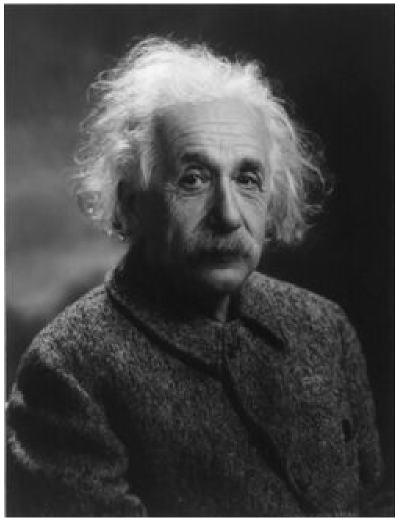
Lecture 2: 01/21/09

- Finish 2-slit interference
- Photoelectric Effect

Robert A. Millikan (1868 –1953) 1923 Nobel Prize for his measurement of the charge on the electron and for his work on the photoelectric effect.



Albert Einstein (1879 – 1955) 1921 Nobel Prize in Physics for his 1905 explanation of the photoelectric effect.

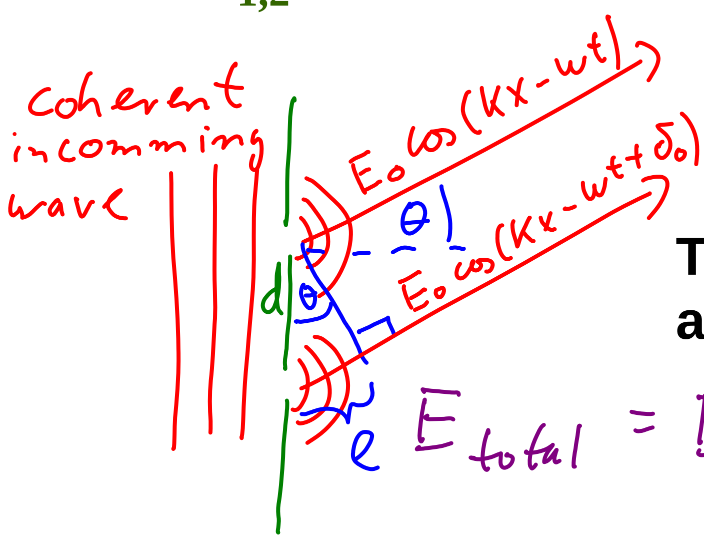
Recap

- some experiments in conflict with classical physics
  ⇒ New theoretical framework: Quantum Mechanics
- Classical Physics works well in its regime of validity.
- Correspondence Principle: Quantum predictions and classical predictions need to agree in the limit of large quantum numbers.

I The Experimental Basis of Quantum Mechanics

I_1 Evidence for photons

$I_{1,2}$ Interference: The double slit



$$\delta_0 = 2\pi \frac{d \sin\theta}{\lambda}$$

Classical picture: Interference of waves

To get total field amplitude on screen: add amplitudes of the two wave (not intensities!):

$$E_{total} = E_0 \cos(kx-\omega t) + E_0 \cos(kx-\omega t+\delta_0)$$

have: $E_{total} = E_0 \cos(kx - \omega t) + E_0 \cos(kx - \omega t + \delta)$

if $\delta_0 = 2\pi$ (integer) $\rightarrow$ $E_{total} = 2 E_0 \cos(kx - \omega t)$
const. interference

if $\delta_0 = \pi$ (odd integer) $\rightarrow$ $E_{total} = 0$: destructive interf.

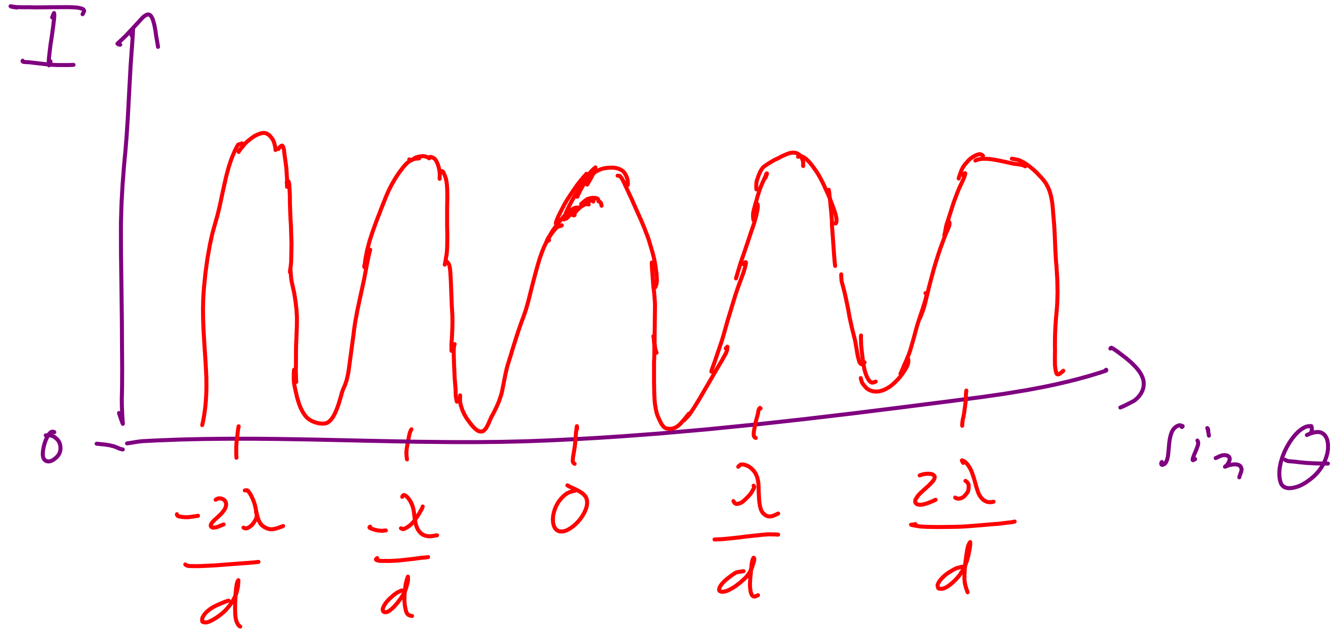
$\Rightarrow$ resultant intensity I at screen $\propto \langle (E_{total})^2 \rangle$

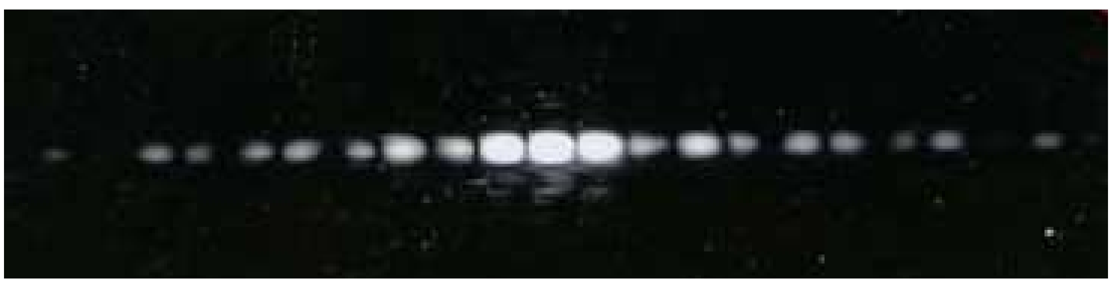
$\Rightarrow$ $I \propto \underline{E_0^2 (1 + \cos \delta_0}) = E_0^2 \left(1 + \cos\left(\frac{2\pi d \sin\theta}{\lambda}\right)\right)$

[$\cos x \cos y = \frac{1}{2} \{ \cos(x-y) + \cos(x+y) \}$

θ : angle to screen

Intensity variation





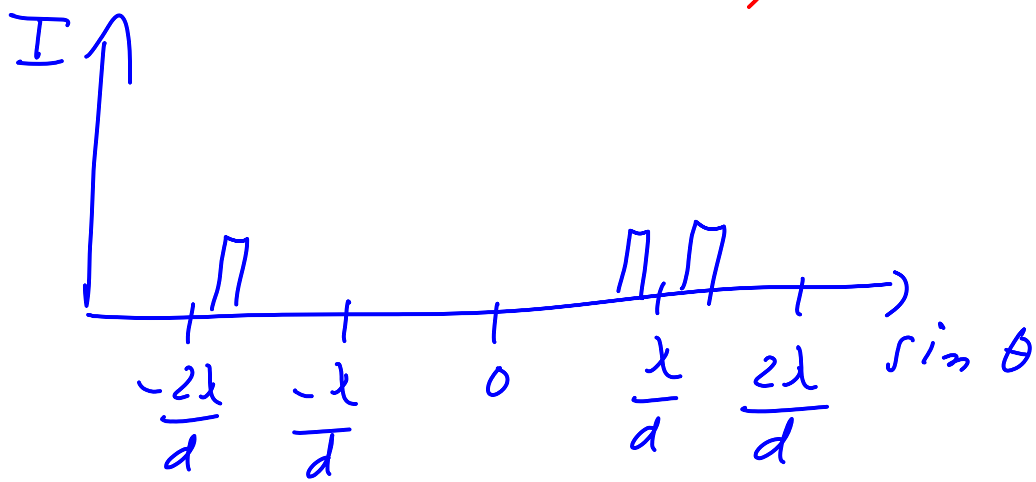
What would one measure if one would turn the intensity of the light source way down (use photo-multiplyer, CCD's, or photographic paper as light detector)?

A. **Same interference pattern with reduced intensity.**
B. **Interference pattern is gradually built up.**
C. **No interference pattern: Intensity is uniform distributed.**
D. **Something else**

Experiments at low Intensity (1909)

⇒ Intensity seems to arrive in bunches / chunks of signal localized in position and time!

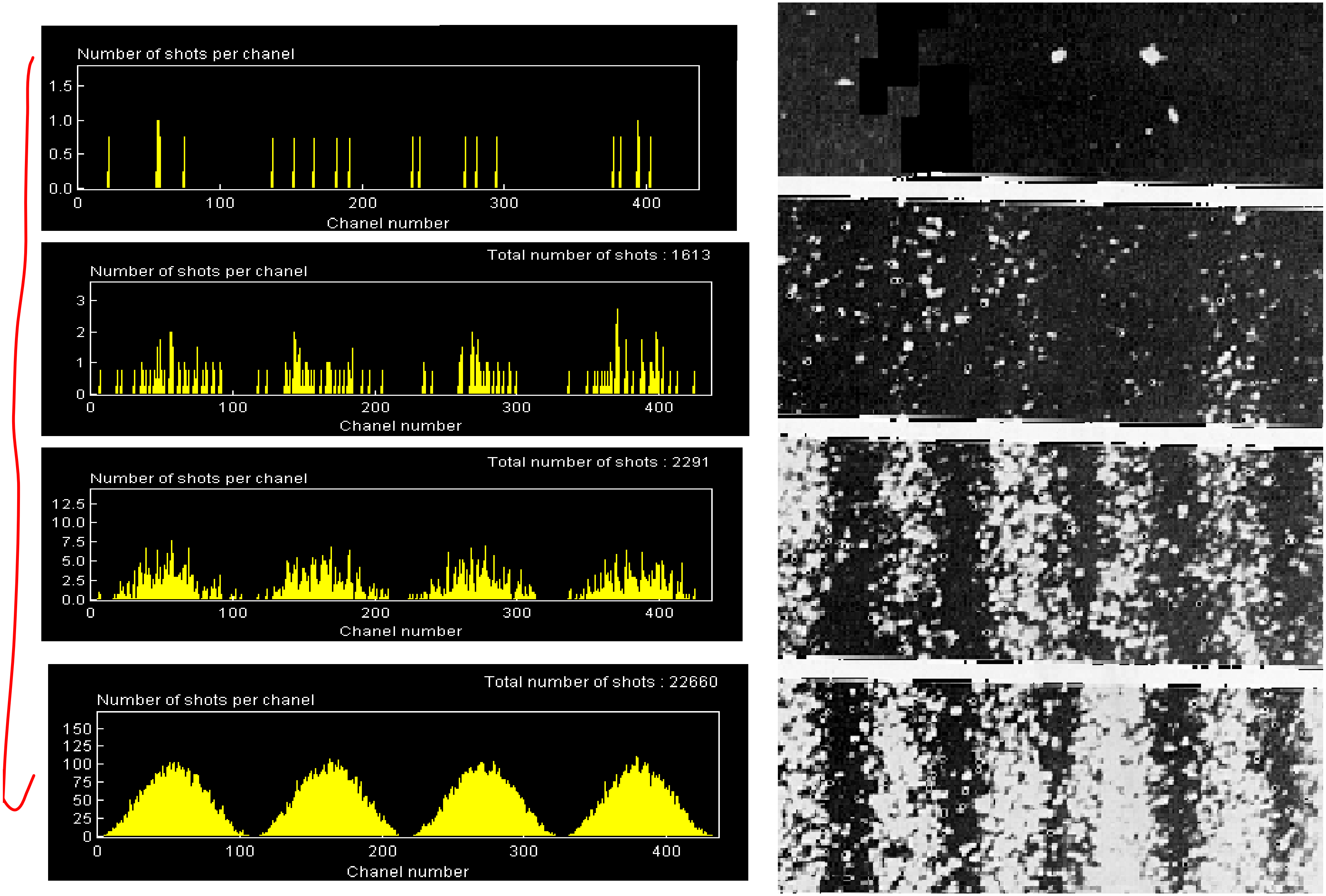
⇒ **Photon**



⇒ classical pattern is built up gradually

⇒ correspondence is good for large number of counts (→ correspondence principle!)

⇒ radiation acts more like a particle when interacting with screen!



Number of shots per chanel
1.5
1.0
0.5
0.0
0
100
200
300
400
Chanel number
Total number of shots : 1613
Number of shots per chanel
3
2
1
0
0
100
200
300
400
Chanel number
Total number of shots : 2291
Number of shots per chanel
12.5
10.0
7.5
5.0
2.5
0.0
0
100
200
300
400
Chanel number
Total number of shots : 22660
Number of shots per chanel
150
125
100
75
50
25
0
0
100
200
300
400
Chanel number

But: Idea of localized intensity goes against the whole concept of Maxwell's equation!

But: If light intensity localized like a particle, how do you get interference pattern?

- need waves!
- Mustn't light – as a particle – travel in a straight line?
- Need both slits open simultaneously to get interference pattern

But: How can a particle go through both slits at once to produce an interference pattern?

Would we get the same interference pattern, if first slit #1 is open and slit #2 is closed, and then slit #2 is open, and slit #1 is closed?

A. Yes

B. No, need to have both slits open simultaneously to get interference pattern.

If light is a particle (the photon), how can a single particle go through both slits at once to produce an interference pattern?

- **A. Photon “splits” in two halves.**
- **B. Need to have at least two photons at any give time to produce interference pattern.**
- **C. Can not conclude that photon must have passed through either one slit or the other.**

Can one predict where a given chunk of light (photon) will arrive at the screen?

A. No

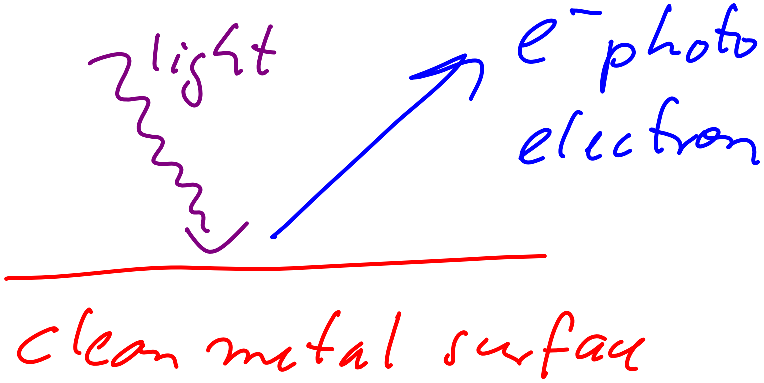
B. Yes

C. Maybe

Quantum Picture:

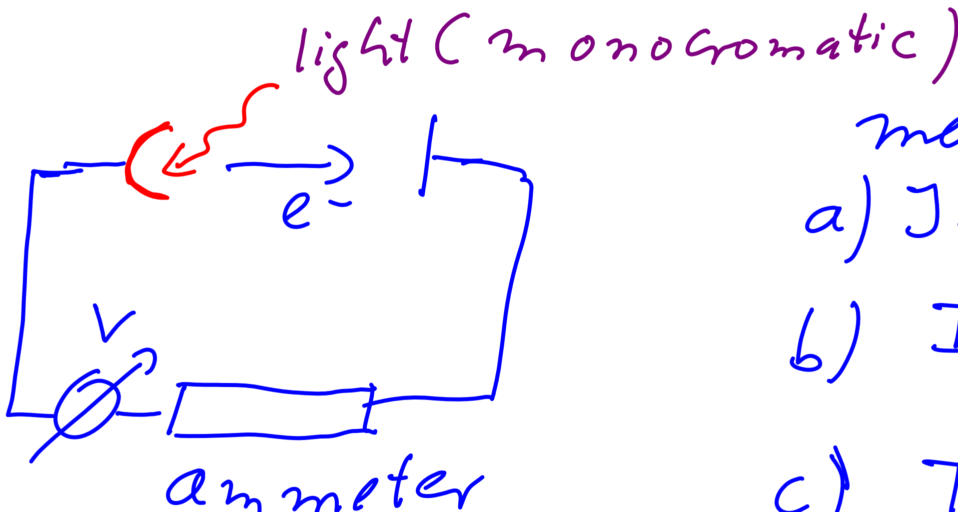
- Example of wave-particle duality:
  - Light is composed of photons whose motion must be described by an analysis that closely parallels the classical wave description in terms of interfering amplitudes from both slits
  - ⇒ "wave equation"
- There is an unpredictability and randomness about where individual photons arrive.
- Classical $I \propto \langle E^2 \rangle$ pattern gives probability distribution for finding photons on the screen

$I_{1,2}$ The Photoelectric Effect



Electrons ejected from metal surface by light of sufficient frequency

1914 Millikan



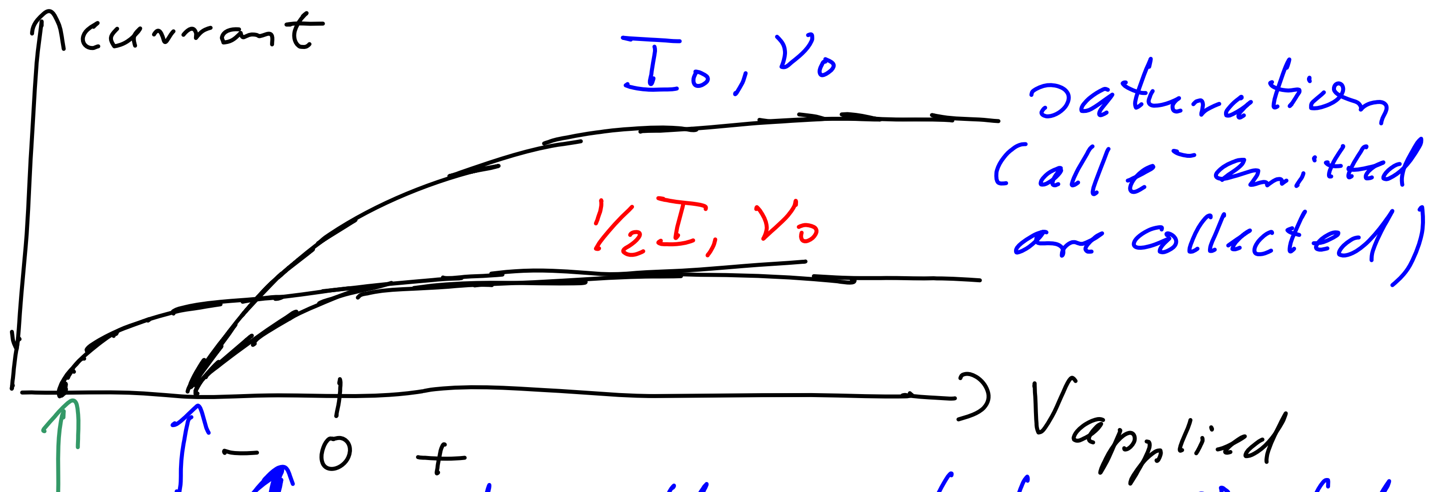
measure current vs. voltage

a) Intensity I_0, frequ. ν_0

b) $I_0/2$, ν_0

c) I_0, $2\nu_0$

Results:

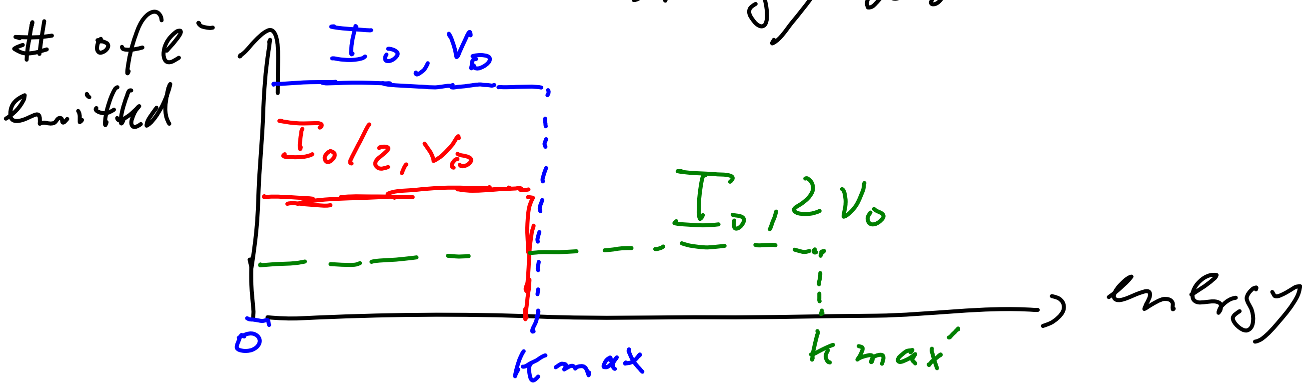


↑ negative voltage ⇒ electrons ejected with kinetic energy

V_0 : stopping potential: all (even fastest) electrons are stopped ⇒ $K_{max} = |eV_0|$

K_{max} depends linearly on light frequency ν, but <u>not</u> intensity I

- convert to energy distribution of emitted electrons:



1) Increase in intensity of light increases # of photoelectrons, but <u>not</u> max kinetic energy!

2) For frequencies below a characteristic <u>cutoff frequency</u> (depends on metal used), the photoelectric effect does <u>not</u> occur, no matter how high the intensity

3) K_{max} goes linearly with frequency ν

4) "No time lag" between initial illumination and first photoelectrons, even at low intensity!

1-4) are in conflict with classical picture!
(Electric wave "shakes" electrons and gives them energy. Eventually electrons have enough energy to escape from the metal)

Photoelectric effect: What would one expect to happen based on classical physics?

see Homework this week

A. A non-zero time lag at low light intensity

B. The kinetic energy of the photoelectron should increase with intensity of light

← more intensity → higher E-field

C. No cutoff frequency

← would need just enough intensity

D. All of the above

E. As measured (no time lag, kinetic energy of e^- does not depend on intensity, cutoff frequency)

Quantum picture (Einstein 1905)

1) Light is made out of concentrated bundles of energy ("photon"), localized in a small volume of space

2) Energy content of a photon is related to its frequency:

$$E = h\nu \leftarrow \text{frequency of light}$$

h = Planck's constant = $6.626 \cdot 10^{-34}$ J sec
$= 4.136 \cdot 10^{-15}$ eV sec

$\Rightarrow$ **Radiant energy is quantized!**