

Fundamental Constants

Name	Notation	Value
Planck's constant	h	$6.62607 \times 10^{-34} \text{ J s} = 4.13567 \times 10^{-15} \text{ eV s}$
Reduced Planck's constant	$\hbar (= h/2\pi)$	$1.05457 \times 10^{-34} \text{ J s} = 6.58212 \times 10^{-16} \text{ eV s}$
Speed of light	c	$2.99792 \times 10^8 \text{ m/s}$

Mass of electron	m_e	$9.10938 \times 10^{-31} \text{ kg}$
Charge of electron	$-e$	$-1.60218 \times 10^{-19} \text{ C}$
Mass of proton	m_p	$1.67262 \times 10^{-27} \text{ kg}$
Charge of proton	e	$+1.60218 \times 10^{-19} \text{ C}$
Mass of alpha particle	m_α	$6.64466 \times 10^{-27} \text{ kg}$

Wave-Particle Duality

Quantum particles have both wave properties and particle properties.

De Broglie Wavelength

- Wavelength of quantum particles:
 $\lambda = \frac{h}{p}$
- Where p is the particle momentum

Founding Experiments of Quantum Mechanics

Photoelectric Effect

Photoelectric effect: Light incident on a material ejects electrons or other charge carriers



- Classical physics predicts that:
 - The kinetic energy of emitted electrons is proportional to the intensity of the light.
 - Electrons are emitted with a time lag for low-intensity light.
- Experiments showed that:
 - The kinetic energy of ejected electrons is linear in frequency.
 - No electrons are ejected below a threshold frequency, no matter the time lag.
- Einstein resolved this puzzle by postulating that light comes in quantized bundles of energy, called **photons**.



- Photons have:
 - Frequency: f
 - Energy: $E_p = hf = pc$
 - If the energy E_p of a photon is greater than the work function Φ of the

material (i.e., the minimum energy required to eject an electron), the electron is ejected.

- Maximum kinetic energy of an emitted electron: $K_{\text{max}} = E_p - \Phi$

$$\text{Momentum: } p = \frac{E_p}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

Compton Scattering

Compton scattering: Scattering of photons from electrons

- The wavelength and momentum of a photon changes and the electron recoils.
- The classical theory of scattering (Thomson scattering) cannot explain Compton scattering.
- By treating light as photons and using special relativity, Compton obtained the correct shift $\Delta\lambda$ in the scattering light:

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{mc} (1 - \cos\theta)$$



Stern-Gerlach Experiment

- The Stern-Gerlach experiment sent a beam of silver atoms through a magnetic field that changes in the z (vertical) direction.
- The magnetic dipole moment of silver is due to its single outer electron.



- The classical prediction is that the beam would be vertically spread on the detector because the orientation of the magnetic moment of the outer electron of the Ag atom should be continuously distributed over all angles.
- The experiment showed that the electron magnetic moment is quantized and has only two possible values:
 - Spin up: S_z
 - Spin down: S_z

Sequential Stern-Gerlach Experiments

- A second Stern-Gerlach apparatus (S.G. 2) oriented in the horizontal (x) direction is placed after the first Stern-Gerlach apparatus (S.G. 1).
- The S_z beam is blocked, allowing only the S_{-y} beam to enter S.G. 2.
- The beam is split horizontally into two beams, S_{+x} and S_{-x} .
- Blocking the S_{+x} beam and running the S_{-x} beam through another S.G. 2 apparatus produces two beams again, S_{+y} and S_{-y} , despite the S_{+y} apparatus being blocked after the first S.G. 2 apparatus.



- The results of the Stern-Gerlach experiment could only be explained by describing the spin states of the electron in terms of vectors in a two-dimensional abstract vector space (not to be confused with normal two-dimensional space).
- Using the notation presented below, the base vectors are conventionally taken to be $|S_{+z}\rangle$ and $|S_{-z}\rangle$ (analogous to $\hat{i}$ and $\hat{j}$ in a two-dimensional (x, y) space). The other possible spin states are expressed as linear combinations with complex coefficients of the basis vectors:

$$|S_{+x}\rangle = \frac{1}{\sqrt{2}}|S_{+z}\rangle + \frac{1}{\sqrt{2}}|S_{-z}\rangle$$

$$|S_{-x}\rangle = -\frac{1}{\sqrt{2}}|S_{+z}\rangle + \frac{1}{\sqrt{2}}|S_{-z}\rangle$$

$$|S_{+y}\rangle = \frac{1}{\sqrt{2}}|S_{+z}\rangle + \frac{i}{\sqrt{2}}|S_{-z}\rangle$$

$$|S_{-y}\rangle = -\frac{1}{\sqrt{2}}|S_{+z}\rangle + \frac{i}{\sqrt{2}}|S_{-z}\rangle$$

Note: The analogy with $\hat{i}, \hat{j}, \hat{k}$ is limited; for instance, although $\hat{i} \cdot (-\hat{i}) = -1$ in normal 2D space, $\langle S_{+z} | S_{-z} \rangle = 0$ in the abstract vector space.

The Language of Quantum Mechanics: Vector Spaces

Quantum mechanical states are described mathematically as vectors or rays in abstract vector spaces.

- "Vector" refers not to the usual three-vector that we use in classical physics (e.g., for velocity), but to an abstract construction that can have anywhere from one to an infinite number of dimensions.
- A vector is denoted $|\lambda\rangle$, which is called a "ket" (i.e., the second syllable of "bracket").
 - An operator acts on one ket to give another ket.

Hilbert Spaces

Hilbert space: The type of vector space used to define quantum mechanical states. For a set of vectors to form a Hilbert space, they must satisfy certain rules:

- The sum of any two vectors in a given Hilbert space gives a vector in the Hilbert space. EX: $|\lambda\rangle + |\mu\rangle = |\nu\rangle$, where $|\nu\rangle$ is in the same Hilbert space as $|\lambda\rangle$ and $|\mu\rangle$.

- There exists a null vector $|0\rangle$, that when added to any vector in a Hilbert space, gives the same vector back: $|\lambda\rangle + |0\rangle = |\lambda\rangle$.
- For every vector $|\lambda\rangle$ in a Hilbert space, there exists a unique vector $-|\lambda\rangle$ that sums with it to give the null vector: $|\lambda\rangle + (-|\lambda\rangle) = |0\rangle$.
- Vector addition is commutative, which means $|\lambda\rangle + |\mu\rangle = |\mu\rangle + |\lambda\rangle$.
- Vector addition is associative, which means $(|\lambda\rangle + |\mu\rangle) + |\nu\rangle = |\lambda\rangle + (|\mu\rangle + |\nu\rangle)$.
- Multiplying a vector in a Hilbert space by a complex number a gives another vector in the Hilbert space: $a|\lambda\rangle = |\mu\rangle$.
- The distributive property holds within the Hilbert space. Thus, for complex numbers a and b :
 - $(a + b)|\lambda\rangle = a|\lambda\rangle + b|\lambda\rangle$
 - $a(|\lambda\rangle + |\mu\rangle) = a|\lambda\rangle + a|\mu\rangle$

Vectors in a Hilbert space are abstract mathematical concepts that may take the form of

functions, numbers, or groups of numbers (anything that satisfies these rules). Note: For rule 6, $|\lambda\rangle$ and $|\mu\rangle$ represent the same physical state because multiplying a ket by a complex number does not change the direction of the ket in the Hilbert space; rather, it modifies the phase of the ket.

Orthonormal Basis States

- Any vector in a Hilbert space can be expressed as a linear sum of the basis vectors of the Hilbert space.

EX: An arbitrary state $|\lambda\rangle$ can be written as $|\lambda\rangle = \sum_i \alpha_i |i\rangle$, where α_i are complex

numbers and $\sum_i |\alpha_i|^2 = 1$.

- This is analogous to a classical velocity vector being written in terms of its components: $\vec{v} = v_x \hat{i} + v_y \hat{j} + v_z \hat{k}$. Note: Like $\vec{v}$, $|\lambda\rangle$ is a physical quantity, whereas the components are abstract quantities used to describe $|\lambda\rangle$.

- The basis states are constructed to be orthonormal, so: $\langle i | j \rangle = \delta_{ij}$
 - Where δ_{ij} is the Kronecker symbol ($\delta_{ij} = 1$ for $i = j$ and $\delta_{ij} = 0$ for $i \neq j$)
 - This is analogous to $\hat{i} \cdot \hat{j} = 0$.
- An example of a quantum system described by vectors forming a Hilbert space is the set of functions that describe the electronic states of a hydrogen atom.

Kets

- Kets can be represented as column vectors, as in: $|\lambda\rangle = \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \end{pmatrix}$
 - Where α_i are complex numbers and the symbol n means "is represented by"
- The number n of elements in the column vector is the number of dimensions in the Hilbert space, which means that the Hilbert space is spanned by n basis states (i.e., any state in the given Hilbert space can be described as a linear sum of the basis states).

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