Chapter 1: Introduction to Quantum Physics

Luis M. Molina

Departamento de Física Teórica, Atómica y Óptica

Quantum Physics

Program of the Course

First Part

1. Brief history of Quantum Physics.
2. Thermal radiation and Planck's postulate: the birth of the quantum.
3. Particle-like properties of radiation: photons.
4. Wave-like properties of particles and the wave-particle duality.
5. The uncertainty principle.
6. Classic atomic models: Thomson's and Rutherford's models.
7. The Bohr model: energy levels and atomic spectra.
8. The one-dimensional Schrödinger equation.
9. Solutions of the time-independent Schrödinger equation.
10. The 3D Schrödinger equation. The armonic oscillator. The H atom.
11. The basic postulates of quantum mechanics.

Program of the Course

Second Part

1. Angular momentum I. General solution to the eigenvalue problem.
2. Angular momentum II. The electronic spin. Sum of angular momenta.
3. Multielectronic atoms. Identical particles. Hartree and Hartree-Fock theories.
4. Molecules. Molecular orbitals. Hybrid orbitals. Molecular vibrations.
5. Solids. Band theory. Bloch's theorem.
6. Theory of semiconductors. Semiconducting devices.
7. Introduction to nuclear physics. Basic nuclear models.
8. Desintegrations and nuclear reactions.
9. Elementary particles and their interactions.

Bibliography

Main textbooks

- *Quantum Physics.* R. Eisberg and R. Resnick. 2nd Ed. John Wiley and Sons
- *Física Cuántica*. C. Sánchez del Río. Ed. Pirámide.
- *An introduction to Quantum Physics.* A. P. Frech and E. F. Taylor. Ed. Reverté.

Other suggested readings

- *The Feynman Lectures in Physics, Vol.* 3. R. P. Feynman
- *Quantum Mechanics.* C. Cohen-Tannoudji, B. Diu and F. Laloe (more advanced level)

Physics at the end of the XIX century

At the end of the nineteenth century, classic physics offered a rather complete view of most processes in the natural world:

- Deterministic newtonian dynamics
- Maxwell's equations of electromagnetism
- Thermodynamics

In 1900, W.Thompson (Lord Kelvin) gave a lecture titled *"Nineteenth-Century Clouds over the Dynamical Theory of Heat and Light"*. He claimed that most of problems at the time were already solved but for two small "clouds":

- The failure of Michelson-Morley's experiment to measure the velocity of light with respect to an absolute "ether"
- The problem of blackbody radiation, i.e., the "ultraviolet catastrophe"

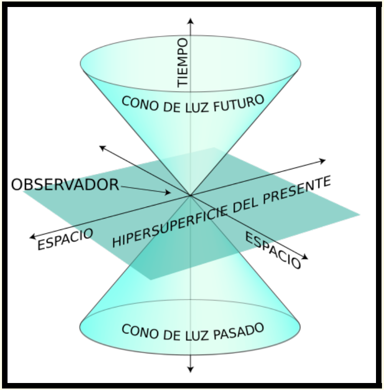
Physics at the end of the XIX century

The attempt to solve such two small "clouds" gave birth to modern physics:

Physics at the end of the XIX century

The attempt to solve such two small "clouds" gave birth to modern physics:

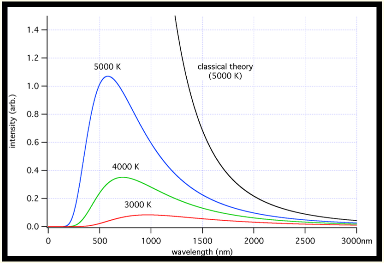
- Einstein's theories of special (1905) and general (1913) relativity, which explain the cinematics and dynamics of fast ($V \approx c$) moving bodies as well as gravity.



Physics at the end of the XIX century

The attempt to solve such two small "clouds" gave birth to modern physics:

- Einstein's theories of special (1905) and general (1913) relativity, which explain the cinematics and dynamics of fast ($V \approx c$) moving bodies as well as gravity.
- Quantum Physics, developed during the first quarter of the century (1900-1926), which provides a conceptual framework to understand the physical processes taking place at the atomic scale.



The "ultraviolet catastrophe": classical vs. experimental results for the blackbody spectrum.

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Solid state physics and material science

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Solid state physics and material science
    - Band theory ⟶ Semiconductor electronics

Why is Quantum Physics important?

Quantum Physics constitutes the "foundation stone" for many fields of modern science:

- Solid state physics and material science
    - Band theory ⟶ Semiconductor electronics
    - Superconductors

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Solid state physics and material science
    - Band theory ⟶ Semiconductor electronics
    - Superconductors
    - Lasers

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Solid state physics and material science
    - Band theory ⟶ Semiconductor electronics
    - Superconductors
    - Lasers
    - Nanotechnology

Why is Quantum Physics important?

Quantum Physics constitutes the "foundation stone" for many fields of modern science:

- Solid state physics and material science
    - Band theory ⟶ Semiconductor electronics
    - Superconductors
    - Lasers
    - Nanotechnology
- Quantum chemistry

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Solid state physics and material science
  - Band theory ⟶ Semiconductor electronics
  - Superconductors
  - Lasers
  - Nanotechnology
- Quantum chemistry
  - Catalysis and surface science

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Solid state physics and material science
    - Band theory ⟶ Semiconductor electronics
    - Superconductors
    - Lasers
    - Nanotechnology
- Quantum chemistry
    - Catalysis and surface science
    - Biochemistry

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Nuclear physics

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Nuclear physics
    - Nuclear weapons

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Nuclear physics
    - Nuclear weapons
    - Nuclear fission and fussion for peaceful applications

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Nuclear physics
    - Nuclear weapons
    - Nuclear fission and fussion for peaceful applications
    - Medicine

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Nuclear physics
    - Nuclear weapons
    - Nuclear fission and fussion for peaceful applications
    - Medicine
- Particle physics

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Nuclear physics
  - Nuclear weapons
  - Nuclear fission and fussion for peaceful applications
  - Medicine
- Particle physics
  - Quantum chromodynamics

Why is Quantum Physics important?

Quantum Physics constitutes the "foundation stone" for many fields of modern science:

- Nuclear physics
    - Nuclear weapons
    - Nuclear fission and fussion for peaceful applications
    - Medicine
- Particle physics
    - Quantum chromodynamics
    - Quarks. The standard model

Why is Quantum Physics important?

Quantum Physics constitutes the “foundation stone” for many fields of modern science:

- Nuclear physics
  - Nuclear weapons
  - Nuclear fission and fussion for peaceful applications
  - Medicine
- Particle physics
  - Quantum chromodynamics
  - Quarks. The standard model
- and many more...

Quantum Physics. Range of application.

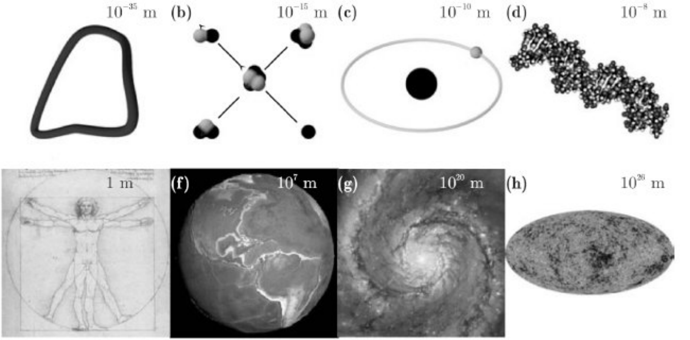
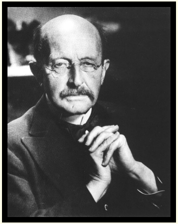


Fig. 1.1 Quantum physics describes Nature at all scales. Pictorial representation of (a) a superstring, (b) a nuclear reaction (fusion of deuterium and tritium), (c) a hydrogen atom, (d) a biological molecule, (e) a human being, (f) a planet (image credit: NASA), (g) the 'whirlpool' galaxy (image credit: NASA/JPL), (h) the microwave blackbody radiation map (image credit: NASA/WMAP Science Team).

Birth of Quantum Physics

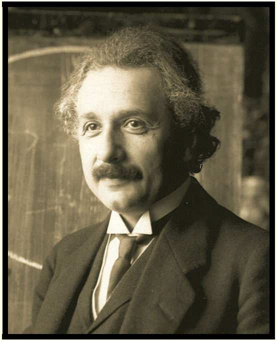
- The birth of the Quantum Theory can be dated to December, 14, 1900 when Max Planck presented his paper *"Zur theorie des Gesetzes der Energieverteilung im Normalspektrum"* (On the theory of the Energy Distribution Law of the Normal Spectrum).
- This paper tries to solve the problem found in classical physics with diverging blackbody energy radiance at high freqencies.
- Planck hypothesized that the total energy of a vibrating system cannot be changed continuously. Instead, the energy must jump from one value to another in discrete steps, or quanta, of energy.
- With this hypothesis, which Planck's later called "an act of desperation", the results from theory for the baclbody's spectral radiancy $R_\nu(T)$ nicely fit the experiments.
- A new characteristic constant h appears (Planck's constant). $h = 6{,}626 \cdot 10^{-34}$ Joules $\cdot$ second.



Max Planck

Photons and the photoelectric effect

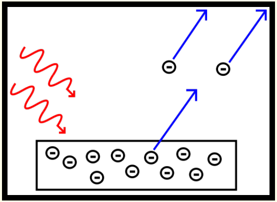
- In 1905, A. Einstein postulated that when light interacts with matter, it behaves as a collection of photons (i.e, particle-like entities) with energy $h\nu$ each.



A. Einstein

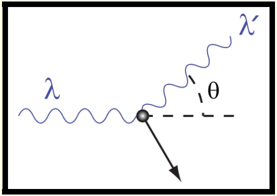
Photons and the photoelectric effect

- In 1905, A. Einstein postulated that when light interacts with matter, it behaves as a collection of photons (i.e, particle-like entities) with energy $h\nu$ each.
- This allows to explain the photoelectric effect: when light is adsborbed by a metallic surface, electrons are emitted by it, but only if the frequency of light is larger than a minimum quantity.



Photons and the photoelectric effect

- In 1905, A. Einstein postulated that when light interacts with matter, it behaves as a collection of photons (i.e, particle-like entities) with energy $h\nu$ each.
- This allows to explain the photoelectric effect: when light is adsborbed by a metallic surface, electrons are emitted by it, but only if the frequency of light is larger than a minimum quantity.
- Assigning to the photons a certain energy and momemtum, the Compton effect can also be successfully explained.



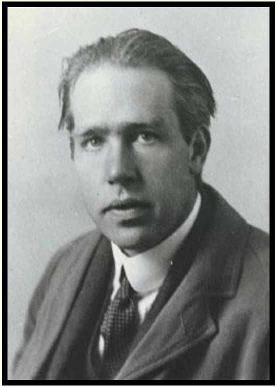
The Bohr model for the atom

- In 1911, Ernest Rutherford's experiments proved that the atoms are composed by a very small, very massive positively-charged nucleus, with an electron cloud orbiting it at large distances. This fact represented to be a problem for classical physics

E. Rutherford

The Bohr model for the atom

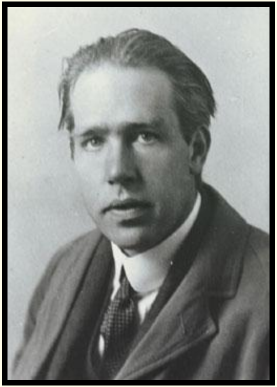
- In 1911, Ernest Rutherford's experiments proved that the atoms are composed by a very small, very massive positively-charged nucleus, with an electron cloud orbiting it at large distances. This fact represented to be a problem for classical physics
- Then, In 1913 Bohr proposed a radical hypothesis to overcome the problems associated with the stability of atoms: Electrons in an atom exist **only in certain stationary states**, including a ground state. Electrons change their energy by "jumping" between the stationary states, emitting light whose wavelength depends on the energy difference.



Niels Bohr

The Bohr model for the atom

- In 1911, Ernest Rutherford's experiments proved that the atoms are composed by a very small, very massive positively-charged nucleus, with an electron cloud orbiting it at large distances. This fact represented to be a problem for classical physics
- Then, In 1913 Bohr proposed a radical hypothesis to overcome the problems associated with the stability of atoms: Electrons in an atom exist **only in certain stationary states**, including a ground state. Electrons change their energy by "jumping" between the stationary states, emitting light whose wavelength depends on the energy difference.
- By combining known laws with bizarre assumptions about quantum behavior, Bohr swept away the problem of atomic stability. Bohr's theory was full of contradictions, but it provided a quantitative description of the spectrum of the hydrogen atom.



Niels Bohr

The wave-particle duality of matter: De Broglie's hypothesis

- In 1923, Louis de Broglie, in his Ph.D. thesis, proposed that the particle behavior of light should have its counterpart in the wave behavior of particles. He associated a wavelength with the momentum of a particle: The higher the momentum, the shorter the wavelength.

Louis de Broglie

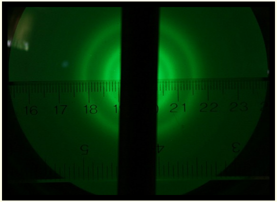
The wave-particle duality of matter: De Broglie's hypothesis

- In 1923, Louis de Broglie, in his Ph.D. thesis, proposed that the particle behavior of light should have its counterpart in the wave behavior of particles. He associated a wavelength with the momentum of a particle: The higher the momentum, the shorter the wavelength.
- The idea was intriguing, but no one knew what a particle's wave nature might signify or how it related to atomic structure. Nevertheless, de Broglie's hypothesis was an important precursor for events soon to take place.

Louis de Broglie

The wave-particle duality of matter: De Broglie's hypothesis

- In 1923, Louis de Broglie, in his Ph.D. thesis, proposed that the particle behavior of light should have its counterpart in the wave behavior of particles. He associated a wavelength with the momentum of a particle: The higher the momentum, the shorter the wavelength.
- The idea was intriguing, but no one knew what a particle's wave nature might signify or how it related to atomic structure. Nevertheless, de Broglie's hypothesis was an important precursor for events soon to take place.
- Afterwards, G. P. Thomson, C. Davisson and L. Germer showed experimentally that electrons can be diffracted by the surface of a crystal, giving support to the de Broglie's hypothesis.



Quantum Mechanics is born

Suddenly, a tumultuous series of events occurred, culminating in a scientific revolution. In the three-year period from January 1925 to January 1928:

- Wolfgang Pauli proposed the exclusion principle, providing a theoretical basis for the Periodic Table.

Wolfgang Pauli

Quantum Mechanics is born

Suddenly, a tumultuous series of events occurred, culminating in a scientific revolution. In the three-year period from January 1925 to January 1928:

- Wolfgang Pauli proposed the exclusion principle, providing a theoretical basis for the Periodic Table.
- Werner Heisenberg, with Max Born and Pascual Jordan, discovered matrix mechanics, the first version of quantum mechanics. The historical goal of understanding electron motion within atoms was abandoned in favor of a systematic method for organizing observable spectral lines.

Werner Heisenberg

Quantum Mechanics is born

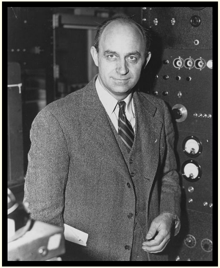
Suddenly, a tumultuous series of events occurred, culminating in a scientific revolution. In the three-year period from January 1925 to January 1928:

- Wolfgang Pauli proposed the exclusion principle, providing a theoretical basis for the Periodic Table.
- Werner Heisenberg, with Max Born and Pascual Jordan, discovered matrix mechanics, the first version of quantum mechanics. The historical goal of understanding electron motion within atoms was abandoned in favor of a systematic method for organizing observable spectral lines.
- Erwin Schrödinger invented wave mechanics, a second form of quantum mechanics in which the state of a system is described by a wave function, the solution to Schr̈dinger's equation. Matrix mechanics and wave mechanics, apparently incompatible, were shown to be equivalent.

Erwin Schrödinger

Quantum Mechanics is born

- Electrons were shown to obey a new type of statistical law, Fermi-Dirac statistics. It was recognized that all particles obey either Fermi-Dirac statistics or Bose-Einstein statistics, and that the two classes have fundamentally different properties.



Enrico Fermi

Quantum Mechanics is born

- Electrons were shown to obey a new type of statistical law, Fermi-Dirac statistics. It was recognized that all particles obey either Fermi-Dirac statistics or Bose-Einstein statistics, and that the two classes have fundamentally different properties.
- Heisenberg enunciated the Uncertainty Principle.

Werner Heisenberg

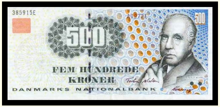
Quantum Mechanics is born

- Electrons were shown to obey a new type of statistical law, Fermi-Dirac statistics. It was recognized that all particles obey either Fermi-Dirac statistics or Bose-Einstein statistics, and that the two classes have fundamentally different properties.
- Heisenberg enunciated the Uncertainty Principle.
- Paul A. M. Dirac developed a relativistic wave equation for the electron that explained electron spin and predicted antimatter. He also laid the foundations of quantum field theory by providing a quantum description of the electromagnetic field.

Paul A. M. Dirac

Quantum Mechanics is born

- Electrons were shown to obey a new type of statistical law, Fermi-Dirac statistics. It was recognized that all particles obey either Fermi-Dirac statistics or Bose-Einstein statistics, and that the two classes have fundamentally different properties.
- Heisenberg enunciated the Uncertainty Principle.
- Paul A. M. Dirac developed a relativistic wave equation for the electron that explained electron spin and predicted antimatter. He also laid the foundations of quantum field theory by providing a quantum description of the electromagnetic field.
- Bohr announced the complementarity principle, a philosophical principle that helped to resolve apparent paradoxes of quantum theory, particularly wave-particle duality.



Niels Bohr