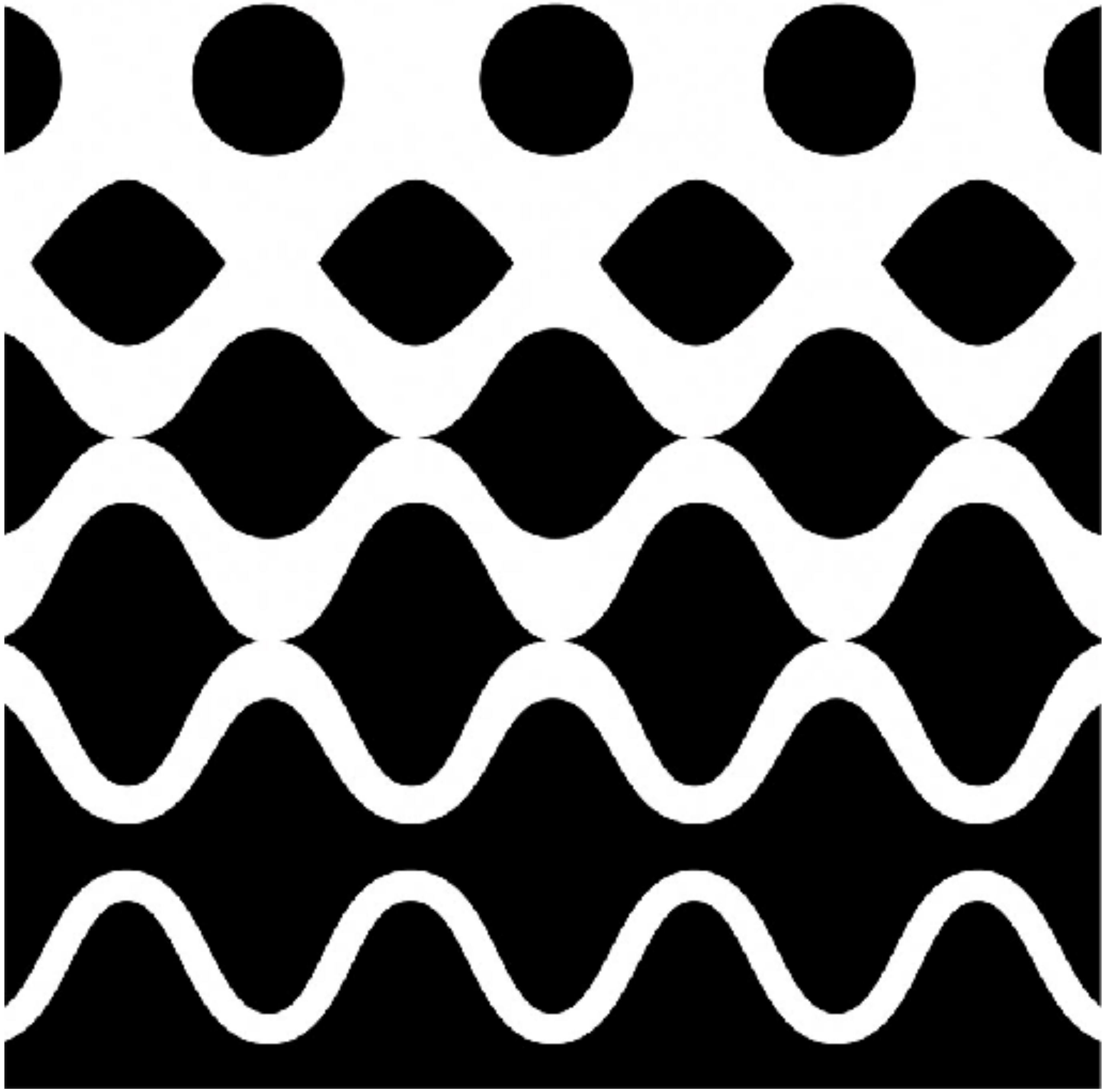
Part 3: Particles as Waves



Artist's impression, inspired by the work of the artist Maurits Cornelis Escher, of the continuous morphing between particle- and wave-like behaviour of light
Credit: Nicolas Brunner and Jamie Simmonds

de Broglie waves

Louis de Broglie

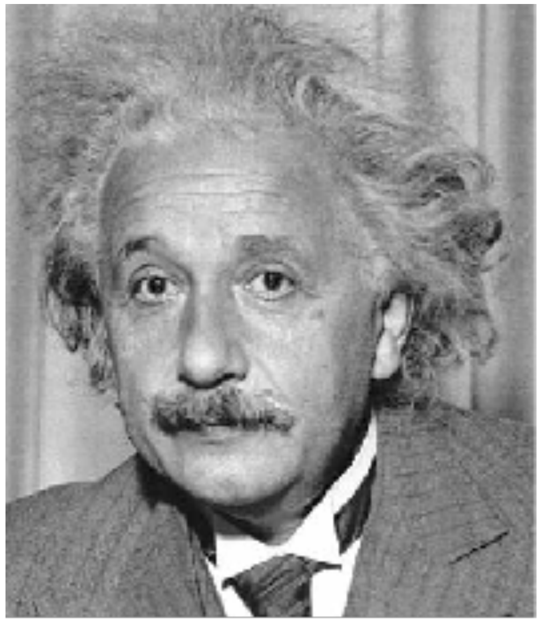
- **1920s: Bohr model** the **best attempt** at an atomic model, but its **flaws** were acknowledged.
- A **better model** was needed.
- By 1920s, **wave-particle duality** of **photons** was growing in acceptance (though before Compton Effect).
- de Broglie (1926: Nobel-prize-winning PhD thesis). Matter (atoms, electrons, etc.) should satisfy **wave-particle** duality **too**.

Images from Wikipedia

Straw poll

– Have you studied **de Broglie waves** before?

Photon Momentum



- In part 1, we saw that special relativity predicted that photons, as **massless particles,** should carry **momentum**

- And thus:

$$p = \frac{E}{c} \quad \textbf{where} \quad E = hf$$

$$p = h\frac{f}{c} = \frac{h}{\lambda}$$

de Broglie waves

- de Broglie’s idea: (1924 - PhD Thesis)
  - Matter should exhibit “**wave-particle duality**” just like photons.
  - Particles (e.g. electrons, atoms etc.) with momentum **p** should have wave-like behaviour with a **de Broglie wavelength**

$$\lambda = \frac{h}{p}$$

  - NB This is precisely the **same relationship** as **photon** momentum:

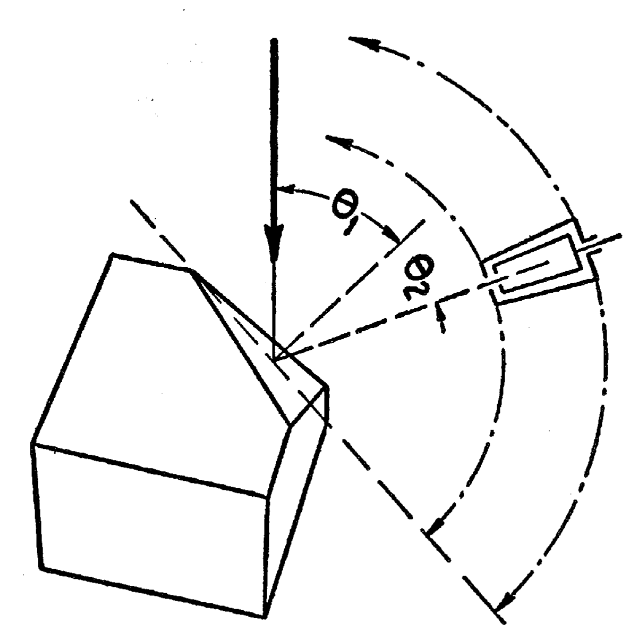
$$p = \frac{h}{\lambda}$$

de Broglie waves

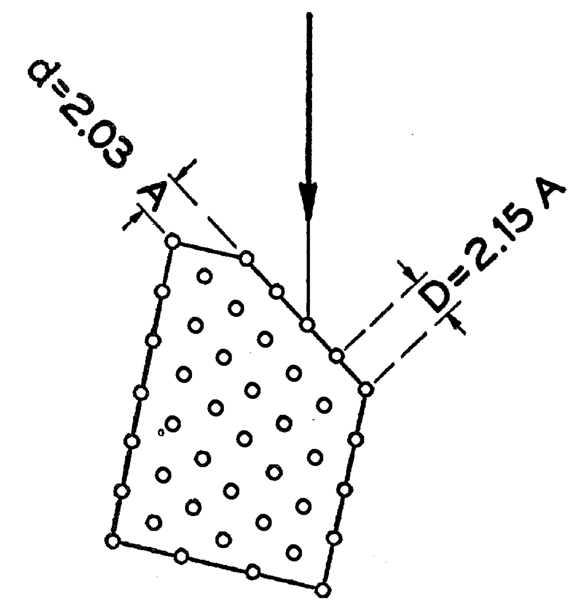
- **de Broglie wavelength**

$$\lambda = \frac{h}{p}$$

- This startling suggestion, was confirmed experimentally surprisingly quickly.
- In 1927 **Davisson** and **Germer** scattered an electron-beam from Nickel.
- Their aim was not to investigate de Broglie’s formula.
- They thought the electrons would scatter as particles, allowing them to image the surface of the crystal.



(c)



(d)

Figures from Davisson and Germer, PNAS, vol 14, page 317 (1928)

de Broglie waves

- This is what Davisson and Germer saw:
- It has the same structure as the **diffraction pattern** from a **grating**.
- The distance between peaks was consistent with de Broglie!

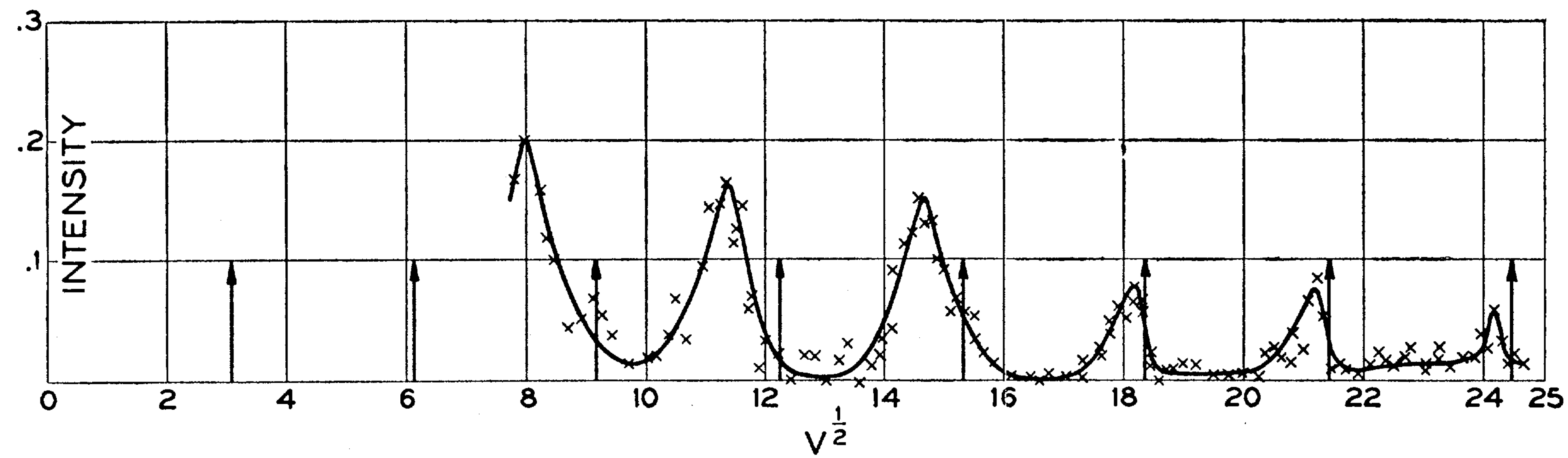


FIGURE 3

Variation of the intensity of the regularly reflected electron beam with bombarding potential, for 10° incidence—Intensity vs. $V^{1/2}$.

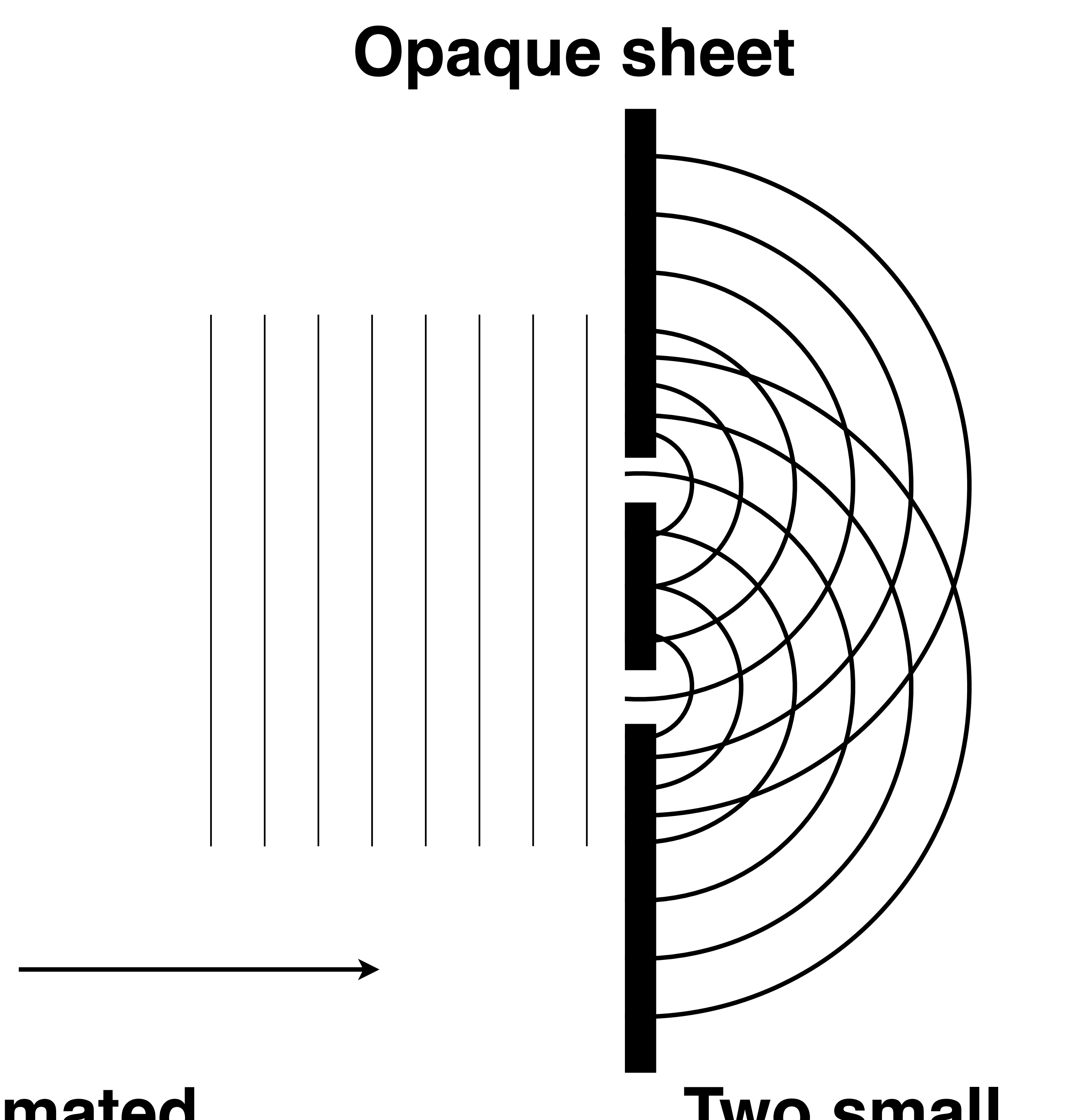
Figure from Davisson and Germer, PNAS, vol 14, page 317 (1928)

λ(OBS.)	λ(CAL.)	$\frac{\lambda(\text{OBS.})}{\lambda(\text{CAL.})} - 1$
0.956 Å	0.953 Å	+0.003
1.064	1.074	−0.01

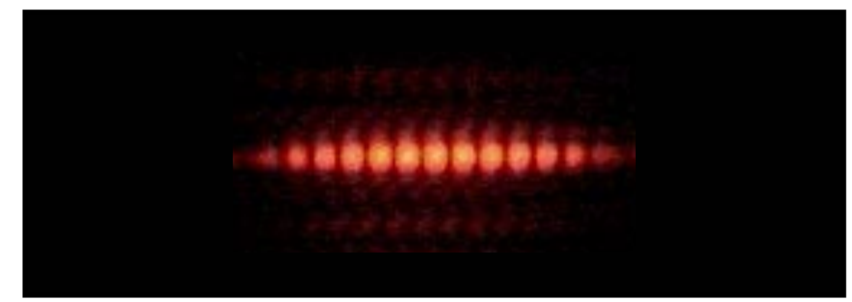
Davisson and Germer, PNAS, vol 14, page 317 (1928)

The Young Two-slit experiment

– The Young experiment is the classic demonstration of the wave nature of light.



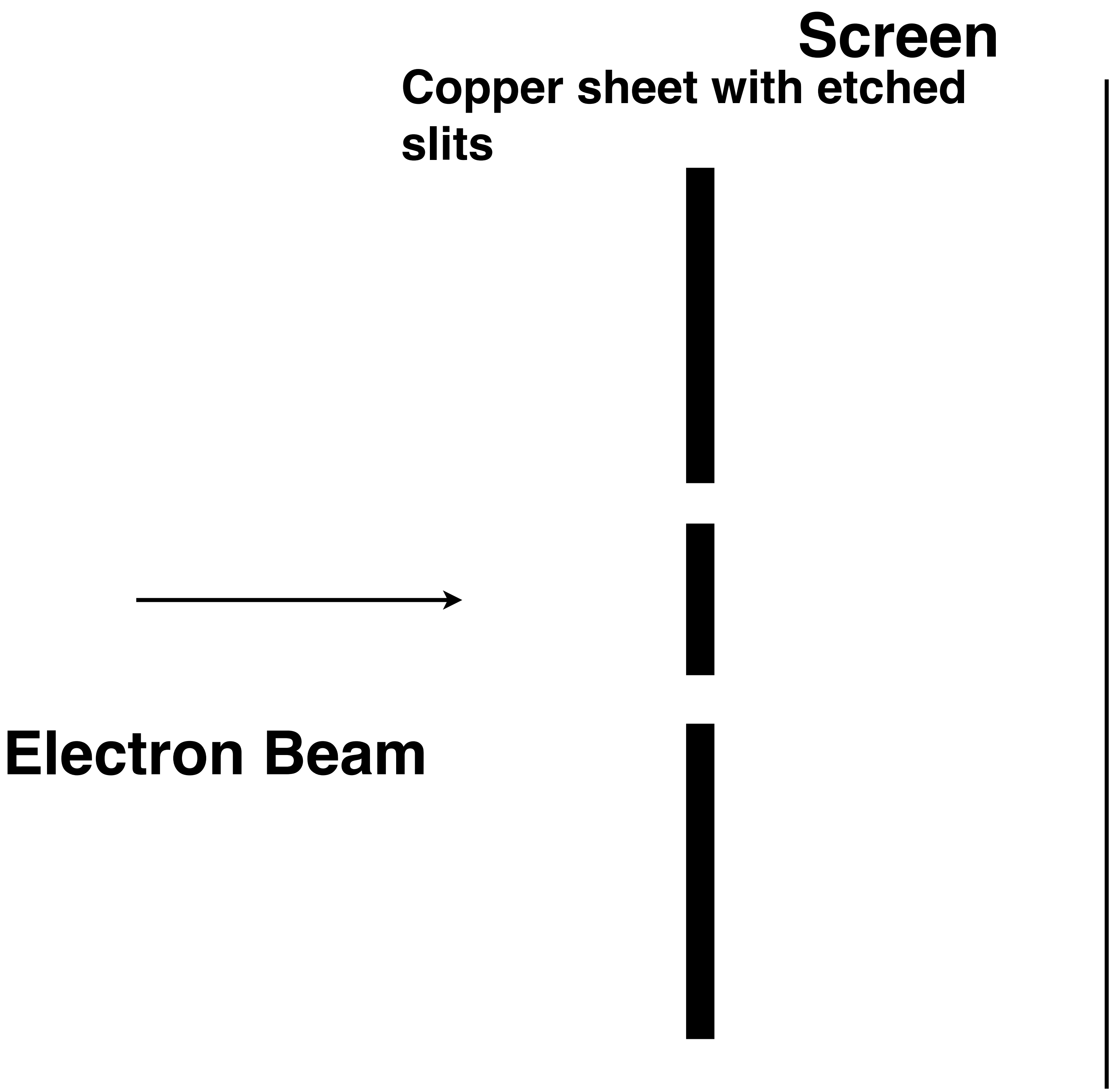
T. Young



Young two slit diffraction pattern observed when slit separation is on the order of wavelength.

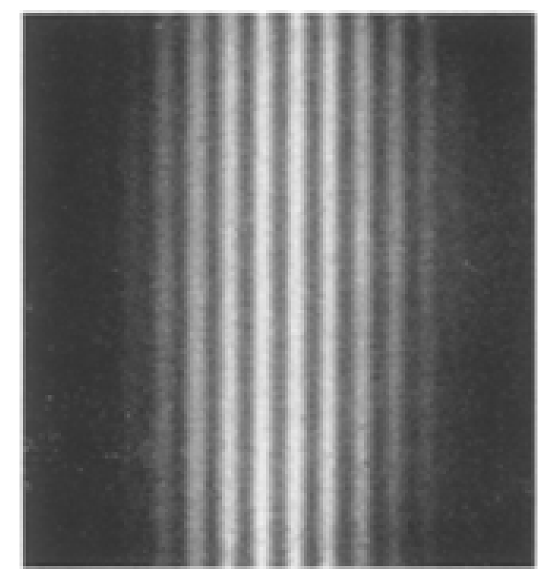
The Young Two-slit experiment

- Can it be performed with matter ?
- **Jönsson** (1961): **Electrons**



Claus Jönsson

Results



C. Jönsson, Zeitschift für Physik, vol. 161, page 454 (1961)

de Broglie wavelength

$$\lambda = \frac{h}{p} \qquad h = 6.626 \times 10^{-34}\,\mathrm{Js}$$

- Examples
  - An electron in an old TV screen (cathode ray):
    - Mass: 9.1×10^{-31} kg
    - Velocity: 100 ms^{-1}
    - Momentum: 9.1×10^{-29} kg ms^{-1}
    - de Broglie wavelength: 7.3 microns (= 7.3×10^{-6}m)
  - A tennis ball during serve
    - Mass: 60g = 6×10^{-2} kg
    - Velocity: 233 km $hour^{-1}$ = 64.7 ms^{-1}
    - Momentum: 3.9 kg ms^{-1}
    - de Broglie wavelength: 1.7×10^{-34} m

de Broglie wavelength

$$\lambda = \frac{h}{p} \quad h = 6.626 \times 10^{-34}\,\mathrm{Js}$$

- Examples
  - Usain Bolt
    - Mass: 94 kg
    - Velocity: 12.4 ms^{-1}
    - Momentum: 1184.4 kg ms^{-1}
    - de Broglie wavelength: 5.6×10^{-37} m

Discussion

– Why do we **not** see wave-like behaviour in matter in everyday life?

de Broglie wavelength

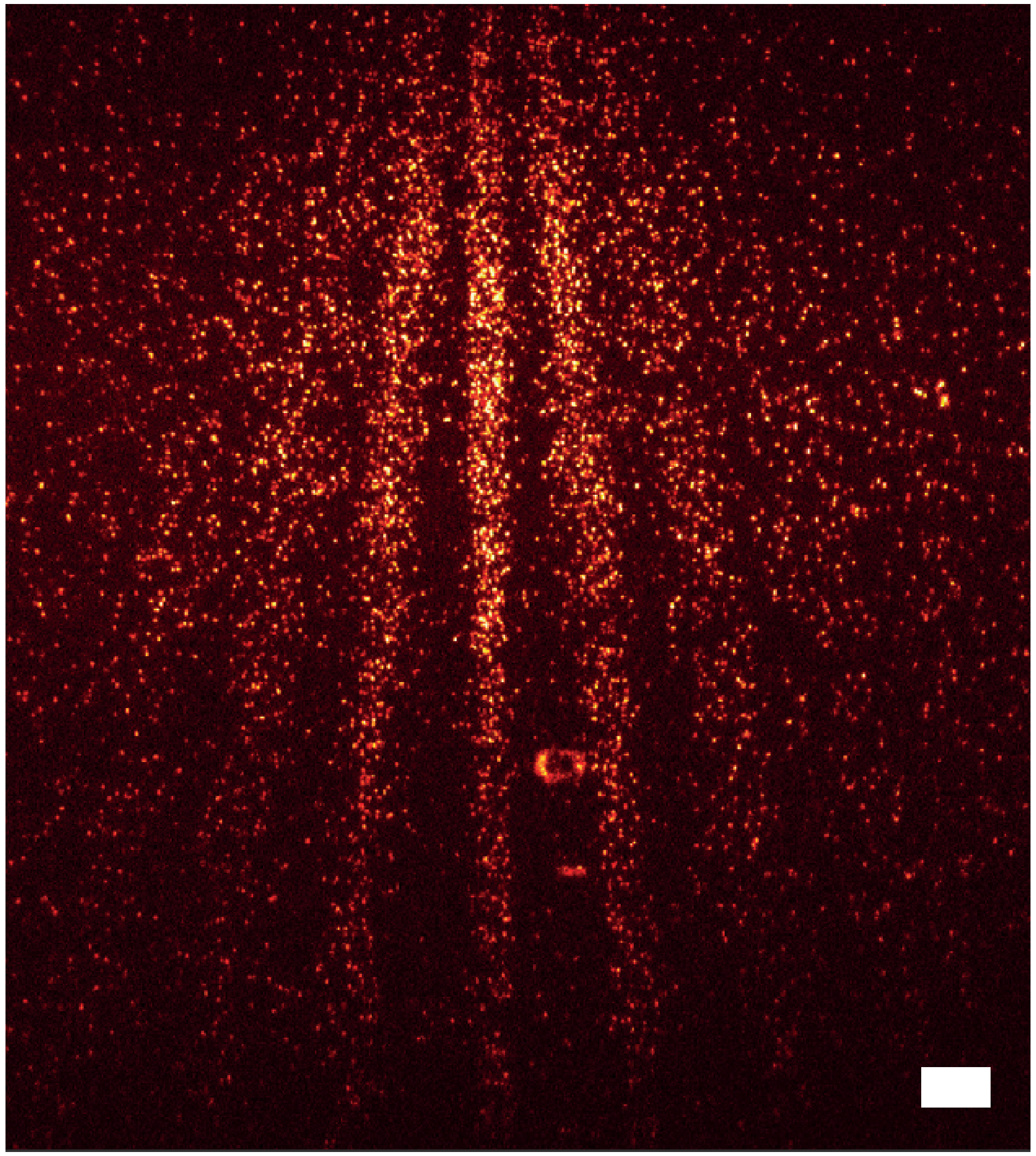
- To observe two-slit **interference** effects, slit **separation** must be approximately the **same size** as the **wavelength**.
- Human-scale objects have such **tiny** de Broglie wavelength that interference effects are **never observed**.
- Still, scientists are managing to achieve 2-slit interference with ever **larger** objects.

T. Juffman et al, Nature Nanotechnology, (2012)

- **Examples**
  - **Phthalocyanine**
    - **Mass:** 8.5 x 10^{-25} kg = approx 1 million electron masses
    - **Velocity:** 150 ms^{-1}
    - **Momentum:** 1.2 x 10^{-22} kg ms^{-1}
    - **de Broglie wavelength: 5.2 pm = 5.2 x 10^{-12} m**

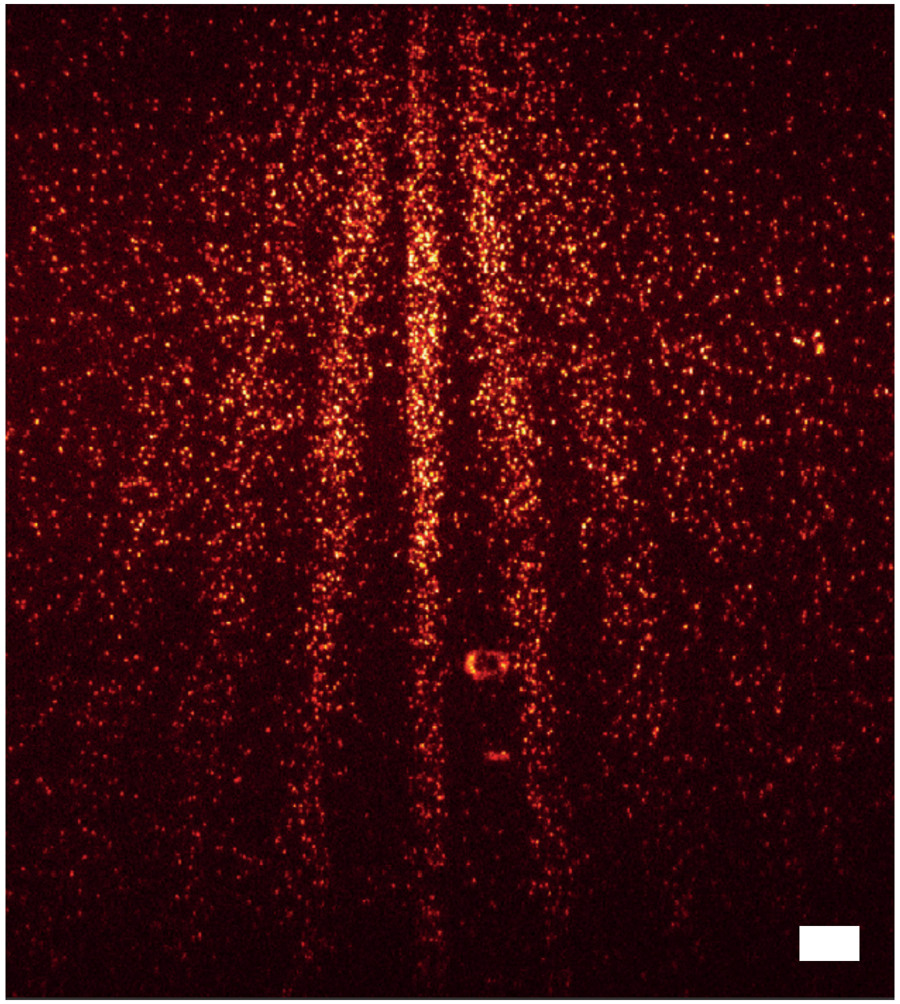
Single molecules
in a quantum movie

Wave-particle Duality



- In a Young's double slit experiment with matter:
  - Behaviour is analogous to photons.
    - ***Wave-like*** behaviour (while **unobserved**)
    - ***Particle-like*** behaviour (when detected).

Summary of Part 3



- Matter is observed to undergo wave-like interference with **de Broglie wavelength**:

$$\lambda = \frac{h}{p}$$

  - There is nothing in classical physics which can behave like this.
- **Fundamentally new physics** is needed:
  - **Quantum Mechanics!**
    - the dramatic **new theory** which, in Parts **4** and **5**, we start to introduce.