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The Exciting World of Quantum Science

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The Birth of Quantum Science

Classical physics, dominated by Newtonian mechanics, Maxwell's electromagnetism, and thermodynamics, effectively explained most natural phenomena. However, by the late 19th and early 20th centuries, it began to falter when addressing certain problems.

One key issue was the "ultraviolet catastrophe," where classical physics predicted that blackbody radiation at high frequencies would emit infinite energy, a result that clearly contradicted experimental observations. Another problem was the photoelectric effect, where classical physics couldn't explain why light could eject electrons from a metal surface only if it had a frequency above a certain threshold, regardless of its intensity.

These failures led to the birth of quantum science, initiated by Max Planck in 1900, who proposed that energy is quantized, existing in discrete packets called "quanta." Planck's Quantum Hypothesis, introduced by Max Planck in 1900, was a revolutionary idea that marked the beginning of quantum theory. It was proposed to solve the problem of blackbody radiation, specifically the "ultraviolet catastrophe," which classical physics could not explain. In classical physics, it was assumed that energy could be emitted or absorbed in any continuous amount. However, when applying this idea to blackbody radiation (the radiation emitted by a perfect black body), the theory predicted that the energy emitted at high frequencies (short wavelengths) would become infinite, a result that was clearly not observed in experiments.

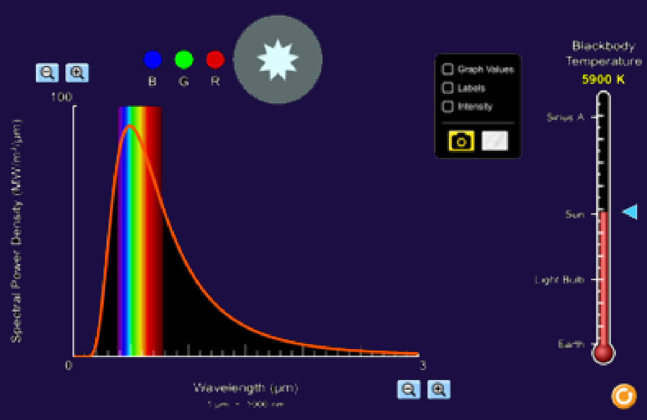
To resolve this, Planck proposed that energy is not continuous but is instead quantized. According to his hypothesis, energy is emitted or absorbed in discrete packets, or "quanta," rather than in a smooth, continuous flow.

The energy (E) of each quantum is directly proportional to the frequency (f) of the radiation:

$$E = h \times f$$

where:

- E is the energy of the quantum,
- f is the frequency of the radiation,
- h is Planck's constant, a fundamental constant of nature with a value of approximately 6.626×10^{-34} Joule-seconds.



Blackbody Spectrum

(Source: PhET Interactive Simulation for Blackbody Radiation)

This idea was revolutionary because it challenged the classical view that energy is continuous. Planck's hypothesis successfully explained the observed spectrum of blackbody radiation, avoiding the ultraviolet catastrophe by predicting that energy at very high frequencies would be emitted in such small quanta that it would be negligible.

Planck himself initially considered this hypothesis a mathematical trick, but it was later validated and expanded upon by other physicists, leading to the development of quantum mechanics. The idea that energy is quantized became a cornerstone of quantum theory, fundamentally altering our understanding of the physical world.

Photoelectric Effect

The photoelectric effect is a phenomenon where light striking a metal surface causes the emission of electrons from that surface. This effect was observed in the late 19th century, but it could not be explained by classical physics. According to classical wave theory, light is considered a wave, and its energy is related to its intensity (brightness). The classical explanation predicted that increasing the intensity of light should increase the energy of emitted electrons, regardless of the light's frequency. It also predicted that, given enough time, even low-frequency light should eventually provide enough energy to eject electrons.

However, experiments showed that:

- Electrons were emitted only if the light had a frequency above a certain threshold regardless of its intensity. Below this threshold frequency, no electrons were emitted, no matter how intense the light.
- Electrons were ejected almost instantaneously when exposed to light above the threshold frequency, with no noticeable delay.
- The kinetic energy of the emitted electrons depended on the frequency of the light, not its intensity. Higher frequency light produced more energetic electrons.

Einstein's Explanation of the Photoelectric Effect

In 1905, Albert Einstein provided an explanation for the photoelectric effect that built upon Max Planck's quantum hypothesis. Einstein proposed that light is not just a continuous wave but is made up of discrete particles called photons. Each photon carries a specific amount of energy, proportional to the light's frequency:

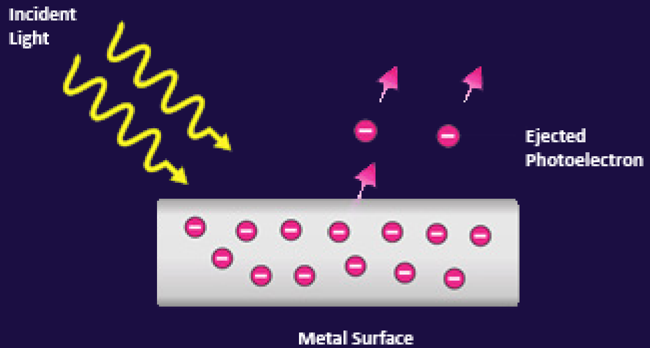
$$E_{photon} = h \times f$$

where:

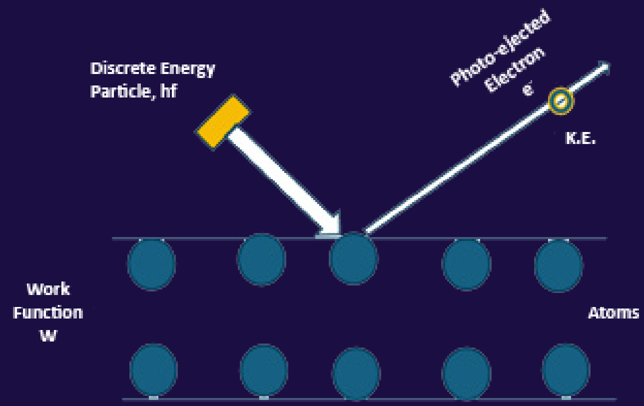
- E_{photon} is the energy of the photon,
- f is the frequency of the light,
- h is Planck's constant.

Einstein explained the photoelectric effect as follows:

- **Photon Energy and Electron Ejection:** When a photon strikes the surface of the metal, it transfers its energy to an electron. If the photon's energy is greater than the work function (the minimum energy required to eject an electron from the metal), the electron is emitted. If the energy is below the work function, the electron remains bound to the metal, regardless of the light's intensity.
- **Threshold Frequency:** The threshold frequency corresponds to the minimum energy (work function) needed to eject an electron. Thus, only light with a frequency higher than this threshold can cause the emission of electrons.
- **Kinetic Energy of Electrons:** If the photon has more energy than the work function



A schematic diagram of Photoelectric Effect
(Source: https://byjus.com/jee/photoelectric-effect/)



A schematic diagram for the Einstein's explanation of photoelectric effect

(W), the excess energy is converted into the kinetic energy of the emitted electron:

$$K.E. = h \times f - W$$

This equation shows that the kinetic energy of the emitted electrons depends directly on the frequency of the incident light and not on its intensity. Thus Albert Einstein further advanced the quantum theory by explaining the photoelectric effect using Planck's idea, proposing that light itself is quantized into photons.

The Development of Quantum Mechanics

Einstein's explanation of the photoelectric effect was significant because it provided strong evidence for the quantization of light and supported the concept that light exhibits both wave-like and particle-like properties (wave-particle duality). His work on the photoelectric effect earned him the Nobel Prize in Physics in 1921, and it played a crucial role in the development of quantum mechanics.

Quantum mechanics continued to develop with contributions from scientists like Niels Bohr, who introduced the Bohr model of the atom, and Werner Heisenberg, who formulated the uncertainty principle. Erwin Schrödinger and Paul Dirac also made significant contributions, establishing the foundations of quantum mechanics as a robust framework that successfully explains phenomena at atomic and subatomic scales, where classical physics fails.

Bohr's Model of the Atom (1913)

- Niels Bohr proposed a model of the atom in which electrons orbit the nucleus in quantized energy levels. This model successfully explained the spectral lines of hydrogen and introduced the idea of quantized atomic states.

Wave-Particle Duality (1924-1926)

- Louis de Broglie proposed that particles such as electrons have wave-like properties, leading to the concept of wave-particle duality.
- Erwin Schrödinger formulated the wave equation (Schrödinger equation), which describes how the quantum state of a physical system evolves over time. This established the wave mechanics formulation of quantum mechanics.

Quantum mechanics

Heisenberg's Uncertainty Principle (1927)

- Werner Heisenberg introduced the uncertainty principle, stating that the position and momentum of a particle cannot be simultaneously measured with arbitrary precision. This principle highlighted the fundamental limits of measurement in quantum mechanics.

Matrix Mechanics and Quantum Formalism (1925-1926)

- Werner Heisenberg, Max Born, and Pascual Jordan developed matrix mechanics, an early form of quantum mechanics that used matrices to describe the physical properties of particles.

Dirac's Relativistic Quantum Theory (1928)

- Paul Dirac developed a relativistic quantum theory that combined quantum mechanics with special relativity. His equation predicted the existence of antimatter, later confirmed with the discovery of the positron.

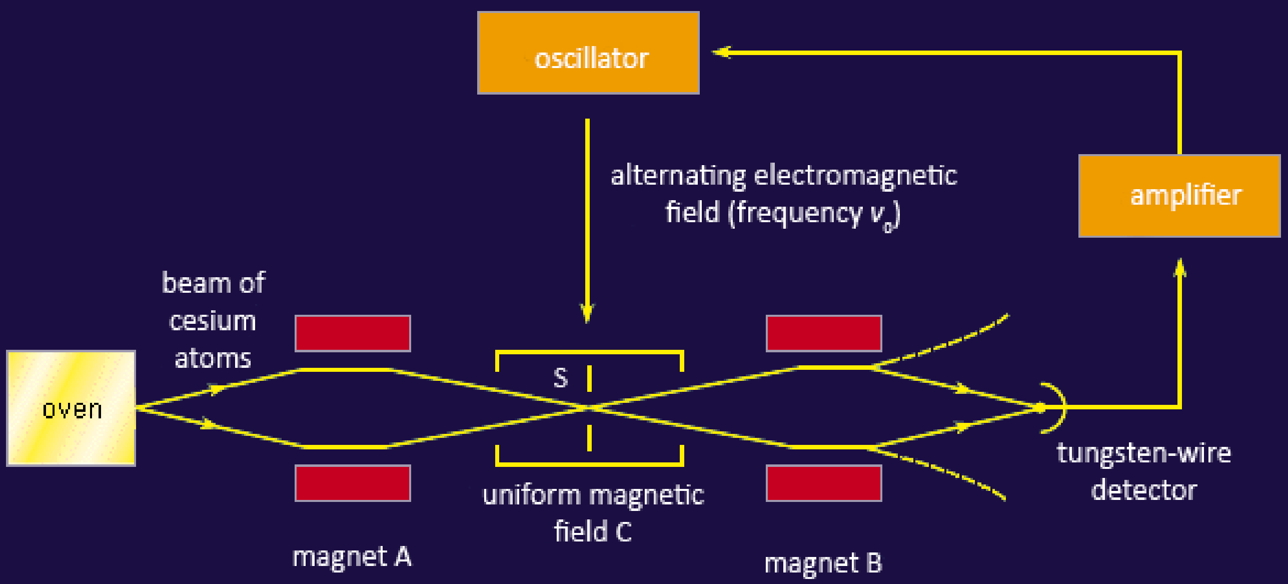
Quantum Electrodynamics (1940s)

- Quantum electrodynamics (QED) was developed by Richard Feynman, Julian Schwinger, and Sin-Itiro Tomonaga. QED is a quantum field theory that describes the interaction of light (photons) with matter, providing a highly accurate description of electromagnetic interactions.

Quantum Mechanics: Impact and Legacy

Quantum mechanics revolutionized our understanding of the microscopic world, explaining phenomena such as atomic and molecular structures, chemical reactions, and the behaviour of particles at the atomic and subatomic levels. Its important features are mentioned in the following:

- **Tiny Particles:** Quantum science studies incredibly small particles, like electrons, protons, and photons (particles of light).
- **Wave-Particle Duality:** These tiny particles sometimes behave like particles and sometimes like waves, meaning they don't have a definite position but rather exist in a spread-out wave of probabilities.
- **Quantization:** Energy levels in atoms are quantized, meaning they can only exist at certain discrete levels, not in between.
- **Superposition:** Particles can be in multiple states at once. For example, an electron can spin both clockwise and counterclockwise at the same time until it is observed.
- **Entanglement:** Particles can become entangled, meaning the state of one particle is instantly connected to the state of another, no matter how far apart they are. This puzzled



even Einstein, who called it “spooky action at a distance.”

- **Uncertainty Principle:** We can’t measure both the exact position and the exact momentum of a particle simultaneously. The more precisely we know one, the less precisely we know the other.

Quantum Mechanics also laid the foundation for modern technologies like semiconductors, lasers, and quantum computing. Its development marked a fundamental shift from deterministic classical physics to a probabilistic framework, where particles and waves are described by probabilities and uncertainties, forever changing our understanding of the universe.

Quantum science challenges our classical understanding of the universe and opens up new possibilities for technology and our comprehension of reality itself. It shows that the world at its most fundamental level behaves in ways very different from our everyday experiences. Some of the most important applications of Quantum Science in our day-today lives are:

- **Electronics:** Quantum mechanics is the foundation of modern electronics, including transistors and semiconductors that power computers and smartphones.
- **Lasers:** The principles of quantum mechanics are used in lasers, which are integral to various technologies like CD players and medical equipment.
- **MRI Machines:** Medical imaging techniques like MRI scans are based on quantum principles.

Quantum Technologies

While quantum science might seem strange and counterintuitive, it is a powerful and essential part of modern physics that has profound implications for technology and our understanding of the universe.

Key Principles:

- **Superposition:** Quantum systems can exist in multiple states simultaneously. For example, a quantum bit (qubit) can be both 0 and 1 at the same time.
- **Entanglement:** Quantum particles can be interconnected in such a way that the state of one instantaneously affects the state of another, regardless of the distance between them.
- **Quantum Interference:** The phenomenon where quantum states can combine and interfere with each other, leading to probabilities that differ from classical expectations.

Types of Quantum Technologies

- **Quantum Computing:** Uses qubits to process information in ways classical computers can’t, solving complex problems like cryptography, optimization, and drug discovery much faster. Companies like Google and IBM are developing quantum computers for tasks infeasible for classical computers.
- **Quantum Cryptography:** Uses quantum mechanics to secure communication, providing theoretically unbreakable encryption through Quantum Key Distribution (QKD).
- **Quantum Sensing:** Uses quantum phenomena to make highly sensitive measurements, improving medical imaging, navigation systems, and geological exploration.
- **Quantum Simulation:** Uses quantum computers to simulate complex quantum systems, aiding in understanding complex phenomena and developing new materials and drugs.

Unleashing the Future: The Quantum Computing Revolution

Quantum Healthcare:

Quantum computing, harnessing quantum mechanics, promises to revolutionize various sectors, notably healthcare.

- **Potential in Drug Discovery and Development:** Quantum simulations can accurately predict molecular behaviours, expediting drug discovery and treatment development for diseases like Alzheimer's, cancer, and genetic disorders.
- **Enhancing Diagnostic Accuracy:** Quantum computing can improve diagnostic accuracy by efficiently analysing vast medical data, crucial for early disease detection.
- **Quantum Sensors:** Revolutionizing Healthcare Monitoring: Quantum sensors, leveraging quantum mechanics for high sensitivity, can revolutionize healthcare by improving medical imaging and real-time health monitoring.

- **Applications in Medical Imaging:** Quantum sensors enhance MRI and CT scan resolution, aiding in early disease diagnosis.
- Real-Time Health Monitoring: Wearable quantum sensors provide continuous monitoring of vital signs, aiding in chronic condition management.

Quantum Entanglement: The Future of Secure Communication

Quantum entanglement, interconnecting particles in a way that the state of one affects the other, even over vast distances, revolutionizes secure communication.

- **Quantum Key Distribution (QKD):** QKD creates a secure communication channel by alerting parties to any eavesdropping attempts.
- **Enhancing Cybersecurity:** Quantum encryption techniques protect data from cyber-attacks, ensuring secure information transmission.

Quantum Machine Learning: Pushing AI Boundaries

- Quantum machine learning, combining quantum computing and AI, enhances data processing and analysis efficiency.
- **Accelerating AI Training:** Quantum computers expedite AI model training, advancing fields like natural language processing, image recognition, and autonomous systems.
- **Improving AI Accuracy:** Quantum algorithms enable more accurate predictions, benefiting finance, healthcare, and climate modelling.

Quantum Teleportation: The Next Frontier in Technology

Quantum teleportation, transferring quantum information over distances, revolutionizes communication and computing.

- **Applications in Secure Communication:** Quantum teleportation enables secure communication networks, immune to traditional hacking methods.
- **Advancing Quantum Computing Networks:** Quantum teleportation connects

quantum computers, enhancing computational power.

Quantum Internet

The key principles of Quantum Internet are:

- **Quantum Entanglement:** Allows interconnected particles to influence each other's states instantaneously, enabling secure communication channels.
- **Quantum Superposition:** Qubits can exist in multiple states simultaneously, facilitating advanced information transmission and processing.
- **Quantum Teleportation:** Transmits quantum information using entanglement and classical communication.

Its working is based on:

- **Quantum Nodes:** Devices that create, process, and measure qubits.
- **Quantum Channels:** Links transmitting qubits, like fiber-optic cables or free-space links.
- **Quantum Repeaters:** Extend quantum communication range by correcting errors and preserving entanglement.

The advantages of quantum internet are:

- **Unhackable Communication:** Quantum key distribution provides theoretically immune communication to eavesdropping.
- **High Computational Power:** Connecting quantum computers to solve complex problems.
- E**nhanced Security:** Securing data transmission beyond classical methods.

It has the following applications:

- **Secure Communication:** For governments, military, and businesses.
- **Distributed Quantum Computing:** Harnessing combined computational power.
- **Quantum Cloud Services:** Remote access to powerful quantum computers.
- **Precision Timekeeping and Synchronization:** Synchronizing global clocks with unprecedented accuracy.

The quantum internet, still in its infancy, promises to revolutionize communication, computation, and security, leading to groundbreaking innovations.

INTERNATIONAL YEAR OF
Quantum Science
and Technology

The United Nations Proclamation of 2025 as the International Year of Quantum Science and Technology

On June 7, 2024, the United Nations declared 2025 as the International Year of Quantum Science and Technology (IYQ). This year-long initiative aims to enhance global awareness of quantum science and its applications, marking a century since the inception of quantum mechanics. The proclamation follows widespread support from several scientific societies and international organizations. Mexico led the effort, with UNESCO's Executive Board endorsing the resolution in May 2023, followed by the UNESCO General Conference's support in November 2023. In May 2024, Ghana formally submitted a draft resolution for official proclamation of the International Year to the U.N. General Assembly which, with co-sponsorship from six countries, was approved on June 7, 2024.

The entire process of preparation of documents and placing them before various committees of UNESCO, leading to the proclamation of 2025 as IYQ by the United Nations, was accomplished by Professor John Dudley (Professeur à l'Université de Franche-Comté ; Chargé de Mission Communication Scientifique, France) and Professor Joseph Niemela (Abdus Salam International Centre for Theoretical Physics, Italy).

The U.N. declaration invites individuals, groups, schools, institutions, and governments to use 2025 to promote quantum science and technology. The IYQ Steering Committee is organizing global initiatives and events, especially for audiences less familiar with quantum science. As 2025 approaches, this website will feature events, resources, and activities related to quantum science.

Quantum science will play a crucial role in addressing major global challenges outlined in the U.N.'s 2030 Sustainable Development Goals, such as climate change, energy, food security, and clean water. Inspiring the next generation of quantum pioneers will be key to driving innovation and making a positive impact on society.

The International Year offers a unique chance for people of all ages to explore how quantum science influences our world, technology, policies, economy, and culture. Leading up to 2025, individuals, groups, organizations, and governments are encouraged to create events and resources to enhance understanding of quantum science and technology.

Conclusion

Quantum science and technology are poised to transform our world in unimaginable ways. From revolutionizing healthcare with quantum computing and sensors to ensuring secure communication through quantum entanglement, the potential applications are vast. As research and development continue, we can expect groundbreaking innovations that will reshape industries and improve lives. The role of the United Nations in declaring 2025 as the International Year of Quantum Science and Technology is particularly very significant as the IYQ events organized throughout the world will connect various nations in understanding the importance of quantum science and technology. ◆

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