Recap I

- **Single Slit Diffraction:**
  \[ \sin \Theta_{\text{min},m} = \frac{m \lambda}{a} \quad m = \pm 1, \pm 2, \ldots \]

- **Diffraction by a Circular Aperture:**
  1st minimum:
  \[ \sin \Theta_1 = 1.22 \frac{\lambda}{a} \]
  Rayleigh's criterion for diffraction limited resolution:
  \[ \Theta_R \approx 1.22 \frac{\lambda}{a} \]

- **2-Slit Interference:**
  Maxima:
  \[ \sin \Theta_{\text{max},n} = \frac{n \lambda}{d} \quad n = 0, \pm 1, \pm 2, \ldots \]
  from 2-source interference.
  Minima:
  \[ \sin \Theta_{\text{min},n} = (n + \frac{1}{2}) \frac{\lambda}{d} \quad n = 0, \pm 1, \pm 2, \ldots \]
  from single slit.
  Additional Minima:
  \[ \sin \Theta_{\text{min},m} = \frac{m \lambda}{a} \quad m = \pm 1, \pm 2, \ldots \]
  from single slit.
Recap II

- **N-slit Interference:**
  - Principal maxima: \( \sin \theta_{\text{max}} = \frac{n \lambda}{d} \quad n = 0, 1, 2, ... \\
  - Minima: \( \sin \theta_{\text{min}} = \frac{s \lambda}{Nd} \quad s \neq 0 \)
  - Additional minima from single slit: \( \sin \theta_{\text{min}} = \frac{m \lambda}{d} \quad m = 1, 2, ... \\

\[=\text{for large } N: \text{Diffraction grating} \]

- **Bragg Diffraction:**
  - Scattering and interference of x-rays by atoms in a crystal
    - Maxima at: \( \sin \theta_{\text{max}} = \frac{n \lambda}{2d} \quad n = 1, 2, ... \) (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
- So far: "classical" physics - extend of physics before ~1900
  - mechanics: motion of objects (Newton's law)
  - electricity, magnetism (Maxwell's equations)
  - waves, light
  - (special relativity)

• But then: Nature behaves very differently at small scales
  - at small sizes, energies
  - waves act as particles; particles act like waves
  - Quantized energies: only certain values of energy are possible

• Same initial conditions => different results possible

• Only probability descriptions seem possible
Energies at small scales

Recall: change in potential electric energy of a charge

\[ \Delta U = q \Delta V \quad \text{and} \quad \sum \Delta U_j = \Delta V = \frac{e}{C} \]

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

\( \Delta V = 1 \text{V} \)

\( \Rightarrow \quad \Delta U = 1.6 \cdot 10^{-19} \text{J} \quad \text{... tiny!} \)

\( \Rightarrow \) Use new energy unit: the electron-volt (eV)

\[ 1 \text{eV} = 1.6 \cdot 10^{-19} \text{C} \]

(1 eV is the change in potential energy of an elementary charge when it moves through a electric potential difference of \( 1 \text{V} \).)

\( \Rightarrow \) For example above: \( \Delta U = e \cdot 1 \text{V} = 1 \text{eV} \)
Lesson I: Electromagnetic Radiation (light) is quantified and exists in concentrated bundles of energy ("photons")

\[ E_{ph} = h \cdot f \]

\[ h = \text{Planck's constant} = 6.626 \times 10^{-34} \text{ J s} = 4.136 \times 10^{-15} \text{ eVs} \]

\[ \text{fundamental constant of nature} \]

\[ \text{frequency of given light} \]

\[ P_{ph} = h \frac{f}{c} = \frac{h}{\lambda} \]

\[ \text{wavelength of light} \]

\[ \text{Momentum of a photon} \]

\[ \text{(even though a photon has no mass!)} \]
Evidence for Photons (1): Two-slit Interference

Classical Picture

\[ \Rightarrow \text{Interference of waves explains intensity pattern on screen.} \]

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 photomultiplier, 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
2-slit Interference at Low Intensity (1909)

\[ I / \text{counts} \]

\[ \sin \theta \]

\[-\frac{2\lambda}{d}, -\frac{\lambda}{d}, 0, \frac{\lambda}{d}, \frac{2\lambda}{d} \]

\[ \Rightarrow \text{Intensity seems to arrive in bundled (chunks) of signal localized in position and time!} \]

\[ \Rightarrow \text{Photons} \]

\[ \Rightarrow \text{Classical intensity pattern is built up gradually} \]

\[ \Rightarrow \text{radiation acts more like a particle when interacting with the screen!} \]

\[ \Rightarrow \text{light still shows wave-like behaviour of interference!} \]
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 = "wave equation"

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

- Classical $T(\theta) = (E^2)$ any 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 the 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.

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

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

D. All of the above.

*Classical picture:* $\vec{E} \rightarrow \vec{E}_{e} = q \vec{E}$

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