Wave-Particle Duality:
Is Light a Wave or a Particle?

Light makes wave-like interference patterns, yet arrives in discrete energy clicks

Learning goal: weigh the evidence for both models and see why they are complementary

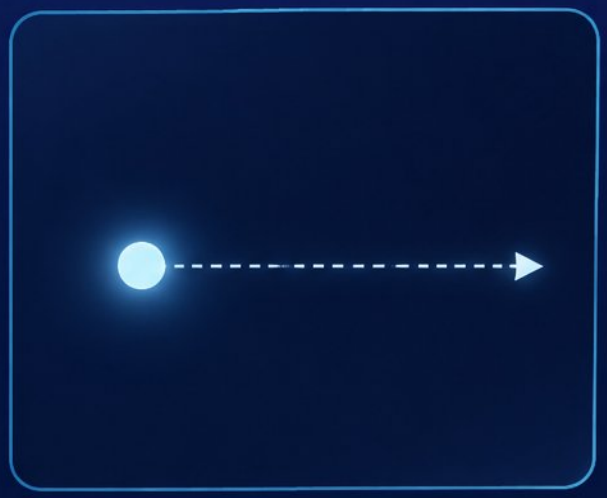
Our journey: three centuries of debate, decisive experiments, quantum interpretation, daily technology

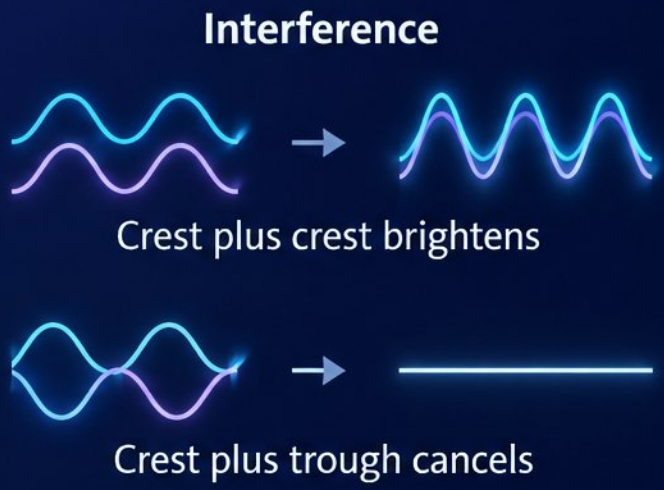
Guiding question: what does it mean for one object to show both wave and particle properties?

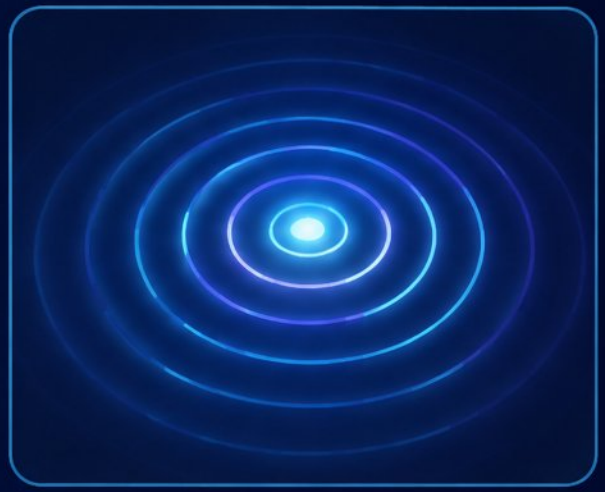
Tone: conceptual, no math needed — every claim tied to an experiment or device you can picture



Waves and Particles: Two Mental Models

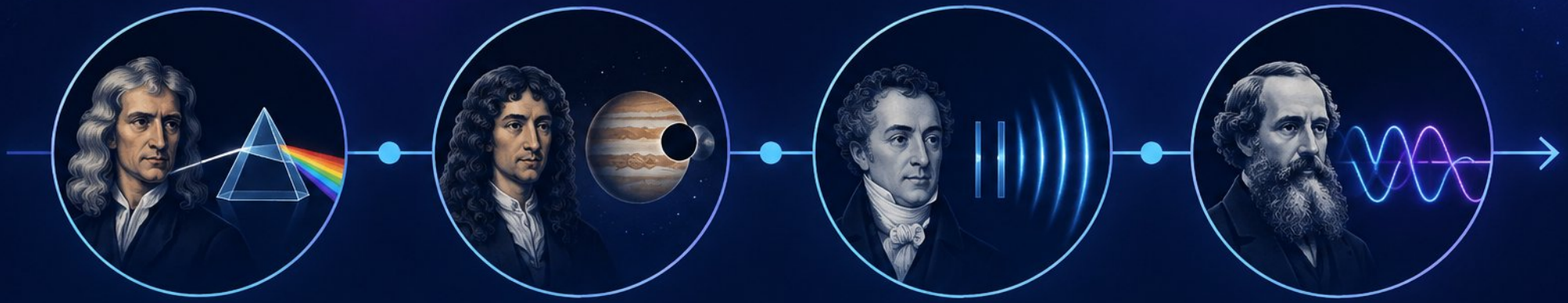






- **Particle model:** localized in space, follows a trajectory, deposits energy at one point
- **Wave model:** spread out, carries energy, can reinforce or cancel other waves
- **Interference is the decisive wave signature:** crest plus crest brightens, crest plus trough cancels
- Students often treat waves and particles as mutually exclusive — we need both
- **Modern answer:** both descriptions are needed, but never at the same time

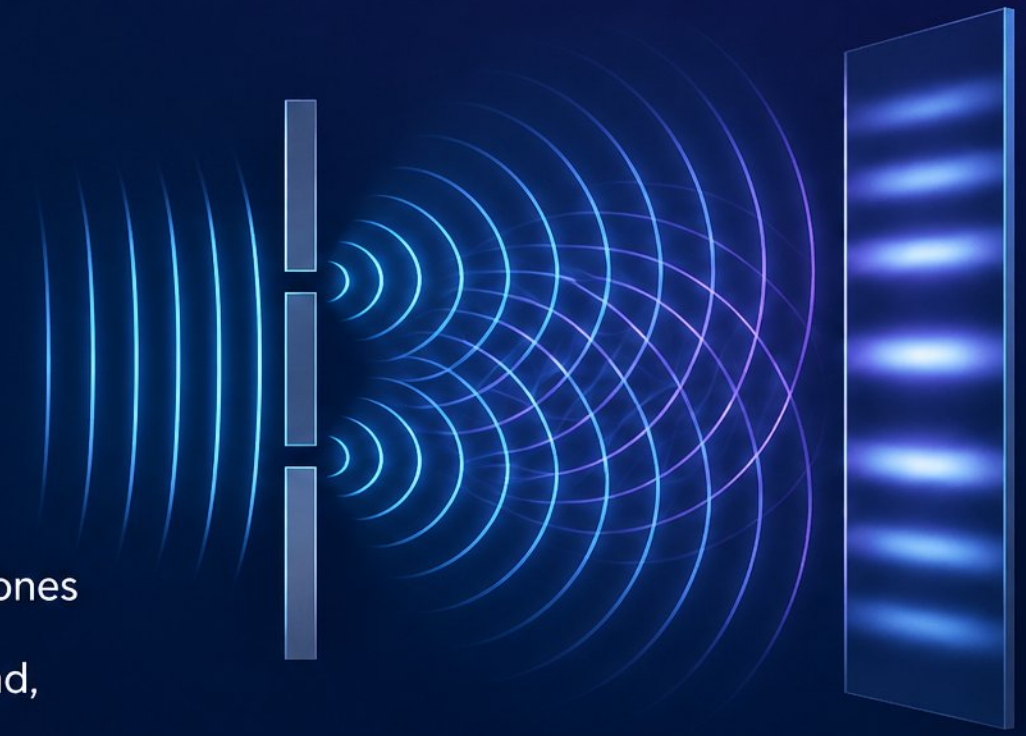
A Short History: Newton, Huygens, Young, Maxwell



- **1670s–1700s:** Newton's corpuscles win over Huygens's wave theory and its all-pervading aether
- **1676:** Rømer times Jupiter's moon eclipses, proving light travels at finite speed
- **1801–1803:** Young's double-slit fringes are taken as proof light is a wave
- **1860s–1880s:** Maxwell makes light an electromagnetic wave; Hertz confirms radio waves
- **By 1900,** the wave model seems settled — setting up the coming reversal

The Wave Case: Interference and Diffraction

- Overlapping ripples: crest plus crest brightens, crest plus trough cancels
- Double-slit: two paths of different length create bright and dark fringes
- Diffraction around edges and through narrow slits — a classic wave signature
- Everyday anchors: soap-film colors, CD iridescence, noise-canceling headphones
- Same math describes water ripples, sound, and light — shared wave behavior









The Particle Case:
Photons and the Photoelectric Effect

- Planck (1901): energy comes in discrete packets, E proportional to frequency
- Einstein (1905): light itself is quantized — each photon carries $E = hf$
- Three puzzles waves can't explain: no time lag, electron energy independent of intensity, cutoff frequency
- Dim high-frequency light works; intense low-frequency light never does
- Everyday payoff: solar cells and smartphone camera sensors



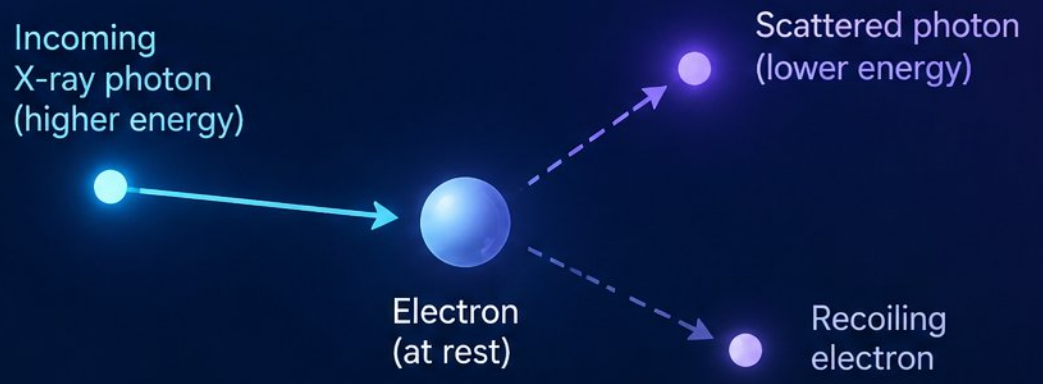






Light as Bullets: Compton Scattering and Photon Momentum

- Compton scattering: X-rays bounce off electrons like billiard balls, losing energy exactly as predicted
- Light carries momentum, not just energy — a particle property waves lacked
- Low-energy radio photons behave wavelike; high-energy X-rays and gamma rays behave particle-like
- A photon is not a tiny glowing ball with a path — it is a massless quantum of energy
- New puzzle: if light is particles, how do single photons build an interference pattern?

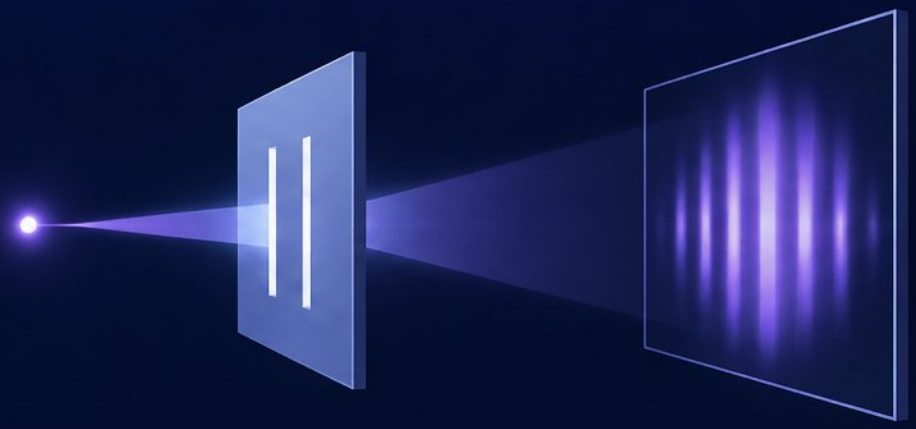


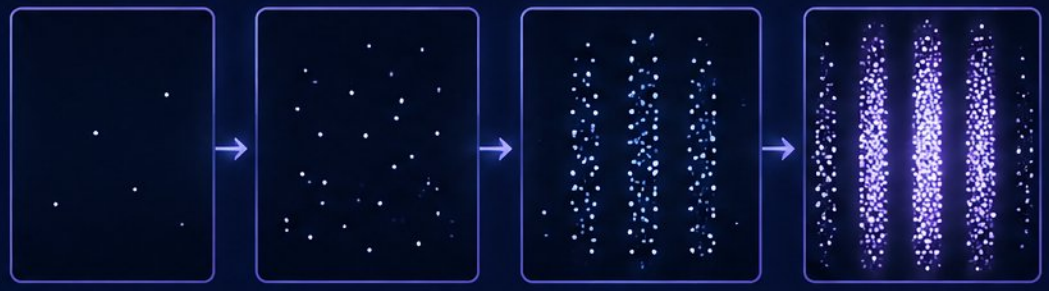




One Photon at a Time: The Central Experiment

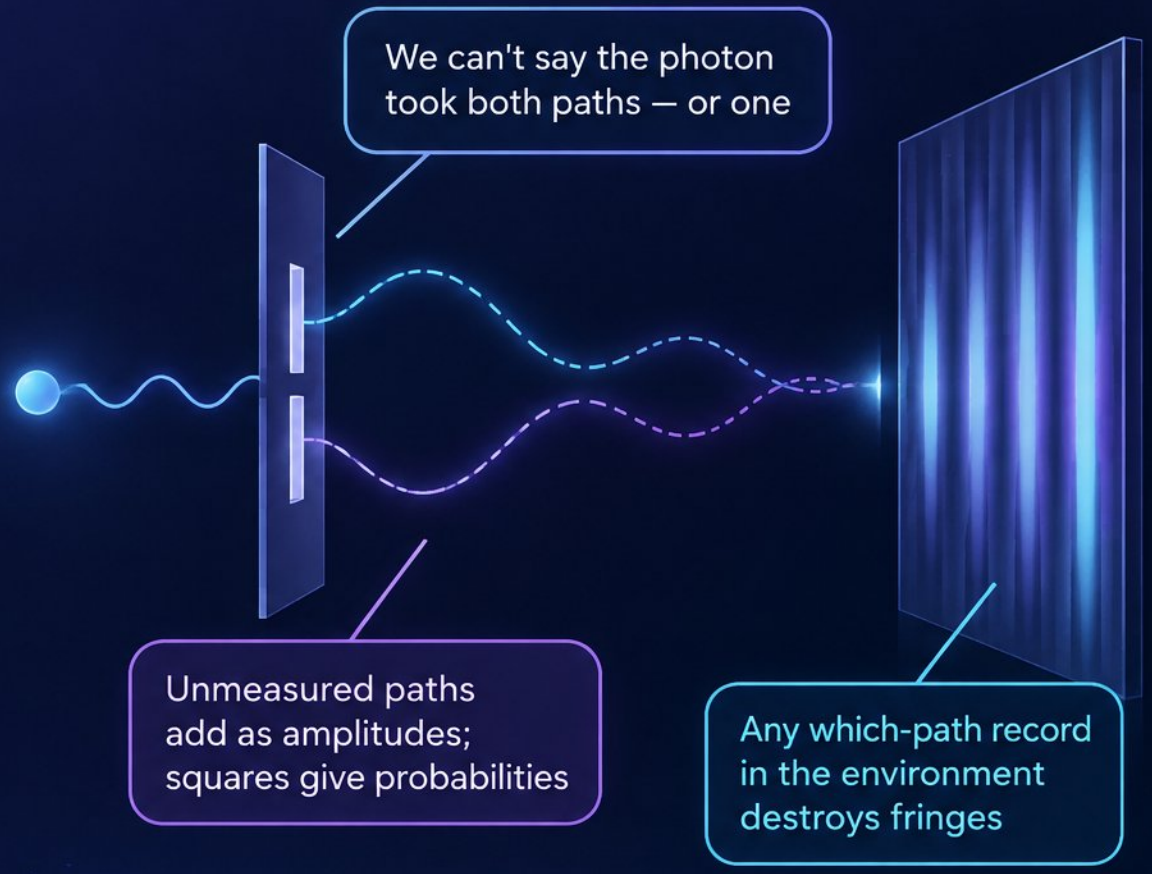
- G. I. Taylor (1909) dims light until one photon passes through at a time
- Single dots appear; over hours they build the full interference pattern
- The pattern is not photons interfering with each other
- Each photon, in a sense, interferes with itself
- If which-path information is available, fringes vanish and two clumps appear
- Quantum eraser: erasing the path information brings interference back
- The wave predicts probabilities; individual detections are random and discrete





Why 'Going Through Both Slits' Is Misleading

- We can't say the photon took both paths — or one
- Unmeasured paths add as amplitudes; squares give probabilities
- The interference term is what classical particles can't produce
- Any which-path record in the environment destroys fringes
- Feynman: this is the only mystery at the heart of quantum mechanics



Complementarity: Both Descriptions, Never at Once

- Bohr (1927): wave and particle views are both valid, but never at once
- Ask a wave question, get a wave answer; ask a which-path question, get a particle answer
- More path information means less fringe visibility — bounded together
- Vase/faces figure: you can switch views, never see both
- The experimental setup, not light itself, decides what you observe
- Avoid saying light "decides" or "changes"

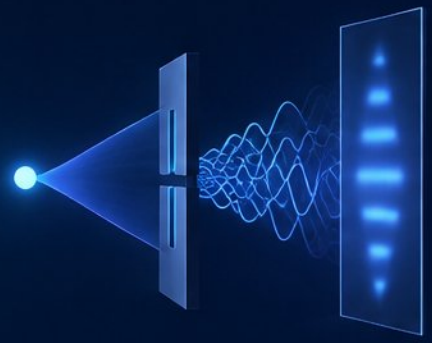




Quantum Interpretations in Brief

Different stories. The same experimental results.

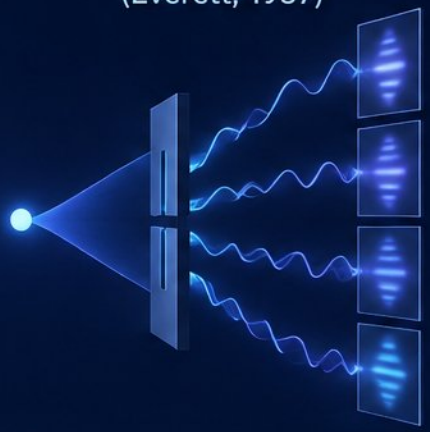
Copenhagen



Wavefunction predicts; measurement yields one outcome (textbook default)

Many-worlds

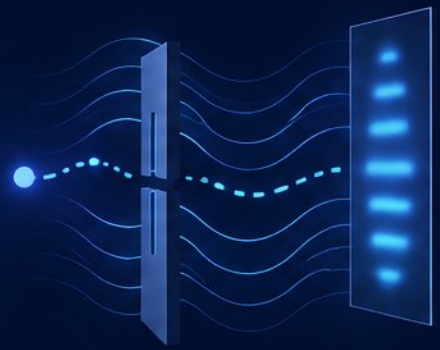
(Everett, 1957)



No collapse; the wavefunction branches, observers see one branch

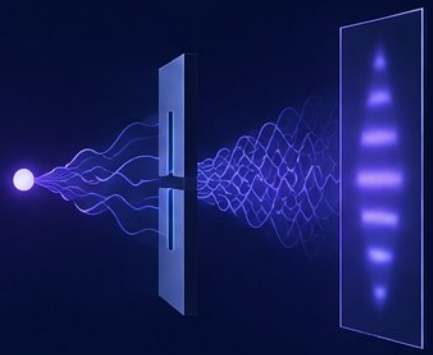
Pilot wave

(de Broglie 1927, Bohm 1952)



Definite particles steered by a real, nonlocal wave

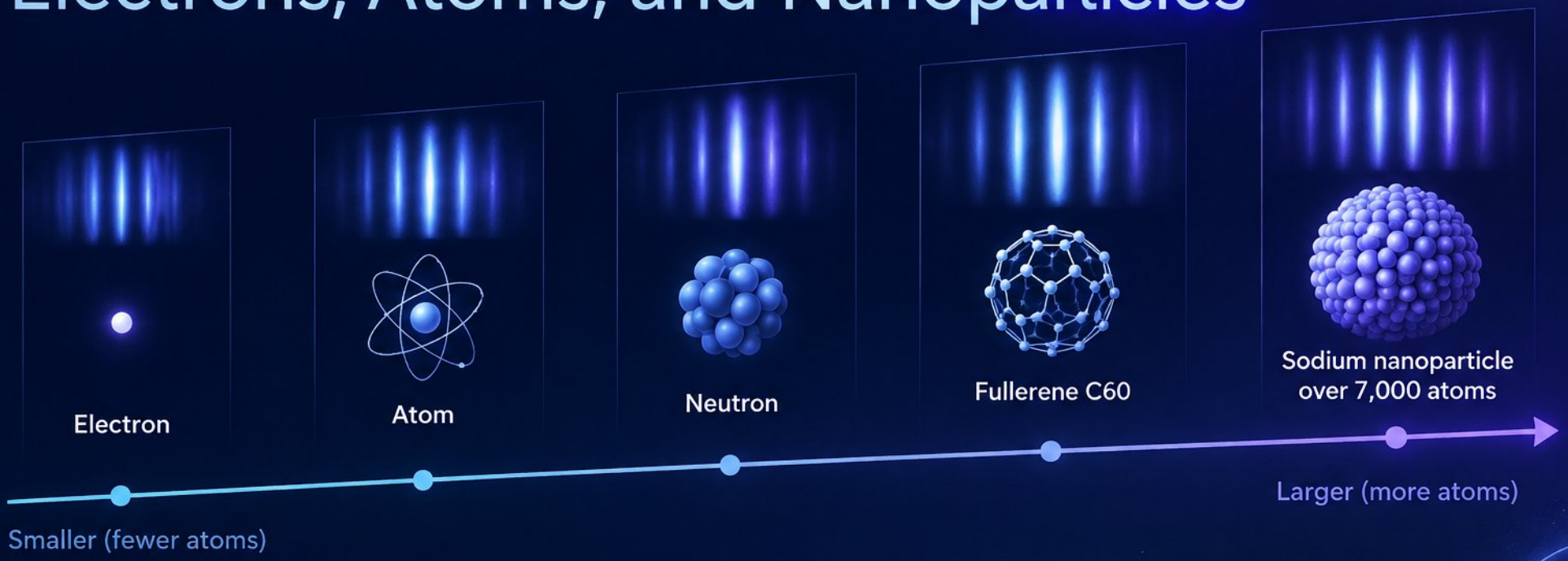
Others



Objective collapse (GRW), QBism, relational quantum mechanics

Same Schrödinger equation and Born rule; identical predictions — experiments can't yet decide

Duality Beyond Light:
Electrons, Atoms, and Nanoparticles



- de Broglie (1924): every moving particle has a wavelength
- Electron diffraction through crystals confirmed it within years
- Interference seen in neutrons, atoms, and the fullerene C60
- 2026 record: sodium nanoparticles over 7,000 atoms show fringes
- Macroscopicity $\mu = 15.5$ — an order of magnitude beyond past work
- Decoherence: the environment records position, washing out fringes
- Duality is universal — the quantum-to-classical boundary is a frontier

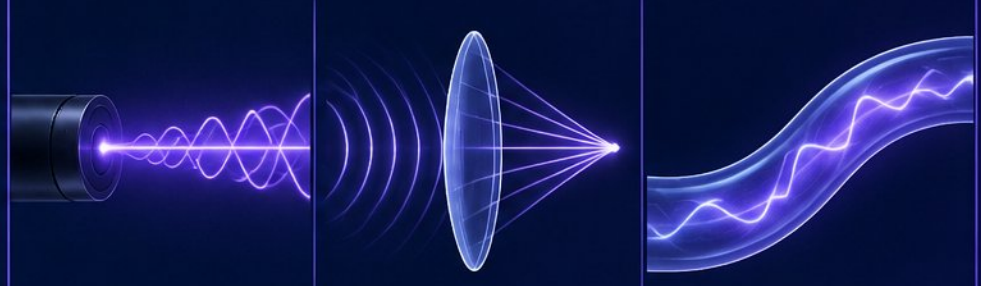
Duality at Work: Technologies Built on Both Pictures

Particle picture — individual photon absorption



Cameras | Solar cells | Photomultipliers

Wave picture — interference, diffraction, and coherence



Lasers | Lenses | Optical fibers

- Cameras, solar cells, and photomultipliers: engineered around individual photon absorption (particle picture)
- Lasers, lenses, and optical fibers: designed with wave optics — interference, diffraction, and coherence
- **Interferometry:** gravitational-wave detectors and optical clocks exploit wave interference at extraordinary sensitivity
- Quantum photonics in 2026: on-chip single-photon sources, quantum-dot emitters, and photonic quantum computing use single photons as qubits
- Engineers switch models by task — duality is a daily design choice

Key Takeaways and Misconception Check

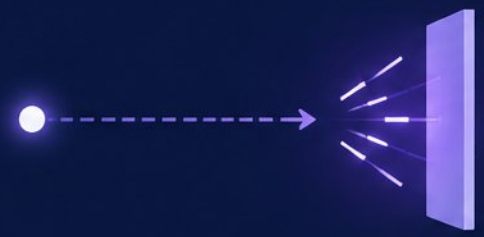
Light is neither classical wave nor classical particle — quantum theory needs both descriptions for a complete account

Wave Evidence



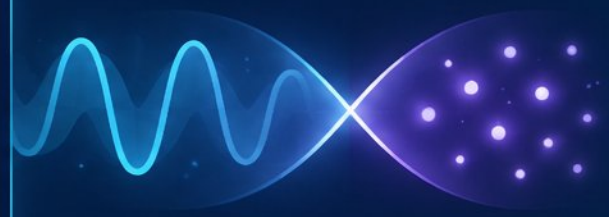
interference, diffraction, Maxwell's electromagnetism

Particle Evidence



photoelectric effect, Compton scattering, single-photon detection

Quantum Synthesis



Misconception: photons are not tiny balls with definite paths; light does not 'decide' to be a wave or particle

Misconception: observation does not require a person — any available which-path record destroys interference

Misconception: duality is not vague philosophy — the experimental arrangement sets which behavior appears, and predictions are quantitative

Reflect, Discuss, and Explore Further

- Why does one photon never appear in two places, yet still build fringes?
- Small groups: pick a device — does it assume a wave, a particle, or both?
- Explore: single-photon double-slit demos and Vienna's nanoparticle interference record
- Looking ahead: quantum computing, quantum key distribution, matter-wave sensing
- Light is not forced to choose — the experiment chooses which face we see
- All interpretations share Schrödinger's equation and Born rule, $P = |\psi|^2$
- "Shut up and calculate" remains a common working attitude



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