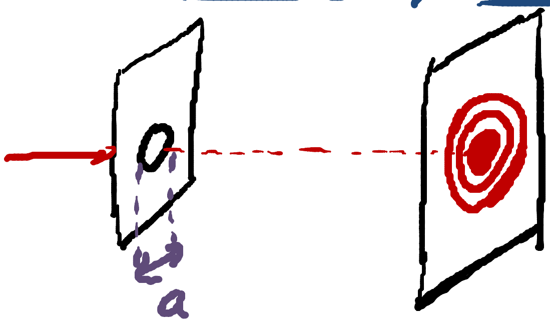
Recap I

Lecture 35

- **Single Slit Diffraction:**

Minima: $\sin\theta_{min,m} = m\dfrac{\lambda}{a}$ $\quad m = \pm 1, \pm 2 \ldots$

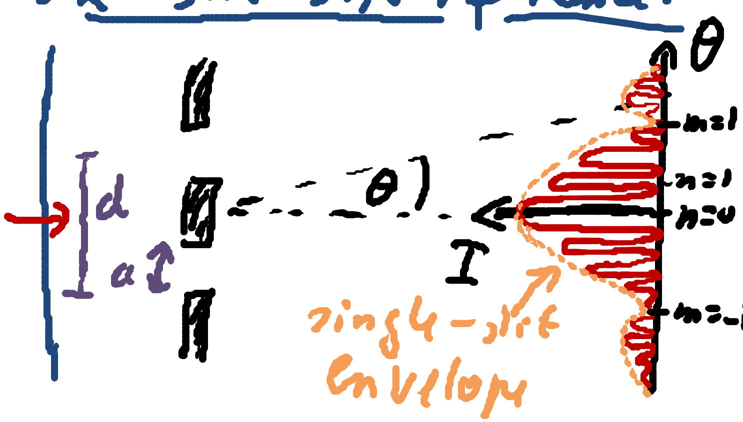
- **Diffraction by a circular aperture:**



1^{st} minimum: $\sin\theta_1 = 1.22\dfrac{\lambda}{a}$

Rayleigh's criterium for diffraction limited resolution: $\Delta\theta_R \simeq 1.22\dfrac{\lambda}{a}$

- **2-slit Interference:**



Maxima: $\sin\theta_{max,n} = n\dfrac{\lambda}{d}$; $n = 0, \pm 1, \pm 2 \ldots$

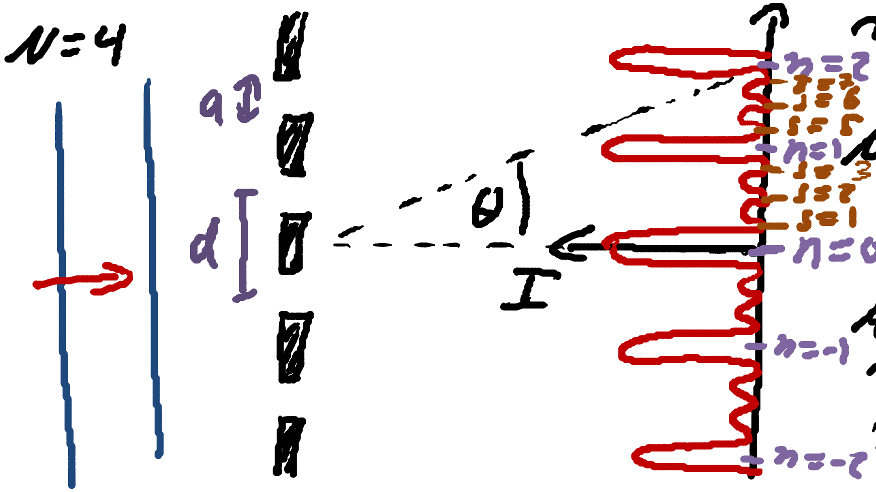
Minima: $\sin\theta_{min,n} = (n+\tfrac{1}{2})\dfrac{\lambda}{d}$; $n = 0, \pm 1, \pm 2 \ldots$

} from 2-source interf.

Additional Minima: $\sin\theta_{min,m} = m\dfrac{\lambda}{a}$; $m = \pm 1, \pm 2 \ldots$ } from single slit

Recap II

- **N-slit Interference:**



θ Principal maxima: $\sin\theta_{max,n} = n\dfrac{\lambda}{d}$ $\quad n = 0, \pm 1 \ldots$

Minima: $\sin\theta_{min,s} = s\dfrac{\lambda}{Nd}$ $\quad s \neq 0$, $s = \pm 1, \pm 2 \ldots$

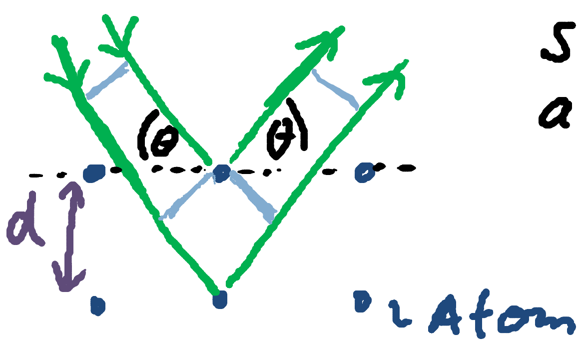
except when $s/N = n =$ integer

Additional minima from single slit: $\sin\theta_{min,m} = m\dfrac{\lambda}{a}$ $\quad m = \pm 1, \pm 2$

$\Rightarrow$ for large N: Diffraction grating

width of n^{th} principal maximum: $\Delta\theta \simeq \dfrac{2\lambda}{Nd\cos\theta_n}$

- **Bragg Diffraction:**



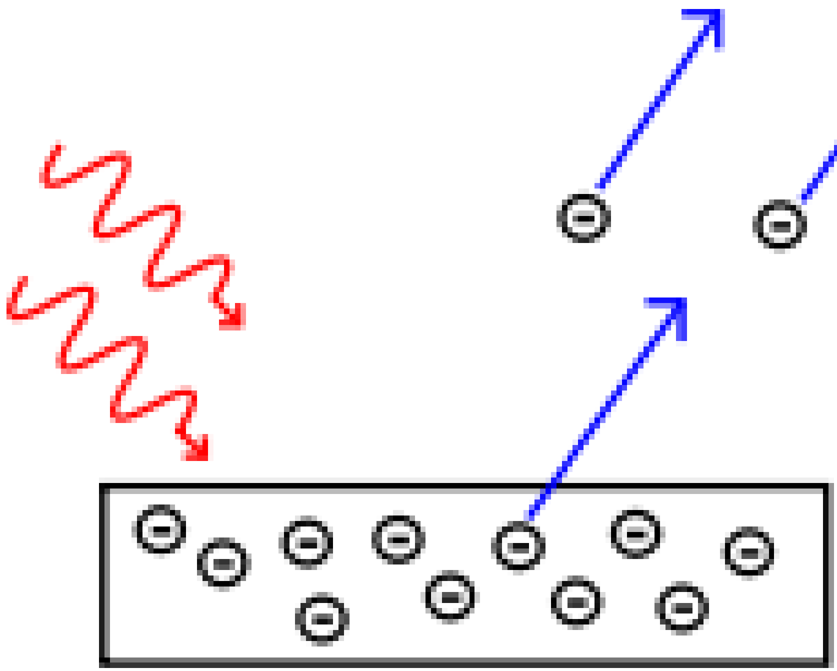
Scattering and interference of x-rays by atoms in a crystal

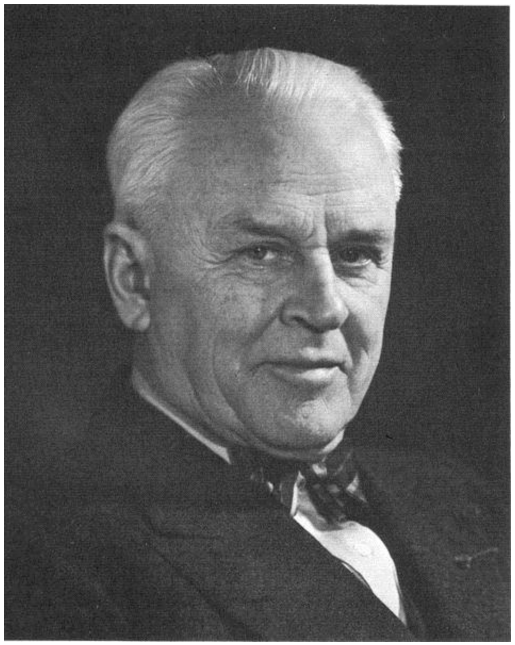
maxima at: $\sin\theta_{max,n} = \dfrac{n\lambda}{2d}$ $\quad n = 1, 2 \ldots$

(Bragg's Law)

Today:

- Enter quantum mechanics:
  - The Photon
  - The photoelectric effect





Quantum Physics

Niels Bohr (1885 - 1962):

``Anyone who is not shocked by quantum theory has not understood a single word.''

“There is no quantum world. There is only an abstract physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.''

- 1864 J.C. Maxwell Light as electromagnetic radiation
- 1885 J.J. Balmer Formula for Balmer series of hydrogen
- 1887 H. Hertz Accelerated charges emit radiation
- 1897 J.J. Thomson Discovery of the electron
- 1900 M. Planck Theory of thermal radiation (first quantization)
- 1905 A. Einstein Special relativity theory, photon concept
- 1909 R.A. Millikan "Oil-drop" experiments (charge *e*)
- 1911 E. Rutherford Rutherford model of atom
- 1912 M. von Laue X-ray diffraction by atoms in solids
- 1913 N. Bohr Quantum theory of hydrogen atom
- 1914 Frank-Hertz Evidence of quantized energy levels in atoms
- 1924 L. de Broglie Theory on particle waves
- 1925 Davisson-Germer Experiments on interference of electrons
- 1925 E. Schrödinger Wave equation

• <u>so far:</u> "classical" physics – extend of physics before ~1900

- mechanics: motion of objects (Newton's Law)
- electricity, magnetism (Maxwell's equations)
- waves, light
- (special relativity)

• <u>But then:</u> Nature behaves very differently at <u>small scales</u>
  ⇒ at small sizes, energies

  - waves act as particles; particles act like waves
  - <u>Quantized</u> energies: only certain values of energy are possible
  - Same initial conditions ⟶ different results possible
  - Only <u>probability descriptions</u> seem possible

Energies at small scales

Recall: change in potential electric energy of a charge:

$\Delta U = q \Delta V$ $\qquad [\Delta U] = CV = \underline{\underline{J}}$

Example: $q = 1.6 \cdot 10^{-19} C$ = elementary charge

$\Delta V = 1V$

$\Rightarrow \Delta U = 1.6 \cdot 10^{-19} J$ ... tiny!

$\Rightarrow$ Use new energy unit: the <u>electron-volt</u> (eV)

$$\boxed{1eV = 1.6 \cdot 10^{-19} J}$$

} 1eV is the change in potential energy of an elementary charge when it moves through a electric potential difference of $\Delta V = 1V$.

$\Rightarrow$ for example above: $\Delta U = e \cdot 1V = \underline{1eV}$

Enter Quantum Mechanics:

Lesson I: Electromagnetic Radiation (light) is quantized and exists in concentrated bundles of energy ("photons")

[Einstein 1905]

$\Rightarrow$ Light has particle-like properties:

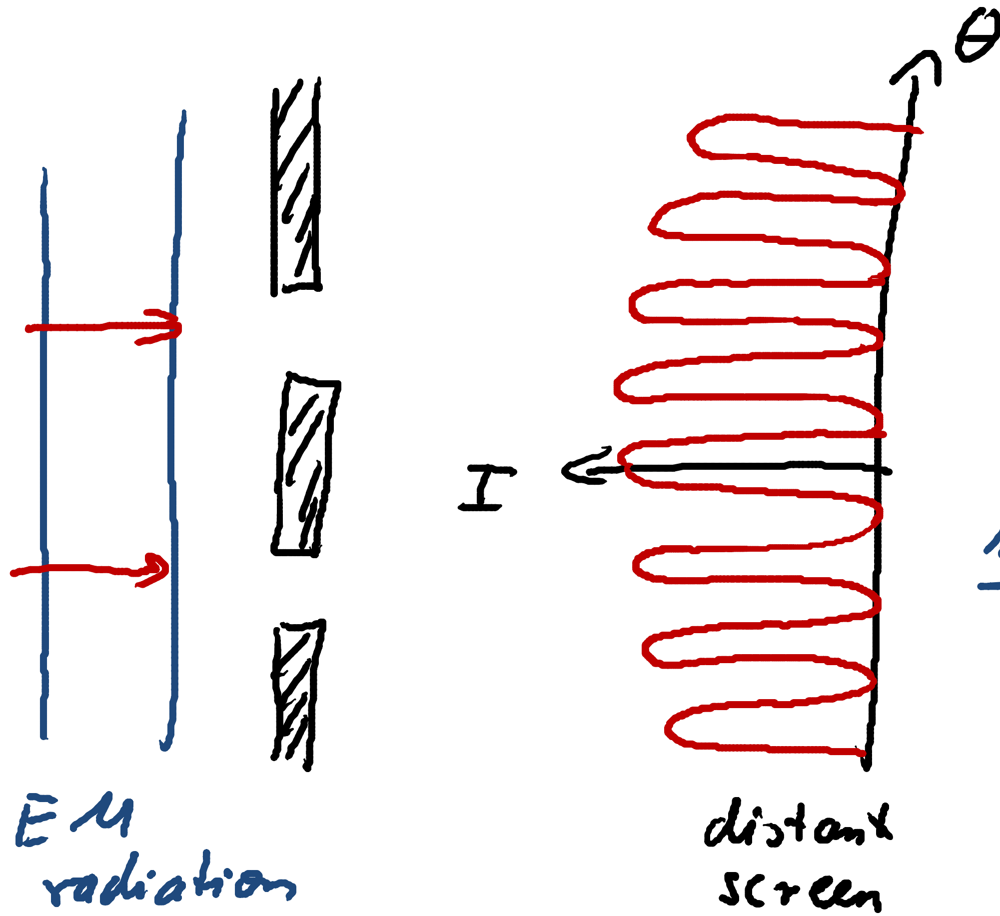
- **Energy of one photon:** $\boxed{E_{ph} = h \cdot f}$ ← frequency of given light

h = Planck's constant $= 6.626 \cdot 10^{-34}\,\text{J}\cdot\text{s} = 4.136 \cdot 10^{-15}\,\text{eVs}$
(fundamental constant of nature)

- **Momentum of a photon:** $\boxed{p_{ph} = \frac{hf}{c} = \frac{h}{\lambda}}$ ← wavelength of light

(even though a photon has no mass!)

Evidence for Photons (1): Two-slit Interference



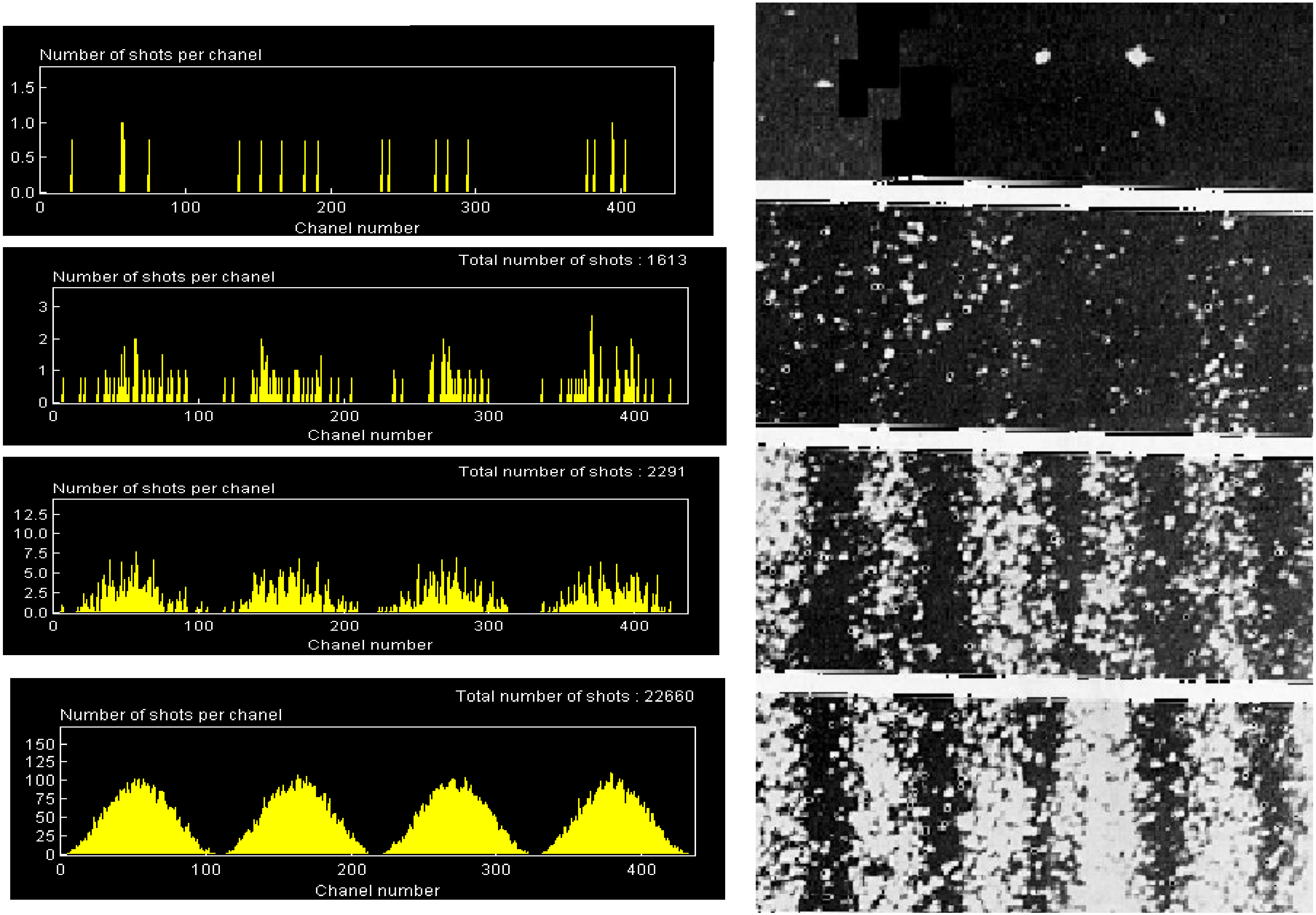
Classical Picture

⇒ Interference of waves explains intensity pattern on screen.

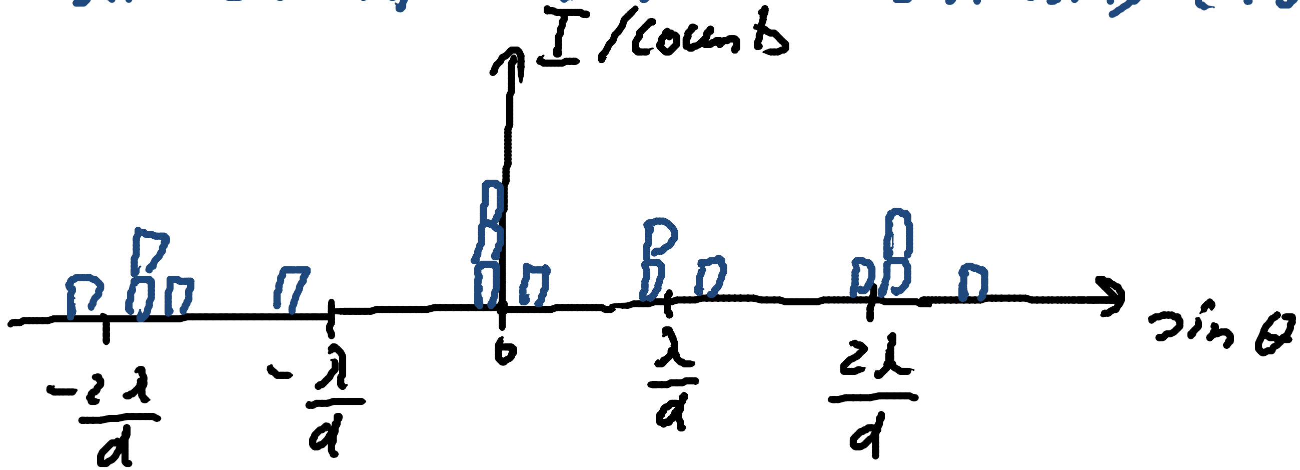
Now: What would you measure if the intensity of the incoming light is turned way down?

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


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

2-slit Interference at Low Intensity (1909)



⇒ Intensity seems to arrive in bundels (chunks) of signal localized in position and time!

⇒ Photons

⇒ classical intensity pattern is built up gradually

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

⇒ but: light still shows wave-like behaviour of interference!

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:

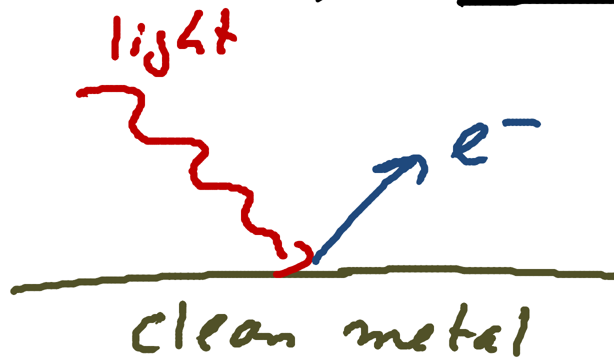
- Example of wave-particle duality:

  Light is composed of photons whose motion is described by an analysis that closely parallels the classical wave description in terms of "interfering amplitudes" from both slits $\Rightarrow$ "wave equation"

- There is an unpredictability about when individual photons will arrive on the screen.

- Classical $I(\theta) \propto \langle E^2 \rangle_{avg}$ pattern gives the probability distribution for finding photons on the screen.

Evidence for Photons (2): The Photoelectric Effect



Light energy is used to eject an electron ("photoelectron") from the metal.

Q: How does this photoelectric effect depend on the frequency f and intensity I of the light?

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

A. It should take time for an electron to gain enough energy to escape the metal. would take time to give e− sufficient energy to escape

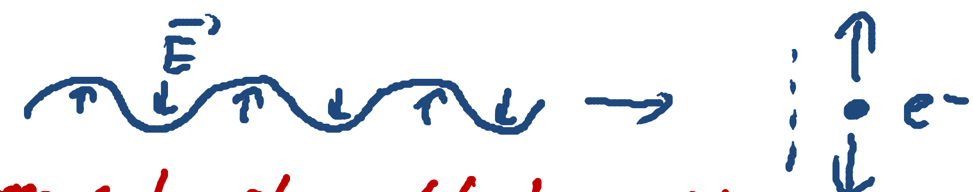
B. The kinetic energy of the photoelectron should increase with light intensity. since $I \propto E^2 \Rightarrow$ higher I = larger E $\Rightarrow$ larger Force $\Rightarrow$ larger KE

C. Photoemission should occur for any frequency f of light as long as the intensity is high enough.

↑ would just need to wait long enough...

D. All of the above.

classical picture:



$\vec{F}_e = q\vec{E}$

But Experiments show that neither A, B, or C are true!