Int. j. adv. multidisc. res. stud. 2025; 5(2):1056-1061

Received: 06-02-2025
Accepted: 16-03-2025

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

2025 – The International Year of Quantum Sciences and Technologies

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Abstract

The United Nations (UN) has proclaimed 2025 as the International Year of Quantum Science and Technologies to commemorate the centenary of the development of quantum mechanics, one of the most fundamental theories in contemporary physics. This initiative was driven by the recognition that quantum physics has not only revolutionized our understanding of the universe at the microscopic level, but is also at the forefront of emerging technologies that promise to transform many aspects of modern life. This article aims to make some considerations about quantum physics in the year of its centenary.

Keywords: Heisenberg, Born, Jordan, Schrödinger, Pauli, Feynman, Quantum Mechanics

Introduction

As Stariolo [1] mentions, in 1925, matrix mechanics was introduced by Werner Heisenberg, Max Born and Pascual Jordan, marking a significant advance in the understanding of quantum mechanics. This new theoretical approach was able to explain phenomena observed at subatomic scales, such as the behavior of atoms and elementary particles. Quantum mechanics stood out for its ability to describe the discrete nature of energy, challenging previous conceptions that characterized energy as a continuous flow.

The work of Heisenberg, Born and Jordan in 1925 was fundamental to the consolidation of theories and observations that had emerged between 1900 and 1925, marking the beginning of a new era in physics. This formalization unified previous concepts and laid the foundations for modern quantum mechanics, which has become an essential pillar of contemporary science. Quantum mechanics not only revolutionized the field of physics, but also had a significant impact on several areas of science and technology.

Its implications go beyond theoretical physics, influencing the development of new technologies and research methods that shape the world today. Furthermore, quantum mechanics has transformed our understanding of reality, challenging classical notions and introducing new paradigms about the nature of matter and energy.

This shift in perspective continues to resonate in philosophical and scientific debates, highlighting the depth and relevance of the discoveries made by Heisenberg, Born and Jordan. Between 1900 and 1925, renowned physicists such as Albert Einstein, Niels Bohr, and Louis de Broglie contributed significantly to the development of quantum theory. Einstein proved that light is composed of particles called photons, while Bohr developed an atomic model that explained the energy levels of electrons. According to Ostermann *et al* [2], de Broglie introduced the theory of wave-particle duality that describes how electrons can exhibit characteristics of both particles and waves.

The development of quantum theory formally began in 1925 with Heisenberg, Max Born and Pascual Jordan who introduced matrix mechanics to describe the behavior of subatomic particles. The year 1925 became a landmark in the history of quantum mechanics and is considered the year of the quantum revolution. Probability plays a fundamental role, with the squares of the matrices representing the probability of a particle being in a certain position or energy.

In 1926, Schrödinger developed an equation for quantum waves, confirming the equivalence of his theories to those of Heisenberg, thus solidifying the foundations of quantum mechanics and driving scientific and technological advances.

1. Brief Biography of Some of the Great Names of the New Quantum Theory

1.1 Werner Karl Heisenberg

According to Beyler [3], Werner Karl Heisenberg was born in Würzburg, Germany, on December 5, 1901 and died in Munich on February 1, 1976.

Heisenberg was the son of Annie Wecklein and Karspar Ernst August Heisenberg, a high school teacher of classical languages who became a professor of medieval studies and modern Greek in the German university system. In 1924 Heisenberg became an assistant to Max Born at the Göttingen University Center, then moved to Copenhagen, where he worked with Niels Bohr. The following year he developed matrix mechanics, which was the first development of quantum mechanics.

In 1927 he began teaching physics at the University of Leipzig, where he enunciated the Uncertainty Principle, according to which it is impossible to measure simultaneously and with absolute precision the position and linear momentum of a particle, that is, the joint determination of the momentum and position of a particle necessarily contains errors no smaller than Planck's constant. These errors are negligible in the macroscopic sphere, but become important for the study of atomic particles; the two quantities can be determined exactly separately, but the more accurate one is, the more uncertain the other becomes.

In 1927, he published the article “Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik”, in which he presented the Uncertainty Principle. He also made important theoretical contributions in the fields of hydrodynamics of turbulent flows, in the study of the atomic nucleus, ferromagnetism, cosmic rays and subatomic particles. In 1932, he received the Nobel Prize in Physics for "the creation of quantum mechanics, the application of which made possible, among other things, the discovery of the allotropic forms of hydrogen". From 1942 to 1945, he directed the Max Planck Institute.

During the Second World War, he worked with Otto Hahn, one of the discoverers of nuclear fission, on the design of a nuclear reactor. He was the leader of the German atomic bomb construction program, which even motivated Niels Bohr to end their friendship. He also made a fundamental contribution to the planning of the first German nuclear reactor in Karlsruhe and a research reactor in Munich in 1957.

After the war, he was appointed director of the Kaiser Wilhelm Institute for Physics, which later became the Max Planck Institute for Physics. He directed the institute until its relocation to Munich in 1958, when it was expanded and renamed the Max Planck Institute for Physics and Astrophysics. Heisenberg was also president of the German Research Council, chairman of the Commission for Atomic Physics, chairman of the Nuclear Physics Working Group, and president of the Alexander von Humboldt Foundation.

In 1958, the scientist focused on research into the theory of elementary particles, making discoveries in several areas such as: the structure of the atomic nucleus, the hydrodynamics of turbulence, cosmic rays and ferromagnetism.

1.2 Max Born

According to Schweber [4], Max Born was born in Wroclaw on December 11, 1882 and died in Göttingen on January 5, 1970. He was a German physicist and mathematician, important for quantum mechanics, as well as contributing to solid-state physics and optics. He supervised the work of prominent physicists in the 1920s and 1930s and won the Nobel Prize in Physics in 1954 for his research in quantum mechanics. He was the son of Gustav Born, a professor of embryology, and Margarethe, who came from an industrial family. His mother died when he was four years old. He studied at the König-Wilhelm Gymnasium and, in 1901, entered the University of Wroclaw.

The university system in Germany allowed students to change universities easily. Born spent summer semesters in Heidelberg and Zurich before entering the University of Göttingen in 1904, where he met famous mathematicians. He wrote his thesis on the stability of rubber bands, winning a prize. In 1905, he began researching special relativity and wrote a thesis on Thomson's atomic model. In 1918, a meeting with Fritz Haber led to a discussion of the formation of ionic compounds, known as the Born-Haber cycle. In 1921, Born returned to Göttingen and helped his friend James Franck secure a chair.

In Born's time, Göttingen became one of the world's most important centers of physics research. In 1925, Born and Werner Heisenberg formulated the matrix mechanics representation of quantum mechanics. The following year, he formulated the now standard interpretation of the probability density function for $\psi^*\psi$ in the Schrödinger equation, for which he was awarded the Nobel Prize in 1954. His influence extended far beyond his own research. Max Delbrück, Siegfried Flügge, Friedrich Hund, Pascual Jordan, Maria Goeppert-Mayer, Lothar Wolfgang Nordheim, Robert Oppenheimer and Victor Weisskopf all received their doctorates under Born at Göttingen and his assistants included Enrico Fermi, Werner Heisenberg, Gerhard Herzberg, Friedrich Hund, Pascual Jordan, Wolfgang Pauli, Léon Rosenfeld, Edward Teller and Eugene Wigner.

In January 1933, the Nazi Party came to power in Germany and Max Born, a Jew, was suspended from his post. He then moved to Britain, where he worked at Cambridge and wrote science books. In 1936, he became a professor at the University of Edinburgh. In 1939, he became a naturalized British citizen. He retired to Bad Pyrmont in West Germany and died in 1970 in Göttingen.

1.3 Pascual Jordan

As Kojevnikov [5] mentions, Pascual Jordan was born on October 18, 1902 in Hannover, Germany and died on July 31, 1980, in Hamburg. He was a German theoretical physicist who was one of the founders of quantum mechanics and quantum field theory. Jordan received his doctorate (1924) from the University of Göttingen, working with German physicists Max Born and James Franck on problems of quantum theory.

In 1925, Jordan published two seminal papers, one in collaboration with Born and the German physicist Werner Heisenberg and one with Born alone, which developed Heisenberg's initial idea of noncommutative variables into a formulation of quantum theory in terms of matrix mechanics—the first working version of quantum mechanics. Over the next few years, at Göttingen and as a Rockefeller Fellow in Copenhagen, Jordan helped push the new theory toward completion, incorporating the wave mechanics approach of the German physicist Erwin

Schrödinger with the matrix formulation.

The comprehensive mathematical formalism of non-relativistic quantum mechanics was first achieved in the transformation theory published by Jordan and independently by the English physicist P.A.M. Dirac in 1927.

Jordan also did pioneering work on the relativistic generalization of quantum mechanics and its application to electromagnetic radiation. In 1925, he used matrix mechanics to quantize electromagnetic waves. This method was developed to great success in Dirac's 1927 paper on the quantum theory of radiation, in which also the idea of a second quantization (many-body formalism) for bosons made its first appearance. Jordan then presented the general program of quantum field theory, proposing that relativistic quantum theory should describe all subatomic particles—matter and radiation—as quanta of wave fields. Working toward the implementation of this idea, he and the Hungarian-born American physicist Eugene P. Wigner showed in 1928 how second quantization can describe fermions in addition to bosons, introducing the technical idea of an anticommutator (a special matrix operator).

Jordan was a professor of theoretical physics at the University of Rostock from 1928 to 1944. Although some of his closest friends and professional colleagues were Jewish, he joined the National Socialist German Workers' Party (Nazi Party) in 1933 when Adolf Hitler came to power. In his popular writings on science, Jordan argued that modern physics, including relativity and quantum mechanics, is ideologically compatible with National Socialism.

During the Second World War he carried out military research for the Luftwaffe (German air force). Jordan then became a professor at the Humboldt University of Berlin (1944–51) and the University of Hamburg (1951–71) in West Germany. He also served in the West German Bundestag (1957–61), representing the conservative Christian Democratic Union.

1.4 Erwin Rudolf Josef Alexander Schrödinger

According to Bernstein [6], Erwin Rudolf Josef Alexander Schrödinger was born on August 12, 1887, in Erdberg, Vienna, Austria. His mother was of mixed Austrian and English descent, while his father was Austrian. He was raised in a Lutheran family, but later declared himself an atheist.

Schrödinger received the Nobel Prize in Physics for his contributions to quantum theory, including the Schrödinger equation that displays the wave function of a system. He also published research on several areas of physics, including statistical mechanics and thermodynamics.

In addition to his scientific contributions, Schrödinger wrote about the philosophical aspects of science and its philosophical interpretations related to ancient and Eastern times. In the field of biology, he discussed the concepts of genetics from the perspective of physics. His most popular work was the thought experiment with Schrödinger's cat.

He shared his philosophical and scientific thoughts on various topics, such as ethics and religion. Schrödinger approached theoretical biology, seeking to answer existential questions on a scientific basis.

Other topics he explored in his work were general relativity, dielectric physics, color theory, and electrodynamics. He also attempted to describe a unified field theory, which was considered a major achievement in his time. Schrödinger was known for his great personality. His conversations on various topics were always fascinating.

In his work, Schrödinger expressed profound thoughts about life and its realities. In his famous 1944 work "What is Life", he discussed the phenomena of life and genetics through physical theory. Schrödinger developed and utilized his theoretical strategies at a landmark time in his century. Early in his academic career, Schrödinger worked with his former professor Franz Exner on electrical engineering, atmospheric electricity and radioactivity.

In 1912, he wrote a paper on dielectrism and estimated the distribution of radioactive substances, confirming his theories in experiments carried out in 1913, receiving the Haitinger Prize in 1920. In 1914, he verified capillary pressure formulas and studied properties of soft beta radiation.

In 1919, he performed his last physical experiment on coherent light, and then devoted himself to theoretical studies. In 1920, he became an assistant to Max Wien in Jena, and in 1921, he became a full professor in Wrocław, Poland. In 1921, he moved to the University of Zurich. In 1927, he succeeded Max Planck at the Friedrich Wilhelm University in Berlin. In 1934, Schrödinger taught at Princeton University, where he was offered a permanent position.

He became the director of the School of Theoretical Physics in 1940 and there wrote about 50 additional publications on various topics, including his explorations of unified field theory. In 1944 he wrote "What Is Life", which contains a discussion of negentropy and the concept of a complex molecule with the genetic code of living organisms.

According to James D. Watson's memoir "DNA, the Secret of Life", Schrödinger's book gave Watson the inspiration to research the gene, which led to the discovery of DNA's double helix structure in 1953. Similarly, Francis Crick, in his autobiographical book "What Mad Pursuit", described how he was influenced by Schrödinger's speculations about how genetic information might be stored in molecules.

Schrödinger remained in Dublin until his retirement in 1955. Schrödinger suffered from tuberculosis and stayed at a sanatorium in Arosa several times in the 1920s. It was there that he formulated his wave equation. On 4 January 1961, Schrödinger died of tuberculosis, aged 73, in Vienna. He was survived by his widow Anny and buried in Alpbach, Austria.

2. Heisenberg's Atomic Model

According to Jammer [7], the Heisenberg Atomic Model is an important theory of quantum physics, created by physicist Werner Heisenberg in the 1920s. It introduces the uncertainty principle, which states that it is impossible to know exactly both the position and the movement of a subatomic particle. The more accurately the position is measured, the less is known about the movement, and vice versa.

This shows that there is a limit to what we can know about subatomic particles and that the world at this level is uncertain and unpredictable, defying our understanding. As such, the behavior of particles such as electrons cannot be accurately predicted. This is due to the Heisenberg uncertainty principle, which states that it is impossible to determine both the position and momentum of a particle simultaneously with absolute precision.

In the Heisenberg model of the atom, electrons are described as probability clouds that indicate the region where an electron is most likely to be found at a given instant. The wave function of a particle shows that if its position is well defined, its momentum is less uncertain, and vice versa. This means that the more we know about the position of the particle, the less we know about its momentum, and vice versa. This idea changes the way we understand atomic structure, moving away from the notion of precise motion of subatomic particles. Furthermore, the linear momentum and the position of a particle cannot be measured at the same time. The relationship between the two variables is given by an inequality.

According to Heisenberg, the product of the change in momentum and the change in position of the particle is always greater than the ratio of Planck's constant as detailed in the following mathematical expression

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

where Δp represents indeterminacy of linear momentum, ΔX denotes indeterminacy of position and $h = 6.626 \times 10^{-34}$ J.s represents Planck's constant.

Heisenberg's uncertainty principle is perfectly applicable to the energy-time pair, as detailed below:

$$\Delta E \Delta t \geq \frac{h}{4\pi},$$

where ΔE represents energy indeterminacy and Δt represents time indeterminacy.

3. Schrödinger's Atomic Model

Schrödinger's atomic model is based on quantum mechanics and introduces the idea that atoms are described by wave functions that represent the probability of finding a particle in a given region of space. Unlike previous models, which described atoms deterministically, Schrödinger's model considers that the position and energy of a particle are uncertain and can be described only by a probability distribution.

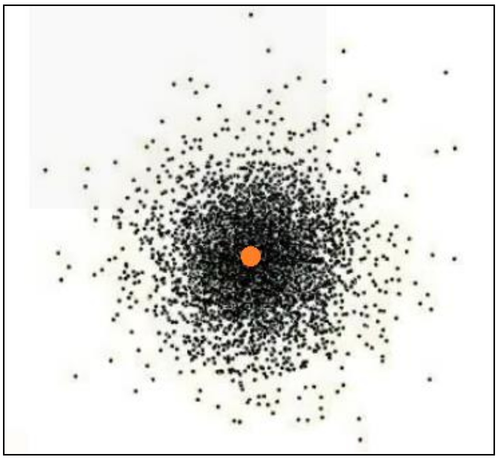

Fig 1: Schrödinger's atomic model and the probability distribution of the electronic position

This probabilistic approach makes it possible to explain phenomena that classical models could not, such as the behavior of electrons around the atomic nucleus. Furthermore, the Schrödinger model is able to accurately predict the properties of atoms and molecules, and was fundamental to the development of quantum chemistry and modern physics.

However, Schrödinger's atomic model has some limitations, such as the mathematical complexity involved in its practical application and the difficulty of physically interpreting wave functions. Despite this, the probabilistic description of atoms remains a fundamental feature of Schrödinger's model, allowing a deeper understanding of the microscopic world.

The current model accepted by the scientific community is based on Erwin Schrödinger's theory of wave mechanics. He suggested that atoms have regions where electrons are likely to be located, called electron orbitals. An orbital is a region where an electron is most likely to be found, since it is not possible to know its exact position and velocity at the same time. Schrödinger used mathematical functions, winning the Nobel Prize in 1933.

Heisenberg's uncertainty principle also helped in this formulation, explaining that electrons behave as both waves and particles. Schrödinger defined the region with the most electrons as the electron cloud which helped to better understand the properties of atoms and provide a mathematical interpretation for observed phenomena associated with particles.

Schrödinger's studies helped explain the energy of atoms and electrons. Solving the equation confirms Bohr's atomic model for hydrogen and other one-electron atoms, but Bohr's atomic model cannot explain atoms with more than one electron due to repulsion between electrons. Schrödinger introduced quantum concepts such as particle duality and defined atomic orbitals, helping to understand the structure of atoms.

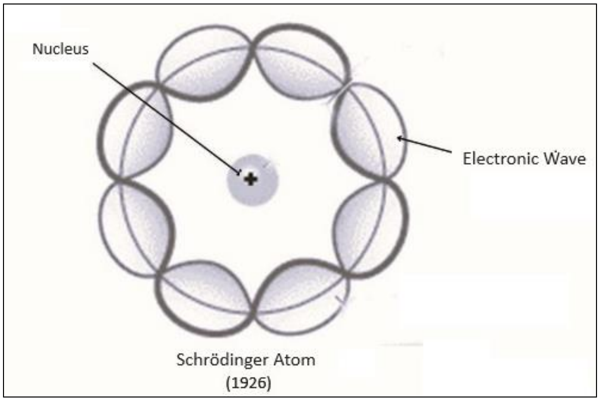

Fig 2: Schrödinger's atomic model and its quantization

Probability density (ψ^2) is fundamental to understanding how electrons occupy orbitals in multi-electron atoms, providing detailed information about the electron energy.

In order to calculate the wave function Schrödinger developed an equation written in simplified form as follows

$$\hat{H}\Psi = E\Psi,$$

where $\hat{H}$ represents the Hamiltonian operator, Ψ denotes the wave function and E symbolizes the energy.

or

$$i\hbar\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

or

$$-\frac{\hbar^2}{2m}\nabla^2\Psi + \text{V}\,\Psi = i\hbar\frac{\partial\Psi}{\partial t}$$

4. Max Born's Interpretation of the Wave Function

Max Born’s interpretation of the wave function is an important theory in quantum mechanics that explains the probability of finding a quantum system in a certain position. Proposed by Max Born in 1926, this interpretation is considered an accurate explanation of the quantum world.

In this view, the wave function does not represent the physical state of the system, but rather the odds of finding it in a specific position. Thus, when we measure the position of a quantum particle, such as an electron, the wave function tells us the probabilities, but does not allow us to predict its exact position. To understand the explanation, it is essential to remember about complex numbers. They have a real part and an imaginary part, and their conjugate has the reverse sign of the imaginary part.

For example, given the complex number Z = 2 + i5, its conjugate would be Z* = 2 - i5. Multiplying Z by its conjugate eliminates the imaginary part, resulting in a real number, which Max Born suggested could be done with the wave function. This interpretation is vital to understanding quantum superposition, where a system can be in multiple states at once and it is also crucial to the uncertainty principle which states that it is impossible to measure both the position and momentum of a particle precisely at the same time.

Born’s interpretation is fundamental to quantum mechanics, offering a clear insight into the probabilities of quantum nature. Schrödinger hoped that his wave mechanics would help restore some sense of visualization of the physics that goes on inside the atom. In his search for a suitable interpretation of the wave function, he focused on the density of electric charge that he associated with the wave function ψ multiplied by its complex conjugate. Hidden in his words is the interpretation that would eventually dominate our understanding of the wave function. Max Born did not hesitate to conclude that the only way to reconcile wave mechanics with the description of the particle is to interpret the modulus squared of the wave function as a probability density.

It was Wolfgang Pauli who proposed to interpret this fact not simply as a transition probability or as the probability of the system being in a specific state as Born had done but as the probability of "finding" the electron in a specific position in its orbit within an atom. The wave function is given a probabilistic interpretation: the squared modulus of the wave function corresponds to a probability density over the location of the particle in space (at a given instant).

In short, the Max Born interpretation of the wave function is a fundamental theory of quantum mechanics that describes the probability of finding a quantum system in a region. It is widely accepted as an accurate explanation of the nature of the quantum world.

5. Some Applications of Quantum Mechanics

As mentioned by Caldeira [8], in 1981, Richard Feynman, a famous physicist, challenged the idea of using quantum computers to simulate quantum systems, something difficult with ordinary computers. He said that nature is quantum and to simulate it, a quantum computer is needed, highlighting the complexity of the challenge. This speech is seen as a milestone that started the search for quantum computing, a great scientific and technological challenge of the 21st century, which uses principles of quantum physics to improve traditional computers.

Quantum computers promise to simulate physical systems with speed and quality superior to classical computers and to quickly break encryption, something that is difficult for traditional computing. However, a practical quantum computer is still far from being a reality. In 2024, companies are making progress in qubit stability and error correction, but it could take ten to fifteen years to have a quantum computer for general applications. Experts believe that these computers will not pose a major risk to encryption in the next twenty years.

Other quantum technologies such as sensors and quantum communication are more advanced. Quantum communication includes quantum key distribution (QKD), which ensures the security of cryptographic keys. These areas are less popular than computing but require fewer physical resources. According to experts, quantum computing is complicated and disruptive. The technical difficulties and constant development of classical computing make it difficult to surpass current technologies. The advantages of quantum computing are similar to those of classical computing. Although the finish line is still far away, the race for quantum computing generates parallel results. This includes the development of new hardware, algorithms, materials and the advancement of the understanding of quantum laws and their technological applications.

From a scientific perspective, studies developed based on this theory have answered countless questions about how the universe works, from its tiniest particles to the giants of cosmic matter. In technology, the advances it has made possible are ubiquitous, including the chips and lasers that allow us to use cell phones and surf the internet.

According to Duarte Gomes *et al* [9], knowledge of quantum mechanics is essential for humanity's daily life and promises to continue playing an important role in the future, whether by providing answers to questions still open about the universe or through the development of new technologies.

According to Maceti *et al* [10], the understanding and application of the basic concepts of quantum mechanics can help to complement and envision new ways of approaching and teaching various phenomena described by science in general, notably phenomena associated with physics and chemistry.

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