Supplemental material A - Questionnaire used in the study

Instructions: select the only option that, in your opinion, better fits the question. Please, do not select any option if you do not know the answer.

|  |  |
| --- | --- |
| 1. In your opinion, which experimental evidence do we have that a quantum particle sometimes behaves as a particle and sometimes behaves as a wave? |  |
| 1. The position of the particle is described by a wave equation | ❑ |
| 1. The particle propagates as a wave does | ❑ |
| 1. The particle has the same speed of an electromagnetic wave | ❑ |
| 1. The particle may interfere with other particles and with itself as a wave does | ❑ |
|  |  |
| 2. What is the wave function of a particle? |  |
| 1. The wave function describes the possible positions of the particle | ❑ |
| 1. The wave function allows to predict the probability of a measurement of any physical quantity associated with the particle, since we do not yet have sufficiently sophisticated instruments to measure it | ❑ |
| 1. The wave function allows to predict the probability of a measurement of any physical quantity associated with the particle | ❑ |
| 1. The wave function describes the possible states of the particle | ❑ |
|  |  |
| 3. The wave function of a free particle evolves with time oscillating as a wave: |  |
| 1. With a frequency equals to its wavelength | ❑ |
| 1. With a frequency proportional to its energy | ❑ |
| 1. Whose vibrations give the possible positions of the particle | ❑ |
| 1. Whose vibrations give the possible energy levels of the particle | ❑ |
|  |  |
| 4. Do superpositions in quantum mechanics differ from those in classical physics? |  |
| 1. Yes, because, contrarily to what is expected from classical dynamics, the particle is in all possible states simultaneously and the outcome of a measurement on the system will be consistent with only one of the states | ❑ |
| 1. No, since also in classical mechanics, two forces acting simultaneously on a particle add up | ❑ |
| 1. No, since also in classical mechanics, the state of a particle is a vector with different components | ❑ |
| 1. Yes, because, contrarily to what is expected from classical dynamics, the particle is in all possible states simultaneously and, until we make a measurement, the states can interfere constructively or destructively | ❑ |
|  |  |
| 5. The uncertainty principle establishes that there is an intrinsic limit |  |
| 1. To the precision with which you can simultaneously measure position and velocity of a particle | ❑ |
| 1. To our experimental capacity, which is not able to know, simultaneously and with arbitrary precision, position and velocity of a particle | ❑ |
| 1. To our experimental capacity, which it is not able to establish whether position and velocity of a particle depend on one another | ❑ |
| 1. To the numerical precision with which you can simultaneously measure position and velocity of a particle | ❑ |
|  |  |
| 6. Does the measurement process in classical physics have the same characteristics as the measurement process in quantum physics? |  |
| 1. No, because in quantum mechanics there are currently few instruments suitable for measurements | ❑ |
| 1. Yes, because also in quantum mechanics the measurement process is affected by experimental errors | ❑ |
| 1. Yes, because also in quantum mechanics the measurement is a process ruled by probability | ❑ |
| 1. No, because in quantum mechanics the state of the system irreversibly changes after the measurement | ❑ |
|  |  |
| 7. What does “collapse” of the wave function mean in quantum physics? |  |
| 1. The state of a particle during the measurement makes a sudden transition into one of its components and then returns to the same initial state occupied before the measurement | ❑ |
| 1. The state of a particle during the measurement makes a sudden transition to a new state in which its wavelength decreases and then eventually vanishes | ❑ |
| 1. The state of a particle during the measurement makes a sudden transition into one of its components and such transition is irreversible | ❑ |
| 1. The state of a particle during the measurement makes a sudden transition to a new state in which there is a correspondence between observed and expected data | ❑ |
|  |  |
| 8. When you calculate the energy of an electron in an atom, you do not take into account the gravitational attractive force exerted by the nucleus because |  |
| 1. The gravitational force is by many orders of magnitude smaller than the electrical force | ❑ |
| 1. The nucleus has enough energy to attract the electrons and we can neglect the gravitational attraction | ❑ |
| 1. The energy of an electron in an atom is greater than the gravitational energy of the nucleus | ❑ |
| 1. The gravitational attraction is balanced by the centrifugal force due to the rotation of the electron | ❑ |
|  |  |
| 9. Classical physics cannot explain the structure of the atom and its stability. This happens because, classically: |  |
| 1. The electrostatic force of the nucleus would attract the electron until it falls on the nucleus | ❑ |
| 1. Electrons do not follow the uncertainty principle | ❑ |
| 1. We only treat charged particles with a mass greater than the electronic one | ❑ |
| 1. A charged particle, moving along an orbit, emits radiation, thus losing energy and eventually falling on the nucleus | ❑ |
|  |  |
| 10. How does quantum physics explain the structure of the atom and its stability? |  |
| 1. Through stationary waves associated to the electrons | ❑ |
| 1. Through more precise measurements of the atomic energy levels | ❑ |
| 1. Through the orbitals associated to the trajectories of the electrons | ❑ |
| 1. Through more precise calculations of the atomic electric and magnetic fields | ❑ |

Supplemental material B – Correspondence between questionnaire items and levels of the hypothesized and revised LPs

# Table S1: correspondence between questionnaire answer choices and LPs levels.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Answer choices** | **Scoring** | **Hypothesized LP big ideas** | | | | |  | **Revised LP big ideas** | | |
|  |  | ME |  | A&E |  | WF |  | A&E - H |  | WF - M |
| 1a | Limited |  |  |  |  | LA |  |  |  | LA |
| 1b | Partial |  |  |  |  | L1 |  |  |  | L1 |
| 1c | Incorrect |  |  |  |  | LA |  |  |  | LA |
| 1d | Best |  |  |  |  | L3 |  |  |  | L3 |
| 1Blank | No answer |  |  |  |  | ND |  |  |  | ND |
| 2a | Incorrect |  |  |  |  | L1 |  |  |  | L1 |
| 2b | Partial |  |  |  |  | L4 |  |  |  | L3 |
| 2c | Best |  |  |  |  | UA |  |  |  | UA |
| 2d | Limited |  |  |  |  | L1 |  |  |  | L1 |
| 2Blank | No answer |  |  |  |  | LA |  |  |  | LA |
| 3a | Incorrect |  |  |  |  | L1 |  |  |  | L1 |
| 3b | Best |  |  |  |  | L3 |  |  |  | L3 |
| 3c | Limited |  |  |  |  | L1 |  |  |  | L1 |
| 3d | Partial |  |  |  |  | L2 |  |  |  | L2 |
| 3Blank | No answer |  |  |  |  | LA |  |  |  | LA |
| 4a | Partial |  |  |  |  | L4 |  |  |  | L3 |
| 4b | Limited |  |  |  |  | LA |  |  |  | LA |
| 4c | Incorrect |  |  |  |  | LA |  |  |  | LA |
| 4d | Best |  |  |  |  | UA |  |  |  | UA |
| 4Blank | No answer |  |  |  |  | ND |  |  |  | ND |
| 5a | Best | L3 |  |  |  |  |  | L2 |  |  |
| 5b | Partial | L2 |  |  |  |  |  | L1 |  |  |
| 5c | Incorrect | L1 |  |  |  |  |  | LA |  |  |
| 5d | Limited | L1 |  |  |  |  |  | LA |  |  |
| 5Blank | No answer | ND |  |  |  |  |  | ND |  |  |
| 6a | Partial | L1 |  |  |  |  |  |  |  | L1 |
| 6b | Limited | LA |  |  |  |  |  |  |  | LA |
| 6c | Incorrect | LA |  |  |  |  |  |  |  | LA |
| 6d | Best | UA |  |  |  |  |  |  |  | L3 |
| 6Blank | No answer | ND |  |  |  |  |  |  |  | ND |
| 7a | Partial |  |  |  |  | L4 |  |  |  | L3 |
| 7b | Incorrect |  |  |  |  | L3 |  |  |  | L2 |
| 7c | Best |  |  |  |  | UA |  |  |  | UA |
| 7d | Limited |  |  |  |  | L3 |  |  |  | L2 |
| 7Blank | No answer |  |  |  |  | L2 |  |  |  | L1 |
| 8a | Best |  |  | L2 |  |  |  | L2 |  |  |
| 8b | Incorrect |  |  | LA |  |  |  | LA |  |  |
| 8c | Partial |  |  | L1 |  |  |  | L1 |  |  |
| 8d | Limited |  |  | LA |  |  |  | LA |  |  |
| 8Blank | No answer |  |  | ND |  |  |  | ND |  |  |
| 9a | Partial |  |  | L2 |  |  |  | L2 |  |  |
| 9b | Incorrect |  |  | L1 |  |  |  | L1 |  |  |
| 9c | Limited |  |  | L1 |  |  |  | L1 |  |  |
| 9d | Best |  |  | L3 |  |  |  | L3 |  |  |
| 9Blank | No answer |  |  | LA |  |  |  | LA |  |  |
| 10a | Best |  |  | UA |  |  |  | UA |  |  |
| 10b | Limited |  |  | L1 |  |  |  | L1 |  |  |
| 10c | Partial |  |  | L3 |  |  |  | L3 |  |  |
| 10d | Incorrect |  |  | L1 |  |  |  | L1 |  |  |
| 10Blank | No answer |  |  | LA |  |  |  | LA |  |  |

Legend for big ideas: ME = Measurement; A&E = Atoms and Electrons; WF = Wave Function; A&E – H = Atoms and Electrons including Heisenberg’s principle; WF - M = Wave Function and its properties in the Measurement process. Legend for LP levels: LA = lower anchor; UA = upper anchor; ND = not defined. See Tables 1, 10 and 11 for the description of the LPs levels.

# Supplemental material C - Description of the QM courses included in this study

Introduction to quantum theory – QM1

QM1 is a 64-hour sophomore course, with a broad program spanning from electromagnetic waves to the transition from classical physics to QM, to statistical physics. The aim is to familiarize students with the phenomena that led to the development of quantum mechanics. In particular, the course addresses semi-classical explanations of phenomena, which will be later deepened in Fundamentals of Theoretical Physics (QM2) using the full quantum mechanics formalism. Exercise sessions are included within the lectures and are carried out by the same instructor, for a total of about 20 hours. During such sessions the instructor works out and discusses selected exercises and problems in front of the whole class.

In the first part, which covers about one third of the course, the black body radiation problem, Thomson and Rutherford experiments and atomic models are exploited to introduce the issues that QM would have later addressed. Moreover, atomic line spectra are discussed and compared to continuous spectra of solids, giving some indications on how they are related to the problem of atom stability. De Broglie hypothesis of electrons behaving as standing waves on circular orbits around the nucleus is used to explain the wave nature of matter.

Specific contents addressed by the course are:

1. A phenomenological introduction to quantum mechanics. Black body problem. Photoelectric effect. Specific heat of solids. Rutherford and Bohr atomic models. Davisson and Germer experiment.
2. Introduction to special relativity: The Michelson and Morley experiment. Einstein postulates. Lorentz transformations. Velocity transformations. Relativistic invariants and four-vectors. Four-vectors and events in space-time. Causality preservation. Linear momentum. Forces, work, energy. Relativistic collisions. Compton effect. Current density and potential. Relativistic formulation of electrodynamics. Inertial mass and gravitational mass. Equivalence principle.
3. Statistical physics and introduction to statistical mechanics: Kinetic theory of gases. Combinatorial method for counting the states. Maxwell-Boltzmann distribution, Bose-Einstein and Fermi-Dirac statistics. Perfect gases. Energy equipartition theorem. Drude’s theory. Theory of polarization by orientation. Paramagnetic materials. Principles of statistical mechanics. Microcanonical ensemble. Canonical ensemble and partition function.

Fundamentals of Theoretical Physics – QM2

QM2 is a 96-hour third-year course that focuses on non-relativistic QM. The course is divided into lecture-based sessions (about 64 hours) devoted to the full formalism of QM and separate exercise sessions (about 32 hours), aimed at the solution of quantitative problems and exercises. During the exercise sessions, the instructor – a different faculty member – is at the board talking to the class, while the students work individually, taking notes on a given exercise. They are also encouraged to ask questions about the concepts they have learned in the lectures. The number of students who attend the exercise sessions is usually the same as that of the lectures.

Wave function big idea is the main structural element of QM2. In this framework, superposition, evolution and collapse of the wave function are introduced. The measurement in QM is re-interpreted as a process that, on one hand, extracts information from the wave function, and on the other irreversibly modifies it (namely, the wave function “collapses”). We stress that the measurement process is associated to the highly abstract formalism of Hermitian operators (the observables) acting on vectors in a Hilbert space.

Specific contents addressed by the course are:

1. Experimental foundations of quantum theory: black-body radiation; Photoelectric effect; Compton effect; the particle-like behaviour of radiation; atomic spectra and the Bohr hypothesis; the experiment of Franck and Hertz; wave-like behaviour and the Bragg experiment; the experiment of Davisson and Germer; interference phenomena with matter waves.
2. Schrödinger formalism and probabilistic aspects: from classical to wave mechanics; probability distributions associated with vectors in Hilbert spaces; uncertainty relations for position and momentum; transformation properties of wave functions; the Heisenberg picture; quantum states in the Heisenberg picture; the Dirac formalism.
3. Integrating the equations of motion: Green’s functions for the Schrödinger equation, integrating the equations of motion in the Heisenberg formalism - the harmonic oscillator.
4. Elementary applications: one-dimensional problems; boundary conditions for a particle confined to a square-well potential; reflection and transmission coefficients; step-like potentials; tunnelling effect; the one-dimensional harmonic oscillator; the Schrödinger equation in a central potential; the Hydrogen atom; the isotropic harmonic oscillator in two and three dimensions; algebraic treatment of the harmonic oscillator; harmonic oscillators and coherent states.
5. Introduction to the spin: Stern–Gerlach experiment and electron spin; wave functions with spin; addition of angular momenta.
6. Symmetries in quantum mechanics: meaning of symmetry; transformations of reference frames and corresponding quantum symmetries; roto-translations; time translation; spatial reflection; time reversal.
7. Perturbation theory: approximation of eigenvalues and eigenvectors of a Hamiltonian operator; Stark and Zeeman effects; Time-dependent formalism.

Elements of Modern Physics – MP course

MP course (48 hours) features a syllabus that includes special relativity and fundamentals of QM, including most of the topics addressed in QM1, as the De Broglie hypothesis or Heisenberg’s principle. Exercise sessions are included within the lectures and are carried out by the same instructor, for a total of about 20 hours. Also the teaching style is mostly traditional, with the instructor at the board solving and discussing quantitative tasks.

After attending this course, a student should: (i) know and understand the phenomenological and experimental foundations of the theory of relativity and quantum mechanics; (ii) be able to apply this knowledge in the general approach of a relativistic / quantum physics problem; (iii) be able to communicate in a clear, rigorous and effective way ideas related to the contents of the course; (iv) be able to identify the most appropriate methods to analyze and solve a problem concerning the course topics and correctly interpret the results.

Specific contents addressed by this course are:

1. Elements of special relativity: The covariance of electromagnetism. Michelson-Morley’s experience. Extension of the principle of relativity. Lorentz transformations. Relativistic kinematics and dynamics. Relativistic Doppler effect. Overview of general relativity.
2. Classical physics crisis and elements of quantum mechanics: The black body radiation. Photoelectric effect. Specific heat of solids. The Compton effect. The Rutherford experiment. Bohr's atom. Fundamental experiments with matter waves. Wave-particle dualism and De Broglie relationship. Heisenberg uncertainty principle. Schrödinger equation. Probabilistic interpretation of the wave function. Simple one-dimensional problems. Angular momentum. Hydrogen atom. Identical particles. Pauli exclusion principle.
3. Elements of statistical physics: basics of thermodynamics. Microscopic reversibility and macroscopic irreversibility. Kinetic theory of an ideal gas. Boltzmann postulates. Statistical interpretation of the second principle of thermodynamics. Boltzmann distribution and its applications. Overview of quantum statistical mechanics.