Quantum

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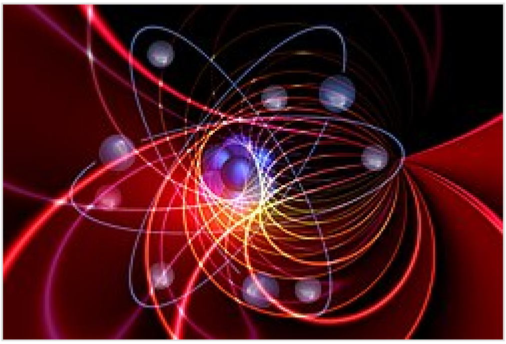
The Unreality of the Quantum World

The quantum world is not like anything we experience in daily life. Energy, matter, and other physical quantities are not continuous, but exist in tiny, indivisible packets called quanta. Quantum Mechanics, the science of these building blocks, shows a universe where particles can behave like waves and even become entangled at a distance.

History

Quantum mechanics emerged in the early 20th century to resolve puzzles that classical physics could not explain, such as black-body radiation, atomic spectra, and the photoelectric effect.



Physics-3871216 1920

- In 1900, Max Planck proposed that energy is emitted in discrete packets called *quanta* to solve the ultraviolet catastrophe.
- In 1905, Albert Einstein used the quantum idea to explain the photoelectric effect, showing that light itself behaves as particles (later called photons).
- Niels Bohr incorporated quantization into his 1913 model of the atom, explaining atomic emission lines.
- The complete mathematical framework arrived in the mid-1920s: Werner Heisenberg developed matrix mechanics (1925), Erwin Schrödinger formulated wave mechanics (1926), and Max Born introduced the probabilistic interpretation of the wave function.
- Paul Dirac later unified quantum mechanics with special relativity, laying the groundwork for quantum field theory.

Foundational developments

Transformed physics and enabled technologies like transistors, lasers, and MRI. In recent decades, experimental advances have allowed direct observation of ultrafast quantum processes on attosecond (10−18 s) timescales.

- **Henry C. Kapteyn**, together with **Margaret M. Murnane**, pioneered high-harmonic generation (HHG) techniques that produce coherent extreme-ultraviolet and soft X-ray light using tabletop lasers, generating attosecond pulses that capture electron motion in real time.[1][2]

- **Tenio Popmintchev** extended phase-matched HHG into the soft and hard X-ray regions, demonstrating bright, coherent tabletop X-ray sources and pushing toward zeptosecond resolution.[6][7][8][9]

- **Dimitar popmintchev** is a physicist at TU Wien's Photonics Institute, specializing in high-harmonic generation (HHG) for coherent EUV/soft X-ray sources.[10][11][12][13]

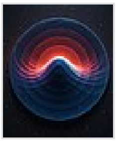
Key contributions:

- Efficient soft X-ray HHG in ionized plasmas (*Science*, 2015).[14]
- Resonant attosecond dynamics (*Phys. Rev. Research*, 2025).[15]
- Tabletop zeptosecond X-ray sources (Popmintchev LABS).[16]These breakthroughs have revolutionised coherent X-ray science and the study of quantum dynamics in matter. Ongoing work by researchers like these continues to bridge foundational quantum principles with cutting-edge experiments and applications.

Core Concepts and introduction to the Quantum World

- **Quantum**: The smallest unit of a physical property. Imagine a single “portion” of energy or matter that cannot be broken down any further.
  For introduction to Quantum Mechanics (QM) and learning about its behaviour this course is highly recommended (https://www.fisica.net/mecanica-quantica/Griffiths%20-%20Introduction%20to%20quantum%20mechanics.pdf)
- Above lecture does not include Schödingers Time Dependant formula, if you follow this lecture it will show you a formula to predict the future. (https://oyc.yale.edu/physics/phys-201/lecture-24#:~:text=Overview,of%20definite%20energy)%20is%20discussed.)
- **Physics** is the scientific study of matter, its fundamental constituents, its motion and behavior through space and time, and the related entities of energy and force.[17] It is one of the most fundamental scientific disciplines.[18][19][20]

- **Quantum Physics (QP)** studies energy and matter at the fundamental level. To reveal the behaviors and properties of the building blocks of the universe. Quantum experiments involve very small objects, named electrons and photons, quantum phenomena are everywhere, on every scale.

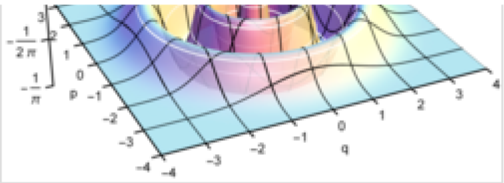


QP

- **Quantum field theory**, here the state of the system is described by a state vector in Fock space, which includes states with different numbers of particles.
  The vacuum state (no particles) is denoted $|0\rangle$, and satisfies $a_p|0\rangle = 0 \quad \text{for all momenta } p$ (where a_p is the annihilation operator for mode p). The quantum field $\phi(x,t)$ is an operator that can create or destroy particles. It is built from creation and annihilation operators:

$$\phi(x,t) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2\omega_p}} \left[a_p\, e^{-ip\cdot x} + a_p^\dagger\, e^{ip\cdot x}\right]$$

  (with appropriate relativistic conventions for the 4-vector $p \cdot x = \omega_p t - \mathbf{p} \cdot \mathbf{x}$ and $\omega_p = \sqrt{\mathbf{p}^2 + m^2}$ for a scalar field).Its action on the vacuum creates a superposition of one-single-particle state $|\psi\rangle$ (say with wavefunction $\psi(p)$ in momentum space), the field can annihilate the particle (giving vacuum) or create an extra one (giving two particles). Roughly speaking, the annihilation part of the field acts like:



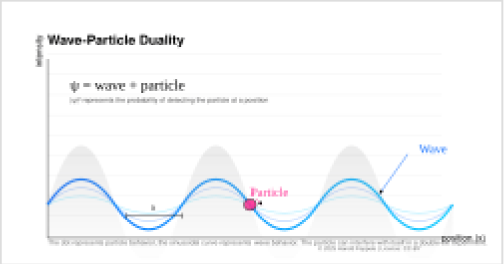
Wigner function for a Fock state with photon number n = 4 (shows structure for non-vacuum Fock states).

$[\textbf{annihilation part of } \phi(x)]\ |\textbf{particle at/near } y\rangle \ \approx\ \delta(x-y)\ |0\rangle$ This is why field operators are said to "probe" for particles at a point — but always remember the full ϕ contains both creation and annihilation parts.

- **Quantum Mechanics**: can describe many systems that classical physics cannot. Classical physics can describe many aspects of nature at an ordinary (macroscopic and (optical) microscopic) scale, but is not sufficient for describing them at very small submicroscopic (atomic and subatomic) scales. Classical mechanics can be derived from quantum mechanics as an approximation that is valid at ordinary scales.

QM

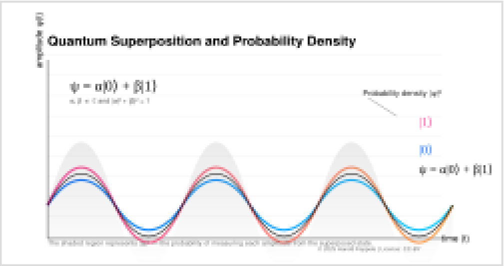
- **Wave–particle duality**: Particles like electrons sometimes act like solid objects and sometimes like waves. The famous double-slit experiment shows this: electrons send through two narrow openings create an interference pattern, behaving like waves, but when measured, they appear as particles. The observation itself seems to influence reality.



Wave-Particle Duality

Superposition and Quantum entanglement

- **Superposition:** A quantum particle can exist in several different states simultaneously. Schrödinger captured this strangeness with his famous thought experiment: a cat sealed in a box, tied to a random quantum event. Until the box is opened and observed, the cat is, in a very real quantum sense, both alive and dead at the same time. This dramatically illustrates how quantum logic defies our everyday intuition.



Quantum Superposition and Probability Density

- **Quantum entanglement**: Two or more particles can become linked so that the state of one influences the other, even at a distance. Einstein called this “spooky action at a distance.” Experiments have confirmed it, as the basis of quantum computing and secure communication.

entangled, particles stay correlated indefinitely, as long as their quantum states are not disturbed by interactions with the environment (a process called decoherence). This is true even across large distances, since entanglement is a property of the quantum wave function and doesn't rely on signals traveling between the particles, it's instantaneous and non-local. The key point is that no information can be transmitted faster than light via entanglement (due to the no-communication theorem), preserving causality in relativity. In principle, entanglement could span the entire universe, limited only by practical challenges like maintaining coherence.

Entanglement via (APT)

Practical Limits and Experimental Distances

While theory allows unlimited distance, real-world experiments face limitations from decoherence (e.g., due to interactions with air molecules, fiber optic losses, or noise). Photons (light particles) are commonly used for long-distance tests because they travel far with minimal interaction, often via optical fibers, free space, or satellites. Here's a summary of key achievements:

Artist impression of Quantum internet

- **Short to Medium Distances (Lab-Scale)**: Early tests, like Alain Aspect's 1982 experiment, confirmed entanglement over meters. More recent ion-based entanglement has reached 230 meters in labs, useful for quantum computing prototypes. Atomic entanglement over 33 km of fiber optic cable was achieved in 2022, setting a record for matter-based systems.

- **Long-Distance Ground-Based**: In 2022, researchers entangled photons over 248 km of optical fiber, a new record for fiber-based transmission. This doubled the previous 100 km mark and is a step toward practical quantum networks. Atmospheric tests have reached 144 km (e.g., between Canary Islands in 2007).

- **Space-Based and Satellite Records**: The farthest confirmed entanglement is about 1,203 km, achieved in 2017 using China's Micius satellite. Photons were beamed from space to ground stations in China, violating Bell inequalities (a test for true entanglement) and demonstrating survival over extreme distances. This shattered earlier records like 88 miles (142 km) in 2012.

- **Even Heavier Particles**: In 2024, the CMS experiment at CERN observed entanglement between top quarks (the heaviest known particles) at the Large Hadron Collider. While the physical distance is tiny (subatomic), their high relative speeds mean the effective "distance" for any classical signal would exceed light-speed limits, confirming non-local action.

Uncertainty Principle

One of the discoveries in quantum mechanics is the **Heisenberg Uncertainty Principle** (1927), formulated by Werner Heisenberg. It states that there are fundamental limits to how precisely we can simultaneously know certain pairs of properties of a particle, most famously, its **position** and **momentum** (mass × velocity).

The mathematical statement is:

$$\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$$

where:

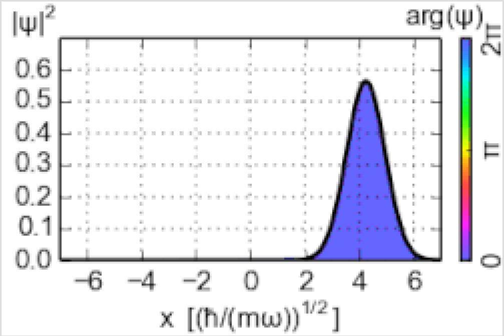
- Δx is the uncertainty (spread) in position,
- Δp is the uncertainty in momentum,
- $\hbar = h/2\pi$ (reduced Planck's constant).

This inequality means the product of the uncertainties is **at least** a small but non-zero constant, Δx and Δp can not be arbitrarily small at the same time.

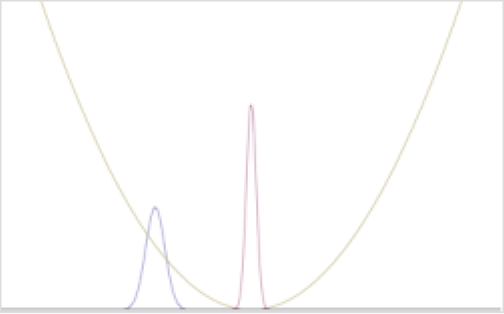
The following images illustrate how a narrow position uncertainty forces a large spread in momentum (and vice versa), shown with Gaussian wave packets:

This is **not** a limitation of our measuring instruments, it is a fundamental property of nature. Particles do not have definite position **and** momentum simultaneously in the classical sense; their quantum state is described by a wave function that inherently spreads out these properties.

A thought experiment illustrating this is **Heisenberg's microscope**: To pinpoint a particle's position very accurately, you need short-wavelength (high-energy) light, but that high-energy photon kicks the particle hard, disturbing its momentum wildly. Longer-wavelength light is gentler but gives blurry position information.



QHO-coherentstate3-animation-color



Position and momentum of a Gaussian initial state for a QHO, wide

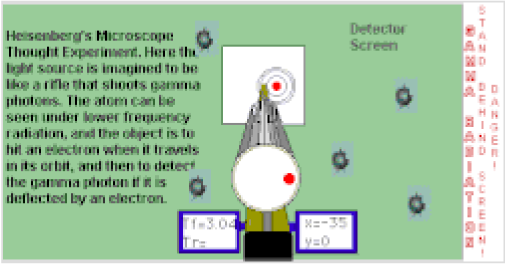
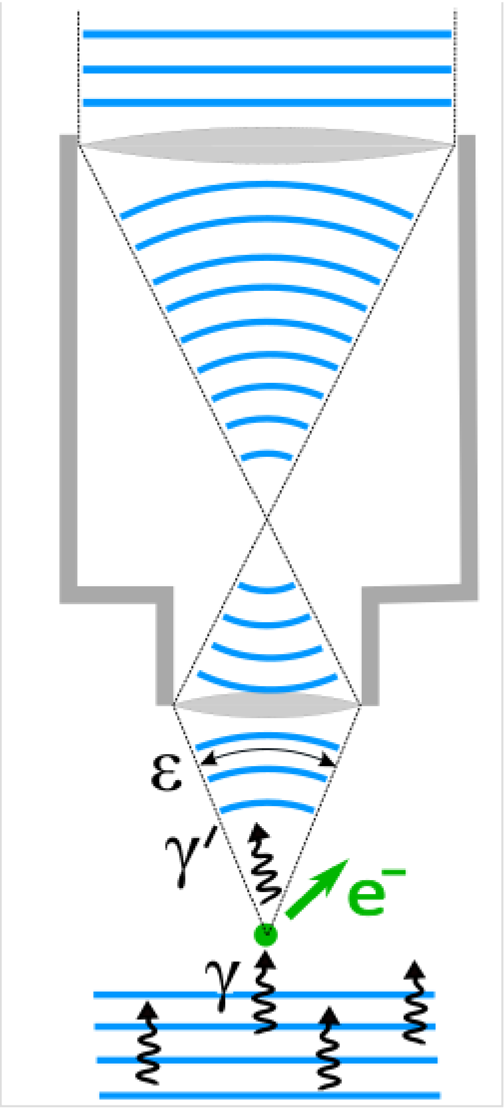


Illustration of Heisenberg's gamma-ray microscope thought experiment: high-resolution light disturbs momentum. Source: Wikimedia Commons.

The uncertainty principle: applies to other conjugate pairs too (e.g., energy and time: $\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$), explaining phenomena like virtual particles, quantum tunneling, and the stability of atoms (electrons not to be localized near the nucleus without huge momentum uncertainty). The quantum world is not just "small classical physics", it has built-in fuzziness and trade-offs that challenge our intuitions about reality.

shapes everything. It directly feeds into the probabilistic nature of quantum mechanics: since perfect certainty is impossible, nature deals in uncertainty rather than fixed paths. This built-in fuzziness is why observation is so important, measuring one property forces the system to "choose" in a way that blurs the complementary one.



Heisenberg microscope with wavefronts and electron scatter

The Quantum Revolution

For centuries, scientists saw the universe as a precise, predictable apparatus. Newtonian physics suggested that if you knew the position and motion of every object, you could predict the future perfectly. But the early twentieth century shattered this view. Experiments with atoms and light revealed that classical laws no longer applied. Energy was quantized, light sometimes behaved like a wave and sometimes like particles, and certainty gave way to probability.

Quantum Mechanics emerged as a revolutionary framework, changing how we understand nature. Unlike classical physics, it does not give precise predictions. Instead, it provides probabilities, the propability of finding a particle in a particular place at a particular time. This uncertainty is not a flaw; it is the fundament of reality.

The Weirdness That Works

Though abstract, Quantum Mechanics touch our daily lives. Semiconductors in computers, lasers in medical devices, and the atomic clocks that power GPS systems all rely on quantum principles. Superposition and entanglement are no longer just theoretical oddities, quantum computing, promising machines that solve certain problems far faster than any classical computer. Quantum communication uses entanglement to create ultra-secure information channels resistant to eavesdropping.

Even as quantum theory transforms technology, it challenges our intuition. Cause and effect, certainty, and even the very notions of space and time seem different at the quantum level. Particles can appear in two places at once, outcomes can seem random, and yet an underlying order governs it all.

Quantum Mechanics challenges our way of thinking about reality itself. While the world we see follows simple, predictable rules, the universe at its smallest scales is based on principles that seem almost unreal. It is a place where observation shapes reality, where distant particles are linked, and where probabilities replace certainties.

Exploring quantum is not just about physics; it is traveling into the nature of the universe. Every discovery, from quantum computers to secure communication systems, shows a world more intricate than our everyday experience suggests.

The quantum world may not be intuitive, but it shows the elegance of nature.With its rules, new technologies evolve, and a deeper understanding of reality, a universe more subtle than we ever imagined.

See also

- Quantum
- Quantum A Matter Of Size
- Quantum A Spooky Action at a Distance
- Quantum: A Walk Through the Universe
- Number of independent spatial modes in a spherical volume
- Quantum Computing Algorithms in the NISQ Era
- Quantum Formulas Collection
- Quantum Matter Elements and Particles
- Quantum mechanics
- Quantum mechanics/Timeline
- Quantum mechanics measurements
- Quantum Noisy Qubits
- Quantum optics beam splitter experiments
- Quantum: The Secret of Cohesion: How Waves Hold Matter Together
- Quantum Ultra fast lasers
- Template:Quantum optics operators
- Physical Sciences

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16. Hernández-García, C.; Popmintchev, T.; Murnane, M.; Kapteyn, H. C. (2013). "Zeptosecond High Harmonic keV X-Ray Waveforms Driven by Midinfrared Laser Pulses". *Physical Review Letters* **111** (3): 033002. doi:10.1103/PhysRevLett.111.033002.
17. Maxwell 1878, p. 9 "Physical science is that department of knowledge which relates to the order of nature, or, in other words, to the regular succession of events."
18. Young & Freedman 2014, p. 1 "Physics is one of the most fundamental of the sciences. Scientists of all disciplines use the ideas of physics, including chemists who study the structure of molecules, paleontologists who try to reconstruct how dinosaurs walked, and climatologists who study how human activities affect the atmosphere and oceans. Physics is also the foundation of all engineering and technology. No engineer could design a flat-screen TV, an interplanetary spacecraft, or even a better mousetrap without first understanding the basic laws of physics. (...) You will come to see physics as a towering achievement of the human intellect in its quest to understand our world and ourselves."
19. Young & Freedman 2014, p. 2 "Physics is an experimental science. Physicists observe the phenomena of nature and try to find patterns that relate these phenomena."
20. Holzner 2006, p. 7 "Physics is the study of your world and the world and universe around you."

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