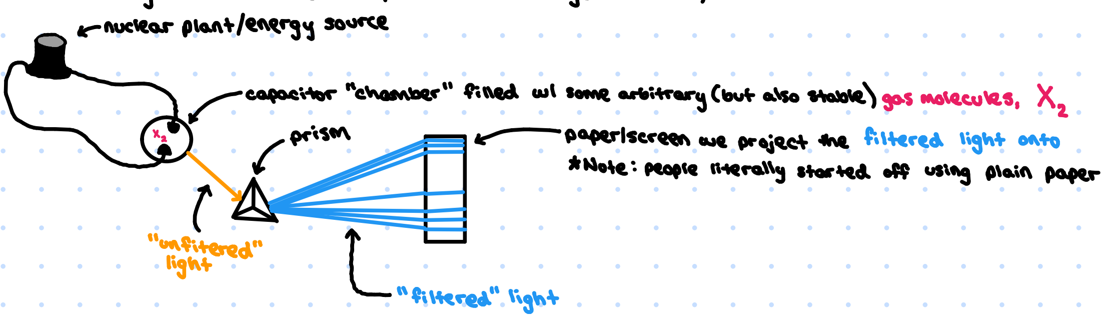
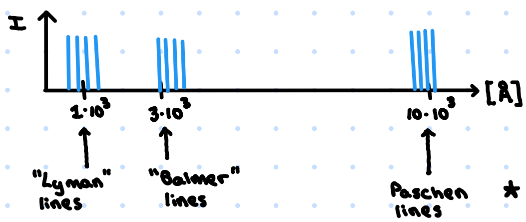
Lecture 2: Experimental Facts of Life (starting at 16:00) 10/4/18

3. Atomic Spectra: Disrete, Structured

- Consider the following scenario (Note: set up is like the Geiger counter):



- Say we record the intensity of the light incident on our "recording screen" as a function of wavelength [Å]:



★ Note: this distribution arises for X = Hydrogen

★ Line "types" are named after the people who first identified them

- Importantly, these lines are unique to the type of gas molecules we put in our "conductor chamber"
- Balmer also made the following observation: Balmer lines can be written in terms of a wavelength λ_n where n is an integer btwn 3 and 36 as follows:
  - ~ For X = Hydrogen, $\lambda_n = 3646\,Å\left(\frac{n^2}{n^2-4}\right)$, $n = 3\ldots36$
    - ⇒ plugging in these integers gives a pretty good approximation for this series of lines (For H_2 gas ONLY)
      - ⇒ where did he get these numbers from? ⇒ he was either a geniuss, obssed, divinely inspired, or a combination of the three
- Later, some guys named Rydberg and Ritz found the following general relation describing all three "line"-types:

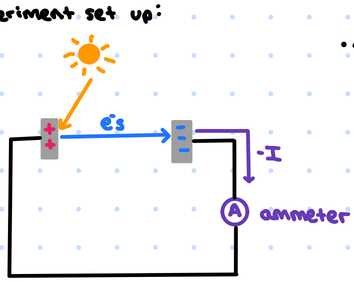
$$\frac{1}{\lambda} = R\left(\frac{1}{m^2} - \frac{1}{n^2}\right),\ n > m \quad \text{where } R \text{ denotes the Rydberg constant}$$

⇒ Why?

⇒ Specifically, we need to model that describes quantum systems as being discrete in a structured manner that perfectly predicts the spectral lines

4. Photoelectric Effect

* Experiment set up:

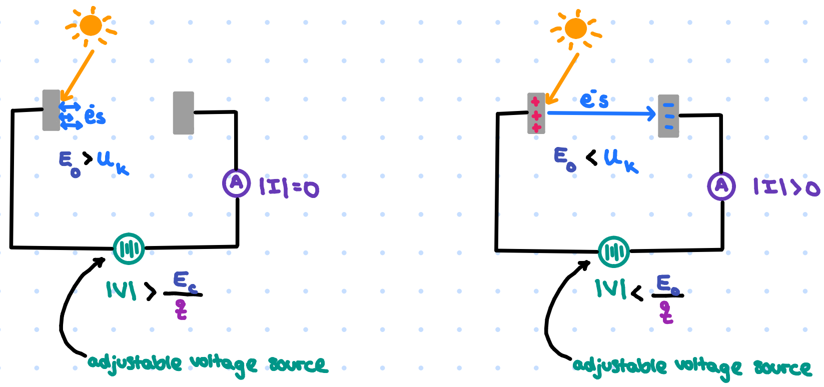


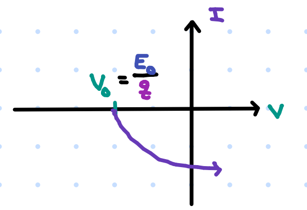
- Shining light on the left piece of metal induces a photoelectric effect where electrons are emitted from the leftmost bar w/ a kinetic energy U_k and collide onto the rightmost metal bar
  - ⇒ consequently, the leftmost bar is left w/ a net positive charge and the rightmost bar is left w/ a net negative charge

4. Photoelectric Effect cont.

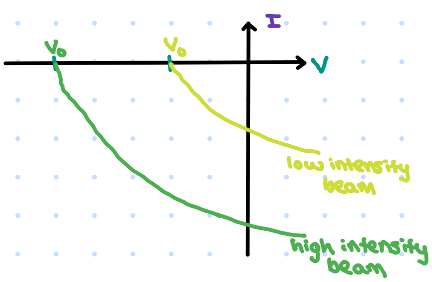
* Last Page cont.:

⇒ if we set up a potential difference V across this circuit, the amount of energy it takes for a charge q on the left beam to overcome this potential difference is $E_0 = q|V|$

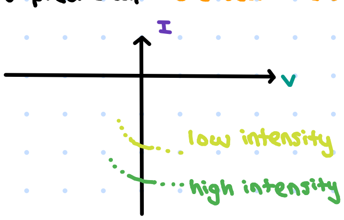




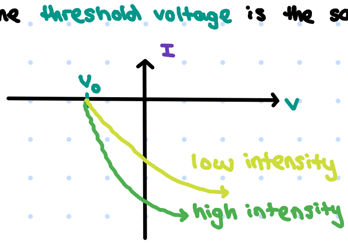
- Goal of experiment: For a given beam of light, find the threshold voltage $V_0 = \frac{E_0}{q}$ where the current passing through the circuit is $I = 0$ A
- Things we can vary in term of our light source
  - Intensity $\mathcal{I} \sim \vec{E}^2 + \vec{B}^2$ $[W/m^2]$
    - ~ Also called radiant flux
  - Frequency ν $[1/s]$
- Aside: frequency "cancels out" in the total energy of a classical EM wave
  - ⇒ the energy of an EM wave can be modeled as a harmonic oscillator
    - ⇒ thus, the kinetic energy of the emitted e's should behave like a harmonic oscillator
- Expected Results (according to Maxwellian Dynamics)
  - As the intensity of the beam increases, $U_K \uparrow \Rightarrow E_c \uparrow \Rightarrow |V_0| \uparrow$



  - V_0 should be independent of ν
- Actual Results:
  - As predicted, increased intensity corresponded w/ increased current



⇒ BUT the threshold voltage is the same for both conditions!!!



⇒ this infers that U_K is independent of light intensity (and thus, E_y)

4. Photoelectric Effect cont.

- Summary of actual results:
  - V_0 is independent of intensity of incident light [W/m^2]
  - V_0 varies linearly w/ ν (frequency of incident light) [$1/s$]

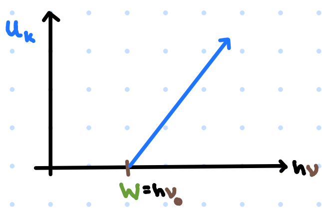
=> i.e., a high-intensity EM beam w/ low ν will produce a high current, but will be easy to turn OFF (low $|V_0|$) and a low-intensity EM beam w/ high ν will produce a low current, but will will be difficult to turn ON (high $|V_0|$)

- Eienstien's 1905 paper proposed a simple idea to explain these results:
  - Light exists in discrete packets w/ definite energy proportional to the frequency of the light: $E_\gamma = h\nu$ where h is a constant
    => increasing the intensity of this light corresponds w/ increasing the number of "packet" or photon
  - Thus, the kinetic energy of the emitted e^-s must equal the amount of work necessary to "extract" the e^- from the metal subtracted from the energy of the photon:

$$U_k = E_\gamma - W = h\nu - W$$

=> since kinetic energy is strictly a positive quantity, there exists a critical $E_\gamma = h\nu_0 = W$

★Note: W is a property of the metal bar

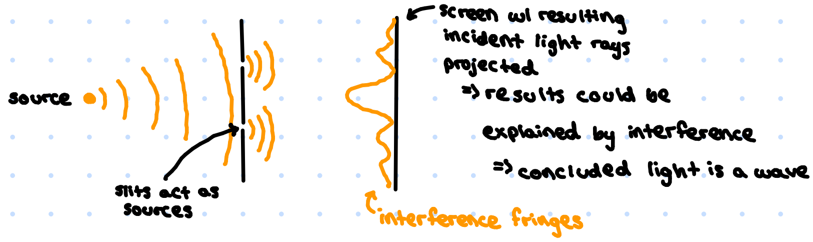
=> 

=> thus, if the frequency of a given EM wave is insufficiently high, no e^-s are emitted (technically, this isn't true since some photons interfere at just as they collide w/ the metal and the increase in energy is enough to excite an electron) => doesn't happen nearly enough to generate a "circuit AP"
=> unless we are at "insanely" high intensities, this prob. of spontaneously starting a circuit AP remains extremly low

- Recall:
  - The energy of an EM wave is equal to the speed of light times the momentum carried by the EM-wave: $E_\gamma = cp$
  - The wavelength associated w/ an EM wave times the frequency of the EM wave is equal to the speed of light: $\lambda\nu = c$
  => These facts combined w/ Eienstien's idea, $E_\gamma = h\nu$ gives...

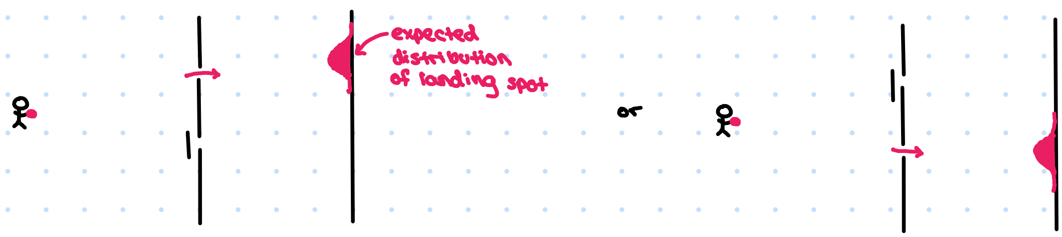
$$\left.\begin{aligned} \boxed{E_\gamma = h\nu} &= \frac{hc}{\lambda} \\ &= cp \end{aligned}\right\} cp = \frac{hc}{\lambda} \Rightarrow \boxed{p = \frac{h}{\lambda}}$$ where h = Planck's constant

- Aside: Up until Einstien's paper, mainstream physics was convinced light was purely a wave-like phenomena
  - Recall: Double-slit experiment (Young, 1803)

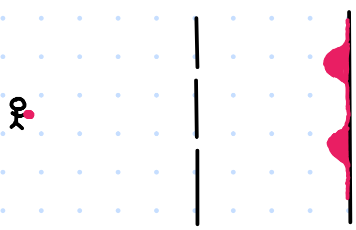


4. Photoelectric Effect cont.

- Two important ways light behaves as a wave
  - ① Q: where did the wave hit the screen?
    - A: The wave didn't hit the screen at any specific point ⇒ i.e., it is distributed across the entire screen (non-localized)
      - ⇒ the reason a wave can interfere w/ itself is by virtue of the fact that it is not a point/localized object
  - ② Consider our double-slit experiment set up, except this time, we are throwing a ball through one of the slits (assume the other slit is blocked
    - •Diagram:



- Now, consider the case where we throw the ball randomly towards the screen w/ both slits exposed
  - ⇒ assuming the number of throws is large enough, about half of the balls that make it through a slit will go through the top slit and likewise for the bottom slit:



- •We know that for any given "successful" throw, there is a 50% chance it went through the top slit and a 50% chance it went through the bottom slit
  - ⇒ "whole" objects are localized
    - ⇒ no interference

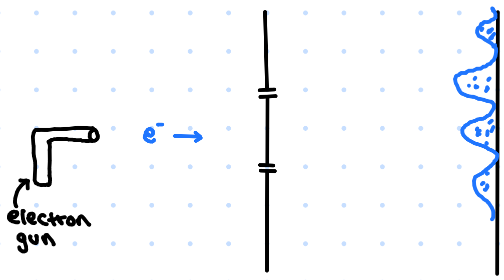
- Summary of conclusions so far:
  - •Waves ⇒ do have interference ⇒ the intensities (and thus, amplitude) of these waves add together: $A = A_1 + A_2$ and $I = (A_1 + A_2)^2$
  - •Objects ⇒ do not have interference
  - ⇒ BUT, Einstein's 1905 paper said light behaves as a particle wheras, Young's 1803 experiment suggested that light behaves as a wave
  - ★★ ⇒ Quantum Mechanics needs to account for this

5. Electron Diffusion

- Q: do e^-s behave as waves or particles?
  - •We know e^-s are localized
    - ⇒ when we throw electrons at a CRT (cathode ray tube), it doesn't hit the whole tube w/ a wavy distribution ⇒ they land in individual positions
  - •we also know localized phenomena doesn't lead to interference
  - •Hitachi Technology (developed a few decades ago) allowed a way for empircally testing a traditional thought experiment
    - ~ Shot e^-s one at a time towards a double-slit setup
      - ⇒ cumulative trials of shooting e^-s through this setup ends up displaying an interference effect
        - ⇒ if an e^- was purely a particle, then we would get a distribution like the one for the ball being thrown at a double slit experiment
  - •Conclusions: in some contexts, it more useful to think of an e^- as a wave, and in other contexts, its more useful to think of an e^- as a particle
    - ⇒ an e^- isn't a wave or a particle, its an electron!!
      - ⇒ think of trying to identify an elephant w/ your eyes closed
        - •trunk may feel like a snake (for example), but it is something completely different ⇒ would need to see the elephant to get an actual sense of what the trunk is

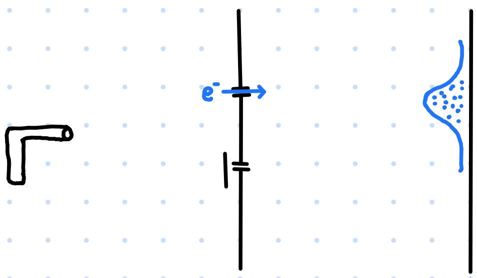
5. Electron Diffusion cont.

- According to Heisenburg, the two mental pictures we get from experiments w/ e^-s is an electron behaving as a particle, an the other as a wave (1930)
  - One single interpretation of an e^- is incomplete and can only have validity w/ analogies which are accurate only in limiting cases
  - The apparant wave-particle duality arises in the limitation of our language
    - ⇒ thus, we need to resort to mathematics to develop a scheme for the treatment of atomic processes - called quantum theory
    - ⇒ unfortunately, as far as visualization is concerned, we are stuck w/ either a wave visualization or corpusculor visualization
- Consider a Hitachi double-slit experiment
  - Consecutive trials of firing e^-s should result in a distribution w/ an interference pattern:

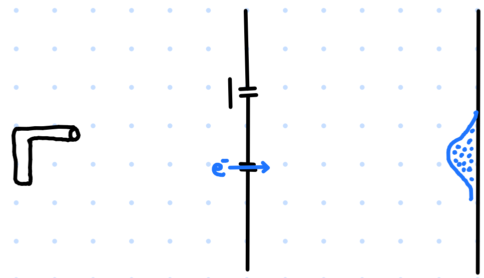


shows interference

- Q: Assuming a e^- passes through one of the slits, how do we know which one it past through?
  - ~ Can look at distribution of incident e^- on the screen while covering one of the screens:



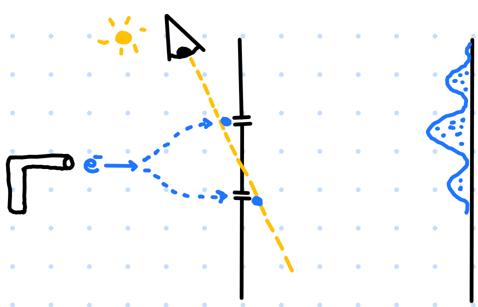
vs.



⇒ both conditions correspond w/ corpuscular behavior

⇒ these results don't match w/ the results from the condition where neither slit was covered

- Using the same argument we made w/ the boxes in Lecture 1, we can say the electron is in a superposition of going through the top and bottom half for the condition where both slits are open
  - In fact, this is a classical example of the two-box experiment
- The following nuance for this experiment has a subtle implication for gravity:
  - Nuance: Lets try to measure which slit the electron went through via a detector that uses very weak light pointed at some appropriate angle:

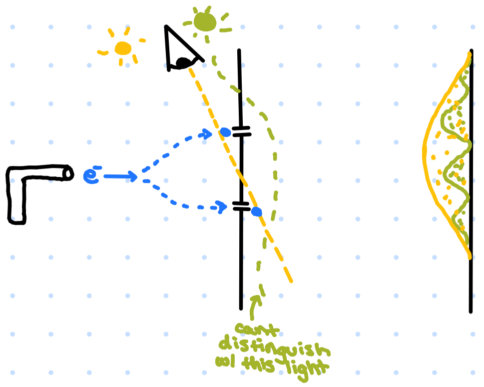


Expected Results

- The problem w/ this experiment is that it doesn't work
  - ~ Recall: The energy of a photon is associated w/ its frequency
    - ⇒ $E_\gamma = h\nu = cp$ ⇒ thus, in order to prevent the light from interacting w/ e^-s (Reccall: $p = \frac{h}{\lambda}$; we want our photons to have as little momentum as possible so it doesn't bounce off the walls and hit e^-s) ⇒ need high λ
      - ⇒ Conundrum: you can't detect e^-s in a localized manner w/ long wavelengths
        - ⇒ we need a wavelength that is comparable to the scale we want to measure

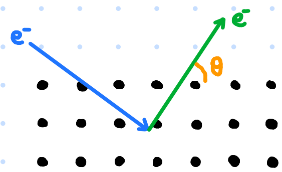
5. Electron Diffusion cont.

- Conclusions: Mathematically, it can be shown that using an EM-wave w/ a wavelength λ just short enough s.t. we can distinguish btwn the two slits, the momentum it imparts precisely "washes" out the interference effect
  - Actual Results:



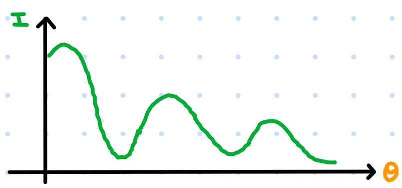
★ It isn't about what we (the experimenter) knows, its about the nature of light and its effects on the experiment

- Q: what if we used some other waveform to detect these e⁻s (e.g., gravity waves?)
  - A: No, since this momentum-wavelength give/take relation applies to all energetic harmonic oscillators (?)
- Now, lets consider another experiment conducted by Davisson and Germer
  - Took a crystal (e.g., diamond, nickel, etc.) of regulary distributed ions and shot a beam of e⁻s at the crystal
  - Diagram:



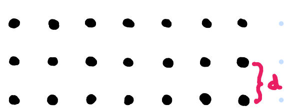
⇒ looked to see how e⁻s scattered at various angles (denoted θ)

- Results: Found that the intensity of the reflected beam I as a function of θ showed interference effects:



★ There is a mathematical expression for this (see problem set)

- Aside: let the distance btwn each crystal plane be d



- The maxima/minima for our I vs. θ curve correspond w/ the wavelength of e⁻s
  - Note: For this experiment, the e⁻s are behaving as if they were waves w/ a definite wavelength λ where...

$$\boxed{\frac{1}{\lambda} = \frac{n}{2d\sin\theta}}$$ where n is a positive integer

★★ our incident electrons also have some definite energy ⇒ corresponds w/ some definite momentum $p = h/\lambda$

⇒ our reflected e⁻s should bounce of w/ this definite momentum

⇒ since momentum is a function of λ, our definite p will be associated w/ a definite λ

⇒ agrees w/ our results

⇒ QM needs to account for this