Lecture 1 – Why is Quantum Weird? 08/31/15

⇨ How does quantum differ from classical in the fundamental sense?

1. Wave-particle duality
2. Planck radiation (Rayleigh Jean)
3. Photoelectric effect
4. Interference

1. Wave-Particle Duality: The Nature of Light

Huygen vs. Newton

↘ ↙

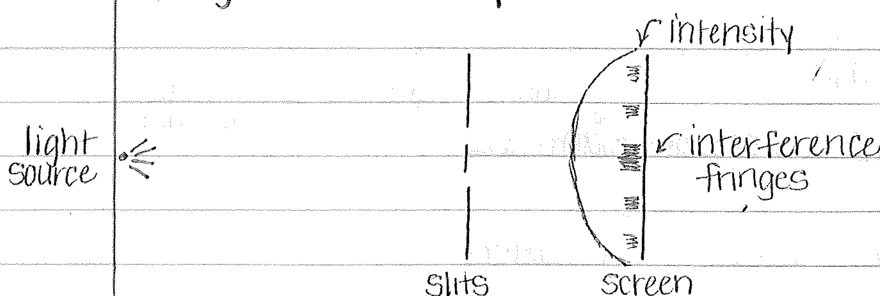
straight lines & refraction

↙ ↘

wave particle

↑ Young's double slit experiment supported wave nature of light

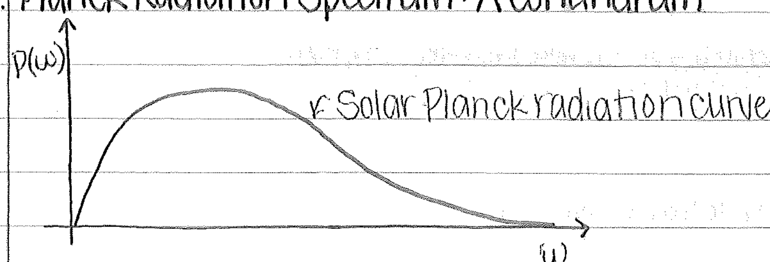
Young's Double-slit Experiment



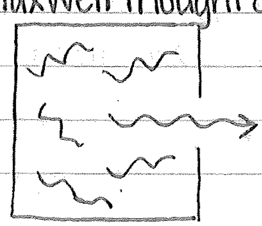
→ Maxwell and his equations solidified the wave theory of light

But scientists still wanted a better understanding of the solar spectrum

2. Planck Radiation Spectrum: A Conundrum



Maxwell thought of the Sun as a cavity for light



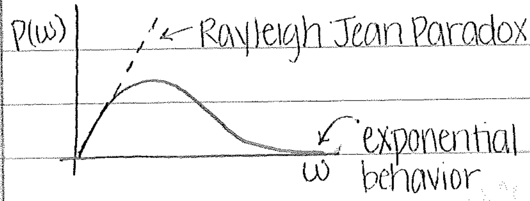
A certain density of wavelengths is allowed – those that escape form the Planck Continuum

Rayleigh Jean Paradox: (after Boltzmann's work)

A thermal system (T) has energy of k_BT for each harmonic oscillator (a.k.a. the equipartition theorem)

⇒ Simple Harmonic Oscillators are modes of the electromagnetic waves

BUT, if you count the density of wavelengths allowed in the cavity, it increases with ω (i.e., $P(\omega) \propto \omega^3$)



We know from Planck that this is not the case!

$e^{-\hbar\omega/k_BT}$

Planck's constant

Planck recognized that the best fit must be

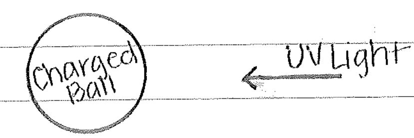
$$\propto \frac{\omega^4}{e^{\beta\hbar\omega}-1}, \quad \beta = \frac{1}{k_BT}$$

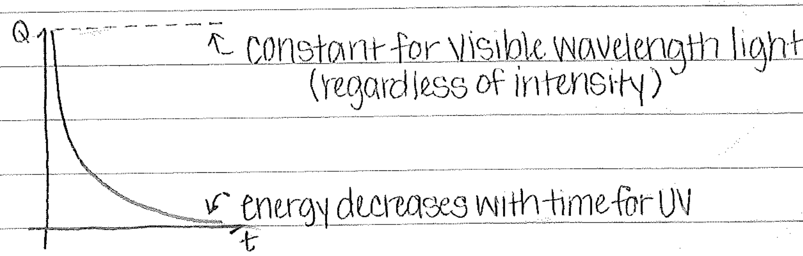
→ This works if the oscillators are quantized ← changed equipartition integral to a summation

$E_n = n\hbar\omega$

└ energy quantizations of the oscillators

3. Einstein's Photoelectric Effect





⇒ Classical explanation: UV light must be ejecting photons

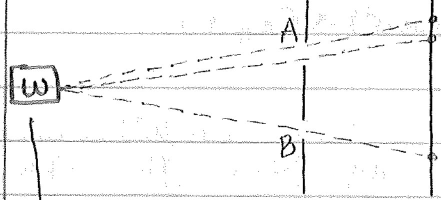
Einstein purports that it is not the oscillators that are quantized, but the electromagnetic waves themselves.

- quantizations called photons (particle behavior)
- Maxwell's equations must be incomplete

⇨ Return to the particle-wave duality problem

4. Interference (again)

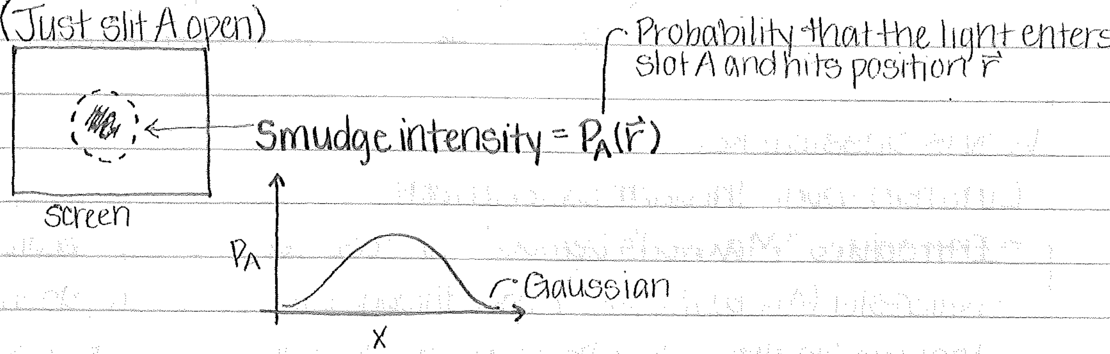
Create interference at very low intensities



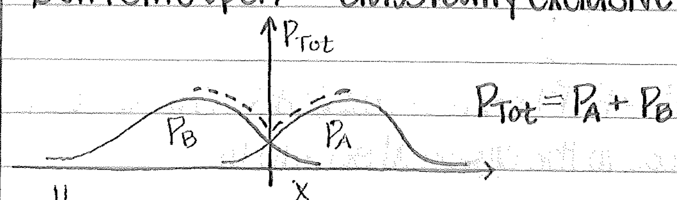
low intensity source; random trajectory

· Classical Explanation:

(Just slit A open)



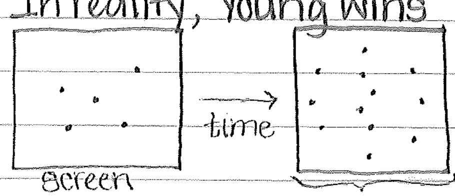
Both slits open → classically exclusive events



↳ This would have been Newton's expectation

(assumes particle goes through one slit or the other)

In reality, Young wins



As time progresses, interference fringes begin to form

Assumption $P_{Tot}(\vec{r}) = P_A(\vec{r}) + P_B(\vec{r})$ must be wrong!

⇨ Must introduce a wave theory for probability

└ probability as intensity for waves

intensity is proportional to the magnitude of the electric field, squared

$P \propto$ intensity $\propto |\vec{E}|^2$

$\vec{E}(\vec{r}) = \vec{E}_A(\vec{r}) + \vec{E}_B(\vec{r})$

↑ calculated from Maxwell's equations

*DeBroglie: You don't need photons for this to work

Introduce: Probability Amplitude $= \varphi_{A,B}(\vec{r}) \propto \vec{E}_{A,B}(\vec{r})$

$P_A(\vec{r}) = |\varphi_A(\vec{r})|^2$; $P_B(\vec{r}) = |\varphi_B(\vec{r})|^2$

⇒ Superposition Principle

$\varphi_{Tot}(\vec{r}) = \varphi_A(\vec{r}) + \varphi_B(\vec{r})$

All this is still just educated guesses by smart people

$$P_{Tot}(\vec{r}) = |\varphi_{Tot}(\vec{r})|^2 = |\varphi_A(\vec{r}) + \varphi_B(\vec{r})|^2$$

$$= \underbrace{|\varphi_A|^2}_{P_A} + \underbrace{|\varphi_B|^2}_{P_B} + \underbrace{2\mathrm{Re}\{\varphi_A^*(\vec{r})\varphi_B(\vec{r})\}}_{\text{interference term}}$$

Why is classical key?

- Einstein-Bohr Thought Experiment.
  - Introduce "Maxwell's Demon" – an observer who keeps record of which slot (A or B) the photon goes through but is completely passive
  - Assume locality – slit B being open or closed does not impact how many photons pass through slit A (N_A)

$N(\vec{r}) = N_A(\vec{r}) + N_B(\vec{r})$

└ divide by N_{Tot} → $P_{Tot}(\vec{r}) = P_A(\vec{r}) + P_B(\vec{r})$; the CLASSICAL RESULT

Adding an observer forces to the classical solution!!

* Quantum Mechanics says that there can be no passive observer; that they have a fundamental effect on the system.