HOW IS RADIATION EMITTED OR ABSORBED?

Introduction to Quantum Physics

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1. INTRODUCTION: How is radiation emitted or absorbed?

Since ancient times people have used very different devices and materials to obtain light. We know that we can produce light in many ways and that matter reacts in many different ways when capturing light: it can be heated, reflect some light, allow its passage (transparency), "store" it for a while (phosphorescence) or produce electrical current (photoelectric plates).

During this course (while studying electromagnetism) we have studied what light is and we have explained several luminous phenomena, but at no time have we analyzed how it is generated or absorbed, and in general how it interacts with matter. We know that matter is made up of atoms, which are formed by a positive nucleus and electrons, and that light is a wave, an electromagnetic field that vibrates with a certain frequency and amplitude. However, we do not know what happens in atoms when emitting or absorbing light.

Logically, our plan to address this problem will begin by looking for situations in which the light is emitted or absorbed.

A1. Say how we can produce light (try to remember all the methods and devices you know)

Comments for teacher A1. - Some videos on light emission can be seen at http://www.youtube.com/user/pacosavall?ob=0&feature=results_main

We want to show that there are many ways of emitting light, indicating devices and phenomena whose operation we will study later. We see that matter emits light in different conditions and we begin to ask ourselves questions about the mechanism that allows us to account for the emission of light: is it always the same? Why does matter sometimes heat up and sometimes not? What can we do to change the color or intensity of the light emitted in each case?.

We can obtain light:

- Heating or burning objects: putting a piece of metal near a flame, burning a piece of paper, etc.
  - Burning salts, as is done in flares or fireworks to get colored lights.
  - Heating objects with an electric current: an ordinary tungsten filament bulb, the tubes of a stove or a toaster, etc.
- By passing a current through a gas (in this case the gas is not heated): a fluorescent tube, a low energy bulb. If we touch the tube or the bulb with our hand, we see that it does not get hot; this can lead us to think that the production of light takes place by means of a different mechanism to that of the filament bulb.
- "Accumulating radiation by absorption": Fluorescent adhesives that glow for a few minutes in the dark.
- By chemical or biological procedures: Animals that have the capacity to produce light, tubes that break and make light for a few hours, etc.
A2. Observe the light emitted by some of the objects mentioned above with a spectroscope. This instrument will allow you to know in detail the frequencies that make up the radiation. Describe what you see and think about how we could change its characteristics (frequencies or colors’ distribution and intensity).

Comments for the teacher A2. - The aim of this activity is to introduce spectra as an instrument for light analysis. Students should learn that the light they observe is formed by several frequencies (which allow us to quantify the magnitude “color”) and that each frequency can have a different intensity (we will work the intensity qualitatively throughout the unit). We will find the following previous or alternatives ideas about the spectra in the students:

- That a spectrum is a ghost: they do not associate the concept of spectrum with the decomposition of radiation.

- That all spectra are equal, all colors are always present: they do not reflect on the position of the lines, the number of lines, the presence of “black zones” in the spectrum... As they always see colors they say that all spectra are equal. Another alternative idea is to believe that they are always observing the rainbow. Because they see many colors, they think all spectra are equal whether they observe a discrete or continuous spectrum.

- They think that a spectrum is continuous if emitted continuously in time. The spectrum of hydrogen is considered discontinuous because it can be only when the lamp is switched on, the contrary for the spectrum of the Sun... Some spectrum would be discontinuous when only seen temporarily (possibly the idea comes from the fact that the Sun always emits, does not go out, while a spectral lamp only emits when connected).

- They consider the lines of the spectrum to be the light, as if the source emitted the lines that are observed in the spectrum (like colored rays). It is necessary to emphasize that the spectrum is the decomposition of the light emitted by the source and that the shape (lines, circles, etc.) depends on the section of the light beam, that is, if instead of a vertical slit the spectroscope had a circular hole, circular colored holes would be observed.

- When studying the absorption spectra, they consider that the gas absorbs all the frequencies and then emits again those that appear in the absorption spectrum, as if it were a fluorescence or phosphorescence.

When we observe the light from outside the classroom with the spectroscope, we verify that all the colors of the rainbow form it. This indicates that all the frequencies are present in the white light. We refer to this spectrum as “continuous spectrum”. Sometimes one color is brighter than another one, indicating that these frequencies are more intense. In these cases, the light is not completely white but it has tonalities.

When observing the light emitted by a tungsten filament bulb, we observe a continuous spectrum, with all colors, but the area corresponding to yellow displays brighter colors, which indicates that these frequencies have greater intensity (the light acquires a yellowish tonality). The same happens when heating any solid (or liquid), with the difference that the light looks yellowish the hotter the material, becoming white for very hot materials and red for colder
materials. In addition, you can see when heating any material that the light becomes less intense as the temperature decreases.

When you heat salts with a Bunsen you can see colored flames (gases). The colors are related to the composition of the salt, the temperature of the flame only affects the intensity of the radiation, but not its color. This shows that the behavior of gases is different from that of solids and liquids. To go deeper into this aspect we are going to use isolated gases.

When we make the decomposition of the light emitted by the gases of the spectral tubes, we observe that the spectrum presents only a few color lines separated by black bands, as it is seen in the figure. This is a discrete spectrum (not continuous). We can also verify that the color of the lines emitted by a gas is always the same, regardless of its temperature and the method used to obtain it. When changing the temperature we only observe a change in the intensity of the lines: the higher the temperature the more intense the lines are. The emission of the spectrum lasts as long as the tube is connected, and, during this time, radiation is emitted "continuously" (it is always being emitted).

![Hydrogen emission spectrum](image)

Considering what we know, we can say that:

- Each gas originates a distribution of different colored lines, in which only a few colors appear (there are only a few frequencies).
- The lines are different in intensity, which implies that there is a different wave amplitude for each frequency.

We can also obtain these "color footprints" by passing white light through a container containing the gas or through a solution. Now, in this case there is a fundamental difference: the complete rainbow was observed (as corresponds to white light) but with a set of superimposed black lines, as shown in the figure.
We cannot observe this when using our spectral tubes. The amount of gas contained in the tube is very low, that makes almost all the light pass through. With a greater amount of gas in the tube, you could see the black lines of the absorption spectrum, or at least darker lines.

**A2b.** Do you see any relation between the emission and absorption spectrum? How will the absorption spectra of the rest of the gases we have used be?

As the spectrum of each gas is always the same and is unique, spectroscopic techniques can be used to determine the composition of material samples. In fact, the introduction of the spectroscope allowed the determination of the Sun's composition and other stars.

However, we must not think that the phenomena of emission and absorption of radiation are only interesting to obtain colored flames or to identify substances. Our daily life is completely flooded with objects that take advantage of the emission and absorption of radiation for their operation, many of them go unnoticed but they are fundamental instruments in our lives.

**A3.** Indicate innovations and technological applications related to the emission and absorption of light that have supposed a scientific advance or an improvement of the quality of life.

**Comments for the teacher A3.** - This activity aims to generalize and go beyond visible light emission, considering other types of non-visible radiation and introducing absorption. It also seeks to "problematize" the field of study, posing questions of interest. Among the possible answers we can find:
• Emission:
  - To obtain light of a certain color (or radiation of a certain frequency) that can be useful for several reasons: emergency signals, advertising signs, fireworks, ultraviolet lights to identify bills, tanning, or X-rays for radiographs, etc. What mechanism allows to control the frequency of the light that is emitted (infrared, visible, UV, etc.)?
  - Identify the composition of bodies, including celestial objects. What is the relationship between the composition of a flame and the color it emits? How do we know the composition of the Sun and the farthest stars?
  - To obtain light with the minimum energy consumption: the fluorescent tube, the led and the low energy bulbs. How do they work? What mechanism allows us to explain that they emit radiation without getting hot? What does the gas inside them do? We observe their spectrum and see that the light they emit is not "white" like that of the Sun.
  - Radiations with technological utility: the laser and all its applications (medical, CD, DVD, pointers, etc.), the microwave, WiFi, bluetooth ...
  - Fluorescent and phosphorescent materials that facilitate visualization in low-light conditions. How can they store light (or energy)?

It is a matter of posing the problem that we will face during the first part of the unit: What mechanism makes it possible to account for light emission? Atoms form all materials, but why they emit light of different colors and by different ways?

• Absorption:
  - Solar panels: What does light do on the panel that allows electricity to be generated? Why isn’t any material valid for building them? Is any radiation valid for making them work?
  - Image recorders: cameras, video cameras, photographic paper for developing photos, old films sensitive to light, etc. What does light do to materials to "mark" them? How is the information transmitted by light recorded?
  - Detectors: Photocell of entrance doors, alarms, counters, etc.
  - The biological effects of radiation: What does light do in our eye that allows us to see? And in our skin to tan us? Why do skin cancers occur?

We pose the second problem: how does light interact with matter in such a way that matter "registers" this interaction? Why is light necessary to achieve these effects and not any other type of energy?

It is necessary to show several of these devices and relate them with the problem: photographic negatives and developed photographs, photoelectric plates, low-energy bulbs, LEDs, fluorescent and phosphorescent objects, danger signs for radiation... We intend to rise questions with two purposes: to trigger students’ interest by showing the everyday problem that we are about to study and to pose questions related to the emission and absorption of radiation to introduce them in the research to be carried out next.

The large number of applications mentioned justifies the importance of the issue: Establish a mechanism to explain the emission and absorption of radiation. Once we have set the goal, we must consider a plan that allows us to move forward.
A logical plan to follow could be:

We will begin by studying the simplest case: the spectrum of gases. It is the simplest because we can consider that gases, formed by isolated atoms or molecules with little interaction among them, is the matter that presents the simplest composition. The spectra of the gases are also the simplest, those that contain fewer frequencies. Of all gases, the simplest is hydrogen, whose atoms have a positive nucleus with one electron orbiting around it.

Bearing this in mind, whenever we tackle a problem concerning the emission and absorption of radiation we must ask ourselves:

- What is the structure of the emitted or absorbed light?
- What is the structure of matter responsible for this emission or absorption?
- What happens between atoms and light so that this emission or absorption takes place?

Once we will have a model that explains the formation of the spectra, we will test it, and will modify it if necessary, to account for other phenomena of emission and absorption of radiation such as the photoelectric and the Compton effects.

If we are successful, we will look for applications of the model (an additional proof of its validity) and will use it to explain the operation of technological devices and everyday phenomena of radiation emission and absorption, many of which we have already observed during our study.

Finally, it will be necessary to analyze how the model affects the field of knowledge in which it has arisen: the nature of light and that of matter, looking for a way to integrate our advances with the physics known until now, avoiding contradictions and searching for a universal conception about light, matter and their interactions.

In a schematic way, the plan to investigate our problem is as follows:

1. **Establishment of a first model to explain the simplest case of radiation emission and absorption: the spectra of the gases.**
2. **Testing the established model.**
   2.1. Does energy quantization in atoms depend on of how we interact with them?
   2.1.1. The Franck and Hertz experiment.
   2.1.2. Illumination of a gas with monochromatic light.
   2.2. Is energy quantized in radiation?
   2.2.1. The photoelectric effect.
   2.2.2. The Compton Effect.
3. **Possible applications of the established model.**
4. **Searching for a coherent body of knowledge.**
5. **Limitations of the new knowledge and open problems.**
1. Establishment of a first model to explain the simplest case of radiation emission and absorption: the spectra of the gases.

Among all the gas spectra, the simplest is that of hydrogen, which only contains four frequencies. Hydrogen atom, moreover, is the simplest of all. It only consists of a positive nucleus formed by a single proton and an electron orbiting around it. Since this is the simplest atom and spectrum, we are looking for a mechanism to explain how a tube containing millions of hydrogen atoms emits electromagnetic waves of four frequencies.

A5. Taking into account what we know about how electric charges generate electromagnetic radiation, suggest a mechanism to explain how hydrogen atoms could emit light when heating hydrogen gas.

Comments for the teacher A5. - The aim of that and subsequent activities is to test a classical mechanism of radiation emission based on the planetary model of the atom and the wave conception of radiation. From the detailed analysis of this mechanism it will be concluded that it cannot satisfactorily account for the formation of the atomic spectra because there are aspects that it cannot explain. In addition to familiarizing students with the classical processes of radiation emission, it should enable them to become aware of the insurmountable difficulties faced by classical physics when trying to explain the processes of radiation emission.

An emission model can be established using electromagnetic theory. Bearing in mind that the electron is a charged particle that makes a periodic movement, the orbital movement will give rise to an electromagnetic wave that propagates at the speed of light and whose frequency coincides with the orbital frequency of the electron.

The electron, in orbital motion, performs an oscillatory motion that generates a wave that spreads through space. The frequency of this wave coincides with the frequency of oscillation of the electron, i.e. the number of turns per second. The spherical wavefront and the wavelength are represented.

The presence of many atoms makes it possible to explain the formation of radiation at different frequencies at the same time, while the electron of each atom may vibrate differently. If the
spectrum has 4 lines we have to conclude that each atom vibrates in one of 4 possible orbits. But why aren’t there more orbits and more frequencies in the spectrum?

Two possible vibration states of the hydrogen atom. The first electron suffers a force F of attraction towards the proton and moves with a velocity v. This makes it turn with a given frequency, emitting radiation from that frequency. In the other state, the electron is closer to the nucleus, the force of attraction is greater and so is the velocity. In this case the rotation frequency is higher, so it gives rise to higher-frequency radiation. The presence of 4 spectral lines can be explained by considering that there are 4 possible forms of vibration (4 states).

If we heat the gas to a higher temperature one would expect all the atoms to vibrate with more energy, and therefore in orbits farther away from the nucleus. This would result in different frequencies and a spectrum with other spectral lines. But that doesn’t happen. The frequency of the lines does not depend on temperature. Another difficulty arises when we stop providing energy to the atoms. We tackle it in the following activity.

A.6. In a diagram of energy, in a qualitative manner, place the energy of the atoms that are emitting radiation. Use the energy diagram to interpret what happens to the electron as it emits radiation, according to the mechanism you have proposed before.

Comments for the teacher A6. - If the electron is orbiting in a fixed orbit around the nucleus it has a certain energy and occupies a fixed position in an energy diagram (as long as its energy is constant), so we represent it in the energy diagram (we represent 4 possible energies corresponding to the values of each orbital movement). Bearing in mind that the red line is the most intense, we can assume that there will be more atoms vibrating with that frequency and emitting more energy at that frequency, this would explain the difference in intensities of the lines. We must bear in mind that the total energy of the atom is negative because the electron is linked to the nucleus and cannot escape if it is not provided with the energy needed to do so.
Energies of the hydrogen atoms and the radiation they emit, according to the proposed model. The atoms that have more energy will oscillate with a lower frequency and emit light of lower frequency.

As long as the electromagnetic wave emitted by an atom carries energy, the atom must be losing it to maintain the emission, this will cause it to oscillate closer and closer to the nucleus until it finally collides with it, as shown in the diagram below.

As the electron emits radiation, it loses energy, which leads it to move in orbits closer and closer to the nucleus, moving through the energy diagram towards lower and lower values and emitting higher frequency radiation.

We can assume that the energy we provide helps compensate for the energy that is lost by radiation. However, what if, suddenly, the supply of energy increases or decreases? Wouldn’t one expect a change in the orbital motion of the electron and in the frequency of the emitted radiation? This would lead to a continuous spectrum, with all colors, since any change in the orbital movement of the electron from one orbit to another supposes the passage through all the intermediate orbits and a progressive change of frequency, so that all frequencies should be reflected in the spectrum.

In addition, the continuous movement of the electron in the orbit implies that an atom always emits radiation (because electrons always spin around the nucleus), therefore, when the energy supply ceases the atom should lose all its energy and collapse, again emitting a continuous spectrum.
A7. Since atoms are stable, the mechanism of light emission cannot be that proposed. Establish a possible mechanism that allows us to overcome the difficulties we face. Specifically, a model to explain why:

- Atoms are stable.
- The radiation emitted by the gas always has the same frequencies.
- Some lines are more intense than others.

A7b. - The physicist Niels Bohr proposed a model to explain the emission and absorption of radiation by atoms. Evaluate if they represent an advance in our problem:

- The electrons of the atoms can only orbit in a few stationary states, characterized by a fixed energy. In them, they orbit around the nucleus according to the laws of mechanics but without emitting energy.
- Any change in the atom implies the passage of the electron from one stationary orbit to another.
- The frequency of the emitted or absorbed radiation depends on the initial and final energies, according to the expression: \( |E_f - E_i| = h \cdot \nu \), where \( E_i \) and \( E_f \) are the energy of the atom in the initial and final state, \( \nu \) the frequency and \( h \) is a constant.

Comments for the teacher A7. - Students face with the need to make hypotheses that are contrary to classical physics and that allow us to overcome the problem we are facing. We further introduce the Bohr hypotheses (activity 7b) as an additional possibility. All the hypotheses will be analyzed to determine the extent to which they account for the experimental results.

Experience tells us that one of the hypotheses the students establish is that electrons orbit around the nucleus without emitting energy. They only emit radiation when they are supplied with energy (they emit radiation for not leaving the orbit in which they are; it is as if they expel the excess of energy so as not to change their movement). With this hypothesis, the problem of the stability of the atom is solved and the existence of 4 lines in the spectrum can be explained if it is accepted that the electron can only orbit in one of 4 possible orbits. The atom can only be in 4 “places” in the energy diagram and cannot leave them because all the energy it absorbs is immediately emitted. We will call it the Constant Orbits Model.

With this model, some spectral lines are more intense than others because there are more electrons in a given orbit than in another, and therefore the gas emits more energy of the frequency corresponding to that orbit. As far as absorption is concerned, each atom will absorb only the radiation corresponding to the frequency at which the electron orbits.

Before using Bohr’s hypothesis to account for the formation of spectral lines, it is necessary to analyze the image of the atom that is derived from it, emphasizing the mechanical and energetic characteristics and the differences with classical physics.

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1 They do not always launch this hypothesis. Insisting on it does not lead to positive results, so we recommend not doing so in case the students do not propose this idea.
According to the first hypothesis (in the order in which they are in activity 7b) the electron cannot orbit at any distance from the nucleus, but only at fixed distances. However, unlike electromagnetism, the electron does not emit energy when it moves in its orbit. While the electron is kept in a stable orbit, the laws of mechanics are satisfied: a centripetal force is responsible for the orbital movement of the electron so that for more distant orbits the attraction force is lower, the rotation speed is lower and the mechanical energy of the system is greater. The atom can only be in a few places on the energy diagram.

The combination of the second and third hypotheses explains the formation of the spectral lines. When there is a change in the atom the electron necessarily passes to another stationary state, there can be no intermediate changes. The energy difference between the two stationary states is emitted in the form of electromagnetic radiation. Its frequency is determined by the expression of the third hypothesis. As we can see, the frequency of radiation is no longer the orbital frequency of the electron, as predicted by electromagnetism, but is determined by the energy difference of the stationary states between which the transition occurs.

When the electron changes from one orbit to a lower energy orbit, it emits radiation. The frequency of this radiation is related to the energy difference of the atom in the initial and final state.

The formation of different lines is due to the existence of different transitions in the collective of atoms. As each atom can make a different transition, the sum of all the emitted radiations gives rise to the different lines of the spectrum. The presence of lines of greater intensity is because there are a greater number of atoms that make the transition responsible for the emission of the radiation corresponding to that frequency, giving rise to a wave of greater amplitude (and greater intensity) because of the sum of all the individual contributions.

This mechanism of emission is completely different from what we consider valid for waves: a wave represents the propagation of a vibration, an energy that is emitted during a certain time and that is propagated through space, which occupies a volume. Now we are proposing that the electron makes a change of orbit and emits light, with a certain frequency. Can light be emitted "all at once", without the need for a vibration?

Despite being contrary to the physics known so far, we will test these hypotheses, as they seem the only ones that prevent the destruction of the atom and can account for the existence of few frequencies in the spectrum.

A8. Find ways to test the established hypotheses.
Comments for the teacher A8. - We can rely on known experimental facts to rule out some of the established hypotheses. If electrons cannot leave their orbit, as the constant orbits model states, we cannot account for electrical phenomena such as ionization or the processes of charging and discharging materials by friction or other procedures. Likewise, it is difficult to understand conductivity as a flux of electrons flowing through a material. The possibility of extracting electrons from an atom with the corresponding energy contribution is contemplated in Bohr's hypotheses.

Another detail to bear in mind is that the presence of 4 lines in the spectrum implies the existence of 4 types of hydrogen atom. The model proposed by Bohr does not imply the acceptance of different atoms.

In addition to the difficulties to explain already known facts, new difficulties are added: the existence of 4 fixed orbits does not make it possible to consider the existence of any other spectral lines. Instead, Bohr's hypothesis allows the emission of more than 4 spectral lines. If there are several stationary states and several possible transitions there must be more than 4 spectral lines. The detection of these spectral lines would be a great step forward in terms of the acceptance or rejection of this model. We will follow this path.

We must not be satisfied with a qualitative interpretation of the results in order to accept the advanced hypotheses, especially when they contradict what has been established in the physics known so far. The audacious hypotheses must be potentially fruitful and, in addition to explaining known phenomena, they must predict unknown results. We will go deeper into the problem, considering the quantitative aspect in order to test it more seriously: How can we ionize atoms? Does the frequency of the radiations measured in the spectrum coincide with that established in our hypothesis? Are there any other predicted radiations in the spectrum that have not yet been observed?

A8a. It is experimentally proved that when a vessel containing hydrogen gas is illuminated with radiation of a frequency higher than $3.28 \cdot 10^{15}$ Hz, the atoms of the gas become ionized. Moreover, this ionization is achieved whenever the gas is illuminated with any radiation of higher frequency than that indicated. Use the hypotheses under study to account for this fact.

Comments for the teacher A8a. - The hypothesis of constant orbits does not explain ionization as it prevents electrons from leaving their orbits. Bohr's hypotheses do contemplate this possibility: a change of energy in the atom requires the absorption or emission of radiation of a certain frequency ($|E_f - E_i| = h\nu$). Therefore, for the electron to go from being bound ($E<0$) to being free ($E\geq 0$) radiation of a minimum frequency will be required, as shown in the figure. This also allows us to determine the energy of hydrogen atoms when they are not excited, which is -13.6 eV.
Radiation of $3.28 \times 10^{-15}$ Hz produces an electronic transition of 13.6 eV, sufficient to ionize the atom according to the experimental results. Radiation with lower frequency is either not absorbed or would produce a lower transition, insufficient to achieve ionization. This allows us to identify the fundamental state of the atom as one that has an energy of -13.6 eV.

**A8b.** Can the hydrogen atom emit radiation of other frequencies besides the 4 observed? Reason, using the models we are probing, if other radiations of non-visible frequencies could be produced.

**Comments for the teacher A8b.** - The constant orbits model only allows the formation of radiation of 4 frequencies, unless we accept that there are more possible orbits and more different hydrogen atoms. On the other hand, Bohr’s hypotheses allow a great number of transitions, and therefore a great number of frequencies.

The use of adequate techniques allows us to measure frequencies of spectral lines located beyond the visible range of radiation. Non-visible radiation can be detected by photographic systems (they can mark photographic films). Using these techniques, it can be verified that hydrogen not only emits the 4 lines of the visible spectrum, but also emits a large amount of radiation with frequencies belonging to the infrared and ultraviolet spectrum. The frequencies of these lines are those shown in the table below.

<table>
<thead>
<tr>
<th>UV</th>
<th>2,47 \times 10^{15} Hz</th>
<th>2,93 \times 10^{15} Hz</th>
<th>3,09 \times 10^{15} Hz</th>
<th>3,16 \times 10^{15} Hz</th>
<th>3,20 \times 10^{15} Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR</td>
<td>1,6 \times 10^{14} Hz</td>
<td>2,34 \times 10^{14} Hz</td>
<td>2,74 \times 10^{14} Hz</td>
<td>2,99 \times 10^{14} Hz</td>
<td>3,25 \times 10^{14} Hz</td>
</tr>
</tbody>
</table>

In order to deepen the quantitative aspect it is necessary to attribute a value to the energy of the atoms in each stationary state, as well as a value for the constant $h$ that relates the energetic transition with the frequency of the emitted radiation. The Danish physicist Niels Bohr, who first proposed these hypotheses, proposed an energy value of

$$E_n = -\frac{13.6\text{ (eV)}}{n^2}$$
for each stationary state\(^2\). This value is consistent with the experimental measure of hydrogen ionization energy: if one considers that the electron of the hydrogen atom is in the fundamental state, the one with the least energy and closest to the nucleus, the energy of the system will coincide in absolute value with the energy that we must provide to ionize the atom. Experimentally 13.6 eV are needed to ionize an atom, so the energy of the fundamental state will be -13.6 eV (\(E_1=-13.6\) eV). The constant \(h\) had been introduced years before by the German physicist Max Planck and its value is \(h=6.62\cdot10^{-34}\) Js.

**A8c.** Calculate the energy of the first 5 stationary hydrogen states and use an energy diagram to relate possible transitions between stationary states with each line of the hydrogen spectrum. See if we can account for visible and non-visible spectral lines.

**Comments for the teacher A8c.** - In carrying out this activity, we must address two possible conceptual errors:

- There are students who attribute to the electron an identical frequency to that of light. Thus, they talk about the frequency of the electron, or that the electron is in an orbit with a frequency of \(X\) MHz and emits light of \(X\) MHz, etc.
- Other students attribute to light the energy that the electron has in its orbit. For instance, an electron that is in the orbit of -13.6eV will emit 13.6eV of radiation, an electron that is in the orbit of -0.85 eV will emit 0.85eV of energy, etc.

The two ideas are largely due to not differentiating between the emitting source and the emitted wave: there are students who consider them all the same thing. It is very important to follow the strategy indicated at the beginning of the unit: 1.- how is the matter (atomic model that we are introducing), 2.- how is the emitted radiation (wave model, for the moment), 3.- what mechanism allows to explain the emission.

This activity aims to introduce on the energy diagram the energies of the possible stationary hydrogen states and to apply the model established as a hypothesis. When an electron is in a certain state it can only make transitions to other states, intermediate states are not possible. This means that only a few frequencies are possible in the emitted radiation. If we calculate the energy differences between the states and the frequencies corresponding to the transitions between them, we can identify some colors of the visible light. We will see that the electronic transition from state 3 to state 2 gives rise to the red line of the spectrum; the transition from state 4 to state 2 gives rise to the blue line, and the transitions from states 5 and 6 to state 2 give rise to the purple lines. It is necessary to emphasize the relationship between the frequency of radiation and the energy difference of the atom to overcome the alternative ideas described at the beginning.

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\(^2\) The electron-Volt (eV) unit is often used to measure the energy of atoms. The equivalence with the international system is 1 eV=1.6\cdot10^{-19} J.
The transition from the fourth stationary state to the second releases 2.55eV of energy. The emitted radiation has a frequency of $6.16 \cdot 10^{14}$ Hz. Each transition has an energy and a frequency. As there are many atoms in the gas, the emitted radiation will transport the sum of the energy emitted by the atoms and will be formed by all the frequencies emitted by the atoms. The most intense lines will correspond to the transitions that take place more times per unit of time.

We must also emphasize that the electron can make any transition; it does not necessarily have to go from a stationary state to the immediately lower one. It can pass from one state to another without passing through intermediate stationary states. The calculation of the frequencies of many of the possible transitions corresponds to frequencies measured outside the visible spectrum that we have previously mentioned.

Not all atoms are having the same transitions: the most intense lines correspond to the transitions that occur most times per unit of time, the most probable transitions. This means that we do not know what transition the electron will make from the stationary state in which it is: two atoms that are in the same stationary state can do a different transition, although the atoms are exactly equal. It is convenient to emphasize this aspect since later we will see that randomness is a characteristic of quantum behavior, and this randomness is already present in spectra and other emission and absorption phenomena.

Here it is necessary to be careful not to give the image that orbits or stationary states exist independently of the electron that occupies them: the electron can be orbiting with certain energies, but there is no energy (and therefore there is no orbit) if there is no electron: the diagram represents the possible energetic states.

Placing the energies corresponding to the stationary states on the energy diagram will also allow us to see that the "energetic distance" (or energetic jump) between adjacent orbits is decreasing all the time. When the atom absorbs enough energy, the electron will be released and its energy will be continuous again. For high energies the classic results that we know are recovered, the variation of energy returns to be continuous.

The introduced model satisfactorily explains the frequencies and intensities of the lines of the hydrogen emission spectrum. However, this is not the only spectrum that can be obtained with hydrogen. Let us remember that when we observe the spectrum of the white light that has passed through a container with heated hydrogen gas, the corresponding absorption spectrum is observed. Let us assess whether the model introduced can explain the formation of this spectrum.
As we had seen at the beginning of our investigation, when illuminating a vessel containing hydrogen gas with white light and analyzing the spectrum of the light that passes through it, we observe the image below. Explain this fact using the elaborated model.

Absorption spectrum of the hydrogen

A9. As we had seen at the beginning of our investigation, when illuminating a vessel containing hydrogen gas with white light and analyzing the spectrum of the light that passes through it, we observe the image below. Explain this fact using the elaborated model.

Comments for the teacher A9. - The absorption spectrum is interpreted in a simple way by inverting the proposed mechanism: if radiation of a certain frequency hits the atom, it can absorb it and make a transition to a higher stationary state. If the frequency is not adequate the energetic jump is not allowed and the radiation cannot be absorbed. Again, we have to follow the same reasoning line: establish the models and the mechanism, relate the microscopic and macroscopic aspects.

To be consistent with the experimental results obtained in hydrogen ionization, we must rule out the possibility of multiple transitions by successive absorption processes. If such processes were common, atoms would be easily ionized. In the specific case of hydrogen, the atoms could be ionized with a beam of radiation with frequencies lower than $3.28 \times 10^{15}$ Hz, but this phenomenon is not observed experimentally. The atom can only make a single transition to a state of higher energy by absorbing radiation, and then emit energy until it returns to the fundamental state. Successive absorption processes are highly improbable or impossible. Only if the gas temperature is highly enough, will there be a sufficient number of atoms which electrons are in the second energy state and transitions corresponding to the absorption of the visible frequencies of the hydrogen spectrum can be produced.
Among all the frequencies that reach the hydrogen atoms, only those that allow transitions between stationary states will be absorbed. For the visible part of the spectrum, there will be atomic transitions from the energy state $E_2$ to the energy states $E_3$, $E_4$, $E_5$ and $E_6$. Other non-visible radiations can produce transitions between other states, as shown by the black lines. It should be noted that if no atom is in stationary state $E_2$, visible lines will not be absorbed. It is necessary to excite the gas to be able to observe the visible absorption spectrum. Likewise, transitions cannot occur that do not lead to a stationary state, as reflected in the black line crossed out. Frequencies that do not produce transitions will not be absorbed and will pass through the gas, giving rise to the registered spectrum. The black lines of the spectrum correspond to the frequencies that have been absorbed.

It must be emphasized that atoms do not absorb radiations that do not correspond to transitions between stationary states. A common error to consider is that atoms absorb any radiation and that they remain in the stationary state closest to that which corresponds to them by using the relationship $E_f - E_i = h \nu$.

Here we can comment that the energy acquired by the atoms will then be re-emitted, either in the form of radiation of the same frequency or of the frequency corresponding to other possible transitions. So, why does not the frequency appear in the spectrum? This emission will take place in all directions, not only in the direction of the incident radiation, so the black line appears in the spectrum. Actually, the line is not completely black, but is much weaker than the radiation around it, so it appears black. This analysis must be made so as not to fall into violation of the principle of energy conservation, we cannot give the image that atoms only absorb energy during all the time we are illuminating them, no matter how long this time. They also emit.

Once we have contrasted the validity of the model to explain the radiation emitted and absorbed by the hydrogen atom, we will consider, at least on a qualitative level, how the spectra of other atoms are formed, explaining why they are different.
A10. Give a qualitative interpretation of the spectra of other gases. Use as an example the images below. Use energetic diagrams in a qualitative way.

Helium, Neon and oxygen visible spectrum.

Comments for the teacher A10. – Here, we relate the frequency of radiation with the energy difference of the stationary states between which the transition occurs and the intensity of each line with the number of atoms that make a given transition. Let us remember that we do this activity qualitatively and that we must follow the guideline of analysis introduced: model for matter (as the atom is formed by more subatomic particles, we must consider that its structure and its diagram of stationary levels is also more complex), model for radiation, mechanism.

The success achieved so far gives us indications that the model developed is correct. This atom model is named after the Danish physicist Niels Bohr, who introduced it. Stationary energy levels are also called quantum levels, a term that refers to the fact that the atom cannot have any energy, but only certain quantities that vary discreetly. However, we must not forget that the developed model has only been used to interpret the emission and absorption of radiation for the hydrogen atom, and, in a merely qualitative way, for the rest of the atoms. Let us remember that, in order to explain the frequencies of light, it has been a need to accept that abrupt changes are produced in the atomic orbits. This is in contradiction with the emission of a wave, which requires the system that emits it to vibrate for a certain period of time. Does that mean that the wave is emitted “all at once”? How is it possible for an amount of energy to be emitted instantaneously but spread through the space to form a monochromatic wave? We cannot accept a model with such a poor experimental base, and even less so in the case of advances that introduce a radical rupture with the physical ideas accepted so far. We have to look for more evidence of “quantum behavior”, and we will do it by analyzing more experiences of interaction between radiation and matter.
2. Testing the established model

The model we have built to explain the hydrogen spectrum (and qualitatively the gas spectra) forces us to consider that when the atom emits or absorbs radiation there are sudden changes in energy that take the atom from one energy state to another. According to our advances, the frequency of the spectral lines of hydrogen can be explained if we consider that the only possible states for the atom are those that respond to equation $E_n = -\frac{13.6 \text{ eV}}{n^2}$ and that the frequency of the emitted radiation is related to the energy difference of the states between which the transition takes place. By setting these conditions we get a satisfactory result when explaining the emission and absorption of radiation, but if the energy is quantized this characteristic should be revealed not only when atoms interact with radiation, but in any other type of interaction.

To test the model we have first established we will analyze how atoms interact with accelerated electrons, assessing whether the exchange of energy between electrons and atoms takes place in fixed amounts (as corresponds to the transition between quantum states) or if, on the contrary, it can acquire any value. When we compare the results obtained by interacting with electrons with those obtained by interacting with radiation we can draw conclusions about the existence of quantum states in the atom and rule out if that is an exclusive feature of luminous phenomena.

Later we will study the problem of energy distribution in radiation. So far we have used a wave model for radiation, according to which energy is distributed continuously in space, making possible the exchange of any amount of energy. On the other hand, according to the model we have established, the atom can only emit and absorb fixed amounts of energy and it seems to do it instantaneously. Does this model have any impact on the radiation model? Are those precise amounts of energy absorbed by the atom already present in the radiation? To advance this we will apply the model developed in the study to explain the photoelectric effect, a process in which high-frequency radiation pulls electrons out of a metal. We will also try to explain the Compton Effect, in which radiation exchanges energy with free electrons (and therefore no longer subjected to the conditions of quantization of the atom).

In addition, we have to remember that our aim is to obtain a model of interaction between radiation and matter that has general validity, that does not limit itself to explaining atomic spectra only, and that serves as a basis to explain other atomic interactions or to design and build technological devices.
2.1. Does energy quantization in atoms depend on how we interact with them?

2.1.1. The Franck and Hertz experiment

To see whether atoms can absorb any amount of energy or just a few fixed amounts we can bombard a low-pressure gas with accelerated electrons and analyze the transfer of energy from electrons to atoms. We must bear in mind that if an electron hits an atom it can transfer energy to it to produce changes in the internal structure or to change the speed of the atom. We are interested in the exchange of energy produced by changes in the internal structure of the atom, so we have to minimize the energy exchanged between electrons and atoms that only contributes to change the speed of atoms.

If mercury gas is used instead of hydrogen gas (as we have done before), the transfer of energy is reduced almost only to that which produces changes in the internal structure of mercury. A mercury atom has a mass much higher than that of an electron so that when an electron hits one of these atoms the shock is completely elastic and the electron only changes the direction in which it moves, but not the speed, leaving the mercury atom virtually unchanged. It is a case similar to the collision of a ball against a wall; the ball bounces off while the wall remains motionless. If there were to be a decrease in the energy of the electrons, it could only be due to a change in the internal structure of the mercury atom. That is to say, to the fact that the mercury atom has absorbed part of the energy of the electron, acquiring a greater internal energy but with the same kinetic energy. If we use again the analogy of the collision between the wall and the ball, it would be the equivalent of the ball producing a fracture inside the wall, and this would cause the ball to lose kinetic energy.

Therefore, we can use a beam of electrons of known energy to bombard a mercury gas and measure the energy transfer. If electrons do not lose energy as they pass through the gas (colliding with mercury atoms) it is because they do not produce any change in the internal structure of mercury atoms. Conversely, a decrease in the kinetic energy of electrons would tell us how much energy mercury atoms are absorbing. To make this experience you can use an experimental setup like the one in the figure.

Setup used by Franck and Hertz to bombard mercury atoms with accelerated electrons.
The setup consists of a container with low-pressure mercury gas. Inside it the electrons are accelerated between the plate C and G by the action of the electric field created by the potential difference $V_o$. By varying this potential difference we select the kinetic energy that we give to the electrons. Electrons collide with mercury atoms throughout their trajectory to G. When they pass through G we apply a braking potential that allows us to measure the kinetic energy of the electrons. If they reach P they pass through the ammeter I.

When the experience is made, at the beginning it is obtained that the number of electrons that arrives at the plate P increases as $V_o$ increases and that the electrons cross the tube almost without losing kinetic energy. But when the potential difference between C and G slightly exceeds 4.9 V there is a sudden drop in the number of electrons reaching P, and the same thing happens every time a multiple of this amount is reached, as the graph below shows.

![Graph showing the relationship between potential difference ($V_o$) and current (I)](image)

The result shows that if the energy of the electrons reaches 4.9 eV or slightly higher values the electrons cannot reach P, and this can only be due to the fact that they have transferred their energy to the mercury atoms. As the electrons acquire a kinetic energy greater and greater than 4.9 V, there is an increase of the number of electrons that reach P, but the energy with which they reach is 4.9 eV lower than the energy they have received when crossing the electric field from C to G. These electrons have lost approximately 4.9 eV when crossing the gas. When the potential difference slightly overcomes 9.8 eV there is a sudden drop in the number of electrons reaching P, and again while a progressive increase of the potential difference between C and G continues to increase. This happens every time a multiple of 4.9 eV is exceeded.

A11. Interpret the results of the experience of Franck and Hertz. Do they evidence that the internal energy of atoms is quantized and that they can only emit or absorb fixed amounts of energy?

The results show that electrons can only transfer 4.9 eV to mercury atoms, as our model predicts, and not any amount of energy. When electrons are given an energy lower than 4.9 eV they pass through the gas colliding with the mercury atoms but without transferring energy to them. The scattering they suffer in the collisions does not allow the electrons to reach P, but as the potential difference increases and the electrons are attracted with greater force to P there
is an increase in the amount of electrons that arrive. When the energy of the electrons exceeds 4.9 eV they are able to transfer this energy to the mercury atoms, which in turn are excited. Thus, electrons are deprived of energy and do not reach P. If electrons are given an energy significantly higher than 4.9 eV (i.e. 6 eV) they will be able to continue towards P after colliding each one with a mercury atom and transferring 4.9 eV (electrons have an energy of 1.1 eV left, according to the previous example). That is why a new increase in the amount of electrons reaching P is detected, as well as a decrease of 4.9 eV in their energy. When the potential difference is greater than 9.8 V, electrons can transfer 4.9 eV in two collisions, leaving them with such low energy that they cannot reach P. This is what happens every time the potential difference exceeds a multiple of 4.9 eV.

If the mercury pressure inside the tube is greatly reduced, it can be seen that mercury atoms, in addition to absorbing 4.9 eV of energy, can also absorb 6.7 eV or 10.4 eV. When the experiment is carried out with other gases, similar results are obtained, although the values of the energy absorbed are different: in the case of potassium the minimum energy absorbed is 1.63 eV, for sodium 2.12 eV and for helium 21 eV. All this shows that the energy of the atoms is quantized, at the same time that it allows to know the difference of energy between the stationary states of the atoms.

A12. - When the experiment is carried out and the electrons are given an energy superior to 4.9 eV, we observe a monochromatic radiation of $1.18 \cdot 10^{15}$ Hz emitted by the mercury gas. Likewise, when surpassing 6.7 eV the emission of a radiation formed by three frequencies is observed, one of $1.18 \cdot 10^{15}$ Hz (equal to the previous one) and two more of $1.62 \cdot 10^{15}$ Hz and $0.4 \cdot 10^{15}$ Hz. Use the established model and the experimental data obtained in the experiment to explain the existence of these radiations.

According to our model and experimental data, we can establish an energy diagram for the mercury atom. We know that the energy difference between the fundamental state and the first excited state will be 4.9 eV and that the difference between the fundamental state and the second excited state is 6.7 eV. We do not know the energy value of the fundamental state because the experiment does not allow us to know it, but we can affirm that the mercury energy diagram is like the one shown in the figure.
Mercury atoms receive 4.9 eV and 6.7 eV when they interact with electrons and subsequently emit radiations of $0.4 \times 10^{-15}$ Hz; $1.18 \times 10^{-15}$ Hz and $1.60 \times 10^{-15}$ Hz. This is what is foreseen according to the radiation emission and absorption model that we have established.

The collisions produced by the electrons cause transitions from the fundamental state to the first and second excited states. When the atoms return from the second stationary state to the fundamental state, according to our model, they will emit radiation whose frequency is given by the expression $E = h \nu$. In the same way, when transitions occur from the third stationary state to the second and from the third stationary state to the first, radiations of the respective wavelengths will be emitted. If we make the pertinent calculations, we verify that these are the radiations emitted by the tube.

When establishing Bohr’s atomic model we related the frequencies of the emitted or absorbed radiation with the energetic transitions of the atoms, but at no time had we been able to measure the energy absorbed by the atoms in a transition. Now we have verified that the atoms can only absorb fixed quantities of energy, and that later they emit characteristic radiation of the spectrum of emission of the gas. In addition, the frequency of the radiation is related to the energy emitted by the atom according to the expression $E = h \nu$; the frequency at which electrons orbit the atom has no influence, only the energy transitions.

In order to consolidate this model of radiation emission and absorption we must prove that mercury gas at low pressure can only absorb radiation of certain wavelengths, which are the ones that produce transitions from the fundamental state to the excited states.

### 2.1.2. Illumination of a gas with monochromatic light.

If we put mercury gas at low pressure inside a spectral tube and we illuminate it with monochromatic light, the radiation will only be absorbed if it produces in the mercury atoms a
transition from the fundamental state to one of the excited states. The atoms excited by this mechanism will not remain excited for long and will return to the fundamental state emitting radiation with the frequency corresponding to each of the possible transitions that take them to the fundamental state.

A13. According to Bohr’s model and taking into account the energy diagram of the mercury atom that we have previously established, what monochromatic radiations will the mercury atoms be able to absorb? What radiations will be observed later in the emission spectra?

Among all the frequencies that the mercury gas can absorb, the lowest of them will be the one that will produce the transition from the fundamental state to the second stationary state and, subsequently, the emitted radiation will have the same frequency as the incident radiation, since the only possible transition back to the fundamental state is the direct transition. Thus, if we illuminate mercury gas with radiation of \(0.4 \cdot 10^{15}\) Hz there should be a transition of 4.9 eV in the atoms and later it should be observed that mercury emits this radiation.

Experimental results show that this is precisely what happens. By illuminating the mercury gas with monochromatic radiation of \(0.4 \cdot 10^{15}\) Hz only the emission of this frequency by the gas is observed, as corresponds to a direct transition. Also, when illuminating with radiation of \(1.62 \cdot 10^{15}\) Hz three frequencies are observed in the emission spectrum, which coincide with those observed when the gas is excited with accelerated electrons. When the experience is repeated for other gases, equivalent results are obtained. For example, when magnesium is excited with electrons accelerated by a potential difference of 3.2 V, the same radiation is emitted as when illuminated with monochromatic radiation of \(0.4 \cdot 10^{15}\) Hz.

A14. Represent in an energy diagram what happens to magnesium atoms when they absorb energy from accelerated electrons by a potential difference of 3.2 V. Check that they subsequently emit radiation of \(0.4 \cdot 10^{15}\) Hz.

The experiments carried out with monochromatic radiation and the Franck and Hertz experiment suggest a curious analogy: the electrons of a certain energy produce on the atoms the same effect that the radiation of a certain frequency. Until now, we have considered that radiation is a wave, and in a wave the energy is distributed continuously in space. But mercury atoms can only absorb 4.9 eV of radiation from \(1.18 \cdot 10^{15}\) Hz and no other. Moreover, when atoms emit 4.9 eV they do so in the form of radiation of this frequency. This suggests that this radiation has the energy concentrated in packages of 4.9 eV and that, when interacting with mercury atoms, these packages are absorbed or emitted.

The possibility of energy being emitted and absorbed at once by atoms had already arisen from studying the hydrogen spectrum. We are going to deepen this hypothesis through the study of other phenomena of interaction between radiation and matter.
2.2. Is energy quantized in radiation?

2.2.1. The photoelectric effect.

As we know, a solar panel (technically called a photoelectric plate) generates an electric current when it is illuminated. What is happening in the plate that generates that current? We know that all electric current is formed by charged particles in motion but, due to its complexity, it is difficult to study directly what happens inside the plate. However, we can make some simple experiences that show that light can affect the electrical charge of an object.

One of these experiences consists of illuminating with ultraviolet radiation a metal sheet connected to a charged electroscope. If the charge of the electroscope is negative it is discharged quickly; however, the discharge does not occur if the charge of the electroscope is positive. The image below illustrates these results.

![Diagram of photoelectric effect](image)

In the upper left, we have a negatively charged electroscope connected to a metal plate. When ultraviolet radiation strikes the electroscope plate is discharged, as shown in the upper right. On the other hand, if the electroscope is positively charged (lower left figure) the radiation does not discharge it (lower right).

A15. Explain, in a qualitative and tentative way, these facts.

Comments for the teacher A15. - Experimental facts show that light is able to extract the electrons that the electroscope has in excess and that are responsible for the negative net charge. On the other hand, if the electroscope has a positive charge, the light does not remove electrons. We suppose that the students know how to interpret the processes of charging of objects. That is, that they know that an object has a negative charge if it has an excess of
electrons and a positive charge if there is a defect of electrons and that positive charges cannot be transferred by friction (this experience also shows that light cannot remove them either). Moreover, by studying Bohr’s atom model it has become clear that electrons can be extracted from atoms.

The aforementioned hypothesis is the one we will consider correct before continuing. However, we cannot discard that the students establish other suppositions that will have to be discussed and rejected before continuing, as they are clearly incorrect. A hypothesis that can be put forward by students is the possibility that light carries positive charge. A detailed analysis of this possibility leads us immediately to discard it: the light would be capable of positively charging the electroscope and would be deflected by an electric or magnetic field, facts that are not observed. The students take very little time to discard this hypothesis on their own.

To give a complete description of the action of light on metal, it is necessary to go further; it is not enough to indicate that the removed particles are electrons. It is necessary to find a mechanism that allows to describe how the radiation interacts with the metal and how the electrons are extracted, from the qualitative and quantitative point of view.

A16. How can we explain, in accordance with classical physics, the extraction of electrons? How can we explain it in accordance with the quantum model that we have established? Use energy diagrams to display both mechanisms.

Comments for the teacher A16. - Two possible explanations are considered here, which are the product of the application of classical models (A) and the introduction of energy quantization (B). The assumptions for both tentative explanations must be clarified:

- For hypothesis A: Completely classical. We consider that light is a wave and that the energy inside the metal is not quantized.
- For hypothesis B: We consider that the energy is quantized inside the metal, with discrete energetic states. We consider that light produces energetic transitions that are proportional to frequency. Within this hypothesis we contemplate two cases: that light is absorbed continuously, as corresponds to a wave, or that light is absorbed “all at once”.

We analyze the extraction of electrons according to the two models:

Hypothesis A:

Taking into account what we have studied so far about the nature of light, we must consider light as an electromagnetic wave with the energy distributed uniformly over the entire wavefront. On the other hand, we know that a metal has some electrons that can move inside it easily, so they are almost free. We must emphasize that in this case electrons can move throughout the metal, so it is a conductor. Therefore, we will not represent the electrons linked to the individual atoms, but to the metal as a whole. With these two models (metal and light), we can consider that the energy (the wavefronts) reaches the metal and is absorbed by the electrons, that can leave the metal when they acquire enough energy. We emphasize again
that, before proposing a mechanism, it is necessary to reflect on how matter is and how radiation is.

Using the energy diagram, we represent what happens to an electron. At first it is in movement inside the metal (negative energy, because it is a linked system), and it cannot leave it spontaneously. Incident radiation provides energy, which is absorbed by electrons. Then, electrons increase their energy up to they take a positive energy value and leave the metal. It should be noted that the points in the energy diagram do not represent the electron, but its energy. Also, the arrow only indicates that the energy of the electron is increasing, not that the electron is making a vertical displacement.

Electrons absorb energy from radiation and progressively increase their energy. They remain bound to the metal while the energy they have is negative (indicating that the electron-metal system is a bound system). When positive energy values are reached the electrons leave the metal.

**Hypothesis B:**

According to the quantization introduced for atoms and other systems, we can consider that electrons are in a stationary state with negative energy. Radiation will produce transitions to a higher state as long as it has the “correct” frequency and, if the frequency is high enough, it can pull electrons out of the metal. Only high frequencies could extract electrons and the electrons would be extracted at once.

**A17. - How can we test the proposed models?**

Since it is not possible to observe electrons directly, we have to test the proposed hypotheses by analyzing the experimental evidence that we can predict. It is to be expected that when modifying the characteristics of the incident light, changes will be produced in the characteristic magnitudes of emitted electrons. The agreement or discrepancy between the predictions and the measures that we carry out experimentally will give us indications of the validity of the proposed emission models.
A17a. Indicate which characteristics of the emitted electrons will be affected by varying the intensity or color of the incident light.

According to each hypothesis, we can make the predictions summarized in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Hypothesis A (classical model)</th>
<th>Hypothesis B (quantum model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase in the frequency of radiation</td>
<td>It will have no effect</td>
<td>• It will force electrons to higher energetic transitions. Electrons will have higher energy.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• If a threshold frequency is not reached, no electrons will be released.</td>
</tr>
<tr>
<td>Increase in the radiation intensity</td>
<td>• More electrons will be released because the wave carries higher energy. &lt;br&gt;• The released electrons will have higher energy because the wave can transfer more energy to them.</td>
<td>• More electrons will be released because more energy is available in the wave, as long as the frequency is higher than the minimum frequency needed to release electrons. It is similar to what happened with the most intense spectral lines in the spectrum, which corresponded to a greater number of transitions.</td>
</tr>
<tr>
<td>Time of illumination until electrons are detected</td>
<td>• We will have to wait a certain time until electrons are released, because the energy arrives continuously and can take a while until the necessary energy is achieved.</td>
<td>• If we consider that light is a wave, we will have to wait a certain time until electrons are released, energy arrives continuously. &lt;br&gt;• If we consider that the energy arrives &quot;suddenly&quot;, it will not be necessary to wait until electrons are released, even if the light has a very low intensity.</td>
</tr>
</tbody>
</table>

Once we have the observable evidence that emerges from the proposed emission mechanisms, we need to look for it experimentally.

A18. What can we do to contrast our predictions? Design an experimental set-up.
Comments for the teacher A18. - This activity will be developed in a dialogic way. If we do not have enough time, the teacher can explain the setup to the students, emphasizing the measures we take and the relationship with the predictions.

Without introducing any additional information or any helpful comments, students come to provide that it would be possible to measure the time it takes to discharge the electroscope and see if it depends on the intensity and frequency of light. To measure the amount of electrons emitted they suggest to use an ammeter, but they do not know how to connect it. They are not able to make any contribution concerning the measurement of the energy of electrons. Taking these contributions as a starting point, it is possible to advance with understanding in the experimental design.

A18a. How can we measure the amount of electrons emitted?

The first step towards counting the electrons emitted is to collect them and pass them through a cable, so that by measuring the intensity we are able to determine the number of electrons emitted in a second (n): $n = I/e$.

We can do this in several ways, but the simplest from the experimental point of view is to put a conductive plate near the emitting plate, as shown in the figure. We can also use a battery that positively charges the plate, and connect everything to the ammeter. By doing so, the electrons will be attracted towards the plate and the detection of all the electrons will be favored.

![Experimental set-up to count the electrons.](image)

Comments for the teacher A18a. We recommend the students to draw the distribution of charges acquired by each plate of the capacitor and the field that is generated inside, both in terms of field lines and equipotential surfaces. Many of the difficulties that the students have in understanding the photoelectric effect, and especially the experimental detection, are related to the misunderstanding of the behavior of electrical charges inside electrostatic fields. Thus, they have difficulties in understanding the meaning of the braking potential and the role of the different elements that appear in the experimental set-up (capacitor, ammeter, battery, etc.).

A18b. How can we measure the energy of the emitted electrons?
To measure the energy of the emitted electrons, we apply a field that opposes their advance. We can achieve this by reversing the polarity of the battery. As we increase the potential difference between the plates there will be more electrons that do not reach the second plate because they do not have enough energy to pass. And when the potential difference is high enough no electron will be detected. Then we reach what we call the braking potential ($\Delta V_f$).

![Diagram of capacitor with applied potential difference and braking potential](image)

We apply a braking potential to measure the energy of the electrons. When the breaking potential is high enough electrons can not reach the negative plate. By measuring $\Delta V_f$ we can determine the electrons initial velocity.

**Comments for the teacher A18b.** - It is highly recommended to represent the charge accumulated on each plate of the capacitor, the field generated inside it and the force and the velocity that the electrons have.

The electrons leave the metal with a certain speed, but the difference of potential applied by the capacitor brakes them, making them return towards the positive plate. As we increase the potential difference less and less electrons will be registered in the ammeter. Just when the ammeter reading drops to zero, we can use the potential difference value (the braking potential) to calculate the maximum kinetic energy with which the electrons leave the plate.

In this case, we can measure the maximum kinetic energy of the emitted electrons.

$$E_{c_{\text{max}}} = e \cdot \Delta V_f$$

**A18c. How can we change the characteristics of incident light?**

With a suitable light source, we will be able to select the intensity and frequency of the incident radiation. We can change the intensity of the incident radiation by changing the bulb for a lower or higher power one or by bringing the light source closer and farther away from the plate. Regarding the frequency, we can use colored light sources or we can use a white light source and select the desired frequencies using luminous filters. The final experimental set-up is shown in the figure.
Once the experiment has been carried out, the following results have been obtained:

- **R1.** There is a minimum frequency of light below which there is no emission of electrons. The time spent irradiating the plate has no effect on this observation.
- **R2.** When the intensity of the light increases, the amount of emitted electrons increases, but not their energy.
- **R3.** When the frequency of light increases, the energy of the emitted electrons increases, but not the quantity.
- **R4.** No delay time is observed. The intensity of the incident light does not have any impact on the delay time. The emission of electrons is always immediate, whenever the frequency is higher than the minimum frequency commented in R1.

The quantitative measurements are summarized in the following table:

<table>
<thead>
<tr>
<th>( \lambda ) (nm)</th>
<th>578 (orange)</th>
<th>546 (yellow)</th>
<th>436 (violet)</th>
<th>405 (violet)</th>
<th>366 (UV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu ) (Hz)</td>
<td>( 5,19 \cdot 10^{14} )</td>
<td>( 5,49 \cdot 10^{14} )</td>
<td>( 6,88 \cdot 10^{14} )</td>
<td>( 7,41 \cdot 10^{14} )</td>
<td>( 8,20 \cdot 10^{14} )</td>
</tr>
<tr>
<td>( \Delta V_f ) (V)</td>
<td>0,585</td>
<td>0,716</td>
<td>1,265</td>
<td>1,420</td>
<td>1,701</td>
</tr>
</tbody>
</table>

**A19.** Analyze the hypotheses previously established in light of the results

We have to accept that light is absorbed "all at once", since this is the only way to explain that there is no time delay. We must remember that we also proposed, when studying the spectra, that light was emitted "at once", when an electron changed from one stationary state to another without contemplating the possibility that it can not pass through intermediate states. If so, can we still maintain a wave image for light? Should not we admit that light does not propagate as waves but as "bits" or "packages" of energy that are emitted or absorbed in whole units?
Historically, Einstein proposed this hypothesis. In his words:

"In the propagation of a ray of light emitted from a source, the energy is not distributed continuously over ever-increasing volumes of space, but consists of a finite number of quanta of energy located at points in space that move without dividing, and that can only be absorbed or generated in entire units".

**A20.** Represent qualitatively the following radiations using the electromagnetic model and the introduced (as hypothesis) quantum model for light. How do we explain the intensity and frequency of light using each model?

a) A blue light of 450nm wavelength.

b) A blue light of the same frequency as the previous one but more intense.

c) A low intensity green light.

Considering only the qualitative aspect, it is difficult to accept a hypothesis that is contradictory with the physics known so far. Some phenomena, such as interference, clearly indicate that light is a wave. At least we must deepen the analysis of results, including the quantitative aspect.

**A21.** Determine quantitatively, according to the hypothesis under study, the energy of the released electrons. Use the experimental data to test the validity of the hypotheses.

According to the quantum radiation hypothesis and taking into account that energy must be conserved for each individual process, the final energy of the electron will be equal to the initial energy plus the energy it has acquired by absorbing the quantum.

\[
E_{\text{final}} = E_{\text{initial}} + E_{\text{quantum}} \rightarrow E_{\text{final}} = E_{\text{initial}} + h \cdot \nu
\]

If we take into account that \( E_{\text{quantum}} = h \nu \) and we designate with \( W \) the minimum energy that must be supplied to extract the electron (which is equal to the minimum energy of the electron within the metal \( E_i = -W \)), we obtain:

\[
E_{\text{final}} = h \nu - W
\]

In our experimental set-up, we measured the final electron energy by applying a potential difference. By introducing it in the previous equation we obtain:

\[
ed \cdot \Delta V_{\text{braking}} = h \nu - W
\]

**A21b** (alternative statement) The graph shows the experimental results and the equation of the line that best fits them. Discuss the validity of the proposed equation.
Despite the validity of the hypothesis of the quantum of radiation to explain the photoelectric effect we are conscious that we cannot just accept it. Until now, we have used the wave radiation model to explain all luminous phenomena. In our explanations, the concepts of frequency and wavelength were fundamental, but they become meaningless when introducing the quantum of radiation. We should review everything we have done so far to see to what extent the quantum can account for known experimental facts, and do whatever we can to establish a coherent and unique radiation model. We cannot accept two radically different models, specially if one of them can only account for a single experimental fact.

A22. As we have commented, it is not easy for the scientific community to accept ideas that contradict the well established knowledge. The following text clearly explains the rejection of the radiation quanta hypothesis, which was introduced by Einstein in 1905. Read it and respond to the proposed activities.

The rejection of Einstein’s hypothesis was still evident in 1913. Thus, when proposing Einstein for the Prussian Academy of Sciences, Planck, Nerst, Rubens and Warburg indicated:

"The signatory members of the Academy have the honor to propose Dr. Albert Einstein, professor of theoretical physics at the Federal Institute of Technology in Zurich, for election as a regular member of the Academy. [...] In short, it can be said that, among the important problems of modern physics, it is difficult to find a single one on which Einstein does not had taken a notorious position. The fact that he had not ever hit the target in his speculations, such as, for example, the hypothesis about the quanta of light, should not be used against him. Without occasionally assuming a risk it is impossible, even in the most exact natural science, to introduce real innovations”.

This lack of consideration of Einstein’s quantum was also noted when Bohr proposed his atomic model, in 1913. To explain the hydrogen spectrum, Bohr used the electromagnetic theory to estate that the electron gains or loses energy when passing from one stationary state to another by absorbing or emitting homogeneous radiation of ondulatory nature, thus avoiding resorting to the quantum of radiation.

The first solid experimental results on the photoelectric effect appear in 1915 when Millikan, after 10 years of rigorous and meticulous work aimed at reaffirming the wave nature of light, demonstrates the validity of the equation proposed by Einstein (
\[ E = h \nu - W \]. But, despite the adequacy of the experimental results to the Einsteinian law of the photoelectric effect, Millikan stated: "The Einstein photoelectric equation [...] seems to predict exactly in all cases the observed results [...] But the semi-corpuscular theory by which Einstein arrived at his equation seems today completely unsustainable".

In 1921, more than 15 years after the quanta hypothesis, when Einstein was awarded the 1921 Nobel Prize, it is claimed that the prize was "for his services to theoretical physics and especially for the discovery of the law of the photoelectric effect", but nothing was said about the quantum of light.

Questions:
- Why was the scientific community so reluctant to accept the quantum hypothesis?
- What experimental evidence did they have to continue accepting the wave radiation model as valid?

### 2.2.2. The Compton effect

So far we have studied the effects of radiation on bound electrons. In accounting for the spectra we consider that electrons are bound to atoms and in explaining the photoelectric effect we consider that electrons are bound to metals. Under these conditions, and always in accordance with our advances, electrons are bounded particles and cannot have any energy, so radiations of certain frequencies are necessary to achieve transformations. This limits the quantization of energy to bounded electrons and prevents us from determining whether the energy of radiation is quantized. To overcome this barrier we must use free electrons (which energy is not quantized) and analyze if there are signs of quantization in the radiation.

When irradiating monochromatic X-rays on free electrons, it is observed that among the diffused radiation there are two frequencies, one coinciding with that of the incident X-rays and another of lower frequency (which we will call “secondary radiation”). The frequencies difference depends on the angle at which the measurement is made. If it is measured in the same direction in which the incidence occurs, the secondary radiation is not observed, but as the angle at which the measurement is made with respect to the incident radiation increases, the frequencies difference increases, as shown in the figure.
When X-rays hit a sheet of graphite, radiation is scattered in all directions. This radiation consists of two frequencies, one equal to that of the incident radiation and a lower one. In addition, the frequencies is not constant, but depends on the scattering angle.

A.23. Interpret these experimental facts. Take into consideration that radiation can be formed by waves or by quanta of energy.

With the wave theory of radiation it is necessary to consider X rays as a wave of high frequency and a certain amplitude. When interacting with free electrons, this wave transfers energy to them and leads them to perform forced oscillations. This results only in secondary radiation of the same frequency as the incident and uniformly distributed in space, there is no room for secondary radiation of lower frequency.

1: X-rays (high frequency waves) reach the electrons and transmit energy to them. 2: The electrons acquire a vibratory movement by being subjected to the action of a wave. They oscillate with the same frequency as the wave. 3: due to the vibratory movement, the electrons, because they are charged particles, emit radiation with a frequency coinciding with that of vibration, in all directions.
A very different explanation is provided by the quantum of radiation hypothesis. If light is made up of energy packages, the scattering of radiation can be interpreted as an individual process of collision between a quantum of radiation and an electron in the medium. When the collision occurs, the electron absorbs the energy of the quantum and releases a second quantum of lower energy. This would explain the formation of lower frequency radiation.

![Diagram of quantum scattering](image)

When hitting the electron, the photon is absorbed and the electron acquires its energy. The electron then releases a second photon with less energy than the previous one, losing part of the energy it had acquired. The second photon has less energy than the first one, and therefore lower frequency.

The difference of energy between the incident quantum and the second quantum must be carried by the electron, which will be dispersed. The detection of these scattered electrons, which the classical theory does not foresee, would make it possible to test both hypotheses.

**A23b.** Predict the characteristics of the scattered electrons: In which direction will they be scattered?

According to the classical theory, there should be no scattering of electrons; the existence of scattered electrons would be a serious problem for the wave model of radiation. According to the quantum hypothesis of radiation we should detect scattered electrons, which energy equals to the difference of energies between the incident quantum and the scattered one. The hypothesis does not tell us of a preferential direction for the scattering of electrons.

![Diagram of scattering angles](image)

Possible interpretation of the interaction between the X-ray quantum and the electron. The electron absorbs the quantum and emits a second quantum of lower energy, resulting in a lower frequency scattered radiation. The interaction satisfies the principle of energy conservation and the principle of linear momentum conservation.
In order to detect the existence of scattered electrons we can carry out the experience of radiation scattering inside a cloud chamber. The cloud chamber allows us to visualize the trajectories of the charged particles that move inside it: the scattered electrons. The set-up we can use is the one shown in the following image.

Experimental set-up for the study of X-ray scattering in the cloud chamber (6). The X-rays hit the target in the cloud chamber, an electron is scattered at θ and, at the same time, X-radiation scattered at Φ can be measured. Both angles have a well-defined mathematical relationship. In addition, the energy of the scattered electrons increases with the scattering angle while the detected radiation contains two frequencies, the difference of which increases with the scattering angle. 1. Lead box containing the X-rays source; 2. Filter; 3. Diaphragm; 4. Lead box containing the cloud chamber; 5. Diaphragm; 6. Cloud Chamber.

The experimental results show that there are scattered electrons. Moreover, they show that for every quantum of radiation detected at angle φ one electron is detected at θ and that the two angles have a strict mathematical relationship.

**A23c.** Give an interpretation of these facts. How can we explain that there is a well-defined relationship between the direction in which each electron is scattered and that of quantum of radiation?

The principle of energy conservation does not impose a relationship between the directions in which each electron is dispersed and each quantum. In order to relate scattering angles it is necessary to rely on the principle of conservation of linear momentum. It is a must to analyse the interaction between the incident quantum and the electron in a similar way as we analyse the collision between billiard balls in previous courses (but taking into account the differences between a billiard ball, which can transfer any amount of energy in a collision, and a quantum of radiation, which must be absorbed and emitted in entire units).
By applying the principle of conservation of linear momentum we admit that the quanta of radiation have linear momentum, such as material particles have. Until now we had considered quanta as energy packages without mass, and we had not taken into consideration the possibility that they had linear momentum. If we attribute linear momentum to the quanta, and according to the experimental scheme that we have introduced in order to study the Compton effect, we can make the following representation of vector $\vec{p}$ before and after the interaction. The relationship between the direction of the scattered electrons and that of the quanta is a consequence of the linear momentum conservation principle.

The electron and the quantum cannot be dispersed in whatever directions, only in that which satisfies the principle of linear momentum conservation. This shows that radiation carries linear momentum and that it must be conserved in each individual process, as shown qualitatively in the diagram, where it is observed that the sum of the linear momentum of the scattered quantum and the linear momentum of the scattered electron is equal to the linear momentum of the incident quantum.

The interpretation of this phenomenon leads us to consider radiation as a flux of entities that have energy and linear momentum, just like any other flux of particles. We must accept the existence of particles of light without mass, which are now called photons.

In all the phenomena analysed so far to support the quantum hypotheses it has become clear that, in the individual interactions of radiation with matter, whenever we account for energy transfer between radiation and matter we have to consider a certain frequency. Now, in spite of the recognition of the existence of the quantum of radiation, the problem of the nature of the light is far from being closed. We cannot accept two models for light that are contradictory, even though both of them are supported by experimental results. We must recover the coherence of scientific knowledge and establish a single model that is able to explain all the experimental facts.

Recapitulation:

- What problem did we have?
- How did we explain the emission and absorption of radiation with our initial knowledge? What experimental facts could we not explain?
- What model have we established, as a hypothesis, to explain the emission and absorption of radiation? Provide arguments that support this model. Does it explain all the light features?
- What problems do we have to deal with because of the introduced models?
RECAPITULATION

What problem did we have?

The problem we had was to find a model to explain the emission and absorption of radiation that could explain phenomena such as spectra, fluorescence and phosphorescence and the operation of technological devices such as light bulbs, lasers, LEDs or photoelectric plates.

How did our initial knowledge explain the emission and absorption of radiation by atoms?

According to classical physics, the atom contains electrons that rotate around the nucleus continuously emitting radiation of the same frequency as the orbital frequency of the electron. This radiation spreads throughout space in the form of waves. However, when emitting radiation the atom must lose energy and this leads the electrons to fall on the nucleus. In addition, as the electrons fall, they spin faster, changing the rotation frequency and causing radiation at different frequencies. According to this model, the emission spectrum of gases should be continuous.

What model have we established, as a hypothesis, to explain the emission and absorption of radiation?

According to the quantum ideas that we have introduced, light is formed by quanta of energy that are emitted or absorbed in entire quantities, called photons, which carry an energy determined by $E=hc$. The energy of atoms is also quantized: electrons can only move in a few orbits around the nucleus, and they do so without emitting energy. These models of radiation and matter help us explain emission and absorption:

- When the atom emits radiation an electron passes from a stationary orbit to another stationary orbit of lower energy giving rise to a photon with a frequency that satisfies the relationship $E_f - E_i = hc$. This photon always propagates in one direction and does not spread in all directions of space.
- An atom can only absorb a photon that produces a transition from one stationary state to another stationary state of higher energy, according to the same expression that rules the emission.

There are limits on the changes that can take place inside the hydrogen atom and it is prevented from being destroyed. Each transition produces radiation of a certain frequency and a coloured line in the spectrum is detected. As the transitions are limited, so are the frequencies that can be emitted, only a few lines will be seen in the spectrum.

According to this model, two radiations that have the same frequency are formed by photons of the same energy, being more intense the radiation that is formed by a greater quantity of photons. When an atom emits radiation of different frequencies (a spectrum of several lines), the more intense one is produced by a greater number of transitions between quantum states within the atom. When an atom absorbs radiation, if the frequency is sufficient to pull up electrons, the higher the intensity of the radiation the more electrons will be pulled up because radiation is formed by more quanta, as observed in the photoelectric effect.
What problems do we have to deal with because of the introduced models?

Because of our advances, we have two contradictory models to explain the behaviour of radiation: a wave model and a model of energy packages. We have to look for a coherent model to explain at the same time phenomena that require a wave model (such as interference, diffraction or the existence of frequency and wavelength in radiation) and phenomena that require a corpuscular model (such as photoelectric effect, the Compton effect and the spectra).
3. Possible applications of the established model

**A24.** When obtaining the spectrum of a laser we see that it is formed only by one frequency. Explain, using the established model, the process by which the atoms that make up the device emit the laser light. The following image shows the spectrum of that laser.

![Spectrum of the red laser. The scale indicates the wavelength of radiation in nanometers](image)

**A24b.** Explain how a green laser works.

![Spectrum of the green laser. The scale indicates the wavelength of radiation in nanometers.](image)

**Comments Teacher A.24 and A.24b.-** The presence of a single frequency in the spectrum shows that the radiation emitted responds to the transition of electrons between two energy levels. From the frequency of the radiation, the energy difference between the levels can be obtained.

The wavelength of the radiation can be determined from the image. With this value, we calculate the frequency and energy of the photons emitted by the laser. We obtain an energy of 1.84 eV. Therefore, according to the quantum model of emission and absorption of radiation, inside the atoms of the laser an electronic transition occurs between levels separated by 1.84 eV. We represent this by using an energy diagram, as shown in the image below.

![Energy diagram of the laser. The electrons make transitions between two levels separated by 1.84 eV. Having a single transition is a must to obtain monochromatic light.](image)
A complete explanation of the operation of the laser involves accounting for its cyclic operation: electrons acquire energy from the electric current that provides energy to the laser, they make a transition to the upper energy level and emit that energy by moving down to the original level, the energy difference between both levels is emitted in the form of photons of a fixed frequency.

Keep in mind that this is a diode laser device. In a gas laser, like the traditional He-Ne, the mechanism is different. The cavity in which the gases are located favors certain transitions of a whole series of possible transitions. We can comment on this aspect to avoid creating a naive image of the applications of quantum physics.

If the light emitted by the laser is green, the frequency of the emitted radiation is greater, which means that the electronic transition has been more energetic, therefore the energy levels will be more distant.

A25. Observe the light emitted by a low-energy bulb and explain how it works. Use the model established during the unit.

![Spectrum of the energy saving bulb. The scale shows the wavelengths in nm.](image)

**Comments Teacher A.25.** - To facilitate the calculation of radiation frequencies we can initially consider only the average value of the position of each line. We will attribute all the lines to the emission of the mercury and we will disregard the presence of the fluorescent substance that covers the tube (we will work the fluorescence and the phosphorescence later). The role of this substance is to absorb part of the radiation that emits the mercury and emit radiation with a larger number of frequencies. In fact, when looking through the spectroscope you can see the mercury lines superimposed on a rainbow (corresponding to the emission of the fluorescent substance that covers the tube).

The value of the frequency of each spectral line, according to the image, as well as the energy of their photons is summarized in the following table.
The frequencies and energies of the photons recorded in the low bulb spectrum:

<table>
<thead>
<tr>
<th>Frecuencia ($10^{14}$Hz)</th>
<th>Energía ($10^{-19}$J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.26</td>
<td>4.80</td>
</tr>
<tr>
<td>6.88</td>
<td>4.55</td>
</tr>
<tr>
<td>6.31</td>
<td>4.17</td>
</tr>
<tr>
<td>5.80</td>
<td>3.70</td>
</tr>
<tr>
<td>5.07</td>
<td>3.35</td>
</tr>
<tr>
<td>4.74</td>
<td>3.13</td>
</tr>
</tbody>
</table>

The presence of photons of 6 different energies implies the existence of 6 possible energetic transitions. The diagram of energy levels of mercury could be (among other possibilities):

It is necessary to make the corresponding reflection about the proposed diagram: the atoms are excited by the electric current that crosses the tube, producing the shift of the electrons from the fundamental level to higher levels. The return to the fundamental level allows explaining the formation of the spectral lines. Again, the transitions are random: we do not know when they occur in time or between what levels will occur. We can only say that the brightest lines correspond to those transitions that occur a higher number of times per unit of time. We can consider that each individual electron has a greater probability of making some transitions than others.

One problem that arises is why transitions between intermediate levels are not observed. Do all transitions occur towards the fundamental level? A more detailed analysis shows that the frequency of intermediate radiations does not correspond to that of visible light. The use of suitable instruments must show that the frequencies corresponding to intermediate radiations are also present.

A26. When illuminating (figure below) a phosphorescent adhesive (1) with red light, it emits no light (2). When doing so with green light, no effect is produced (3 and 4). However, when it is illuminated with blue light we observe that it emits light (5 and 6). Propose a mechanism to
explain this observation. Use the quantum models. If the lights used had been more intense, how would the results had change?

Phosphorescent adhesives only shine when they have been illuminated with blue light. In the first frame, you can see the star lit with red light, in the second frame you can see that when you turn off the light the star does not shine. The same happens when illuminated with green light (frames 3 and 4). But by illuminating it with blue light the star itself shines (5 and 6)

Comments Teacher A.26. - We must begin by explaining the emission of radiation by the material that forms the adhesive. According to what is seen in the image 6 the substance that contains the adhesive emits only green light, and this can be attributed (in a simplified way) to the transition between two stationary levels, according to what is shown in the figure below.

Radiation can only be emitted if we provide the necessary energy to raise the electrons from the level of lower energy to the highest energy level. On this occasion, the energy required for this transition is provided by the incident radiation. Thus, both the red light and the green light used have lower frequency than necessary to produce the transition: their photons are not energetic enough to activate the mechanism.

It is necessary to emphasize that each electron absorbs a single photon, this is an additional quantum hypothesis, an electron can not absorb several photons at the same time and make the transition (in fact, this would be equivalent to return to the continuous model of radiation).

If we had used higher intensity lights we would have obtained similar results. A higher intensity light carries a greater number of photons, but the energy of each photon is the same. By striking the adhesive, the photons of the red and green light can not produce the transition. On the other hand, with the blue light the result would have been slightly different: the higher the number of photons the more transitions to higher states, since each photon can produce a transition. Subsequently, as there are more electrons in higher energy states there are also
more transitions to states of lower energy and therefore more photons in the emitted radiation, the adhesive would shine brighter but with the same colour.

If we want to delve into the details we can pose the following additional problem: Why does it absorb blue light and emit green light? The mechanism that explains phosphorescence and fluorescence is more complex than that considered so far, since we must consider that the transitions take place between energy bands, as shown in the following image. By absorbing high frequency light the electrons can make a transition to the upper energy band. Then, they return to the lower energy band emitting radiation, but not to the lowest part of the band. The rest of the energy is released through non-radiative processes or through non-visible emissions.

An explanation for the emission of a frequency lower than that absorbed is the existence of energy bands. The transition to the higher energy band only occurs when high frequency radiation is absorbed. Later, electrons can make transitions to the band of lower energy emitting photons of lower energy than the photons of the incident radiation. The remaining energy is released through non-radiative mechanisms or non-visible frequencies.

These last mechanisms must be presented as they are necessary to maintain the coherence of what we have done so far, we cannot expect students to make deductions of this type. Also, they serve to illustrate that our model has limitations.

A26b. How can we explain that it shines for a while?

Comments Teacher A.26b. - This phenomenon apparently violates the principle of conservation of energy, the interpretation requires a mechanism that allows the adhesive to store energy and release it slowly. The absorption of the incident radiation allows the electrons of the substance that forms the adhesive to reach higher energy levels. Subsequently, the slow de-excitation releases the accumulated energy for a while. Again, the transitions are of a random nature, we do not know when they are going to take place (that's why it keeps shining for a while) or at what level they will take place (they do not return to the fundamental level, that's why the light emitted is not blue). It can be verified, furthermore, that by increasing the intensity of the radiation, the adhesive still does not shine if the light is red or green. On the
other hand, if the light is blue, the adhesive shines brighter and for longer when it is illuminated with higher intensity light.

**A27.** We know that X-rays, and especially gamma rays, are highly dangerous for health. These radiations are known as “ionizing radiation” because they have the ability to ionize biological molecules vital for cellular functions, such as DNA. Affected cells can die or suffer major disorders in their functions, reproduce uncontrollably and produce a tumour.

But despite its harmful nature, both types of radiation have important medical applications. Specifically, gamma rays are used in radiotherapies. To kill a tumour, the affected area is irradiated in a controlled manner with gamma rays, which causes the death of the irradiated cells.

Why high-frequency radiation are ionizing and low frequency are not? Why do we not refer to intensity when discussing the danger of radiation? Discuss the harmful nature of the most common radiations in our environment.

**Comments Teacher A.27.** - Once again, we relate frequency with the energetic transition, an aspect that has no place in classical physics. It is necessary to differentiate between the effects produced by a high intensity radiation and those produced by a high frequency radiation. We also have the opportunity to analyse the health effects of the most common radiations in our environment: radio and TV waves, mobile phones, WiFi, bluetooth, X-rays, visible radiation, ultraviolet radiation and discuss the capacity of these radiations to cause cancer. We must comment in detail on the case of ultraviolet radiation: UV A is responsible for tanning the skin and is not very harmful because of its ionizing power; the same is not the case of UV B and UV C. We can also note that the ozone layer protects us from such radiation and that sun creams also do, as you can read on their labels.

**A.28.** The diagram shows the stationary states of the crystal of a precious gemstone. Because of the ambient light, its electrons can be in any of the stationary states represented in the diagram.

- What happens if we illuminate it with green light formed by 2.3eV photons?
- What happens if we illuminate it with violet light formed by 3eV photons?
- What if we illuminate it with the previous lights but with a beam that has twice as many photons?
- Explain how the light spectrum emitted by the stone will be.

**Comments Teacher A.28.** - This activity gives account (in a simplified way) of the colour of precious gemstones. Gemstones have a crystalline structure with stationary energy states that are largely reminiscent of the energy states of atoms. Due to radiation and ambient
temperature, all stationary levels are occupied. This is a difference from the cases we addressed so far, in which we considered that the electrons of an atom are in the states of lower energy.

In the situation under consideration, the gemstone will not let the green radiation through as its photons allow the transition between the state of -7.2 eV and that of -4.9 eV. The same does not apply to violet light, which will pass through the stone. We can say, therefore, that the stone is not transparent to green but to violet. This determines its colour, although with this simple model it is difficult to say which would be the colour with which we will see the stone. However, by way of example, we can say that the emerald is not transparent to red and is transparent to green, while the ruby is transparent to red while absorbing all other radiations. We can only affirm that the stone we are studying is not green.

By illuminating with a luminous beam containing twice as many photons produces twice as many transitions, but no higher energy transitions.

In its spectrum we will have a very large number of lines. From the stationary state of higher energy three transitions can be produced that will give origin to three lines. From the stationary state of -4.9 eV two transitions can take place, which will originate two more lines. Finally, a transition can occur between the lower energy stationary states, leading to another line in the spectrum. The most intense lines correspond to the most likely transitions.
4. Searching for a coherent body of knowledge

We have tested how the quantum model of emission and absorption of radiation explains individual processes of radiation emission, absorption or scattering, as well as other phenomena of energy transfer in which radiation is not involved (such as the Franck and Hertz experiment). However, we have also warned that this model is insufficient to explain:

- The formation of interference and diffraction figures (lower image), which require an ondulatory conception of radiation. We have already commented that this was the main cause of the rejection of Einstein’s quantum hypothesis. Even once the photon was accepted, the existence of two models to account for the behavior of radiation posed a problem of coherence within physics. Researchers such as William Lawrence Bragg referred to this situation stating: "physicists use the wave theory on Mondays, Wednesdays and Fridays and corpuscular theory on Tuesdays, Thursdays and Saturdays".

The left image shows a laser mounted on a laboratory support pointing to a screen in the distance. The screen consists of a sheet of graph paper where each square has 0.5 cm long. As we can see in the image above, there is a wire in front of the laser. On the screen, the image showed in the central photograph is formed: a sequence of illuminated and dark areas. This pattern corresponds to an interference phenomenon; the areas of higher intensity correspond to the regions where the interference is constructive while the dark areas correspond to the points where the interference is destructive. If the light consisted of a flux of particles we would expect to obtain a figure like the one that appears in the lower drawing: a circle that reproduces the shape of the laser opening with a central unlit area that corresponds to the shadow of the wire.

- The established model does not predict the structure of the energy levels of atoms, molecules or crystals. They can only be deduced ad hoc, by analyzing their spectrum and inducing the energetic structure that has generated it. In addition, although we can give a qualitative interpretation of the spectra of gases other than hydrogen, the quantum model of emission and absorption of radiations that we have established does not allow us to obtain a satisfactory quantitative result.
• The meaning of the magnitudes that appear in the equation $E=\hbar \nu$. This equation mixes a typically corpuscular magnitude ($E$, energy of the quantum of light as a corpuscle, a magnitude that makes no sense in the wave radiation model) and a wave magnitude ($\nu$, frequency of radiation, meaningless under a corpuscular radiation model). We cannot simply accept an equation that requires two contradictory models to be interpreted.

• The probabilistic character of electronic transitions. From the beginning, many physicists warned that the quantization of energy meant an important rupture with previous physics, and not only in terms of ideas about the structure of matter but also with respect to the deterministic character of the laws of physics. Classical physics made it possible to foresee any change in systems, to advance what was going to happen and when it was going to happen. The new physics only allows us to establish a catalog of possible events, but it does not allow us to know which of them is the one that will occur or when it will occur. Do we have to be satisfied with this? Can we improve our models to recover that predictive character?

• The effect produced by a radiation does not depend on its intensity. The fact that a low intensity radiation can produce an effect that cannot be produced by a high intensity radiation of lower frequency means a rupture of the cause-effect relationship. A high intensity light implies the existence of a high intensity electromagnetic field, much more capable of producing a certain effect than a weak electromagnetic field, corresponding to a low intensity light. Instead, the frequency only indicates at what rate the field oscillates, not the force it can exert on charged particles such as electrons.

In spite of the success achieved, we cannot just be satisfied with models that contradict the knowledge accumulated so far, even if they manage to explain very diverse experimental results. This crisis, experienced by physics during the first decades of the 20th century, could only be overcome when a model was found that made it possible to explain "classical phenomena" and "quantum phenomena". The search for this model is now our objective. We will begin by looking for a model for radiation that can account for emission and absorption phenomena as well as wave phenomena (such as interference and diffraction). Later, we will review the atomic model trying to find a model that allows predicting the structure of energetic states without invoking the inductive strategy used until now.

4.1. What is the nature of photons?

To advance in the resolution of this problem we are going to combine in the same experience two of the phenomena that require contradictory models: the interference of light and the photoelectric effect. Imagine the following situation in which we have placed a light source, a double slit and a detecting screen covered by small photoelectric cells.
We put a light source in front of a double slit. Further back, as a detection system, we place a screen covered with photoelectric cells (each frame of the screen represents a photoelectric cell).

A29. When we carry out the experience and count the quantity of quanta detected in each of the photoelectric plates, we obtain the bar diagrams that are shown in the image below (each bar represents the quantity of photons detected in the corresponding photoelectric plate).

- Each cell registers an integer number of photons.
- The same photon is never recorded on two cells.
- There are detectors that register a large number of photons, while other detectors do not detect any.
- We obtain the same results if we launch many photons at the same time as if we launch the photons one by one, once the first photon is detected the second is emitted\(^3\).

Analyze the result and discuss whether light behaves as a wave or as a particle.

Result obtained by carrying out the experience. The bars shown above the sensing screen indicate the number of photons detected on each photoelectric cell. There are some areas where the cells detect a large number of photons and others where they do not detect any.

\(^3\) There are photoelectric cells that are able to detect a single photon. From 3 to 4 photons are enough to excite the cells of the human retina.
Comments teacher A.29. - Students may think that the interference figure is produced because we launch many photons at once, because of the interference of some photons with others. But let's remember that when we do the experiment by launching the photons one by one (first we launch a photon, wait for it to reach the screen, register the place where it has impacted and then launch another photon) we get the same result.

To account for what the detectors register we must admit that:

- Photons are detected as particles, each in a cell.
- Photons are distributed on the screen in the same way as the intensity of a wave that suffers interference when crossing the double slit.

Going deeper into the analysis, for each individual photon there are places where it is more likely to impact and places where the probability of impact is zero. The points of maximum probability of impact coincide with the regions where the wave that has the same frequency that the radiation suffers a constructive interference, while the places of null probability are those that correspond with the points of destructive interference.

We must therefore conclude that photons are different from waves and particles. There is nothing in our daily surroundings that behaves as photons do. While a photon is not detected it propagates like a delocalised entity that suffers the phenomena of waves (interference, diffraction, polarisation, etc.), that is to say, like a wave. However, at the moment it is detected it is absorbed as an entire unit, as a particle, and at a single point. When we carry out a position measurement, the amplitude of the wave at each point is related to the probability of detecting the photon at that point. This wave, then, must be a probability wave and not a wave that can be detected simultaneously in a wide region of space, since it does not happen so on the screen.

While the photon is not detected we have to accept that it propagates as a probability wave. When arriving at the screen it is detected as a particle, with a greater probability where the wave has a greater square of amplitude.

A.30. When we look through the glass of one window, we can observe what is on the other side. However, if we observe in detail, we also see what is on the same side of the window in which we are (that is, the glass allows light to pass through but also reflects part of the light that hits its surface). In fact, glass is not completely transparent. A manufacturer tells us that the glass of a window has a transparency of 90%. When we throw a photon against it, on which side will we detect it? What will happen if we throw a light beam?
**Comments teacher A.30.** - According to what we have established, while the photon is propagating we must consider that it propagates like a wave. If the transparency of the glass is 90% there will be a probability of 90% for the photon to pass through the glass and 10% for it not to do so and reflect. When arriving at the glass the wave will divide: one part will go through the glass and another part will reflect in it. The photon can be detected on either sides of the glass, with the probabilities indicated, as shown in the image.

![Diagram of photon propagation through glass](image)

We consider that the photon comes from the upper left side. While it is propagating, we consider it has ondulatory behavior. When it reaches the glass, a fraction of the wave will be reflected and another fraction will pass through the glass. According to the manufacturer, the glass has a transparency of 90%. We will detect the photon with a 90% probability in D2 and with a 10% in D1.

When we launch a beam of light we have a high number of photons. Each one of these photons propagates like a wave, a fraction of which will be reflected and another fraction will pass through the glass, so the probability of detection is also divided. Each photon will be detected with a probability of 90% on one side of the glass and a probability of 10% on the side where it has been launched. If the number of photons is high enough we can say that 90% will be detected on one side and 10% on the other. However, it is not possible to predict what will happen to each individual photon.

![Diagram with bar chart of photon detection](image)

With a light beam, 10% of the photons will be detected in D1 and 90% will be detected in D2, according to the amplitude of the wave function that reaches each detector.

There is nothing in our daily reality that behaves as photons do, and that is why we must use analogies with the behavior of particles and waves to understand how they behave. Now, should we renounce any knowledge about the position of the photon before it is detected? Should we accept that its propagation is merely probabilistic?
4.2. What can we know about the trajectory of the quanta?

At primary school we were told that the light spreads in a straight line and to prove it we could align several cardboard holes. Only if the holes and our eye were forming a straight line could we see the light source through them. Perhaps by using very small holes and/or screens with detectors we could know where a photon is and its speed (and therefore know the trajectory it follows). We are going to do everything possible to know in detail the trajectory of a photon in order to establish to what extent we have to be satisfied with a probabilistic knowledge.

A31. We point a beam of light towards a small hole in order to know, with the highest possible precision, the position of the quanta that pass through it. The arrangement is shown in the photograph below. On the screen, the figure that appears below is formed.

Analyze the figure and determine what we can say about the position and linear momentum of the photons just when passing through the aperture.

If we repeat the experiment with a wider hole, we can see the image that appears below. Analyze, again, what we know about the position and velocity of the photons just when passing through the aperture.

What can we say about the trajectory followed by the photons?

We mount a laser and point it at a screen (a sheet of graph paper) that is located at several meters away. We observe that the laser gives rise to a point of light on the paper. By putting in front of the laser a small hole an interference figure appears, as can be seen at the bottom of the image. If we make use of a smaller orifice the figure obtained on the screen changes, the central circle is bigger and the luminous rings are bigger and more separated, as shown in the following image.
In the left part of the image the orifice that has been used in this occasion can be seen, it is smaller than that of the first experience. The central image corresponds to the observed figure on the screen: a very bright central point occupying a surface area of approximately 9 squares and little intense rings around it. The figure on the right reproduces, once again, the result of the experience with the large orifice: the central point occupies less than 4 squares and there is a greater dispersion of light in rings.

We could reflect as follows: we know that any photon that reaches the screen has passed through the hole. Once passed, it advances towards the screen to impact one of the illuminated areas. Let's analyze the possible values of position and linear moment to go deeper into the problem of what we can know about the "trajectory" of the quanta.

If we put a matrix of detectors behind the hole to measure the position of each photon that reaches the hole we will obtain a distribution of position probabilities, as shown in the image below. This distribution has a mean value, which coincides with the center of the hole \((x=0)\), and a deviation from this mean value, which represents the dispersion of the measurements. Thus we have a statistical indetermination (or uncertainty) in the value of the position of a photon before being measured.

![Diagram](image.png)

By representing the probability of detecting a photon in each of the possible positions (in each detector) we obtain a distribution of probabilities, characterized by a mean value (the center of the hole) and a deviation around it (related to the radius of the hole).

The uncertainty cannot be reduced by using more accurate measuring instruments. With more sensitive detectors (smaller, for example) we could distinguish more accurately the position of a photon in the hole, but we always have the same dispersion with respect to the mean value, since the photon can be detected at any point on the wavefront.

Let us now focus on the analysis of the linear momentum vector of the photons (proportional to the velocity vector). Once the hole is reached, each photon moves towards one of the illuminated areas of the screen. Photons have a higher probability of hitting the center of the screen (brightest point) but they also have a certain probability of hitting other points, less luminous, and none in others (dark points). Therefore, the linear momentum of a photon
passing through the hole can have a value among different possible values, each of them with a
certain probability of being measured (as shown in the image below). We have, again, a set of
possibilities that is distributed around a mean value and presents a certain statistical
uncertainty.

In the upper part the possible values of the linear moment of a photon at the hole are represented
(schematically). The most probable values of the linear moment are those that take the photon to the
center of the screen, as this is the area in which the highest luminous intensity is detected. In a similar
way to what happened when measuring the position of the photons (left graph), the possible
measurements of the linear momentum vector are distributed around a mean value, with a certain
uncertainty (right graph).

If we use a smaller hole, the possible values of the position of the photons are less separated
from the mean value (which corresponds to the center of the hole), so the uncertainty of the
position of each photon is lower. However, we observe that the luminous zone on the screen is
larger, which indicates that the points of impact of the photons on the screen are more
separated. This means that the linear momentum of each photon has a greater range of
possible values, a greater dispersion with respect to the mean value and therefore a greater
uncertainty, as shown in the following image.
When using a smaller hole the uncertainty in position decreases because the photons are distributed closer to the mean value (the center of the hole). However, the uncertainty at the linear moment increases: as the impact points on the screen are further away from the center, the possible linear moment vectors may be further away from the mean value.

We could put more obstacles or restrictions aimed at knowing, in as much detail as possible, the position and linear momentum of the photons. However, we would obtain as a result that whenever we reduce the uncertainty in the knowledge of the position we increase the uncertainty in the knowledge of the linear momentum and vice versa. This relationship between the two magnitudes was first introduced by the German physicist Werner Heisenberg and is known as the uncertainty principle. Mathematically it is expressed in form:

$$\sigma_x \sigma_p \geq \frac{h}{4\pi}$$

Where $\sigma_x$ represents the uncertainty in the position and $\sigma_p$ represents the uncertainty in the linear momentum.

**A31b.** - Analyze, using the photon model we have established and the uncertainty principle, the experience of diffraction through a linear slit. Why when putting the slit in vertical the interference figure is horizontal and when putting the horizontal slit the diffraction figure is vertical?
In the upper left part the linear slit can be seen, horizontally located, and to the right the diffraction image observed on the screen. In the lower part you can see the same slit, located in a vertical position, and the corresponding diffraction image to the right. The diffraction image is always perpendicular to the slit.

To determine what we can know in each case about the position and linear momentum of the photons we have to repeat the analysis of the previous activity for the photons passing through the slit. When the slit is horizontal the uncertainty in the vertical position of the photons is very small, therefore the uncertainty in the vertical component of the linear momentum will be large. This is the reason why a vertical diffraction image is produced corresponding to a large dispersion of the linear momentum in a vertical direction. It is not the same in the horizontal direction, the uncertainty in the horizontal position of the photons is high because the slit in this direction is wide, therefore the uncertainty in the horizontal component of the linear momentum is small, the photons do not disperse in the horizontal direction. A similar reasoning can explain why the diffraction pattern is horizontal when the slit is placed in a vertical position.

We have, therefore, that the uncertainty principle is applied to each component of the position and momentum, which is expressed as:

\[ \sigma_x \sigma_{px} \geq \frac{\hbar}{4\pi} \]

The same expression is valid for the other components of the linear position and momentum vectors.

It should be noted that this uncertainty is the result of the quantum nature of photons. In fact, it has been through the use of the model that we have reached it. Uncertainty should therefore not be understood as a consequence of the use of inaccurate measuring instruments. The use of high-precision measuring instruments helps to determine with greater precision the position or linear momentum of each photon, but it does not eliminate the distribution of values of the position and linear momentum around the mean value as these are inherent in the behavior of the quantum.
The quantum model we have just built for photons allows us to account for the processes of emission and absorption of radiation as well as wave phenomena such as interference and diffraction. We now have a single radiation model with which to explain all the phenomena considered so far: we have to consider the photons as particles when analyzing emissions, absorption or detection, but we must think on waves (probability waves) when spreading. We have thus overcome one of the problems generated when establishing the quantum model of radiation emission and absorption.

Recapitulation:
- Draw a light source and the light it emits just when it is being emitted, when it is propagating and when it hits a screen.
- Explain the model that you have used to represent the propagation of light and the impact with the screen.
- Give arguments that justify that model.
- Do state new problems that we still have to address to solve the issues of coherence between the quantum model of radiation emission and absorption and classical physics.
4.3. Why are there stationary states in the atoms?

Although our advances have allowed us to establish a model for the light that gives account of all luminous phenomena, we still have to give account of the quantization of energy within atoms. Why can atoms only have certain values of energy?

The energy of the hydrogen atom, according to the model we introduced to explain the emission and absorption of radiation, depends on an integer number according to the expression: $E(eV) = -\frac{13.6}{n^2}$. In classical physics, the energy of stationary waves that can be formed, for example, in a string held at both ends, also depends on an integer. This analogy suggests a possible strategy to explain the existence of stationary states: can the electron be considered a wave?

If so, we could explain the existence of stationary states of atoms through an analogy between the orbital motion of the electron and the motion of a stationary wave. When a string is fixed at its ends it cannot stationary vibrate at any frequency (and therefore at any energy value). It can only oscillate with certain frequencies, as shown in the image below.

![Image of stationary waves in a fixed string]

In a fixed string at its ends you cannot form any stationary wave but only those that have a specific wavelength, and therefore a specific frequency and energy.

Similarly, if the electron had a wave nature it could not orbit at any distance from the nucleus, but only in a few orbits.
The images show in black the orbit of an electron around a proton in the hydrogen atom. If we consider the electron as a wave, according to the established hypothesis, only those "orbits" in which a stationary wave can be formed would be stable (represented in blue), if the wave is not stationary because there is no room for an entire number of cycles the orbit cannot exist (in red).

By establishing an analogy between the two phenomena, one could explain the existence of the energetic levels of the atom if one imagines the electron as a wave rather than a particle. Such a wave would be confined in space, vibrating around the atomic nucleus. Under these conditions, the wave could only stationary vibrate if the space in which it vibrates can accommodate an entire number of complete cycles, as shown in the picture. Otherwise the vibration is not stable. This would allow to identify the electronic orbits with the stable modes of vibration and the own behavior of the waves would prevent the vibration of the electron where the wave is not stationary. In this way we could get a way to explain and predict the existence of stationary states.

Louis de Broglie advanced the hypothesis of considering the electron, and in general any other particle, as a wave. In addition, he proposed an equation that allowed to calculate its wavelength: \[ \lambda = \frac{h}{mv} \]; where h is the Planck constant, m is the mass and v is the electron velocity.

A32. - Propose an experiment to test the hypothesis that electrons, and in general any particle, have a wave character.

Comments for the teacher A.32. - The students must take into account that this dilemma between a wave and a corpuscular view has already been faced in the case of light. By subjecting light to experiences of interference we have obtained results that can only be explained by accepting that light is a wave. Following the same strategy, we can subdue electrons (or other particles, if necessary) to an interference experience and analyze the results. For example, we can point an electron beam towards a double slit and analyze the figure obtained by making them hit later on a screen. The problem lies in the actual design of the experiment: Which particles to use? What can we use as a slit?
Once the experience to be carried out has been decided, it must be remembered that the wave nature only becomes evident when the waves interact with obstacles of similar width to the wavelength. This forces us to study which are the supposed wavelengths of the waves we want to detect and look for obstacles or slits of similar width.

**A32b.** Consider which "particles" are the most suitable to make an interference experience through a double slit. Use the de Broglie relationship to determine the supposed wavelength of: a) the Earth in its orbit around the Sun; b) A 700 kg car circulating at 90 km / h; c) A 20 g stone that is thrown at 10 m/s, d) An electron with a speed of $3 \cdot 10^6$ m/s.

Data: $M_E = 5.98 \cdot 10^{24}$ kg, $v_E = 29.79$ km/s, $m_e = 9.1 \cdot 10^{-31}$ kg.

**Comments for the teacher A.32b.** - It follows from the results that the predicted wavelength is very small for everyday objects at ordinary velocities, much smaller than the width of any object or slit with which to produce interference (remember that an atom has a radius of about $10^{-10}$ m). Only electrons have longer wavelengths than atomic dimensions. We conclude, therefore, that the experience of interference with electrons must be carried out and that it will be necessary to use obstacles or slits of very small width.

The results obtained when calculating the wavelength of several particles show that the experiment can only be carried out with electrons, because it is not possible to find slits of similar dimensions to the rest of the calculated wavelengths. Moreover, even with electrons the experience is not easy, and this is due to the reduced widths of the necessary slits. The wavelength of the electron at a speed of $10^6$ m/s is in the order of $10^{-10}$ m and coincides approximately with the distance separating atoms in crystalline structures. Therefore, it will be necessary to have a crystal that will play the role of the double slit in the interference experiment. The simplified configuration of the device is shown in the image.

Experimental set-up to test the de Broglie hypothesis with electrons. In the real setup a crystalline material plays the role of the double slit.
A32c. - The figure below shows the images obtained during the experience. In the light of the results, accept or reject the hypothesis under study.

Results obtained by throwing electrons through a double slit. The electrons have been collected on a screen in which they leave a punctual dot. In each case the quantity of electrons indicated in the lower left part has been thrown.

We found that each electron leaves a dot on the screen, which shows that when detection occurs they behave like particles. But the impact points are distributed on the screen showing an interference pattern, which coincides with that expected for a wave having the wavelength predicted by the de Broglie equation.

As with photons, the impact position on the screen is determined by the amplitude of a probability wave. This wave is not detected anywhere in space (since the electron is always detected at a single point, as a particle), but it determines at which positions there is a greater probability of detecting each electron. By carrying out this same experiment with protons, neutrons, ions or even large molecules such as fullerenes \((C_{60})\), similar results are always obtained: impacts on the screen follow the expected interference pattern for a wave having the wavelength predicted by de Broglie. We must conclude, therefore, that particles behave like photons. We will refer to these entities (photons and electrons, and by extension all "particles") with the term quantum. We thus consider that their behavior does not conform to that of classical particles and that they require the use of the model we have just built to interpret the phenomena in which they are involved.

We can ask ourselves, as we did before, what is the trajectory that an electron follows to reach the screen, and conduct experiences to determine it.
A33. Predict, using the quantum model, what will happen if, in the experience of electron interference, we place a detector behind each orifice, which detects the hole the electron has passed through but does not stop the electron, and we maintain the detectors on the final wall.

- What will it record each of the detectors behind the holes?
- What will be recorded on the screen?
- What is the trajectory of an electron?

By considering that the electron is a quantum, it propagates as a probability wave. When reaching the slits, the amplitude of the wave in both slits is the same, so we will have a 50% probability of detecting each electron in each hole, as shown in the image.

Electrons propagate like waves. When the barrier is reached the amplitude of the wave in each hole is the same. We therefore have a 50% likelihood of detecting the electron in each hole.

But when the electron is detected we know what its position is, and the probability wave disappears. If the electron continues to propagate, it does so from the point at which it has been detected, it is again delocalized and we can only consider a new wave of probability, as shown in the following image. When this wave reaches the screen there is no interference figure as long as the other hole is not now a source of waves (because it is certain that the electron has not passed through it). Here’s what happens experimentally:
If the electron has been detected by D1, it will continue to propagate from that orifice. When it hits the screen there is no longer any interference as long as there is no wave from the hole below. Adding the detectors behind the holes has changed the final result.

Surprisingly, adding detectors behind the holes changes the result of the experiment and the interference pattern disappears. Determining the position of the electron prevents the formation of the interference pattern. For the interference to form it is necessary that there are two waves, that the position of the electron take values different from zero through the two slits. However, the same electron is never detected in the two holes at the same time, since the electron is an indivisible particle.

We must conclude, therefore, that the electron does not have a position until it is measured, it is not in one hole or in another until we measure in which hole it is, and if that measure is not carried out the probability wave passes through both holes. If the electron passed through a particular hole there would be no interference pattern. Before the measurement we can only talk about one wave of probability, the possible results of the measurement and the probability of obtaining each result. Again, as was the case with photons, we realize that we cannot talk about trajectories when considering the motion of quanta.

**A34.** Electrons are launched from an electric arc and a detector is placed at a point in space that detects the passage of electrons without stopping them. Further back there is a screen against which the electrons impact leaving a punctual mark. Whenever the detector registers an electron in A will there be an impact in B? Use the quantum model and the uncertainty principle to analyze the electron motion and its point of impact on the screen.

We have an electric arc that releases electrons. The detector detects an electron when it passes close to it, at point A. Will the electron hit the screen at B?
Comments for the teacher A.34. - We must analyze the situation following the established quantum model. When the electrons leave the filament they propagate as waves, they can be detected in any point of the space where the wave front arrives. Our detector will only register the passage of some electrons, since it does not cover the whole wave front. When we detect an electron, we know that its position is in front of the detector. From that moment on the electron will continue to propagate as a probability wave and can hit any position on the screen, as shown in the image.

The electron propagates as a probability wave. After being detected in A, it continues to propagate from that point, but again as a wave. Thus, it can be detected anywhere on the screen since the wavefront reaches all of it.

The quantum propagates as a wave and there is a certain probability to detect it close to the detector, since the probability wave reaches the detector. When making the detection, the quantum continues to propagate from the point where it has been detected as a new probability wave: a new wavefront is formed. It can be detected at any point on the screen, with higher or lower probability depending on the amplitude of the wave, not necessarily in B.

If we analyze the situation based on the uncertainty principle, we can say that when the electron is detected in A, the uncertainty in the position will be low (we know well what position it occupies) and a high uncertainty in the momentum will correspond to satisfy the mathematical expression of the principle of uncertainty. Therefore, the electron could be detected at any point on the screen, as shown in the figure below.

When detecting the quantum we know its position well, the uncertainty in the value of the position is small. By virtue of the uncertainty principle, the uncertainty at the linear momentum will be large, the range of possible values of the linear momentum for the electron is wide. Therefore, the electron can impact on a wide region of the screen. Some possible values of the linear momentum are shown schematically in the figure. We cannot say, therefore, that it will impact on B.
If the quantum model we have established is valid and all material particles behave like quanta, why do we not observe quantum behavior in everyday life? For instance: Why a billiard ball, passing through a door and colliding with a wall that is behind it, does not hit anywhere and follows a well-defined path?

Comments for the teacher A.35. - The purpose of this activity is to reconcile quantum physics and classical justifying why quantum behavior is not observed in everyday objects.

The objects of our environment when moving at ordinary speeds have very small wavelengths, according to the calculations we made previously using the de Broglie equation. When a billiard ball passes through a door (or when a person does) no wave phenomenon can be observed since the dimensions of the door are, in many orders of magnitude, greater than the wavelength. Thus, in the absence of wave phenomena, the billiard ball behaves like a classical particle, and the same happens with any other object of our daily environment. Only in those conditions in which the wavelengths of the entities studied are similar to the slits or obstacles with which they interact can quantum phenomena be observed and quantum analysis become essential.

4.3. Limitations of the new knowledge and open problems

The work done so far has allowed us to establish a model for interpreting the quantum behavior. According to that, quanta:

- Propagate like probability waves.
- Are detected as particles, at a point and with a certain energy and linear momentum.
- Are most likely to be detected in those places where the square of the amplitude of the wave is greater.
- As a consequence of its own nature, it is not possible to know with absolute precision its linear position and momentum (and, therefore, its trajectory).

However, our study has been limited to the qualitative aspect. To contrast our hypotheses it is necessary to go deeper into both the quantitative and qualitative aspect. This implies finding a mathematical expression for the "probability wave", a function that allows us to determine in which regions of space we are most likely to detect the quanta and with what linear moment. This function, which is called "wave function" gives us all the information of the physical system under study, similarly to the equation of motion in classical physics. However, the wave function does not establish the values of the position, linear momentum, or energy of quanta for each value of time, but only a catalogue of the possible values that can be obtained when making a measurement and the probability with
which each of them is obtained. Unfortunately, the mathematics to be used for determining the expression of the wave function and for solving it are very complicated, and far exceed the objectives of this course.

Another problem that remains open is the atom model. We have used an atom model like the one shown in the figure. In it, electrons are particles that follow a defined trajectory, an orbit around the atom. But according to our advances, while the electron is not detected it does not have a position or a velocity, but behaves as a wave of probability. So, we must change the image of the atom.

Current physics does not speak of atoms with electrons that describe circular trajectories, but of orbitals: regions of space in which there is a certain (high) probability to find an electron when making a position measurement. To know the shape of the orbitals it is necessary to solve the wave function. The orbitals can be represented as shaded regions in which the intensity of the shadow is related to the probability of detecting the electron (a darker region means a higher probability of detecting the electron). The image represents the orbital corresponding to the electron of the hydrogen atom in its fundamental state, the orbitals corresponding to the excited states of the atom have different dimensions and shapes.
If we were able to solve the wave equation and determine the wave function we could also see that the predictions that quantum physics makes about the behavior of macroscopic everyday objects and the predictions made by the classical physics are equivalent. Acceptance of quantum physics does not imply rejection of all previous knowledge, but only the recognition of its limitations. When the quantum waves of the objects we are studying are comparable to the dimensions of the space in which they move we must necessarily resort to the quantum physics to explain the observed phenomena. However, when the wavelengths are very small we can analyze phenomena using the classical theory, with the peace of mind that quantum predictions would lead to the same results.
COMPLEMENTARY ACTIVITIES

CA1. The image shows the spectrum of a led emitting red light. Explain how it is produced.

[Image of spectrum of a led emitting red light]

Spectrum of a led emitting red light (wavelengths are measured in nm)

CA2. How does a green led work? And a blue led?

[Image of spectra of a green led and a blue led]

Spectra of a green led and a blue led (wavelengths are measured in nm)

CA2. The following images show cards and banknotes illuminated with ultraviolet light and ordinary light. Explain why with ultraviolet light you can see details that you can’t see with ordinary light.

[Images of cards and banknotes illuminated with ultraviolet light and ordinary light]

CA2. The following images show cards and banknotes illuminated with ultraviolet light and ordinary light. Explain why with ultraviolet light you can see details that you can’t see with ordinary light.
**CA4.** In the image below a glass containing chlorophyll (it has been obtained smashing spinach in alcohol) is illuminated with ordinary light from a low-energy bulb. On the right is the same glass illuminated with ultraviolet light. As you can see, when illuminated with ultraviolet light the chlorophyll emits red light. How can we interpret this phenomenon?

![Image of glass with chlorophyll illuminated with different lights](image)

**CA5.** When performing the diffraction experience through a square slit, the image shown below is observed. Interpret the obtained image.

![Diffraction pattern through a square slit](image)

**CA6.** You know that visible light has a wavelength between 400 nm and 700 nm. With the right lenses, it is possible to act on the light coming from an object to see it magnified, thus we obtain an instrument known as a microscope. With the development of quantum physics, the possibility of using electron beams to magnify small objects was opened up. In an electron microscope, a high-speed electron beam (in a typical electron microscope the electron speed is $6 \times 10^7$ m/s) is directed towards the object to be "observed". These electrons interact with the object and are collected by a sensor that, together with a computer, interprets the information that arrives and gives an amplified image of the object.

What advantage do electrons have over visible light for observing small objects?

**Comments for teacher CA6.** - We can give an answer according to the quantum nature of quanta of light that make possible the "observation" of the object: when quanta interact with objects that have dimensions similar to their wavelength, the wave effects become bigger and thus the quantum effects become more noticeable. Under these conditions, it is not possible to obtain clear images of the objects to be visualized, since interference and diffraction phenomena characteristic of the waves occur. If we determine the wavelength of the electrons used in an electron microscope, we will observe that it is much smaller than that of visible light, which allows us to observe objects of reduced dimensions without the undesired quantum
effects appearing and without distorting the image. It can also be commented that nowadays there are electronic microscopes that provide electrons with 70% of the speed of light and allow observing even smaller objects than those considered in this problem, but in order to determine their wavelength it is necessary to make relativistic considerations.

CA7. - The electron microscope is one of the most important instruments built based on quantum physics. An electron microscope uses electrons instead of light to "observe" small objects. If we want to observe very small objects, we must use lenses (in an optical microscope) or capacitors (in an electron microscope) with very small holes. However, if we reduce the hole in the capacitor or the dimensions of the lens too much, the image given by the microscope is no longer a sharp image, but a blurred image. Why does this happen? Use simpler drawings than the one in the image if you consider it necessary. (Image extracted from the website of the Australian Microscopy and Microanalysis Research Facility).

CA8. We launch two photons in exactly the same conditions towards an area where there are two detectors, as shown in the image. Indicate your agreement or disagreement with the following statements:

- One photon will be detected at the top and another at the bottom because the probability of hitting each place is 50%.
- The two photons are equal and will be detected in the same area.
- Each photon will be detected in both detectors because the light propagates in all directions.

The object on the left represents a photon source. To the right is a screen with two detectors, each as large as half a screen.