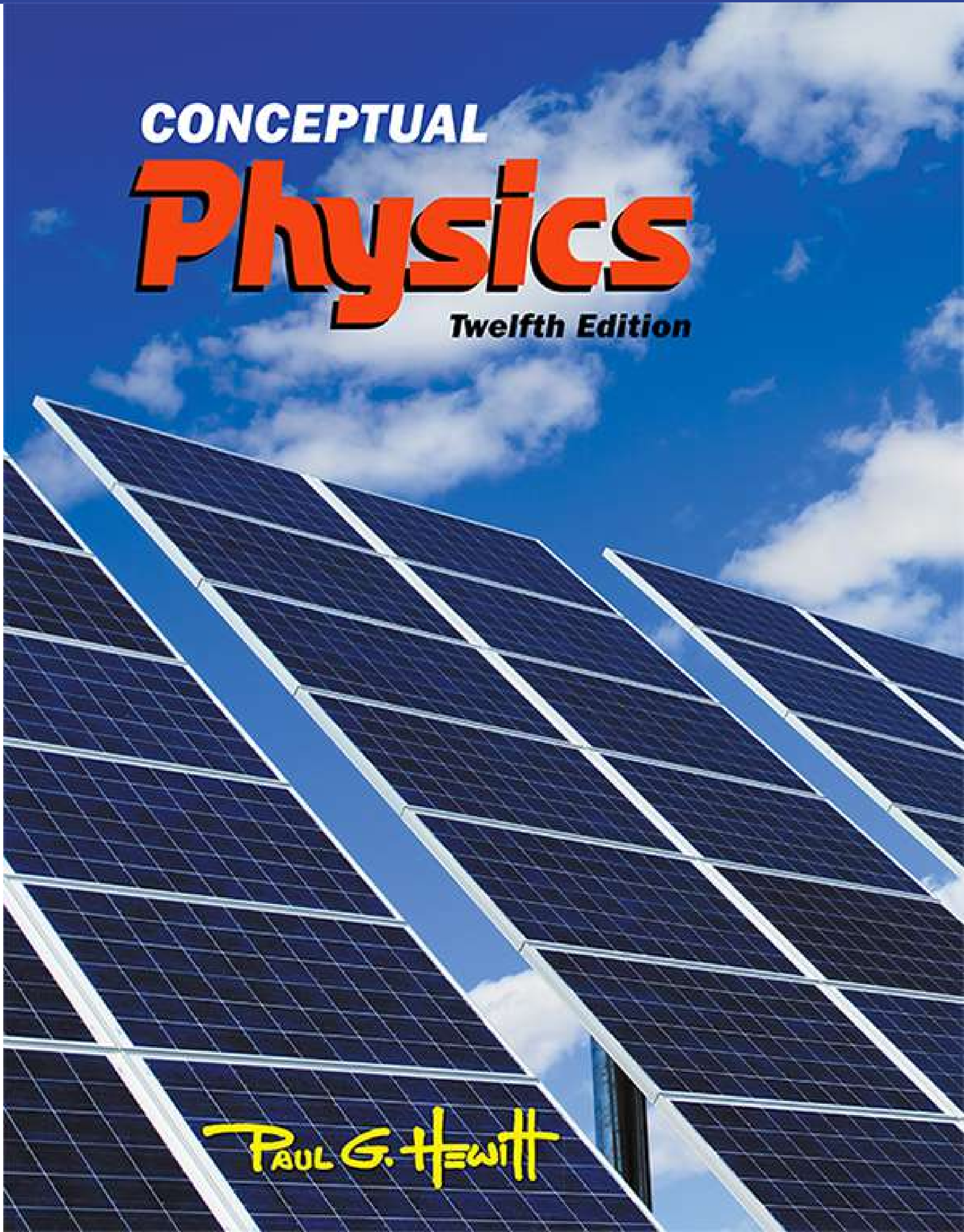
Lecture Outline

Chapter 31: Light Quanta



Matter waves

Since it was known that light can act like a:

A) wave → diffraction and interference

B) Particle (photon) → photoelectric effect

In 1924, Louis de Broglie reasoned that…

….matter can act like a:

A) particle → already assumed to be one

B) wave → diffraction and interference???

de Broglie’s Hypothesis:

Every particle of matter is associated with a corresponding wave. According to Louis de Broglie, a particle's wavelength is related to its momentum.

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

$$= \frac{h}{(mass)(speed)}$$

h = Planck’s constant

Particles as Waves: Electron Diffraction
CHECK YOUR NEIGHBOR

When we speak of de Broglie waves, we're speaking of the wave nature of

A. transverse waves.
B. longitudinal waves.
C. particles.
D. quantum uncertainties.

Particles as Waves: Electron Diffraction
CHECK YOUR ANSWER

When we speak of de Broglie waves, we're speaking of the wave nature of

C. **particles.**

Bullet vs. electron

Wavelength of a 20-gram bullet traveling at 330 m/s:

$$\lambda = \frac{h}{momentum} = \frac{6.63 \, x \, 10^{-34}}{(0.020 \, kg)(330 \frac{m}{s})} = 1.0 \text{ x } 10^{-34} \text{ m}$$

→ a millionth millionth millionth of an atom!

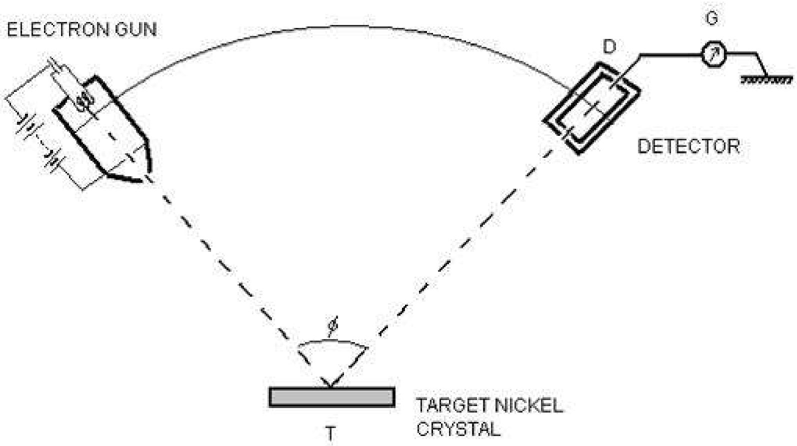
Wavelength of a 9.11 x 10^{-31} kg electron moving at 2% of the speed of light:

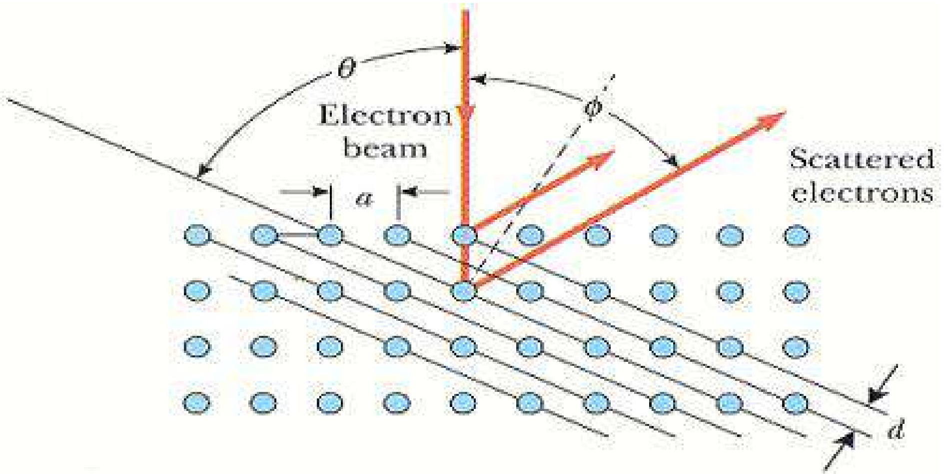
$$\lambda = \frac{h}{momentum} = \frac{6.63 \, x \, 10^{-34}}{(9.11 x 10^{-31} \, kg)(3.0 \, x 10^{6} \frac{m}{s})} = 1.2 \text{ x } 10^{-10} \text{ m}$$

→ about the diameter of an atom

So bullet diffraction is not observed.

…if the electrons are fired at an obstacle that is about the same size as their λ (the surface of a crystal of Ni). This experiment confirmed de Broglie's hypothesis of wave-particle duality, and was a milestone in the creation of quantum mechanics.





The spacing between crystal layers is about 1 x 10^{-10} m, same as the electron λ

Particles as Waves: Electron Diffraction, Continued

- Interference patterns of beams of light

Electron interference pattern:

Firing one electron at a time builds up the same interference pattern as light!

Electrons impact film as particles, but make a wave-like pattern.

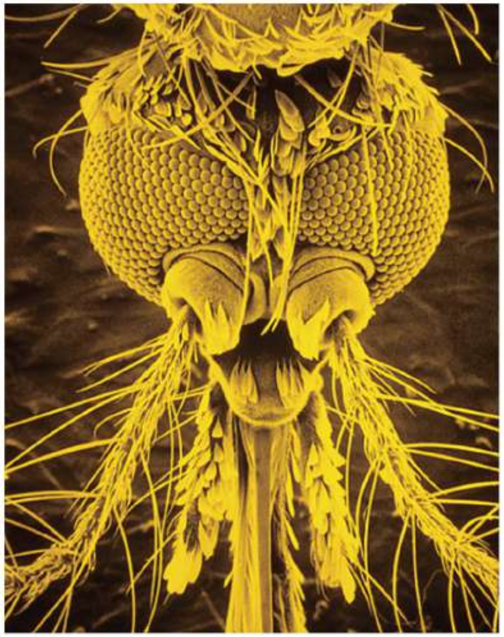
Classwork

14. What evidence can you cite for the wave nature of particles?

15. When electrons are diffracted through a double slit, do they hit the screen in a wavelike way or in a particle-like way? Is the pattern of hits wavelike or particle-like?

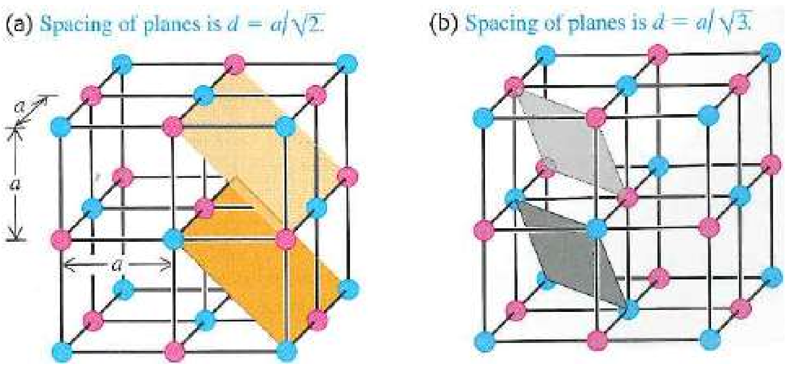
Particles as Waves: Electron Diffraction, Continued-1

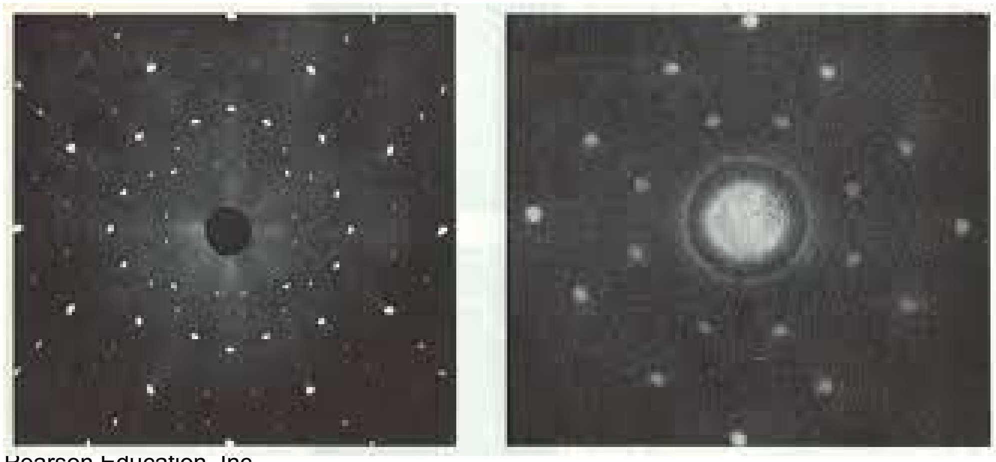
- Electron microscope uses the wave nature of electrons to create images similar to the image of the mosquito shown here.



Neutrons can act like waves, too

When neutrons are fired at salt crystals, they make diffraction patterns when they interact with the crystal planes in salt:



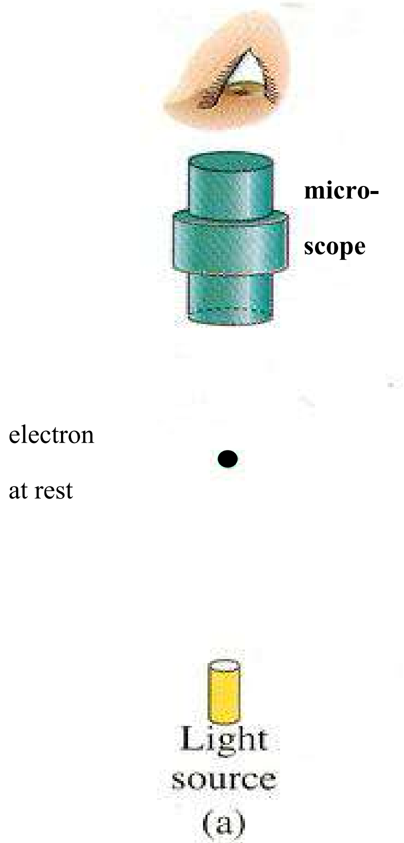


Dr Quantum Explains All:

Video: https://www.youtube.com/watch?v=Q1YqgPAtzho

Heisenberg's Uncertainty Principle

- Uncertainty principle
  - The act of observing something as tiny as an electron probes the electron and, in so doing, produces a considerable uncertainty in either its position or its motion.



Two points:

1. Putting a thermometer to measure the temp of a cup of coffee changes the temp because the thermometer absorbs heat.

→ This is not *quantum* uncertainty.

→ The results can be predicted and easily measured with knowledge of energy and how heat flows

2. Observing steam rising from coffee is different from "probing" it with the thermometer

A) your glance involves no interaction

B) the thermometer interacts with the coffee and changes its temp

Classwork

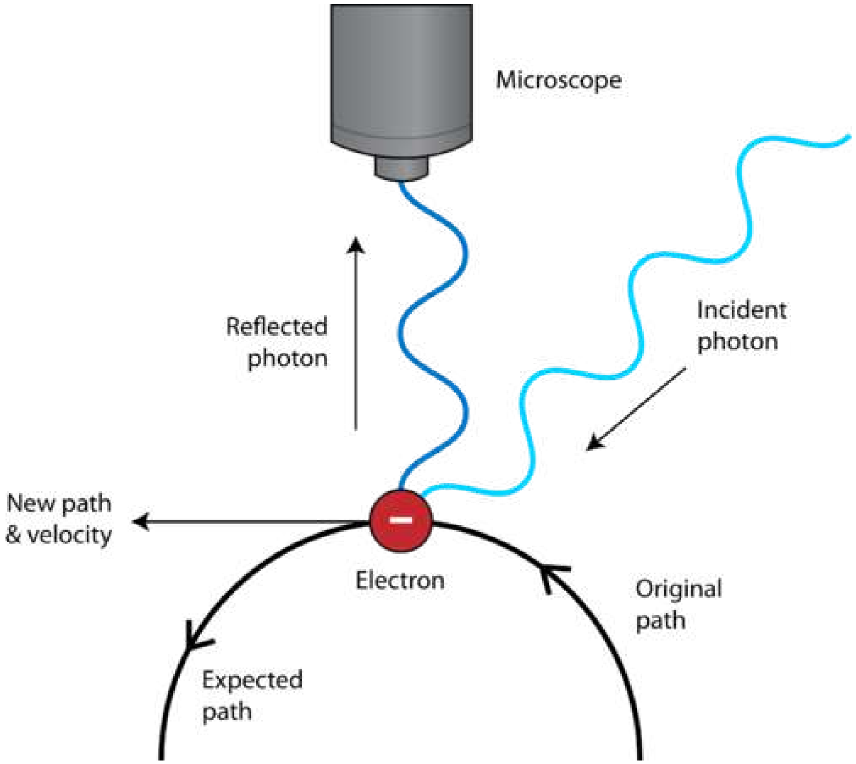
20. What is the distinction in this book between passively and actively observing an event?

Observing vs. Probing

Physicists use light to both observe and probe:

For example: Light is used to observe where a particle is located in space (its Δx).

By doing so, its momentum (Δp) is altered.



Shining light to see where a baseball is would not change its momentum by any measurable amount because a baseball is too big!

Classwork

16. In which of the following are quantum uncertainties significant: measuring simultaneously the speed and location of a baseball; of a spitball; of an electron?

German physicist Werner Heisenberg called this the *uncertainty principle*.

The mathematical statement of it involves:

The symbol Δ = "uncertainty in measurement of"

Δp is uncertainty in measurement of momentum p

Δx the uncertainty in position x

When Δx and Δp are multiplied together, the product must be equal to or greater than Planck's constant, *h*, divided by 2π, which is represented as $\hbar$ (called *h*-bar).

$$\Delta p \cdot \Delta x \geq \hbar$$

Classwork

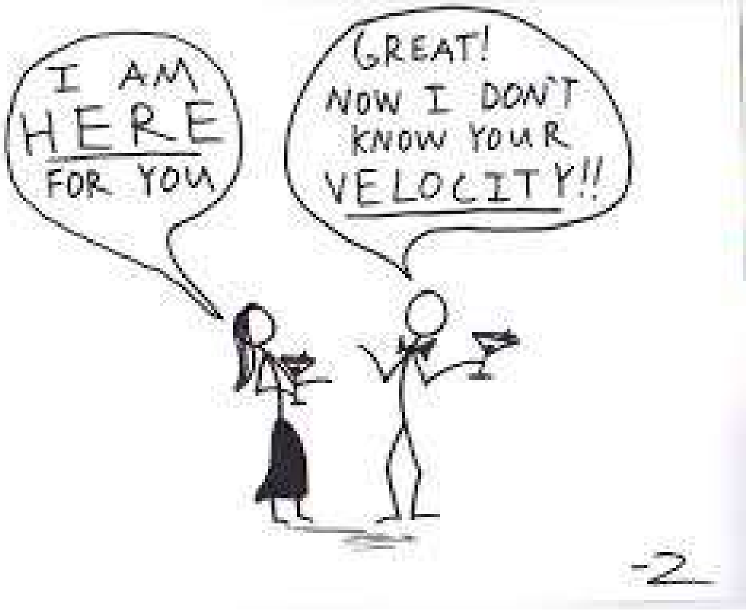
17. What is the uncertainty principle with respect to momentum and position?

The uncertainty principle stated another way:

You cannot simultaneously know the position x and the momentum p (or speed) of a particle.

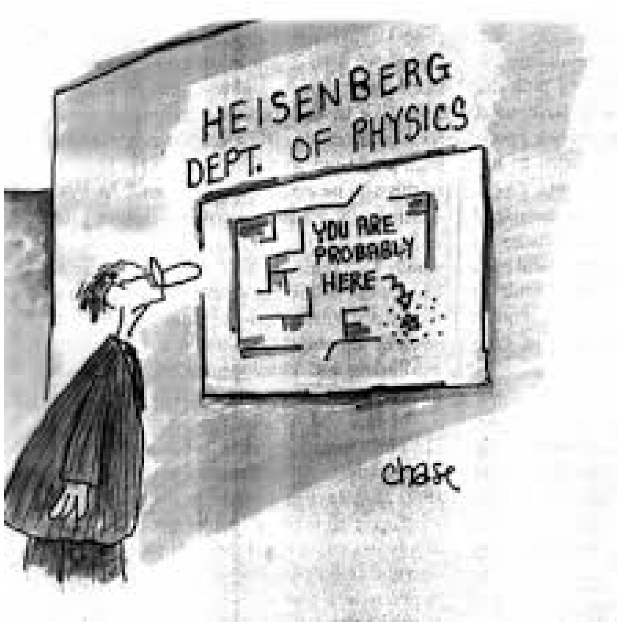
In other words:

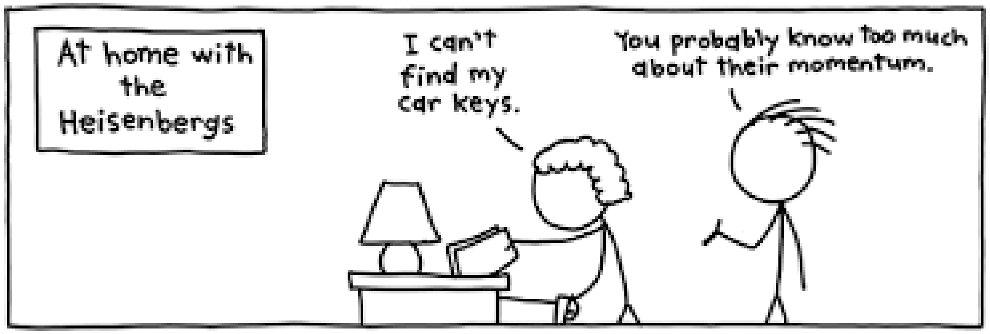
If you decrease the uncertainty in position Δx by measuring something is, you will increase the uncertainty in what you know about its momentum (speed) Δp.



Classwork

18. If measurements show a precise position for an electron, can those measurements show the precise momentum also?





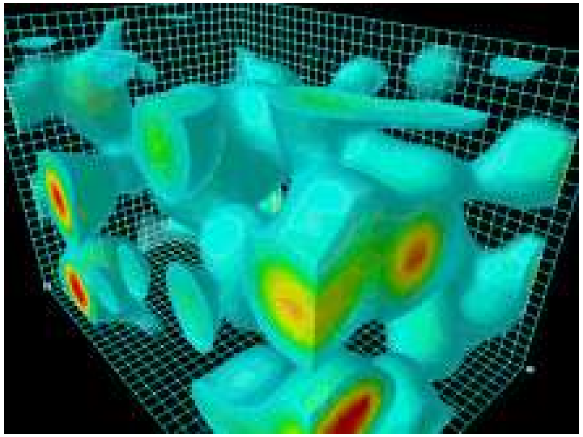
Video:
https://www.youtube.com/watch?v=a8FTr2qMutA

Uncertainty principle (continued)

Applies to uncertainties of measurements of energy E and time t. The uncertainty in knowledge of energy, ΔE, and the duration taken to measure the energy, Δt, are related by the expression:

$$\Delta E \cdot \Delta t \geq \hbar$$

Particles can be created from nothing—in violation of energy conservation—as long as they exist for such a short time that they are not observed!



quantum fluctuations

Classwork

19. If a measurement shows a precise value for the energy radiated by an electron, can that measurement show a precise time for this event as well?

- Uncertainty principle (continued)
  - Heisenberg's uncertainty principle applies *only* to quantum mechanics.
  - It does not apply to:
    - uncertainties of macroscopic laboratory measurements (thermometer in coffee).
    - a shield of nature's secrets.
    - the notion that science is basically uncertain.

Uncertainty Principle
CHECK YOUR NEIGHBOR

To which of these does Heisenberg's uncertainty principle apply?

A. Measuring room temperature with a thermometer
B. Momentum and distances of a high-speed bullet
C. A public opinion survey
D. None of the above.

Uncertainty Principle
CHECK YOUR ANSWER

To which of these does Heisenberg's uncertainty principle apply?

D. **None of the above.**

Explanation:

Heisenberg's uncertainty principle involves the unavoidable interaction between nature at the *atomic level* and the means by which we probe it.

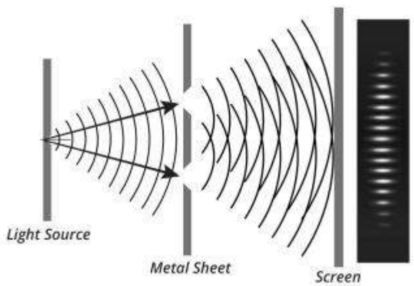
- **Complementarity:**
  - Quantum phenomena have *complementary* (mutually exclusive) properties:

→Light either acts like a wave or a particle.

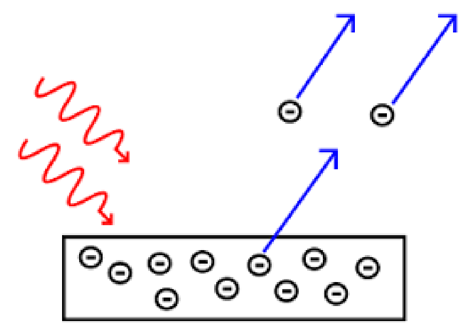
→Matter either acts like a wave or a particle.

→It depends on what the experiment is measuring.

waves: interference and diffraction:



particles: Emitting or absorbing:



→ But together, they form the whole picture

→ Opposite ideas can complement one another (light can be both a wave.

The Yin-Yang diagram

The idea of complementarity is not new.
Ancient Eastern cultures had it in their worldview.

Bohr chose the yin-yang diagram
to illustrate complementarity.
Opposites make up the whole.
Both exist together.
Only the union make us the whole.

Examples: Low and high, dark and light, birth and death, male and female, reason and emotion, cold and heat, wet and dry, etc.

Classwork

21. What is the principle of complementarity?

22. Cite evidence that the idea of opposites as components of a wholeness preceded Bohr's principle of complementarity.