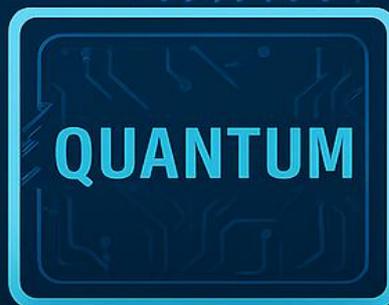
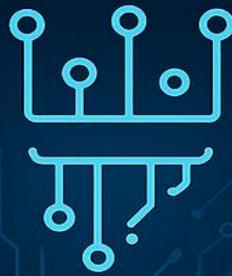


INTRODUCTION TO QUANTUM TECHNOLOGIES AND APPLICATIONS

(Qualitative Treatment)



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SYLLABUS

Unit 1

Introduction to Quantum Theory and Technologies

The transition from classical to quantum physics, Fundamental principles explained conceptually: Superposition, Entanglement, Uncertainty Principle, Wave-particle duality, Classical vs Quantum mechanics – theoretical comparison, Quantum states and measurement: nature of observation, Overview of quantum systems: electrons, photons, atoms, The concept of quantization: discrete energy levels, Why quantum? Strategic, scientific, and technological significance, A snapshot of quantum technologies: Computing, Communication, and Sensing, National and global quantum missions: India's Quantum Mission, EU, USA, China

1.0. Introduction

The course "**Introduction to Quantum Theory and Technologies**" offers a comprehensive foundation in one of the most exciting and transformative areas of modern science. With the rapid emergence of quantum computing, communication, and sensing, understanding the principles of quantum mechanics is no longer limited to theoretical physicists—it has become essential for engineers, computer scientists, and technology professionals.

This course is designed to introduce students to the fundamental concepts of quantum theory while showing how these ideas are being applied in cutting-edge quantum technologies. It begins with the basics of quantum mechanics, covering wave-particle duality, the uncertainty principle, quantum states, operators, and the Schrödinger equation, laying the groundwork for understanding how nature behaves at microscopic scales. The course then transitions into quantum computing, where students learn about qubits, quantum gates, quantum circuits, and algorithms such as Grover's and Shor's that outperform classical solutions. Students are introduced to quantum sensing and metrology, where quantum systems enable ultra-sensitive measurements vital to healthcare, navigation, and defence applications. The final unit discusses real-world industrial applications of quantum technologies, highlighting how companies like IBM, Google, and Microsoft are deploying quantum systems to solve complex problems. It also examines global initiatives and India's strategic efforts, such as the National Mission on Quantum Technologies & Applications.

The course addresses the challenges of scalability, cost, standardization, and workforce readiness, giving learners a realistic view of the current landscape. Importantly, it opens doors to emerging careers in quantum science by equipping students with interdisciplinary skills across physics, math, and programming. By studying this course, learners gain a solid understanding of the theory behind quantum phenomena and the practical knowledge needed to engage with this frontier field. As quantum technology continues to evolve, those equipped with this knowledge will be at the forefront of innovation in industries ranging from computing and cybersecurity to materials science and precision medicine.

1.1. Transition from Classical Physics to Quantum Mechanics

At the end of the 19th century, classical physics was seen as nearly complete. Newtonian mechanics explained planetary motion, Maxwell's equations described **electromagnetism**,

thermodynamics clarified heat and work, and classical optics enabled scientific tools like microscopes and telescopes. Chemistry had a basic periodic table, but the atomic structure and electron behaviour in reactions were not understood.

The transition from classical physics to quantum mechanics marks one of the most profound paradigm shifts in scientific history. Classical physics, which dominated for over two centuries, was grounded in the belief that all natural phenomena could be described by deterministic laws. Concepts such as Newton's laws of motion, thermodynamic principles, and Maxwell's equations provided a complete and elegant framework for understanding the physical world.

Rutherford's experiments revealed atoms had dense, positively charged nuclei with orbiting electrons, raising the question of why electrons didn't collapse into the nucleus—something classical physics couldn't explain due to predicted energy loss. This and other unexplained phenomena, such as **blackbody radiation**, the **photoelectric effect**, and **hydrogen spectral lines**, **molecular spectroscopy** exposed the limitations of classical models.

However, as experiments grew more precise at the atomic and subatomic scales, cracks began to appear in this classical edifice. Phenomena like **blackbody radiation** defied classical predictions, as models such as the Rayleigh-Jeans law led to absurd results like the ultraviolet catastrophe—where infinite energy emission at short wavelengths was expected. Similarly, the photoelectric effect revealed that light could behave like discrete packets of energy, or photons, as Einstein proposed—challenging the continuous wave view held by classical optics.

These challenges led to the development of quantum mechanics in the early 20th century, with major contributions from scientists like Planck, Einstein, Bohr, Schrödinger, and others. Before exploring the key quantum experiments, it introduces the classical wave model of light, which dominated thinking before quantum theory.

The stability of atoms posed another riddle. According to classical electromagnetism, orbiting electrons should continuously emit radiation and spiral into the nucleus, yet atoms remained stable. Moreover, when hydrogen gas was excited, it emitted light in distinct spectral lines rather than a continuous spectrum—something classical theory couldn't explain. These inconsistencies pointed to the need for a new theoretical framework. Enter quantum mechanics: a theory based not on certainty, but probability, where particles like electrons exhibit both wave-like and particle-like properties. Max Planck introduced the idea that energy is quantized, emitted in discrete amounts called quanta. This concept became the seed for a revolution. Niels Bohr refined atomic models using quantized orbits to explain hydrogen spectra. Louis de Broglie suggested

that matter had wave properties, while Werner Heisenberg introduced the uncertainty principle, redefining how we measure physical systems. Schrödinger's wave equation offered a new mathematical tool to describe electron behaviour in atoms.

Quantum mechanics did not just revise physics—it redefined our understanding of reality itself. Unlike classical physics, where outcomes were predictable, quantum theory embraced uncertainty and probability. Observables like position and momentum could no longer be known simultaneously with arbitrary precision. The deterministic worldview gave way to a statistical one, yet this new approach proved incredibly accurate and predictive. Quantum theory provided the foundation for semiconductors, lasers, nuclear energy, and much more. It also laid the groundwork for modern quantum technologies—such as quantum computing, quantum cryptography, and quantum sensing—which are now driving a new technological revolution. The journey from classical to quantum physics reminds us that scientific knowledge evolves, often through radical shifts, as we probe deeper into the fundamental nature of the universe.

1.1.1 Description of Light as an Electromagnetic Wave

As mentioned above, the description of electromagnetic radiation in terms of Maxwell's equation was published in the early 1860s. The solution of these differential equations described light as a transverse wave of electric and magnetic fields. In the absence of charge and current, such a wave, propagating in vacuum in the positive z -direction, can be described by the following equations:

$$\vec{\mathbf{E}} = E_0 \sin(\mathbf{k} \times \mathbf{z} - \omega t) = E_0 \sin(2\pi z/\lambda - 2\pi \nu t) \quad (1.1)$$

$$\vec{\mathbf{B}} = B_0 \sin(\mathbf{k} \times \mathbf{z} - \omega t) = B_0 \sin(2\pi z/\lambda - 2\pi \nu t) \quad (1.2)$$

where the electric field and the magnetic field are perpendicular to each other, as shown in Figure 1.1, and oscillate in phase at the angular frequency

$$\omega = 2\pi \nu \quad (1.3)$$

where ν is the frequency of the oscillation, measured in units of $\text{s}^{-1} = \text{Hz}$. In Eqs. (1.1) and (1.2), \mathbf{k} is the wave vector (or momentum vector) of the electromagnetic wave, defined by Eq. (1.4):

$$k = |\vec{\mathbf{k}}| = 2\pi/\lambda \quad (1.4)$$

Here, λ is the wavelength of the radiation, measured in units of length, and is defined by the distance between two consecutive peaks (or troughs) of the electric or magnetic fields. Vector quantities, such as the electric and magnetic fields, are indicated by an arrow over the symbol or

by bold typeface. Since light is a wave, it exhibits properties such as constructive and destructive interference. Thus, when light impinges on a narrow slit, it shows a diffraction pattern similar to that of a plain water wave that falls on a barrier with a narrow aperture. These wave properties of light were well known, and therefore, light was considered to exhibit wave properties only, as predicted by Maxwell's equation.

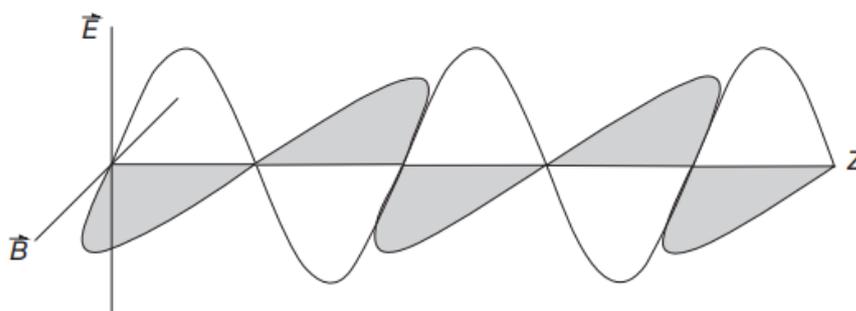


Figure 1.1 Description of the propagation of a linearly polarized electromagnetic wave as oscillation of electric (\vec{E}) and magnetic (\vec{B}) fields.

In general, any wave motion can be characterized by its wavelength λ , its frequency ν , and its propagation speed. For light in vacuum, this propagation speed is the velocity of light c ($c = 2.998 \times 10^8$ m/s). In the context of the discussion in the interaction of light with matter will be described as the force exerted by the electric field on the charged particles, atoms, and molecules. This interaction causes a translation of charge. This description leads to the concept of the “electric transition moment,” which will be used as the basic quantity to describe the likelihood (that is, the intensity) of spectral transition. In other forms of optical spectroscopy (the magnetic transition moment must be considered as well. This interaction leads to a coupled translation and rotation of charge, which imparts a helical motion of charge. This helical motion is the hallmark of optical activity, since, by definition, a helix can be left- or right-handed.

Thus, light as an electromagnetic wave serves as a bridge between classical theory and the quantum view. While Maxwell's equations beautifully describe the propagation and wave behaviour of light, they fall short when explaining phenomena that involve quantized energy exchange, such as the photoelectric effect or atomic emission spectra. These limitations led to the development of quantum theory. However, even in the quantum age, the classical wave model remains foundational for understanding a wide range of light–matter interactions, especially in spectroscopy, communications, and optical engineering.

1.1.2 Blackbody Radiation

From the viewpoint of a spectroscopist, electromagnetic radiation is produced by atoms or molecules undergoing transitions between well-defined stationary states. This view obviously

does not include the creation of radio waves or other long-wave phenomena, for example, in standard antennas in radio technology, but describes ultraviolet, visible, and infrared radiation, which are the main subjects of this book. The atomic line spectra that are employed in analytical chemistry, for example, in a hollow cathode lamp used in atomic absorption spectroscopy, are due to transitions between electronic energy states of gaseous metal atoms. The light created by the hot filament in a standard light bulb is another example of light emitted by (metal) atoms. However, here, one needs to deal with a broad distribution of highly excited atoms, and the description of this so-called blackbody radiation was one of the first steps in understanding the quantization of light. Any material at a temperature T will radiate electromagnetic radiation according to the blackbody equations. The term “blackbody” refers to an idealized emitter of electromagnetic radiation with intensity $I(\lambda, T)$ or radiation density $\rho(T, \nu)$ as a function of wavelength and temperature. At the beginning of the twentieth century,

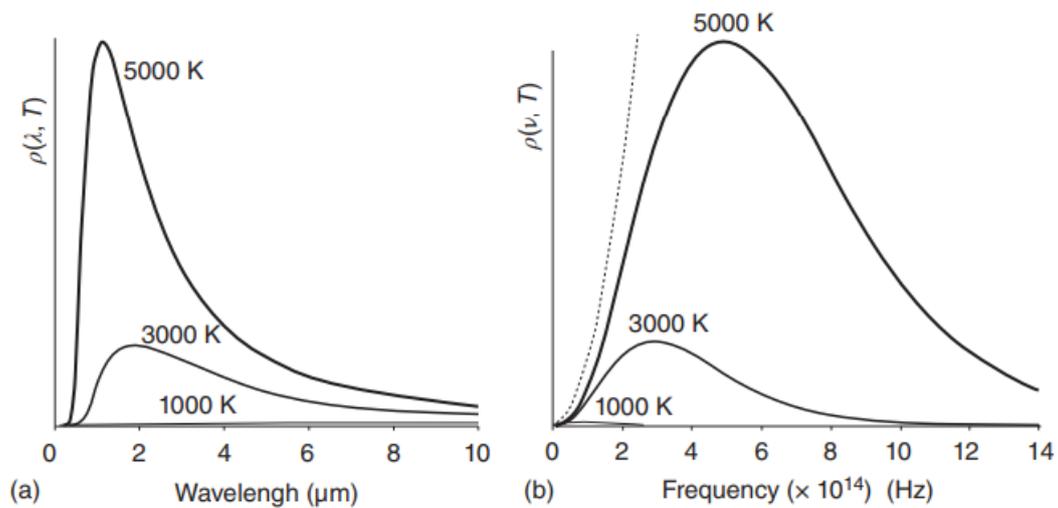


Figure 1.2 (a) Plot of the intensity I radiated by a blackbody source as a function of wavelength and temperature. (b) Plot of the radiation density of a blackbody source as a function of frequency and temperature. The dashed line represents this radiation density according to Eq. (1.5).

it was not possible to describe the experimentally obtained blackbody emission profile by classical physical models. This profile was shown in Figure 1.2 for several temperatures between 1000 and 5000 K as a function of wavelength. M. Planck attempted to reproduce the observed emission profile using classical theory, based on atomic dipole oscillators (nuclei and electrons) in motion. These efforts revealed that the radiation density ρ emitted by a classical blackbody into a frequency band $d\nu$ as function of ν and T would be given by Eq. (1.5):

$$\rho(T, \nu) = \frac{8\pi kT\nu^2}{c^3} \quad (1.5)$$

where the Boltzmann constant $k=1.381 \times 10^{-23}$ [J/K]. This result indicated that the total energy radiated by a blackbody according to this “classical” model would increase with ν^2 as shown by

the dashed curve in Figure 1.2b. If this equation were correct, any temperature of a material above absolute zero would be impossible, since any material above 0 K would emit radiation according to Eq. (1.5), and the total energy emitted would be unrestricted and approach infinity. Particularly, toward higher frequency, more and more radiation would be emitted, and the blackbody would cool instantaneously to 0 K. Thus, any temperature above 0 K would be impossible. This is, of course, in contradiction with experimental results and was addressed by M. Planck (1901) who solved this conundrum by introducing the term $1/(e^{(h\nu/kT)} - 1)$ into the blackbody equation, where h is Planck's constant:

$$\rho(T, \nu) = \frac{8\pi h\nu^2}{c^3} \frac{1}{\left(e^{\frac{h\nu}{kT}} - 1\right)} \approx \frac{8\pi h\nu^2}{c^3} e^{-\frac{h\nu}{kT}} \quad \text{for } \frac{h\nu}{kT} \gg 1 \quad (1.6)$$

The shape of the modified blackbody emission profile given by Eq. (1.6) is in agreement with experimental results. The new term introduced by Planck is basically an exponential decay function, which forces the overall response profile to approach zero at high frequency. The numerator of the exponential expression contains the quantity $h\nu$, where h is Planck's constant ($h = 6.626 \times 10^{-34}$ Js). This numerator implies that light exists as "quanta" of light, or light particles (photons) with energy

$$E_{\text{photon}} = h\nu \quad (1.7)$$

This, in itself, was a revolutionary thought since the wave properties of light had been established more than two centuries earlier and had been described in the late 1800s by Maxwell's equations in terms of electric and magnetic field contributions. Here arose for the first time the realization that two different descriptions of light, in terms of waves and particles, were appropriate depending on what questions were asked. A similar "particle-wave duality" was later postulated and confirmed for matter as well. Thus, the work by Planck very early in the twentieth century is truly the birth of the ideas resulting in the formulation of quantum mechanics.

1.1.3 The Photoelectric Effect

In 1905, Einstein reported experimental results that further demonstrated the energy quantization of light. In the photoelectric experiment, light of variable color (frequency) illuminated a photocathode contained in an evacuated tube. An anode in the same tube was connected externally to the cathode through a current meter and a source of electric potential (such as a battery). Since the cathode and anode were separated by vacuum, no current was observed, unless light with a frequency above a threshold frequency was illuminating the photocathode. Einstein correctly concluded that light particles, or photons, with a frequency above this threshold value

had sufficient kinetic energy to knock out electrons from the metal atoms of the photocathode. These “photoelectrons” left the metal surface with a kinetic energy given by

$$E_{\text{kin}}(\text{photoelectron}) = E_{\text{photon}} - \phi = h\nu - \phi \quad (1.9)$$

where ϕ is the work function, or the energy required to remove an electron from metal atoms. This energy basically is the atoms’ ionization energy multiplied by Avogadro’s number. Furthermore, Einstein reported that the photocurrent produced by the irradiation of the photocathode was proportional to the intensity of light, or the number of photons, but that increasing the intensity of light that had a frequency below the threshold did not produce any photocurrent. This provided further proof of Eq. (1.9). This experiment further demonstrated that light has particle character with the kinetic energy of the photons given by Eq. (1.7), which led to the concept of wave–particle duality of light. Later, de Broglie theorized that the momentum p of a photon was given by

$$p = h\lambda \quad (1.10)$$

Equation (1.10) is known as the de Broglie equation. The wave–particle duality was later (1927) confirmed to be true for moving masses as well by the electron diffraction experiment of Davisson and Germer [3]. In this experiment, a beam of electrons was diffracted by an atomic lattice and produced a distinct interference pattern that suggested that the moving electrons exhibited wave properties. The particle–wave duality of both photons and moving matter can be summarized as follows. For photons, the wave properties are manifested by diffraction experiments and summarized by Maxwell’s equation. As for all wave propagation, the velocity of light, c , is related to wavelength λ and frequency ν by

$$c = \lambda\nu = \nu/\tilde{\nu} \quad (1.11)$$

with $c = 2.998 \times 10^8$ [m/s] and λ expressed in [m] and ν expressed in [Hz = s⁻¹]. The quantity $\tilde{\nu}$ is referred to as the wavenumber of radiation (in units of m⁻¹ or cm⁻¹) that indicates how many wave cycles occur per unit length:

$$\tilde{\nu} = 1/\lambda \quad (1.12)$$

The (kinetic) energy of a photon is given by

$$E = h\nu = hc/\lambda = \hbar\omega \quad (1.13)$$

with $\hbar = h/2\pi$ and ω , the angular frequency, defined before as $\omega = 2\pi\nu$.

From the classical definition of the momentum of matter and light, respectively,

$$p = mv \text{ or } p = mc \quad (1.14)$$

it follows that the photon mass is given by

$$m_{\text{photon}} = p/c = h/(c\lambda) \quad (1.15)$$

Notice that a photon can only move at the velocity of light and the photon mass can only be defined at the velocity c . Therefore, a photon has zero rest mass, m_0 . Particles of matter, on the other hand, have a nonzero rest mass, commonly referred to as their mass. This mass, however, is a function of velocity v and should be referred to as mv , which is given by

$$m_v = \frac{m_0}{\sqrt{1 - \left(\frac{v^2}{c^2}\right)}} \quad (1.16)$$

Equation (1.16) demonstrates that the mass of any matter particle will reach infinity when accelerated to the velocity of light. Their kinetic energy at velocity v (far from the velocity of light) is given by the classical expression

$$E_{\text{kin}} = \frac{1}{2} mv^2 = p^2/2m \quad (1.17)$$

The discussion of the last paragraphs demonstrates that at the beginning of the twentieth century, experimental evidence was amassed that pointed to the necessity to redefine some aspects of classical physics. The next of these experiments that led to the formulation of quantum mechanics was the observation of “spectral lines” in the absorption and emission spectra of the hydrogen atom.

1.1.4 Hydrogen Atom Absorption and Emission Spectra

Between the last decades of the nineteenth century and the first decade of the twentieth century, several researchers discovered that hydrogen atoms, produced in gas discharge lamps, emit light at discrete colors, rather than as a broad continuum of light as observed for a blackbody (Figure 1.2a). These emissions occur in the ultraviolet, visible, and near-infrared spectral regions, and a portion of such an emission spectrum is shown schematically in Figure 1.3. These observations predate the efforts discussed in the previous two sections and therefore may be considered the most influential in the development of the connection between spectroscopy and quantum mechanics.

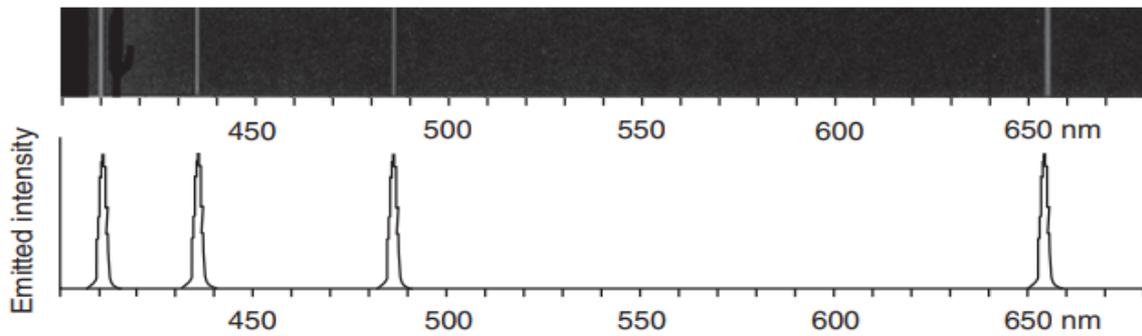


Figure 1.3 Portion of the hydrogen atom emission in the visible spectral range, represented as a “line spectrum” and schematically as an emission spectrum.

These experiments demonstrated that the H atom can exist in certain “energy states” or “stationary states.” These states can undergo a process that is referred to as a “transition.” When the atom undergoes such a transition from a higher or more excited state to a lower or less excited state, the energy difference between the states is emitted as a photon with an energy corresponding to the energy difference between the states:

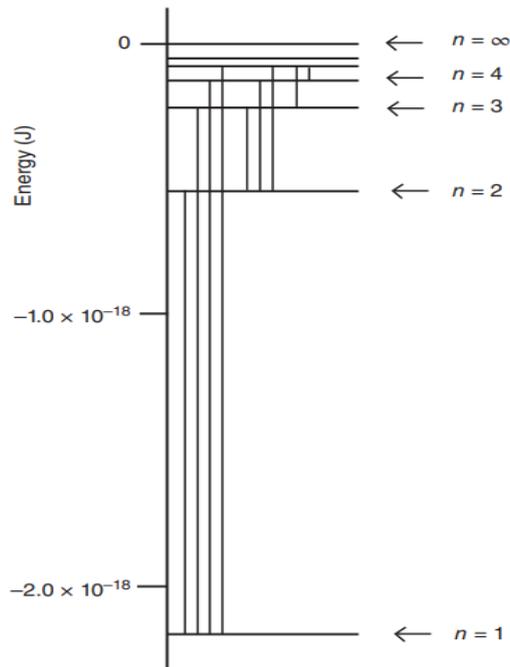
$$\Delta E_{\text{molecule}} = E_f - E_i = E_{\text{photon}} = h\nu = hc/\lambda \quad (1.18)$$

where the subscript f and i denote, respectively, the final and initial (energy) state of the atom (or molecule). Such a process is referred to as a “emission” of a photon. Similarly, an absorption process is one in which the atom undergoes a transition from a lower to a higher energy state, the energy difference being provided by a photon that is annihilated in the process. Absorption and emission processes are collectively referred to as “transitions” between stationary states and are directly related to the annihilation and creation, respectively, of a photon. The wavelengths or energies from the hydrogen emission or absorption experiments were fit by an empirical equation known as the Rydberg equation, which gave the energy “states” of the hydrogen atom as

$$E(n) = -R_y/n_2 \quad (1.19)$$

In this equation, n is an integer (>0) “quantum” number, and Ry is the Rydberg constant, ($R_y = 2.179 \times 10^{-18}$ J). This equation implies that the energy of the hydrogen atom cannot assume arbitrary energy values, but only “quantized” levels, E(n). This observation led to the ideas of electrons in stationary planetary orbits around the nucleus, which – however – was in contradiction with existing knowledge of electrodynamics, as discussed in the beginning of this chapter. The energy level diagram described by Eq. (1.19) is depicted in Figure 1.4. Here, the sign convention is as follows. For $n = \infty$, the energy of interaction between nucleus

Figure 1.4 Energy level diagram of the hydrogen atom. Transitions between the energy levels are indicated by vertical lines.



and electron is zero, since the electron is no longer associated with the nucleus. The lowest energy state is given by $n=1$, which corresponds to the H atom in its ground state that has a negative energy of 2.179×10^{-18} J. Equation (1.19) provided a background framework to explain the hydrogen atom emission spectrum. According to Eq. (1.19), the energy of a photon, or the energy difference of the atomic energy levels, between any two states n_f and n_i can be written as

$$E_{\text{photon}} = \Delta E_{\text{atom}} = E_f - E_i = -R_y \left[\frac{1}{n_f^2} - \frac{1}{n_i^2} \right] \quad (1.20)$$

At this point, an example may be appropriate to demonstrate how this empirically derived equation predicts the energy, wavelength, and wavenumber of light emitted by hydrogen atoms. This example also introduces a common problem, namely, that of units. Although there is an international agreement about what units (the system international, or SI units) are to be used to describe spectral transitions, the problem is that few people are using them. All efforts will be made to use SI units, or at least give the conversion to other units. The sign conventions used here are similar to those in thermodynamics where a process with a final energy state lower than that of the initial state is called an “exothermic” process, where heat or energy is lost. The energy is lost as a photon and is called an emission transition. When describing an absorption process, the energy difference of the atom is negative, $\Delta E_{\text{atom}} < 0$, that is, the atom has gained energy (“endothermic” process in thermodynamics). Following the procedure outlined in Example 1.2 would lead to a negative wavelength of the photon, which of course is physically meaningless, and one has to remember that the negative ΔE_{atom} implies the absorption of a photon.

1.1.5 Molecular Spectroscopy

Molecular spectroscopy is a branch of science in which the interactions of electromagnetic radiation and molecules are studied, where the molecules exist in quantized stationary energy states similar to those discussed in the previous section. However, these energy states may or may not be due to transitions of electrons into different energy levels, but due to vibrational,

Table 1.1 Photon energies and spectroscopic ranges^a.

	ν_{photon}	λ_{photon}	E_{photon} [J]	E_{photon} [kJ/mol]	E_{photon} [m ⁻¹]	Transition
Radio	750 MHz	0.4 m	5×10^{-25}	3×10^{-4}	2.5	NMR ^b
Microwave	3 GHz	10 cm	2×10^{-24}	0.001	10	EPR ^b
Microwave	30 GHz	1 cm	2×10^{-23}	0.012	100	Rotational
Infrared	3×10^{13} Hz	10 μm	2×10^{-20}	12	10^5	Vibrational
UV/visible	10^{15}	300 nm	6×10^{-19}	360	3×10^6	Electronic
X-ray	10^{18}	0.3 nm	6×10^{-16}	3.6×10^5	3×10^9	X-ray absorption

rotational, or spin energy levels. Thus, molecular spectroscopy often is classified by the wavelength ranges of the electromagnetic radiation (for example, microwave or infrared spectroscopies) or changes in energy levels of the molecular systems. This is summarized in Table 1.1, and the conversion of wavelengths and energies were discussed in Eqs. (1.11)–(1.15) and are summarized in Appendix 1. In this table, NMR and EPR stand for nuclear magnetic and electron paramagnetic resonance spectroscopy, respectively. In both these spectroscopic techniques, the transition energy of a proton or electron spin depends on the applied magnetic field strength. All techniques listed in this table can be described by absorption processes although other descriptions, such as bulk magnetization in NMR, are possible as well. As seen in Table 1.1, the photon energies are between 10^{-16} and 10^{-25} J/photon or about 10–4–105 kJ/(mol photons). Considering that a bond energy of a typical chemical (single) bond is about 250–400 kJ/mol, it shows that ultraviolet photons have sufficient energy to break chemical bonds or ionize molecules. Most of the spectroscopic processes discussed are absorption or emission processes as defined by Eq. (1.18):

$$\Delta E_{\text{molecule}} = E_f - E_i = E_{\text{photon}} = h\nu = hc/\lambda \quad (1.18)$$

However, interactions between light and matter occur even when the light's wavelength is different from the specific wavelength at which a transition occurs. Thus, a classification of spectroscopy, which is more general than that given by the wavelength range alone, would be a resonance/off-resonance distinction. Many of the effects described and discussed in this book are observed as resonance interactions where the incident light, indeed, possesses the exact energy of the molecular transition in question. IR and UV/vis absorption spectroscopy, microwave

spectroscopy, and NMR are examples of such resonance interactions. The off-resonance interactions between electromagnetic radiation and matter give rise to well-known phenomena such as the refractive index of dielectric materials. These interactions arise since force is exerted by the electromagnetic radiation on the charged particles of matter even at off-resonance frequencies. This force causes an increase in the amplitude of the motion of these particles. When the frequency of light reaches the transition energy between two states, an effect known as anomalous dispersion of the refractive index takes place.

This anomalous dispersion of the refractive index always accompanies an absorption process. This phenomenon makes it possible to observe the interaction of light either in an absorption or as a dispersion measurement, since the two effects are related to each other by a mathematical relation known as the Kramers–Kronig relation. This aspect will be discussed in more detail in Chapter 5. The normal (nonresonant) Raman effect is a phenomenon that also is best described in terms of off-resonance models, since Raman scattering can be excited by wavelengths that are not being absorbed by molecules. A discussion of nonresonant effects ties together many well-known aspects of classical optics and spectroscopy.

1.2 Fundamental Principles

1.2.1 Superposition

Superposition is a fundamental concept in quantum mechanics, describing the condition in which a quantum system can exist in multiple states or configurations simultaneously. Classical bits can exist in two possible states, typically labelled as "0" and "1". In contrast, because a qubit is a quantum mechanical system, it can exist in the "0" state, the "1" state, or any state that is a linear combination of 0 and 1.

Mathematically, superposition is a linear combination of "0" and "1" and can be written as:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where $|\psi\rangle$ is the state of the qubit, $|0\rangle$ and $|1\rangle$ are the basis states (or the computational basis states), and α and β are complex numbers called **probability amplitudes**. The probability amplitudes determine the probability of measuring the qubit in either state when a measurement is made.

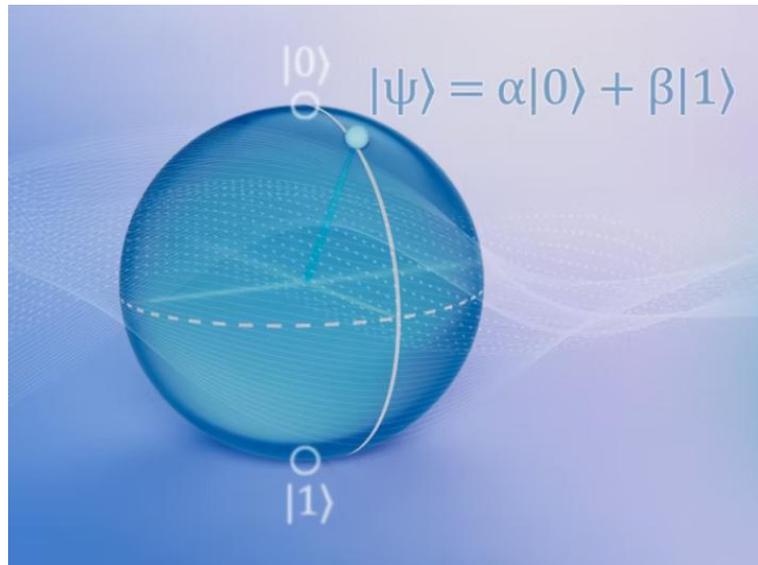


Fig1.5: Qubits

Importantly, the state of superposition can be maintained only while a quantum system is unobserved. Once measured, the wave function of a quantum system in a state of superposition "collapses" into one of the basis states.

For a concrete example of how this might work if superposition could exist in the everyday world, imagine that a coin that is flipped and lands on a table. In classical mechanics -- and in the everyday world as we know it -- the coin ends up in a state of either heads or tails. In a quantum mechanical system, the coin could be both heads and tails at the same time, but only until someone or something observes it or measures it. In this analogy, once observed, the coin would take on the state of either heads or tails.

Superposition is a fundamental attribute of quantum computing systems. One of its benefits or uses is that it allows for the possibility of **quantum parallelism**. Because classical bits can be in only one of two possible states, 0 or 1, classical computers can perform only one computation at a time, e.g., "if the bit is a 1 do this, if not do that, next do this, etc." In contrast, because a qubit can be in a superposition of 0 and 1, the quantum computer can perform multiple computations in parallel by processing all possible states of the qubits at once.

Superposition is central to quantum computing, offering a level of power and parallelism that classical computers cannot match. With classical bits, each bit can represent only a single value at a time, limiting operations to sequential logic. But with qubits in superposition, a quantum computer can evaluate many possible combinations of inputs simultaneously. This effect is known as quantum parallelism. For example, a system of just 3 qubits can represent 8 states at once (2^3), allowing it to process all those configurations in a single operation.

Despite its strangeness, superposition is not magic; it's a natural, observable aspect of the microscopic world. Technologies like quantum sensors, quantum simulators, and quantum cryptography also leverage this principle. As researchers continue to refine hardware and error correction techniques, harnessing superposition will remain key to unlocking the full promise of quantum technologies in the years ahead.

1.2.2 Entanglement

Entanglement is a fundamental concept of quantum mechanics that describes a non-classical correlation, or shared quantum state, between two or more quantum systems (or quantum particles) even if they are separated by a large distance. This phenomenon is also known as quantum non-locality, and it is one of the key features of quantum mechanics that distinguishes it from classical mechanics. Quantum systems are described by a mathematical object called a wavefunction, which contains information about the possible outcomes of measurements that can be performed on the systems. When two or more quantum systems are entangled, their wavefunction cannot be expressed as a product of individual wavefunctions for each system. Instead, the systems are described by a single wavefunction that captures the correlation between them. The fact that entangled systems are described by a single wavefunction means that any actions or measurements made on one of the systems affect the state of the other systems.

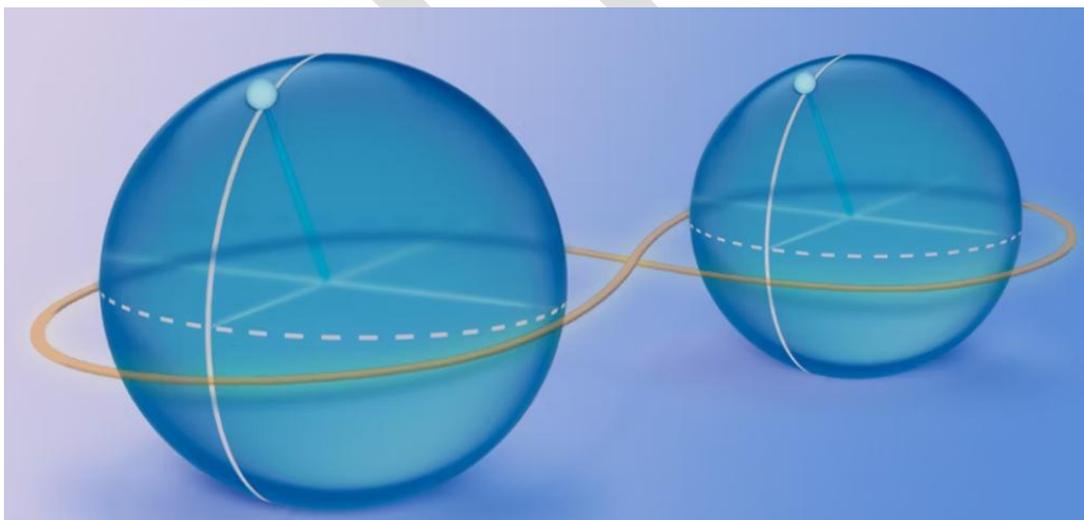


Fig1.6: Entanglement

In quantum computing, entanglement is used to enable quantum parallelism, which is the ability of quantum computers to perform multiple calculations simultaneously. Entanglement allows quantum computers to manipulate many qubits in a single operation, instead of manipulating each qubit individually, as in classical computing. For example, consider two qubits that are

initially prepared in an entangled state. If a measurement is made on one of the qubits, and it is found to be in the state $|0\rangle$, then the state of the other qubit immediately collapses to the state $|0\rangle$ as well. Similarly, if the first qubit is measured to be in the state $|1\rangle$, then the state of the second qubit collapses to the state $|1\rangle$ as well.

In quantum computing, entanglement is a powerful enabler of quantum parallelism and coordination. While classical computers manipulate individual bits, quantum algorithms take advantage of entangled qubits to operate on a vast number of states simultaneously, allowing for exponentially more complex computations. Entanglement also plays a vital role in quantum teleportation, which does not transmit matter but instead transfers a quantum state from one location to another using pre-shared entangled qubits and classical communication.

Entanglement enables quantum computers to implement various protocols and algorithms that are not possible with classical systems. For example, it is used in quantum teleportation, which allows for the transfer of quantum states between two distant systems. Entanglement is also a key resource for quantum error correction, which is necessary to protect quantum information from decoherence and other errors. By creating and manipulating entangled states, quantum computers can detect and correct errors in a way that is not possible for classical computers.

Entanglement is also essential in quantum cryptography, particularly in protocols like Quantum Key Distribution (QKD), where the security of the communication is guaranteed by the laws of quantum physics rather than mathematical assumptions. If an eavesdropper tries to intercept the entangled signal, the disturbance would be immediately evident to the legitimate users.

Another key use of entanglement is in quantum error correction. Quantum information is fragile and susceptible to noise and decoherence. By entangling qubits cleverly, quantum error correction schemes can detect and recover from errors without disturbing the original information—something impossible in classical computing. Entangled states serve as the building blocks for logical qubits, which are more stable and can be used for extended computations.

Overall, quantum entanglement redefines the limits of communication, computation, and information theory. It challenges our classical intuitions and offers a new paradigm where non-local correlations become tools for advanced technologies. As research progresses, entanglement will continue to be the backbone of innovations in secure communication, high-speed computation, and precision measurement in the quantum era.

1.2.3 Uncertainty Principle

The **Uncertainty Principle**, also known as **Heisenberg's Uncertainty Principle**, is a fundamental concept in **quantum mechanics**. It states that:

It is impossible to simultaneously know both the exact position and the exact momentum of a particle.

$$\Rightarrow \Delta p \cdot \Delta x \geq \frac{h}{4\pi}$$

$$\Rightarrow m\Delta v \cdot \Delta x \geq \frac{h}{4\pi}$$

Where, Δp = uncertainty in momentum

Δx = uncertainty in position

m = mass of particle

h = Planck's constant

The Uncertainty Principle also applies to other pairs of observables, such as energy and time, and has deep implications for the behaviour of particles in confined systems, like electrons in atoms. It helps explain phenomena like zero-point energy, where particles have motion even at absolute zero temperature, and quantum tunneling, where particles appear to pass through energy barriers.

In quantum computing, the Uncertainty Principle defines limits on how precisely quantum states can be manipulated or measured. It is also crucial in quantum cryptography, helping to ensure that any eavesdropping attempt on a quantum communication channel can be detected, since measurement disturbs the system.

Ultimately, the Uncertainty Principle reshaped our understanding of the universe by replacing the classical idea of determinism with a probabilistic framework. It teaches us that the act of measurement in quantum mechanics is not passive—it fundamentally changes what we observe. This uncertainty is not a weakness but a feature of the quantum world, revealing its inherently probabilistic and non-deterministic nature.

1.2.4 Wave-particle duality

Wave-particle duality is a fundamental concept in quantum mechanics which reveals that all quantum objects, including light and matter, exhibit both wave-like and particle-like properties. This idea emerged from a series of experiments and theoretical developments in the early 20th century. Light, which was classically understood as a wave due to its ability to interfere and diffract, was shown by Einstein in 1905 to also behave like a stream of particles called photons when explaining the photoelectric effect—where light knocks electrons out of a metal surface. This demonstrated that light has a particle nature as well. Inspired by this, Louis de Broglie in 1924 proposed that matter, such as electrons, should also exhibit wave-like behavior. He introduced the concept of the matter wave, assigning a wavelength to any particle based on its momentum using the relation,

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

where h is Planck's constant.

This duality was dramatically confirmed by experiments such as the electron double-slit experiment. When electrons pass through two slits, they produce an interference pattern typical of waves—even when fired one at a time. However, each electron is detected as a single point-like impact on the screen, showing its particle nature. The interference pattern only emerges after many electrons have passed through, revealing the underlying wave-like behavior. This paradoxical result means that quantum objects cannot be fully described as just particles or just waves. Instead, their behaviour depends on how they are measured. Wave-particle duality challenges our classical intuition and suggests that quantum entities exist in a superposition of possibilities, governed by a probability wave, until a measurement collapses this wave into a definite outcome.

This strange duality means that quantum particles do not behave strictly as particles or waves, but as a blend of both, determined by the measurement setup. If you measure their position, they appear particle-like; if you observe their path indirectly, they exhibit wave-like interference. This dual nature defies classical expectations and forces us to adopt a probabilistic interpretation of nature.

In quantum theory, particles are described by wavefunctions, which represent the probability of finding a particle in a certain state. Only when a measurement is made does this wavefunction “collapse” to a single, definite value. Thus, the wave-particle duality reveals that quantum entities exist in a superposition of possibilities until observed.

This concept not only underpins the foundations of quantum physics but also drives the functioning of quantum technologies like electron microscopes, quantum computers, and even lasers. Ultimately, wave-particle duality challenges our intuitive notions of reality and shows that at a fundamental level, nature behaves in ways that are deeply counterintuitive, yet experimentally proven.

1.3 Classical vs Quantum mechanics – theoretical comparison

Classical mechanics and **quantum mechanics** are two distinct frameworks for understanding physical phenomena. Classical mechanics, formulated primarily by Newton, governs the motion of macroscopic objects like planets, cars, and projectiles. Quantum mechanics, developed in the early 20th century, is essential for accurately describing the behavior of microscopic particles such as electrons, atoms, and photons. The two theories differ fundamentally in their assumptions, mathematical formalisms, and interpretations of nature.

In classical mechanics, objects have definite positions and velocities at all times. The state of a system can be precisely predicted using Newton's laws, and the evolution of that system is deterministic: given initial conditions, the future behavior is uniquely determined. On the other hand, quantum mechanics introduces inherent indeterminacy. A particle does not have a definite position or momentum until it is measured. Instead, it is described by a wavefunction, which encodes a probability distribution over all possible outcomes. The act of measurement collapses this wavefunction, resulting in a specific observed value.

Classical mechanics relies on continuous variables and smooth trajectories in phase space. In contrast, quantum mechanics uses discrete quantized energy levels and operates within a probabilistic framework, governed by operators on Hilbert space and the Schrödinger equation. While classical systems obey the principle of determinism and locality, quantum systems exhibit phenomena like superposition, entanglement, and non-locality, which have no classical analogs.

Moreover, classical mechanics is intuitive and aligns with everyday experiences, whereas quantum mechanics often defies intuition, requiring abstract mathematical tools and accepting that some aspects of nature are fundamentally unknowable. Despite their differences, classical mechanics is actually a limiting case of quantum mechanics—it emerges naturally when dealing with large systems or high energies where quantum effects become negligible. Thus, quantum mechanics is more fundamental and universal, with classical mechanics being an effective approximation in the macroscopic world.

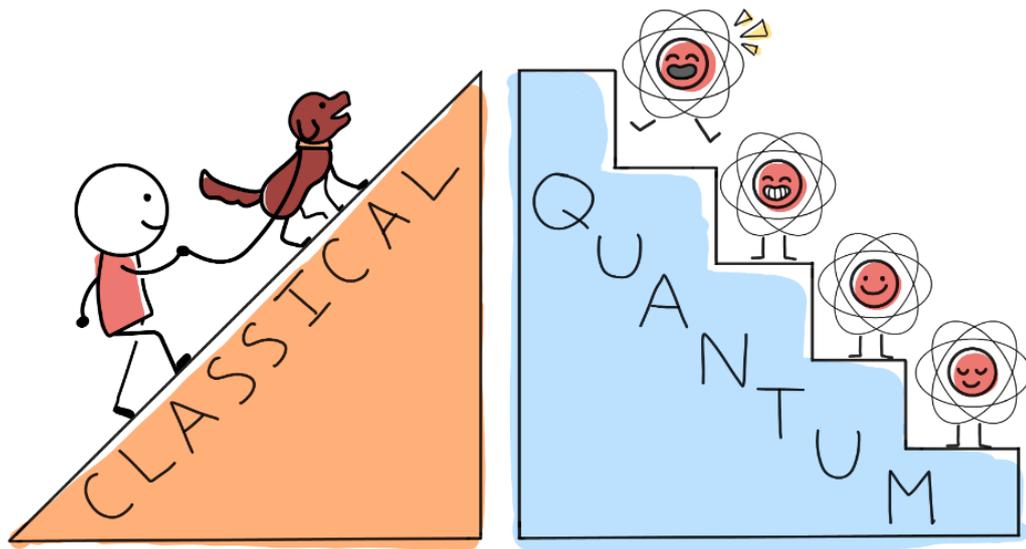


Fig 1.7 : **Classical vs Quantum mechanics**

Classical mechanics treats motion and energy as continuous, and systems evolve along smooth trajectories in space and time. Quantum mechanics, however, reveals that energy is quantized—only specific, discrete energy levels are allowed. It also uses complex mathematical tools like operators, matrices, and Hilbert spaces, along with the Schrödinger equation, to describe the evolution of systems.

Another major difference is that classical physics adheres to local realism, assuming that objects are only influenced by their immediate surroundings. Quantum systems defy this through entanglement and non-local interactions, where particles can exhibit strong correlations even across large distances. Additionally, quantum mechanics introduces superposition, where particles exist in multiple states simultaneously, a concept with no classical counterpart.

Though quantum theory may seem abstract and counterintuitive, it is more fundamental—classical mechanics turns out to be a special case of quantum mechanics, valid only when dealing with large objects or systems where quantum effects are negligible. Thus, while classical physics provides accurate predictions in everyday scenarios, it fails at microscopic scales, where only quantum mechanics can accurately describe the behavior of matter and energy.

In essence, quantum mechanics reshaped our understanding of reality, replacing certainty with probability, and introducing a new framework for describing the strange and fascinating world that lies beneath our everyday experiences.

1.4 Quantum States and Measurement: Nature of Observation

In quantum mechanics, a **quantum state** represents the complete information about a system and is typically described by a mathematical function called a **wavefunction** (denoted by Ψ). This wavefunction encodes the probabilities of finding the system in various configurations. Unlike classical systems, quantum systems can exist in a **superposition** of multiple states simultaneously, meaning a particle can be in many possible states until a measurement is made. The **measurement process** in quantum mechanics is fundamentally different from classical observation—it is not passive. Instead, observing a quantum system **collapses** the wavefunction to a single definite state, chosen probabilistically according to the squared magnitude of the wavefunction. This collapse is instantaneous and unpredictable, highlighting the probabilistic nature of quantum systems and the active role of the observer in defining the outcome. The peculiar nature of measurement leads to non-intuitive phenomena such as wavefunction collapse and quantum entanglement, where the act of observing one particle instantly affects the state of another, even across large distances.

This phenomenon shows that the act of measurement is not simply revealing a pre-existing value but is in fact defining the outcome itself. The system chooses one definite state from the spectrum of probabilities, and all other possibilities vanish upon observation. This nature of quantum measurement gives rise to deeply non-intuitive effects such as quantum entanglement, where two or more particles share a linked state. If one entangled particle is measured, the state of its partner is instantly determined, no matter the distance between them—a phenomenon that baffled even Einstein, who referred to it as "spooky action at a distance."

Furthermore, this interaction between observer and system implies that **objective reality**, as understood in classical terms, does not always exist independently of observation. Instead, the **observer plays an essential role** in shaping the physical outcome. This shift from a deterministic to a **probabilistic and observer-dependent framework** is what marks one of the most fundamental departures of quantum mechanics from classical physics. The study of quantum states and their measurement continues to influence modern fields such as quantum computing, quantum cryptography, and quantum teleportation, where the principles of wavefunction manipulation and collapse are harnessed to perform computations and transmit information in revolutionary ways.

1.4.1 Overview of Quantum Systems: Electrons, Photons, Atoms

Quantum systems consist of microscopic entities such as **electrons**, **photons**, and **atoms**, which all exhibit wave-particle duality and are governed by the laws of quantum mechanics. **Electrons**, though traditionally thought of as point particles, also behave like waves. This wave nature is responsible for phenomena like electron diffraction and atomic orbitals. **Photons** are the quantum particles of light; they have no rest mass and always move at the speed of light, displaying both energy quantization (in packets called quanta) and wave-like behavior such as interference. **Atoms** are more complex quantum systems made of electrons orbiting a nucleus. In quantum mechanics, these electrons occupy discrete energy levels or orbitals, and transitions between levels involve absorption or emission of photons with specific energies. All these systems demonstrate uniquely quantum effects such as superposition, entanglement, and tunneling—none of which can be explained using classical physics. These systems form the foundation of modern technologies such as lasers, semiconductors, quantum dots, and quantum computers.

Electrons, despite being considered point-like particles in classical physics, reveal a wave-like character at small scales, a fact made evident by experiments such as electron diffraction. Their dual nature allows them to form standing wave patterns around atomic nuclei, known as orbitals, which determine the structure of atoms and molecules.

Photons, on the other hand, are massless quantum particles of electromagnetic radiation. They always travel at the speed of light and carry energy proportional to their frequency, as described by $E = h\nu$. Their wave-particle duality manifests in phenomena like interference and the photoelectric effect. Photons can also become entangled, making them important in quantum communication and cryptography. Meanwhile, atoms are composite systems made of nuclei surrounded by electrons. In a quantum view, electrons do not orbit in classical trajectories but instead occupy quantized energy states, transitioning between them by absorbing or emitting photons of discrete energy.

Each of these systems—electrons, photons, and atoms—exhibit hallmark quantum behaviors including superposition (being in multiple states at once), entanglement (non-local correlation between particles), and quantum tunneling (the ability to cross classically forbidden barriers). These phenomena cannot be explained using classical physics and require the probabilistic, wave-based framework of quantum theory. Understanding these quantum systems is critical because they are the foundation of modern quantum-enabled technologies. Innovations such as semiconductors, quantum sensors, lasers, MRI machines, LEDs, and quantum computers all rely on manipulating the quantum properties of these particles. As our ability to control these systems

improves, their role in computation, communication, and sensing will only grow more significant in the future of science and technology

1.5 The Concept of Quantization

Quantization lies at the heart of quantum mechanics, fundamentally changing our understanding of nature. Unlike classical physics—where properties such as energy or momentum can vary continuously—quantum mechanics shows that many physical quantities are restricted to discrete values. This concept was introduced to resolve the inconsistencies observed in classical models, such as the blackbody radiation problem and the photoelectric effect, where the observed results could not be explained without assuming that energy comes in discrete packets called quanta. Max Planck and Albert Einstein were among the pioneers who proposed that light and energy must be quantized to align with experimental data, setting the stage for a new theory of matter and energy.

Quantization is a core principle of quantum mechanics that states certain physical quantities, like energy, angular momentum, and charge, can only take on **discrete values**, rather than any value within a continuous range. This idea is radically different from classical physics, where such quantities can vary smoothly. The earliest evidence for quantization came from the **blackbody radiation** problem and the **photoelectric effect**, which were explained by assuming that energy is emitted or absorbed in discrete units called **quanta**. In atoms, electrons can only exist in specific **quantized energy levels**, and transitions between these levels result in the emission or absorption of photons with fixed frequencies. Quantization is also seen in systems like the harmonic oscillator, where energy levels are separated by fixed intervals. This discrete nature of quantum systems is mathematically expressed using operators with eigenvalues corresponding to observable quantities. Quantization is what gives rise to atomic spectra, the stability of atoms, and the structure of matter itself, making it a cornerstone of all quantum theories.

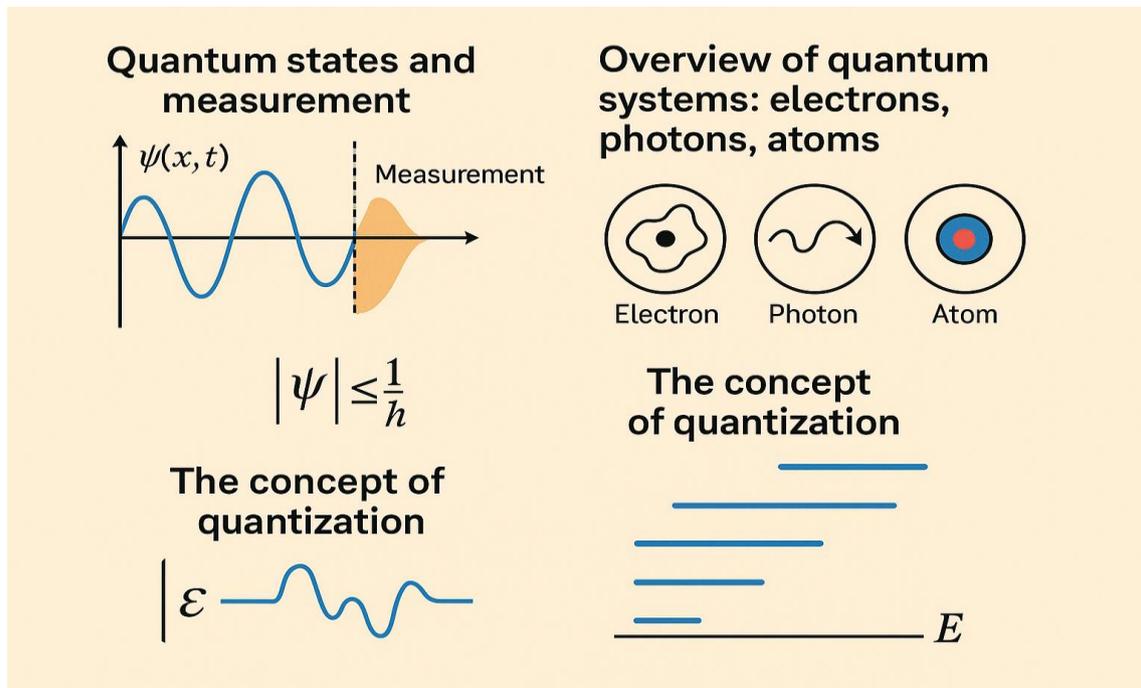


Fig1.8: The Concept of Quantization

In atomic systems, quantization becomes especially evident. Electrons in atoms cannot occupy arbitrary energy levels; instead, they are found only in certain allowed states. When an electron transitions between these levels, it absorbs or emits a photon with a specific frequency, giving rise to the spectral lines seen in emission and absorption spectra. This phenomenon is responsible for the stability of atoms and the unique identity of elements. Similar principles apply to rotational and vibrational states of molecules, which are also quantized and form the basis of various spectroscopic techniques.

Quantization is not limited to energy. Angular momentum, spin, and even electric charge can also be quantized, leading to surprising consequences in both microscopic systems and macroscopic quantum phenomena like superconductivity and quantum Hall effects. The mathematics of quantization involves solving operator equations, where only certain values (called eigenvalues) correspond to physical observables. This discrete nature of reality is not just a mathematical curiosity—it underpins the structure and behavior of matter at the most fundamental level.

Understanding why quantum mechanics is essential goes beyond explaining atomic structure—it is about embracing a radically different view of reality. Classical physics fails to explain phenomena like entanglement, superposition, and tunneling, all of which are routinely observed in quantum systems. Quantum mechanics accounts for these behaviors through a probabilistic and non-deterministic framework, where the act of measurement plays a crucial role in determining outcomes.

Moreover, quantum theory is not just a theoretical success; it has practical, transformative applications. Technologies such as semiconductors, lasers, magnetic resonance imaging (MRI), LEDs, and atomic clocks are direct outcomes of quantum principles. Even more revolutionary are the emerging fields of quantum computing, quantum cryptography, and quantum sensing, which promise to outperform classical technologies in speed, security, and sensitivity.

In essence, quantum mechanics is not just a scientific necessity—it is a technological enabler. It reshapes our understanding of the universe and opens new frontiers in computing, communication, and materials science. Studying quantum concepts is therefore not only vital for physicists, but also for engineers, computer scientists, and innovators of the future.

1.6 Why Quantum?

Quantum mechanics is not just a theoretical breakthrough in physics—it marks a radical shift in how we understand and interact with the universe at the most fundamental level. Traditional classical theories fail to explain the behavior of microscopic particles like electrons, photons, and atoms. Quantum theory fills this gap by accurately describing the probabilistic and non-deterministic nature of such particles. Its predictions have been experimentally verified with extraordinary precision, making it a cornerstone of modern physics. More importantly, quantum mechanics forms the foundation for transformative advancements in technology, computing, and security, answering both scientific curiosity and real-world challenges.

1.6.1 Strategic Significance

The strategic value of quantum technologies is increasingly recognized by governments and industries worldwide. Quantum computing, for instance, has the potential to break classical encryption methods, posing both risks and opportunities for national security. Similarly, quantum communication promises ultra-secure information transfer using Quantum Key Distribution (QKD), which is theoretically unbackable. Nations are investing heavily in quantum research to ensure leadership in this frontier domain, as it offers a significant edge in defence, surveillance, intelligence, and cybersecurity. As a result, mastery of quantum technologies is becoming a critical component of geopolitical power and technological sovereignty.

Governments worldwide are ramping up funding, launching national missions, and forming alliances to stay competitive in this field. The ability to control and implement quantum systems will influence power dynamics globally—shaping military capabilities, intelligence operations,

and secure digital infrastructure. As a result, expertise in quantum science is fast becoming a determinant of geopolitical and economic strength.

1.6.2 Scientific Significance

Quantum mechanics stands as one of the most profound scientific achievements of the 20th century, dramatically expanding our understanding of the physical world. Scientifically, quantum mechanics has revolutionized our understanding of nature. It explains phenomena that classical physics cannot, such as superconductivity, quantum tunneling, and the behavior of particles in extreme conditions. Quantum theory has also laid the groundwork for fields like quantum chemistry, condensed matter physics, and particle physics. It enables the modeling of complex systems with high accuracy, leading to discoveries in materials science, nanotechnology, and fundamental physics. Beyond practical uses, quantum mechanics continues to challenge our philosophical notions of reality, causality, and measurement, making it a profoundly rich area of ongoing scientific inquiry.

Quantum theory allows scientists to model atomic and subatomic systems with remarkable precision, leading to the discovery of new materials and deeper insights into the behavior of matter and energy.

1.6.3 Technological Significance

Quantum technologies are poised to bring transformative changes to the technological landscape. Quantum technologies are set to redefine the future of computation, communication, sensing, and imaging. Quantum computers can solve certain classes of problems exponentially faster than classical computers, with potential applications in drug discovery, optimization, machine learning, climate modelling, and logistics optimization. Quantum sensors can measure time, magnetic fields, and gravitational forces with unprecedented precision, useful in GPS systems, medical diagnostics, and geological surveys. Meanwhile, quantum cryptography offers solutions for secure digital infrastructure. These innovations are not distant dreams—they are already in early stages of development, and their practical impact is beginning to emerge, setting the stage for the next technological revolution.

In communication, quantum encryption could underpin a new era of ultra-secure digital infrastructure. These applications, once theoretical, are now transitioning into real-world pilots and commercial prototypes—marking the beginning of a new age where quantum mechanics powers next-generation innovation.

1.7 A Snapshot of Quantum Technologies: Computing, Communication, and Sensing

Quantum technologies are at the forefront of a technological revolution, harnessing the unique and counterintuitive principles of quantum mechanics—such as superposition, entanglement, and quantization—to build revolutionary tools that far surpass the capabilities of their classical counterparts. These technologies are being developed across three primary domains: **quantum computing**, **quantum communication**, and **quantum sensing**, each offering transformative potential for science, industry, and society everyday life.

Quantum Computing is perhaps the most well-known application of quantum mechanics. Unlike classical computers that process information in binary bits (0 or 1), quantum computers use quantum bits or *qubits*, which can exist in superpositions of 0 and 1. This allows quantum computers to perform many calculations in parallel, enabling them to solve certain problems—like factoring large numbers, simulating molecular behavior, or optimizing complex systems—exponentially faster than classical machines. Although still in early stages, companies and research institutions are racing to achieve "quantum advantage," where a quantum computer outperforms the best classical supercomputers on useful tasks.

Quantum Communication focuses on the secure transmission of information using quantum phenomena. The most notable technique is **Quantum Key Distribution (QKD)**, which allows two parties to share a cryptographic key with security guaranteed by the laws of physics. If an eavesdropper tries to intercept the key, the quantum state is disturbed, alerting the communicating parties. Quantum communication can also involve **quantum teleportation**, where the state of a particle is transferred instantaneously over a distance, using entanglement. As global digital infrastructure becomes increasingly vulnerable, quantum communication promises unprecedented levels of security for sensitive data.

Quantum Sensing exploits the extreme sensitivity of quantum systems to environmental changes, enabling measurements with unprecedented precision. Quantum sensors can detect minute variations in gravitational fields, magnetic fields, acceleration, and time. Applications range from medical diagnostics (e.g., highly sensitive brain scans using quantum magnetometers), to underground exploration, to navigation systems that do not rely on GPS. Atomic clocks—among the most accurate devices ever built—are based on quantum transitions and are crucial for global positioning and timekeeping systems.

Together, these quantum technologies are not isolated innovations—they are part of a rapidly evolving ecosystem that is expected to reshape the technological landscape in the coming decades.

As these technologies mature, they will not remain isolated solutions but will become deeply integrated into a wide range of applications. Quantum computing could redefine how we solve scientific and industrial problems. Quantum communication may establish new standards of digital security. Quantum sensing is set to improve how we measure, observe, and navigate the world. Together, these advances signal a shift toward a new era of quantum-enhanced innovation that will shape the future of multiple sectors including finance, defense, transportation, health, and information technology

1.8 National and Global Quantum Missions

As quantum technologies emerge as a critical area of innovation and national interest, several countries have launched ambitious quantum missions to secure strategic and technological leadership. These initiatives aim to develop quantum computing, communication, and sensing capabilities through coordinated investments in research, infrastructure, and talent development. India, along with major global powers like the USA, China, and the European Union, is actively building its presence in the quantum landscape.

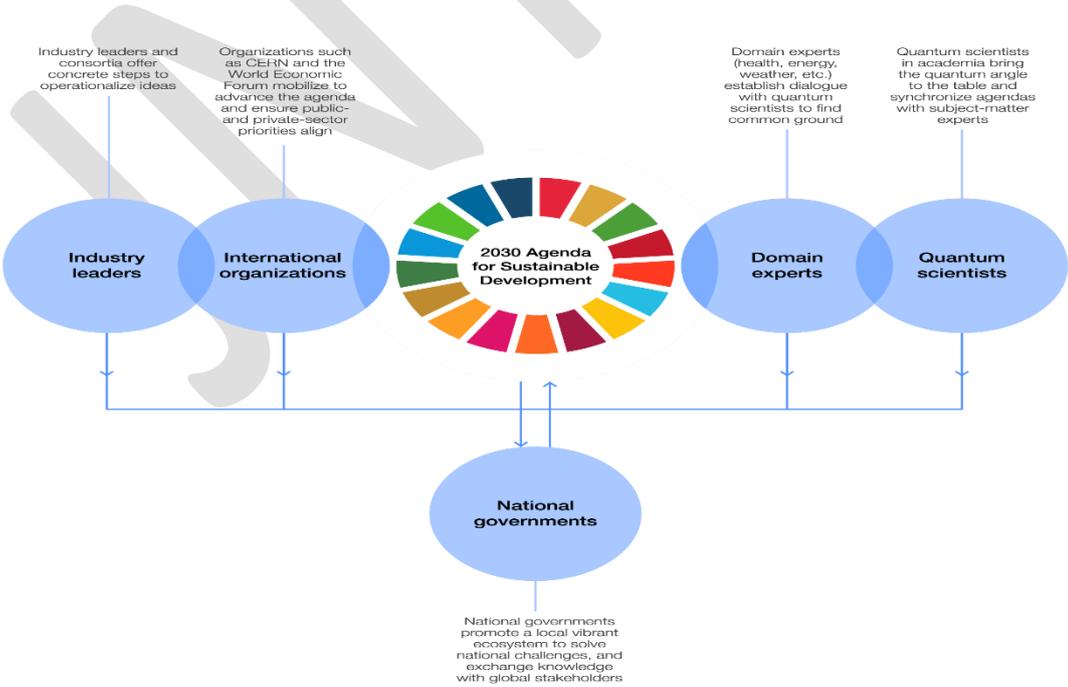


Fig1.9 : Global commitment to accelerate quantum for society solutions

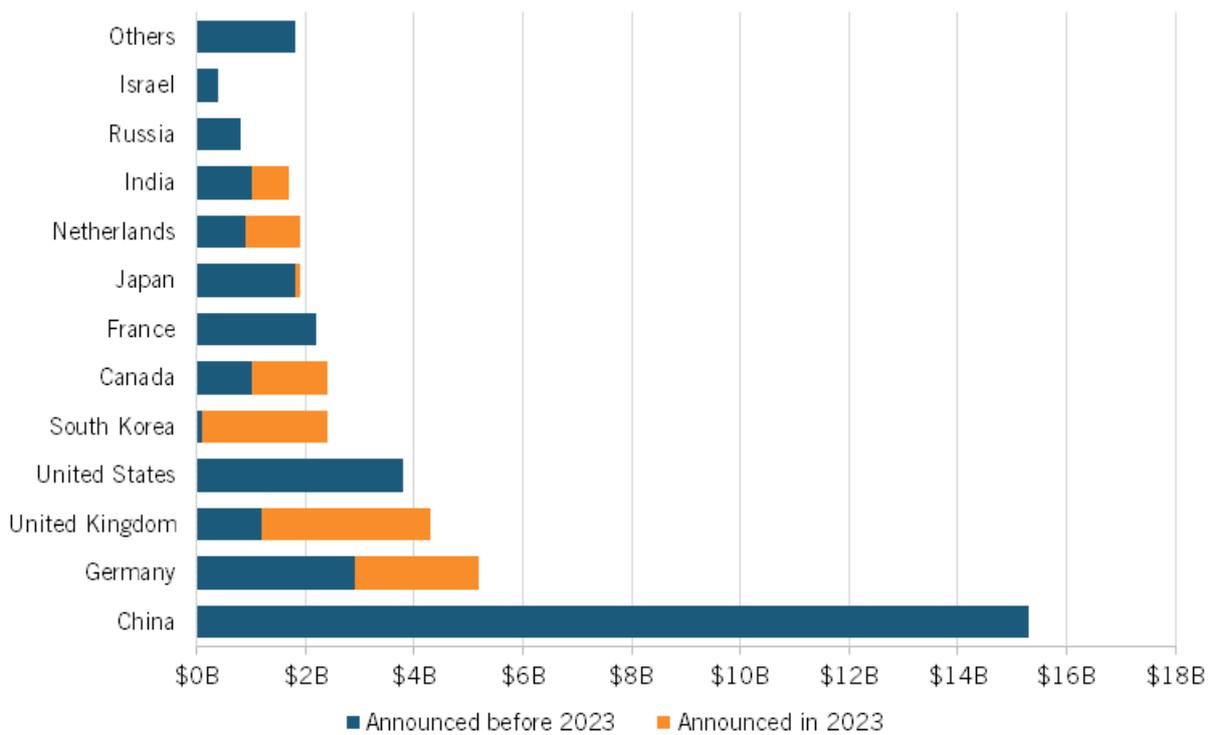


Fig 1.10: Announced government investments in quantum research and commercialization around the world

China leads in quantum communications, lags behind in computing (where the United States excels), and matches the United States in sensing, excelling in market-ready tech, while the United States dominates high-impact areas.

1.8.1 India’s National Quantum Mission (NQM)

India launched its **National Quantum Mission** in 2023, with a budget of **₹6,003 crore (approximately \$730 million)** over eight years. The mission seeks to position India among the top quantum nations by developing indigenous capabilities in quantum computing, quantum communication, quantum sensing, and quantum materials. It aims to establish four **Thematic Hubs (T-Hubs)** in leading academic and research institutions focusing on foundational technologies. The NQM also plans to build intermediate-scale quantum computers (with 50–1000 qubits), develop quantum key distribution networks, and promote workforce training and international collaborations. The mission aligns with India’s larger vision of self-reliance in strategic technologies and aims to boost national security, telecommunications, and advanced research.

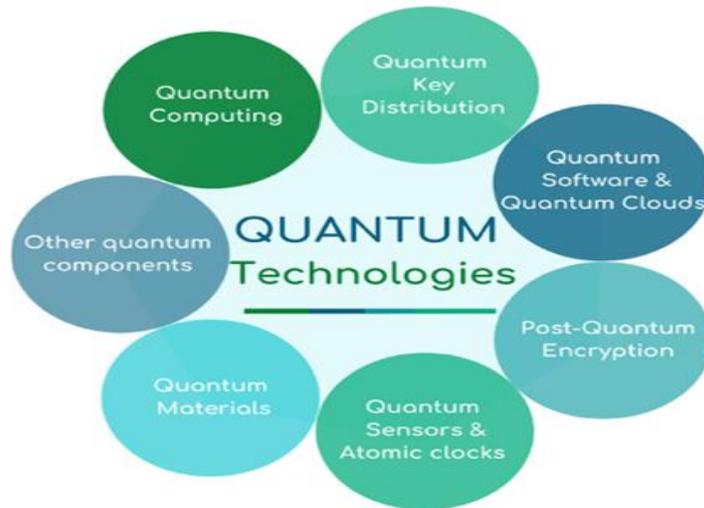


Fig1.11: India Approves National Quantum Mission

1.8.2 European Union (EU) Quantum Flagship

The **EU Quantum Flagship** is a €1 billion, 10-year initiative launched in 2018 to unify Europe’s fragmented quantum research landscape. It supports hundreds of research institutions, startups, and industries across member states. The program focuses on four main areas: **quantum communication**, **quantum simulation**, **quantum computing**, and **quantum metrology**. The EU also promotes infrastructure projects like the **European Quantum Communication Infrastructure (EuroQCI)**, which aims to establish a secure pan-European quantum communication network. This mission reflects Europe’s intent to compete globally while fostering innovation, industrial adoption, and academic excellence in quantum science.

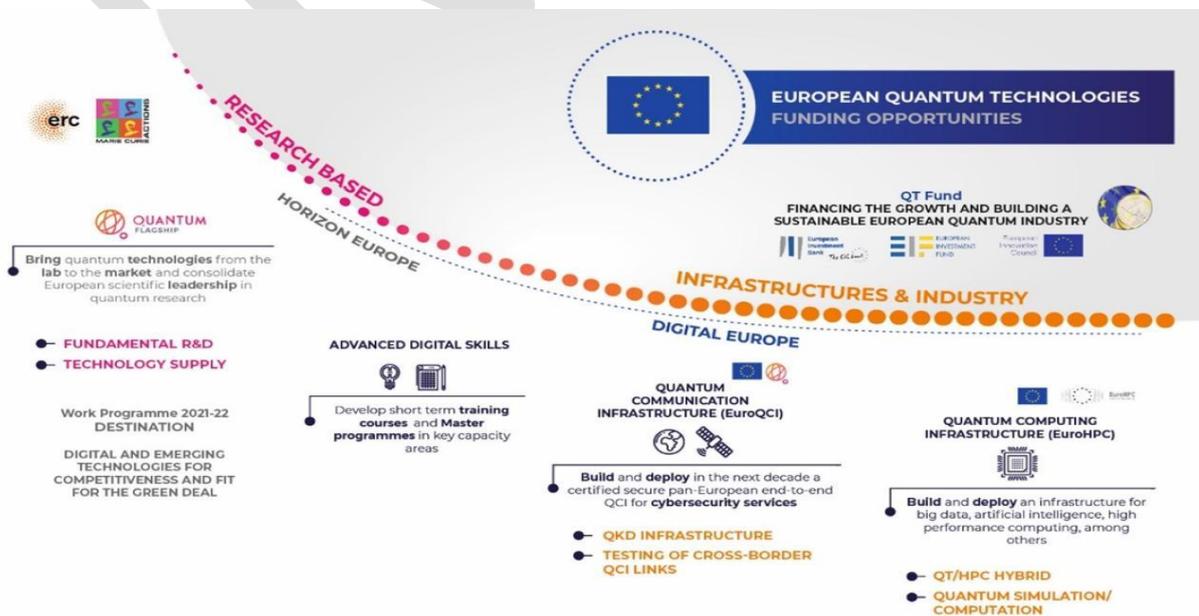


Fig1.12 : European Union (EU) Quantum Technologies

1.8.3 United States: National Quantum Initiative Act

The **United States** formalized its quantum strategy with the **National Quantum Initiative Act** passed in 2018. This act coordinates efforts across government agencies, including the Department of Energy (DOE), National Science Foundation (NSF), and National Institute of Standards and Technology (NIST), with significant funding and collaboration with private sector leaders like IBM, Google, and Microsoft. The **National Quantum Coordination Office** oversees these efforts, focusing on quantum research, technology transfer, education, and the creation of quantum research centers. The U.S. aims to maintain its technological leadership, secure supply chains, and harness quantum advantages for national security, scientific progress, and economic growth.



Fig1.13: USA must dominate quantum technology

1.8.4 China: Quantum Strategic Advantage

China has emerged as a global leader in quantum technology through sustained state-led investment and rapid deployment. It has achieved several milestones, including launching the world's first **quantum communication satellite (Micius)** and demonstrating **satellite-based quantum key distribution** over thousands of kilometers. China also leads in building a nationwide **quantum communication backbone network**, connecting major cities through ultra-secure fiber links. The Chinese government has reportedly invested billions of dollars in quantum R&D, and projects like the **National Laboratory for Quantum Information Science in Hefei** aim to consolidate China's dominance in this space. China views quantum technologies as essential to future economic and military competitiveness.

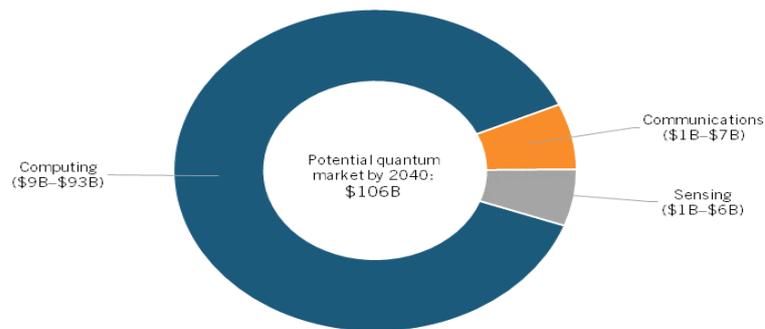


Fig1.14: How Innovative Is China in Quantum?

These missions reflect a global “**quantum race**”, where nations recognize that quantum supremacy could redefine cybersecurity, artificial intelligence, defense, and economic structures. International collaboration, balanced with strategic competition, will shape the trajectory of quantum innovation in the coming decades, with each nation seeking to leverage quantum breakthroughs for economic growth, defense strength, and scientific prestige.

Reference : https://tifac.org.in/images/nmqta/concept_note12.06.19.pdf