Quantum Theory in a nutshell, by Jeffrey Huynh

Quantum Theory refers to the theoretical basis that explains how energy and matter behave at the atomic and subatomic level.

Quantum: The smallest amount of energy that a particle can emit or absorb.

The most significant difference between quantum theory and classical physics is how quantum objects behave. Particles exhibit interference at the quantum level, which defy the laws of classical physics.

Classical Physics	Quantum Physics
• Energy is carried via. wave and particles • Waves exhibit interference, particles do not • Particles deliver energy in discrete amounts, waves deliver continuously	• Microscopic particles • All quantum objects (such as EM radiation and electrons) exhibit interference and transfer energy in discrete amounts

Wave-Particle Duality: All matter exhibit the properties of particles that have mass as well as waves that transfer energy.

Work Function: The minimum energy to remove a single electron from a piece of metal. Measured in electron-volts (1 eV = 1.60×10^{-19} J)

The work function of an electron can be described with the equation:

$$W = e\Delta V$$

,where
- W is the work function of the metal (J or eV)
- e is the charge on an electron (1.6×10^{-19} C)
- ΔV is the potential difference (V)

Photoelectric Effect: Phenomenon in which electrons can be ejected from a material when exposed to EM radiation. Requires a certain frequency for this to occur, called the threshold frequency (f_0).

- f_0 is independent of light intensity (brightness)
- E_k of ejected electrons are independent of light intensity

Photon: Proposed by Einstein, a discrete bundle of energy carried by light, does not have mass and exhibits interference effects.

The energy of a photon can be described with the equation:

$$E_p = hf = \frac{hc}{\lambda}$$

, where
- E_p is the amount of energy possessed by a photon (J)
- h is Planck's Constant (6.63×10^{-34} J·s)
- f is the frequency of the photon (Hz)
- c is the speed of light (3.00×10^{8} m/s)
- λ is the wavelength of the light (m)

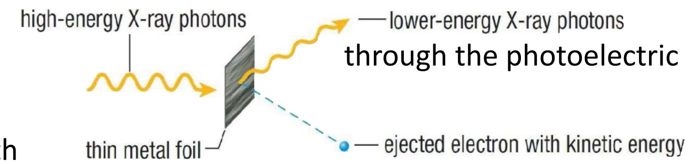
Einstein's photon proposal explains that the photoelectric effect occurs as a collision between a photon and an electron. The energy of the photon corresponds to the energy of the ejected electron.

The energy of an ejected electron can be described with the equation:

$$E_k = hf - W$$

, where
- E_k is the maximum kinetic energy of an ejected electron (J)
- h is Planck's Constant (6.63×10^{-34} J·s)
- f is the frequency of the EM wave (Hz)
- W is the work function of the metal (J)

$E_{photon} < W$ Electron does not escape.
$E_{photon} = W$ Electron barely escapes ($E_k = 0$)
$E_{photon} > W$ Electron escapes and flies off ($E_k > 0$)



<u>Compton Effect</u>: The elastic scattering of photons and electrons by higher energy photons through the photoelectric effect. Energy and momentum are conserved.

The momentum of a photon can be described with the equation:

$$p_p = \frac{hf}{c} = \frac{h}{\lambda}$$

, where
p_p is the momentum of a photon (kg·m/s)
h is Planck's Constant (6.63×10^{-34} J·s)
f is the frequency of the photon (Hz)
c is the speed of light (3.00×10^{8} m/s)
λ is the wavelength of the photon (m)

There are five interactions that can occur as a result of photons coming into contact with matter.

1. Reflection – A photon undergoes a perfectly elastic collision with an object
2. Photoelectric Effect – A photon is absorbed into the material and in turn releases an electron
3. Compton Effect – A photon is absorbed and emerges with a lower energy level along with an electron, while following the law of conservation of momentum
4. Absorption – A photon is absorbed into the material and excited an electron by elevating it to a higher energy level
5. Pair Creation – A photon gets converted into two particles with mass while following the law of conservation of momentum

<u>Matter Wave</u>: The wave-like behavior exhibited by particles with mass. Represented with the de Broglie wavelength.

This can be described with the equation:

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

, where
λ is the wavelength associated with a moving particle (m)
h is Planck's Constant (6.63×10^{-34} J·s)
p is the momentum of the particle (kg·m/s)

An experiment involving aiming electrons at a crystal showed that electrons exhibit wave-like properties of interference. This was a cause of uncertainty due to particles violating the Classical Theory of Physics (objects with mass do not have interference). This was interpreted in multiple ways.

Collapse Interpretation • Electron leaves source as a particle, but spreads into a wave, and upon arrival it collapses back into a particle.	Pilot Wave Interpretation • Electron motion is dependent on a mysterious pilot wave that can determine the circumstance.
Many Worlds Interpretation • A parallel universe exists for every possible state of every electron.	Copenhagen Interpretation • A quanta exists in all states until observed. When observed, it has predictable results.

Bohr's Atom Model: Electrons orbit the nucleus at certain energy levels, and transition by absorbing photons.

Antimatter Model: A particle of equal mass and opposite charge. For example, the positron is the counterpart to the electron.

Standard Model: Nature consists of quarks, leptons, and bosons, that interact through fundamental forces of nature. Quarks combine to form hadrons (protons and neutrons) while Leptons include electrons and neutrinos. Bosons mediate the fundamental forces.

Fundamentally, almost everything we understand of our universe comes from quantum mechanics and the theory of relativity. A Theory of Everything predicts interactions in both the macroscopic and quantum worlds by combining quantum mechanics with the theory of general relativity.

Applications of Quantum Theory

- Quantum Information Technology
  - Cryptography - Photons are polarized in certain directions to create a message. When the message is sent, it can be deciphered by using a key that is recognized by both the sender and the receiver. If the message is intercepted, it will change due to the quantum system being fundamentally changed.
  - Computing - In quantum computing, bits are not limited to the 0's and 1's of binary. Instead, they can exist as both a 0 or 1, or a superposition of it. These are called qubits. Information in these qubits can be stored in multiple states simultaneously, allowing for large amounts of computing power with even smaller amounts of qubits.
- Light Technology
  - Lasers - By exciting an electron via. the photoelectric effect, a photon is absorbed and then released. The electron returns back to its lower energy level, and the photon causes a chain reaction among the atoms that creates a stream of photons that we see as a laser.
  - Light Meters - Measures the intensity of light by determining how many photons strike a metal area on the detector, which increases the current and determines the intensity of the light.
- Medicine
  - Magnetic Resonance Imaging – Produces and image by causing hydrogen nuclei in the body to align with a superconducting magnet. Used to detect illnesses in the body, such as tumors that would be difficult to see otherwise.