits added together:



> **Test your knowledge:**
> what happens w/ two big slits?

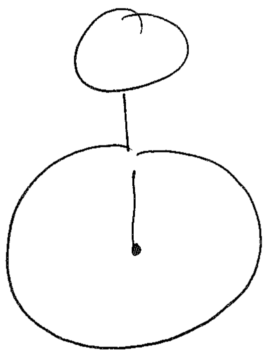
conclusions:

light behaves like a wave that passes through both slits

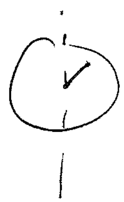
can use what we know about water waves (ripple tank) to help us calculate things

Photo electric Effect

setup:



add electrons → needle moves to right



(needle measures charge on plate)

shine light on plate
- white light (low energy)
- UV light (high energy)

~~white light~~

predictions:

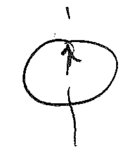
white light: ________

UV light: ________

find:

white light: nothing

UV light: needle moves back to left (immediately)



what can we say about this?

UV somehow affects charge on plate (decreases it) - electrons are leaving plate

how could light decrease charge?

→ does light pull electrons off?

→ light transfers its energy to plate, releasing electron

~~how much energy does it take to~~

why did white light not release electrons?

→ not enough energy

→ but if light is wave, we just have to wait long enough for wave to deliver energy.

find: no matter how long we wait,
white light does not have enough
energy to release electrons

conclusions:

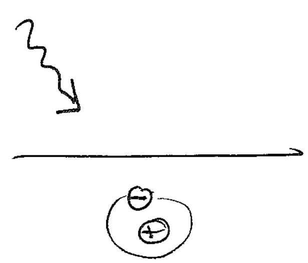
doesn't work to think of light as wave

New description: particle of light = <u>photon</u>

each particle of light has a fixed
amount of energy

photon $E_{ph} = hf$ — higher frequency (wave property)
higher energy of photon (particle)

think of photons as packets of energy (like water balloons)



photon gives all of its energy
to electron - electron has enough
energy to escape plate

1 photon ⟷ 1 electron

so if photon doesn't have enough
energy (low frequency), electron
won't leave

> to think about:
> what happens if the photon has more than the energy
> required to release electron

<u>conclusions:</u>

light can behave like particle
(call photon)

each particle has a certain
energy and momentum

particle: $E_{ph} = hf$ (wave)

$P_{ph} = \frac{h}{\lambda}$

$E = pc$
$= p\lambda f$
$= hf$
$\rightarrow p = \frac{h}{\lambda}$

Wave or Particle ?

diffraction

concl. : light/matter behaves like wave

photoelectric effect

concl. : light/matter behaves like particle

	wave	particle
light	double slit diffraction	photo electric effect
electrons	diffraction through crystal	photo electron effect

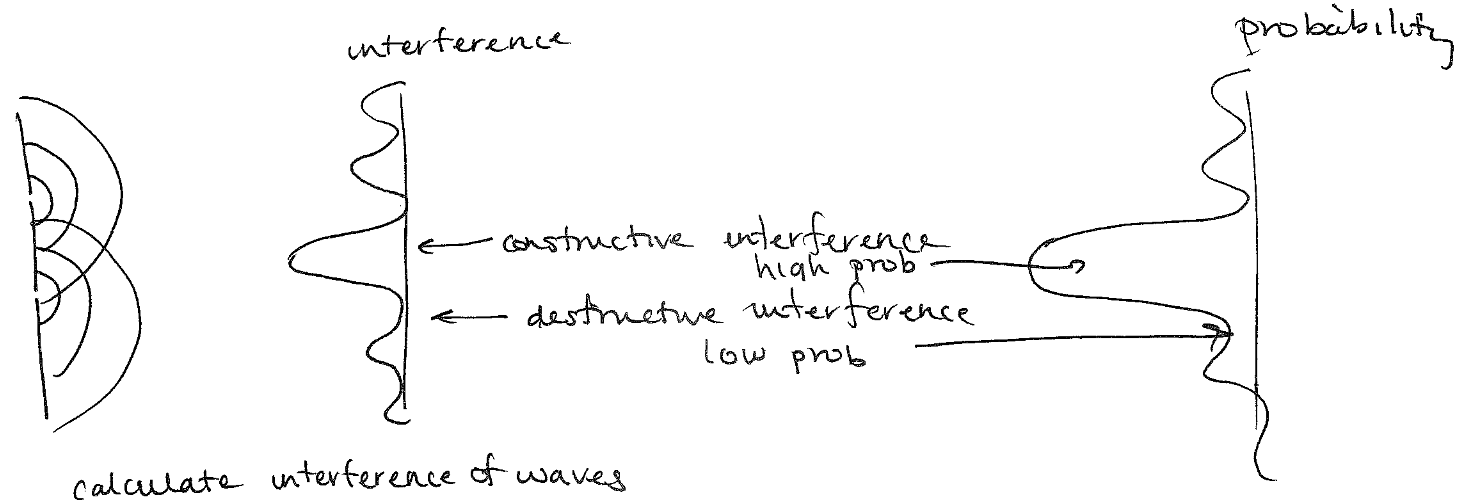
how do we rectify these two ~~obs~~ sets of observations ?

If we can describe light as a particle ~~[illegible]~~ or a wave, can we explain diffraction assuming light is made of particles ?

Try sending individual particles through slit

Calculations

Method 1: wave ⟶ particle
(interference ⟶ probability)



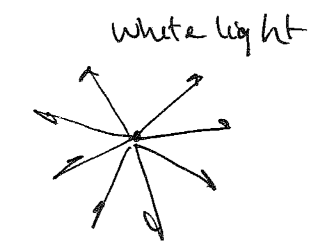
Method 2: particle ⟶ wave
(probabilities ⟶ interference pattern)

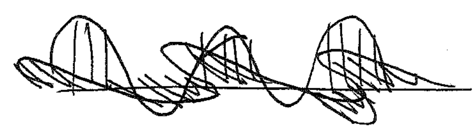
power point

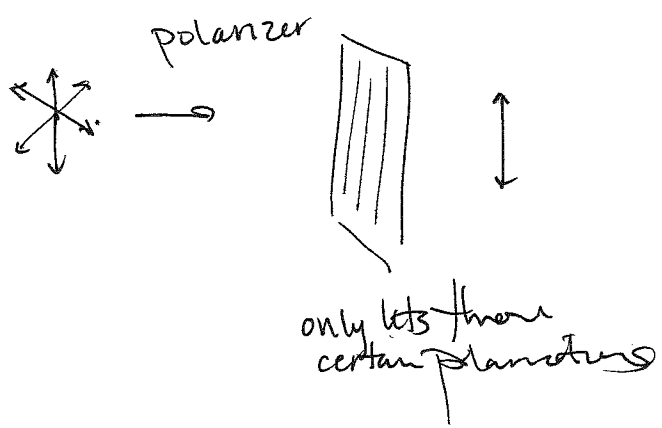
Polarizers

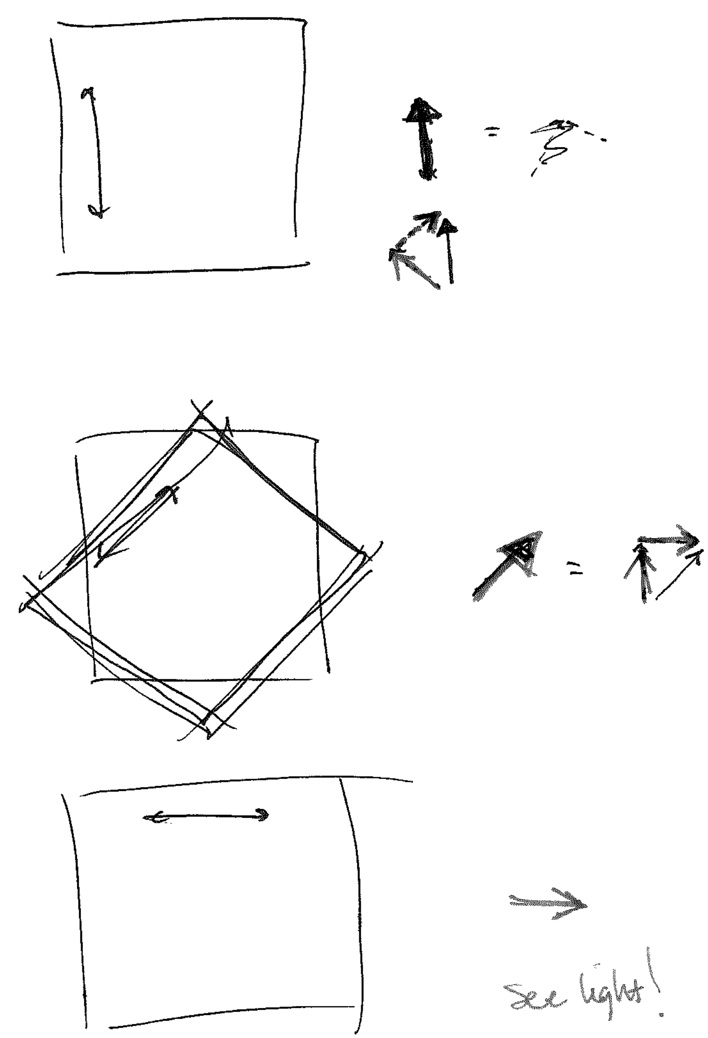
(test your knowledge)

setup:

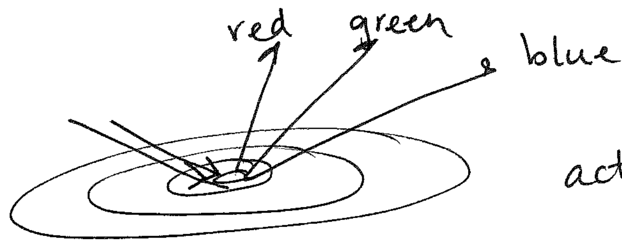








shine light on CD

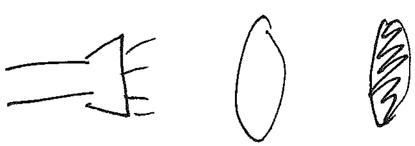


acts like diff. grating

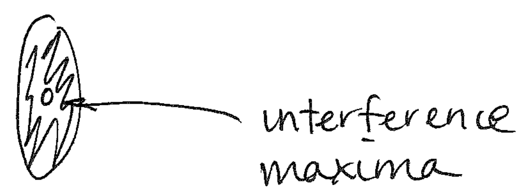
separates maxima (bright spots

shine light on disk

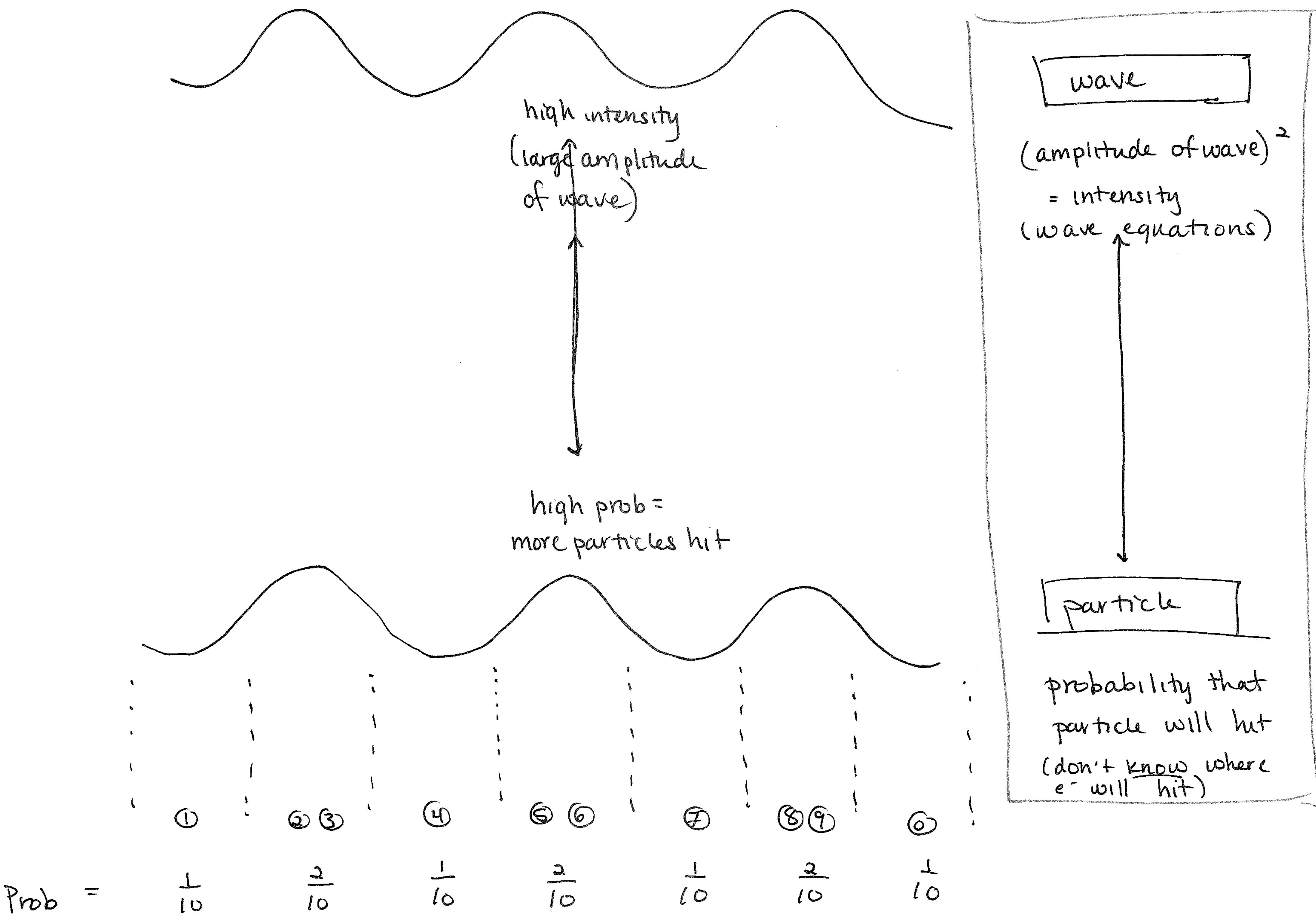
expect shadow



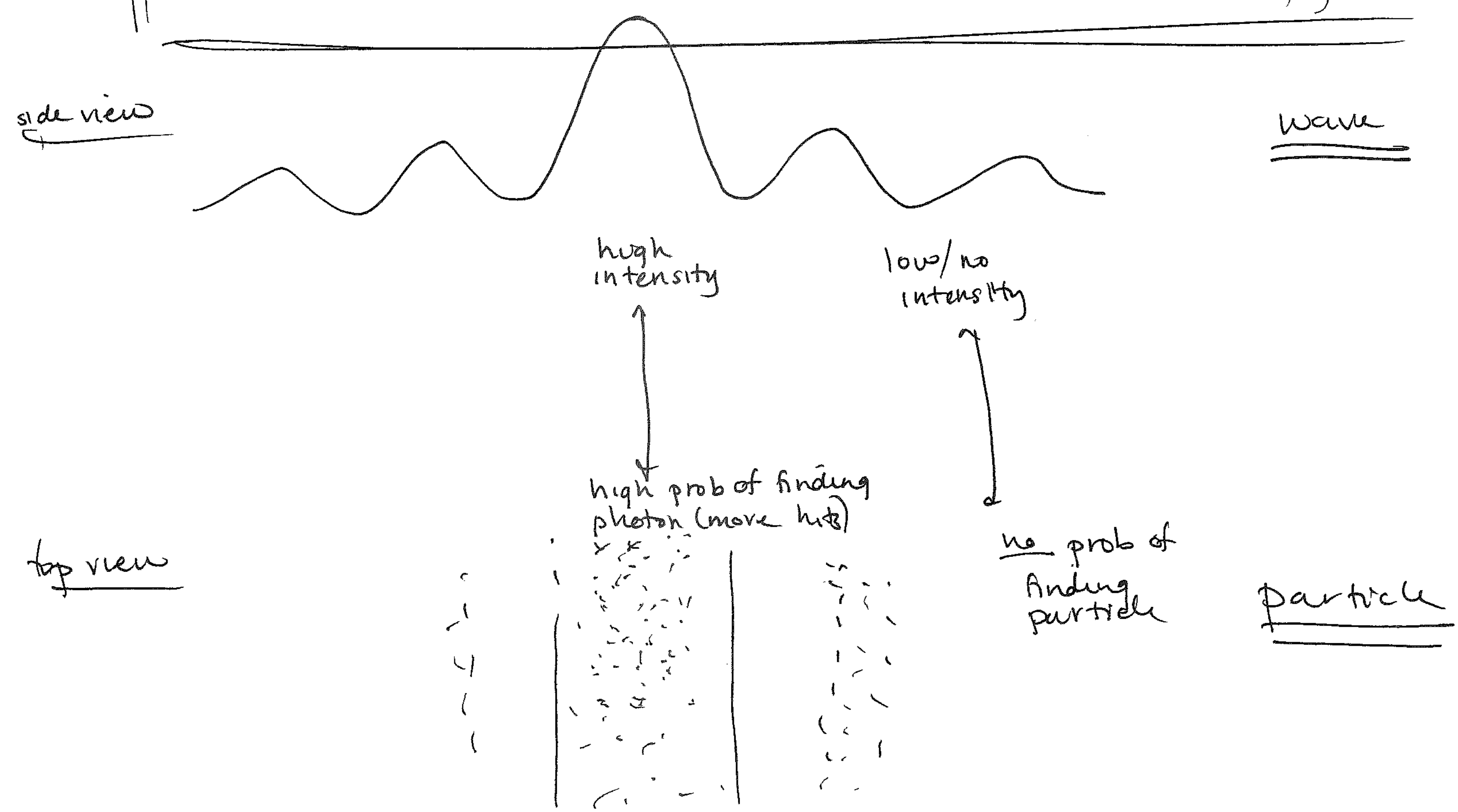
see shado w/ bright spot



Slow Motion Diffraction



wave		particle
intensity of light	⟷	probability of finding photon



mathematically → if we can find mathematical expression for wave, can find probability of finding particle
(how: wave equation (diffusion eqn))

Aside: Measurement

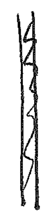
need both slits open
to see interference
(wave property)

here, measure
individual particles

don't know which slit
particle went through

what if we measure what is happening at slits?

detectors on slits
(not covering slits)



lose interference!

detect particle in either
A or B (not both)

Quantum Nature

- ~~we can~~ to see interference, we cannot know which slit the particle passed through
- particle is in a superposition of slit A and slit B:

$$|\text{particle}\rangle = |A\rangle + |B\rangle$$

have to assume that particle ~~is equally likely to pass through A or B~~ exists in some combination of passing through A and B

- measurement affects system – if we want to track individual particles, we lose wave behavior
we cannot see both!

Summarize Results

	wave	particle
light	laser diffraction (interference)	photoelectric effect photon = particle of light
matter (electrons	crystal diffraction (interference)	photo electric effect

		particle property		wave property
photons + electrons	energy	E	$=$	hf
	momentum	P	$=$	$\frac{h}{\lambda}$

Duality

two descriptions for light + matter

wave		particle
assume wave behavior ↓ calculate interference pattern	method ① →	interference pattern ↓ calculate probabilities
use probabilities ↓ build up interference	method ② ←	calculate prob of finding particle @ every point in space

duality: <u>two</u> descriptions that are consistent (both predict <u>same</u> behavior)

⟹ good news: we can <u>choose</u> which description to use

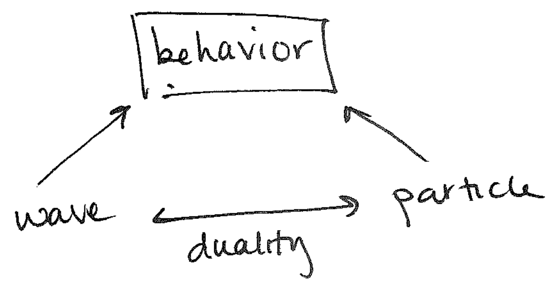
choose <u>easiest</u> for any given problem

in QM, our problems lend themselves to method ①

What's the Big Picture?

- Can perform experiments to reveal particle-like or wave-like behavior
- scientists have developed two approaches (QM + particle physics) to describing ~~these~~ the different facets of the behavior

  This is called a <u>duality</u>



use whichever is easier

- We will be using a wave description (QM)
- To use this description, we must understand what wave means

  wave ⟶ probability of finding <u>particle</u>

- The very idea that we use a wave description implies that we are uncertain as to the outcome of any measurement

~~The very best~~

We can never be certain: The best we can do is calculate probabilities