INTRODUCTION

Motion. At first sight it is something incredibly uninteresting and trivial. People have been studying motion for thousands of years, but it was not until 1687, when Isaac Newton formulated his three laws of motion, that people finally started to understand it more deeply. Newton's laws of motion were so ahead of their time that some scientists still consider Newton the most revolutionary physicist of all time. But even Newton's laws are not perfect, and in 1905 came the special theory of relativity, which brilliantly describes the motion of objects moving at high speeds, formulated by Albert Einstein. But there is another theory that started to develop at the same time. A theory that completely changed our perception of reality. In 1900, the cornerstone of quantum mechanics was laid.

Quantum mechanics deals with objects from the so-called microworld, like particles or atoms. These objects behave nothing like objects of "classical" proportions from the so-called macroworld we ordinarily deal with, and thus cannot be described by classical physics.

In this app, you will be able to explore the world of this ground-breaking theory. And if you at any point struggle to comprehend some its peculiar phenomena, do not worry, you are not the only one. Richard Feynman, one of the greatest contributors to quantum mechanics, once said:

"I think I can safely say that nobody understands quantum mechanics."

THE ORIGIN OF QUANTUM MECHANICS

QUANTIZATION OF ENERGY

"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement." This sentence was pronounced by a famous Scottish physicist William Thomson on the verge of the 20th century, and many contemporary physicists undoubtedly agreed with him. Classical physical theories had been tested many times and seemed to describe reality tolerably. Not until later, when these theories started to fall apart, did come to light how horribly wrong Thomson was. The first phenomenon which classical physics failed to explain is called the black-body radiation.

To understand this phenomenon, it is necessary to know that all tangible bodies in the universe emit energy in the form of electromagnetic radiation (light). The amount of energy emitted by a body depends on several factors, such as temperature or colour of the body. The higher the temperature of a body, the higher the average frequency (and thereby energy) of the light it emits. The reason we usually cannot observe this radiation is that bodies at room temperature emit predominantly light from the infrared spectrum, which is not visible to the naked eye. Visible light is emitted by metals during melting, for example, when their temperature reaches several hundreds of degrees Celsius, making it possible for us to see them glow.

Physicists of the 19th century were trying to ascertain the spectral composition emitted by a body in relation to its temperature. To accomplish that, they used a simplified model of a body - the black body. A black body is a hypothetical body that has to meet the following two conditions:

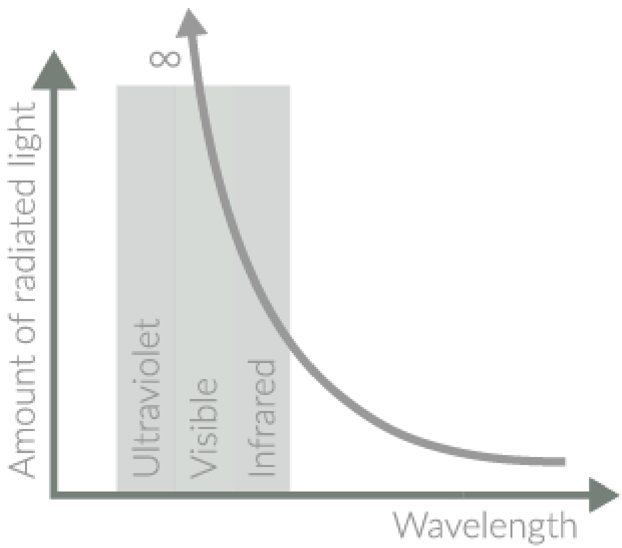
1. A black body absorbs all the electromagnetic radiation that strikes it (other bodies absorb merely a certain part of the whole spectrum and reflects the remaining light).

2. A black body stays in thermal equilibrium with its surroundings (i.e. has the same temperature as all the bodies located within the same system).

These conditions ensure that spectrum emitted by a black body is determined purely by the temperature of the body. However, when physicists tried to establish the composition of such a spectrum using classical physics, they obtained a result that did not coincide with reality whatsoever. According to classical physics, a black body would emit the same amount of light of each frequency. However, the higher the light's frequency, the more energy the light has. A black body would therefore emit huge quantities of energy in the form of high-frequency radiation – infinite, in fact.

This, however, has dire consequences - classical physics thereby basically states that every single object in the universe should immediately emit all of its energy in the form of light from the ultraviolet spectrum. Luckily, the universe does not work that way, otherwise we would not exist.

This realisation was a huge milestone for the evolution of modern science. Physicists were at last unwillingly forced to admit that classical theories were simply wrong. Today, we have an apt name for this huge failure of classical physics – the ultraviolet catastrophe.

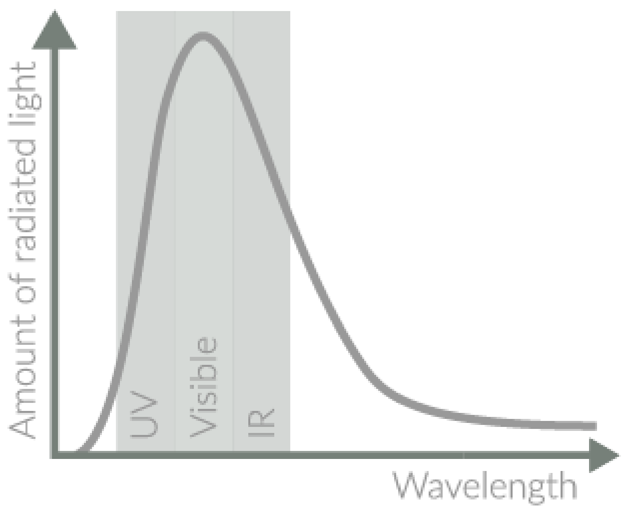


The black-body radiation problem was solved by a German physicist Max Planck. He came up with an idea that bodies do not emit electromagnetic radiation continuously, but via small packets called quanta. The size of these quanta is given by the following Planck's equation:

$$\mathbf{E = h \cdot f}$$

$$\mathbf{(h = 6{,}626 \cdot 10^{-34}\ Js)}$$

Electromagnetic wave can essentially be thought of as a set of very small energy "packets" (quanta) whose total energy determines the energy of the wave itself. The size of a quantum is specific for each frequency. From the equation above, it is apparent that radiation of higher frequencies is composed of larger quanta than radiation of lower frequencies. This solves the problem with black-body radiation – it is increasingly difficult for a black body to emit radiation of higher frequencies, as it often cannot "feed" high-frequency quanta with enough energy, and thus sticks with low-energy light.



Quantization of energy is just the very beginning of a whole new world of physics. It presents a fundamental rule to quantum mechanics - as we will learn in the following chapters.

BORH MODEL OF THE ATOM

Imagine that you have an object that you then start dividing into smaller and smaller parts. Would you be able to divide the object forever, or would you eventually reach some peculiar indivisible building blocks? Scholars of ancient Greece have asked themselves the same question and eventually have come with a correct assumption: all matter in the universe is made up of very small "grains". They called these grains atoms (atomos = indivisible).

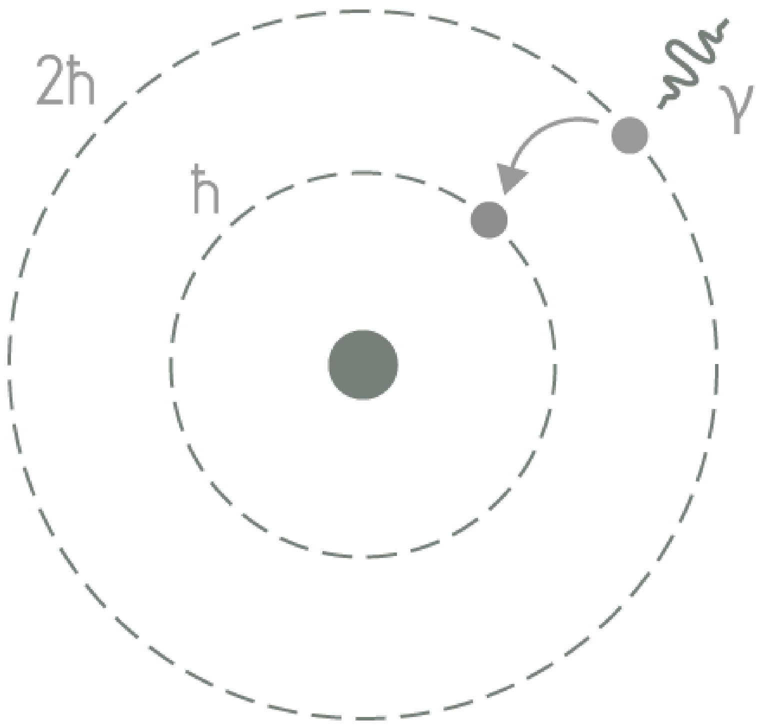
Later, when scientists thought to have discovered these indivisible blocks, they adopted the Greek name. It was then revealed that atoms are actually not indivisible, but consist of positively charged protons, negatively charged electrons, and neutrons, which are uncharged. However, there was uncertainty regarding the structure of the atom, and the physicist living at the beginning of the 20th century were trying to clarify it.

In 1911, Ernest Rutherford proposed the so-called planetary model of the atom. According to this model, every atom consists of a positively charged nucleus around which orbit negatively charged electrons like planets around stars. However, this model has one major flaw – if atoms obeyed the model, they would be extremely unstable, since their electrons would radiate all of their energy as a result of constant acceleration and almost immediately fall into the nucleus.

In 1913, a Danish physicist Niels Bohr came with his own model of the atom. The Bohr model is greatly similar to the planetary model. However, Bohr specified three rules that must be strictly adhered to for the stability of atoms to be maintained:

1. Electrons orbit around the nucleus following circle-shaped orbitals without radiating light.
2. Orbitals are not located at an arbitrary distance from the nucleus, but purely on allowed energy levels that are multiples of the reduced Planck constant (reduced Planck constant has a value of the Planck constant divided by two π). From this phenomenon, it is obvious that quantization applies to objects with mass as well (in this case, electrons).

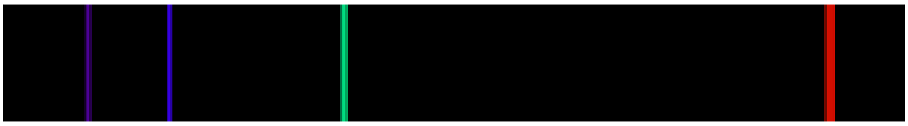
3. Electrons may jump from one orbital to another. When jumping from an orbital of lower energy to a high-energy one, an electron absorbs a quantum of light. This process is called excitation. Electrons that are located at a higher energy level than their original level are called excited electrons. In contrast, when jumping from a higher energy orbital to a lower one, an electron emits a quantum of light. Electrons that are on their original energy level are said to be in the ground state.



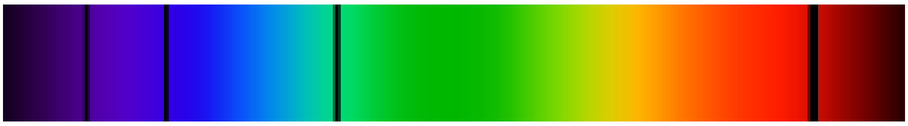
Scheme of an electron transitioning from an orbital of higher energy to a low-energy one while emitting a photon.

Using the Bohr model, the existence of the so-called spectral lines can be easily explained. A spectral line is a dark or light line disrupting an otherwise continuous electromagnetic spectrum. For example, if we expose an atom (let us consider a helium atom, for instance) to the whole spectrum, a part of this spectrum is filtered out after interacting with the atom, since certain frequencies of the spectrum have the exact amount of energy that is needed by helium electrons to move to an orbital with higher energy. Consequently, this part of the spectrum is absorbed. These disruptions of the continuous spectrum are called absorption lines. Helium electrons may never absorb the remaining radiation, because by doing so, they would find themselves outside of the allowed energy levels.

However, the radiation that was previously absorbed by the electrons is emitted after a while, when the electrons move from the orbitals with higher energy back to the ones with lower energy. Consequently, the so-called emission lines are created. Emission and absorption lines are unique for each element. This fact is used when determining the composition of remote objects in space – scientists point their telescopes at a distant cosmic body and ascertain its chemical make-up based on the spectral lines they receive.



Emission lines



Absorption lines

However, even the Bohr model is not perfect and shortly after it had been published it was replaced by a more accurate model - the quantum mechanical model. Despite its imperfections, the Bohr model still presents an important transition between the classical and quantum mechanics, as it applies Planck's findings regarding quantization to atoms.

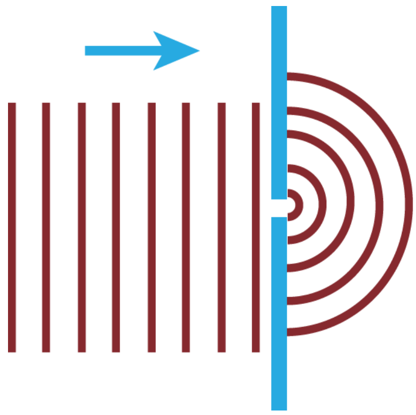
WAVE-PARTICLE DUALITY

For centuries, physicists all over the world were leading a heated debate about the nature of light and for many years there were two opinion groups among them. Supporters of the first group believed that light was a wave, while members of the other group believed that electromagnetic radiation had a particle nature. However, quantum mechanics showed that neither of the groups was completely right and that the real answer to this question is much stranger and much more complicated than any of the contemporary thinkers could have ever imagined.

YOUNG'S EXPERIMENT

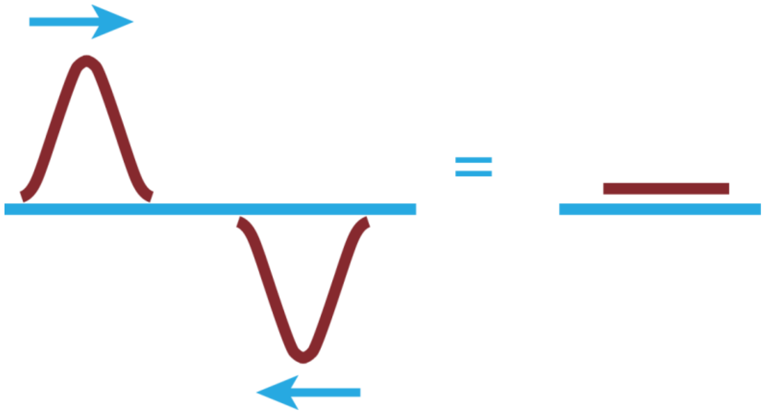
Young's experiment, often referred to as the double-slit experiment, is a relatively simple experiment. It was used at the beginning of the 19th century to prove that light exhibits wave properties. This experiment exploits two specific properties of waves:

1. If a wave reaches a small opening, it bends. This phenomenon is called diffraction. The size of the opening has to be comparable to the wave's wavelength for diffraction to occur.

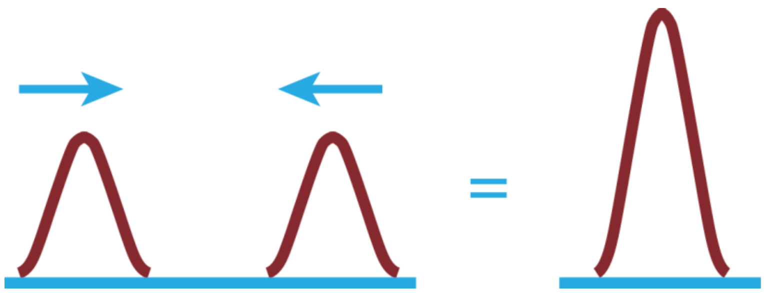


Scheme of diffraction – a wave bends after passing through an opening between two walls.

2. When two waves encounter, they do not collide but strengthen or weaken each other depending on what the displacement ("height") of both waves is. This phenomenon is called interference. For example, when two waves with opposite displacements meet (i.e. a crest of one wave meets a trough of another wave), they cancel out. If interfering waves weaken each other, we are talking about destructive interference. The opposite of destructive interference is constructive interference (waves strengthen each other).

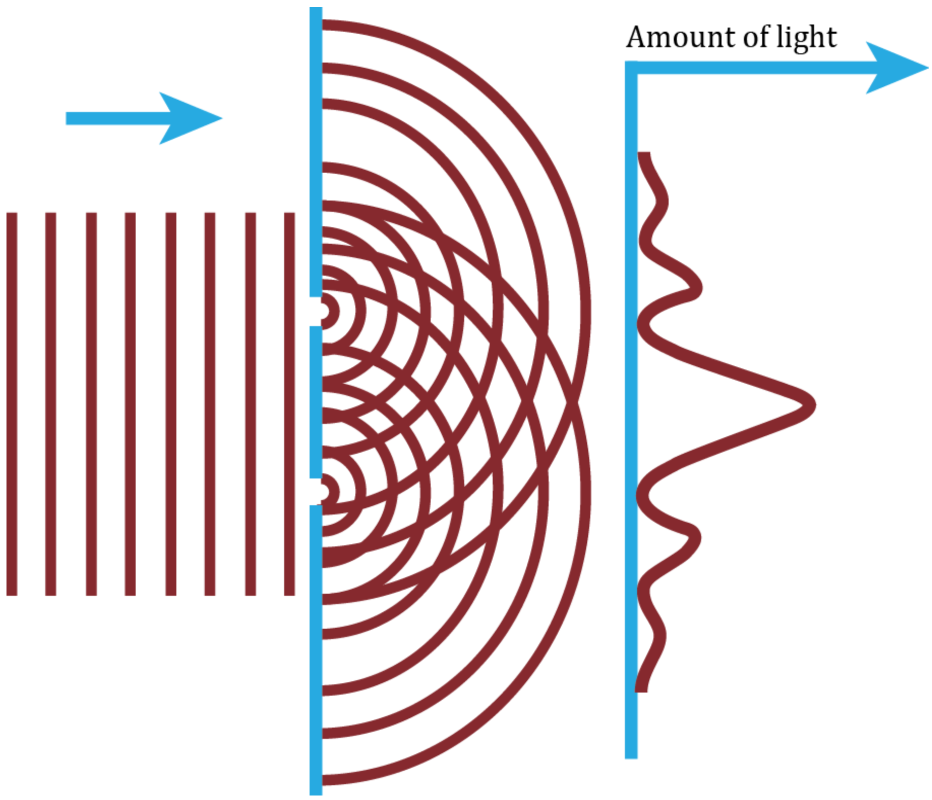


Scheme of destructive interference – two waves weaken each other.



Scheme of constructive interference – two waves strengthen each other.

In the double-slit experiment, two slits, which are very close to each other, are used. Light passes through both slits and spreads to the medium behind the opening thanks to diffraction. Due to small distance between the slits, the waves from the first slit meet the waves from the second slit and interference occurs. If we situate a plate detecting the position of individual beams of light that strike it, a specific pattern is created, the so-called interference pattern, which consists of light and dark stripes. Light stripes on the plate are located in places where constructive interference of light waves occurs (waves strengthen one another, thereby increasing the intensity of light incident on these places), dark stripes are caused by destructive interference (waves weaken one another, thereby decreasing the light intensity). If light did not exhibit wave properties, interference pattern would not be created.



Scheme of Young's experiment - light goes through two slits and diffraction occurs. Then, light from one slit interferes with light from the other slit and interference pattern is created on the plate. Behind the detection plate, there is a graph showing the amount of light incident on certain places of the plate. The graph shows that between the slits, constructive interference occurs. In areas directly behind the slits, destructive interference prevails.

Young's experiment is a simple experiment demonstrating the wave nature of electromagnetic radiation. The original version of this experiment is not related to quantum mechanics, but using its modifications, we can easily prove some of the strange phenomena of the microworld, as we shall see in the following chapters.

PHOTOELECTRIC EFFECT

According to the Bohr model of the atom, it is necessary to provide electrons with energy in the form of electromagnetic radiation in order for them to get to orbitals with higher energy. However, if an electron absorbs a wave of high frequency (and thus energy), sometimes this energy is sufficient for the electron to abandon the atom entirely. This phenomenon, when electrons are released from the shell of an atom, is called the photoelectric effect. Electrons that are released in this manner are called photoelectrons.

Let us imagine an experiment where one shines light on electrons inside of an atom, whereby some of these electrons are released from the atomic shell and become photoelectrons. Classical physics states that the energy of photoelectrons should be dependent on the intensity of light, since it assumes that the higher the intensity of radiation (i.e. the brighter the light is), the higher the energy of the electromagnetic wave that is then absorbed by the electrons. Nevertheless, this dependency has not been observed. It was experimentally proven that the energy of the emitted electrons depends purely on the frequency of radiation. Also, the existence of the so-called threshold frequency has been observed. If one provides an atom with light that has lower frequency than the threshold frequency, no electrons are released, again regardless of the intensity of radiation. Classical physics is not able to explain this phenomenon.

Young's experiment presents a very convincing evidence that light is a wave. However, in order to explain the photoelectric effect, we need to perceive light as a set of particles. Electrons do not absorb electromagnetic waves as predicted by classical mechanics. They absorb particles of light, called photons. Photons are identical to the energy quanta Planck proposed to solve the problem with black-body radiation. Einstein, however, was the first one to realize the particle nature of these quanta, and it was him who managed to clarify the photoelectric effect.

If we perceive light as a stream of particles, the photoelectric effect can be explained quite easily. Increase in intensity of radiation raises the number of photons (quanta) in an electromagnetic wave, but individual photons still carry the same amount of energy. That is to say, if one uses more intense light, the energy of photoelectrons stays unchanged, since electrons may absorb only one photon, in accordance with the third Bohr's rule. However, by increasing the intensity of light, the number of emitted electrons (photoelectrons) is increased as there are now more photons in electromagnetic waves to be absorbed.

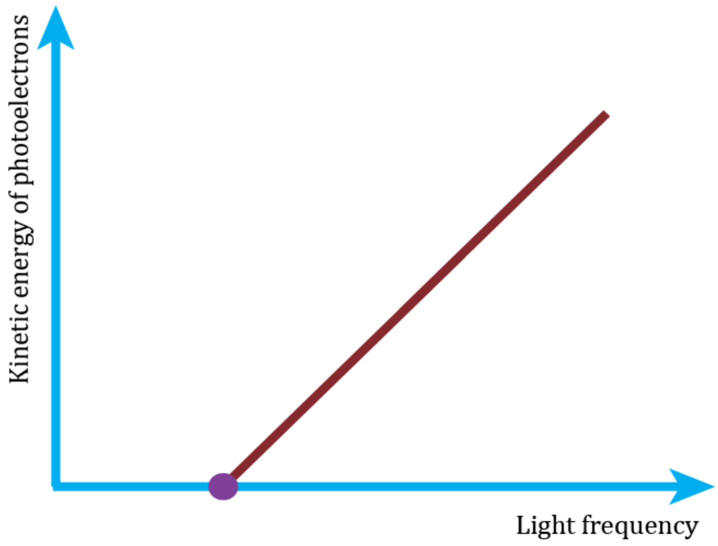
If we wanted to raise the energy of photoelectrons, we would have to raise the energy of individual photons. We could achieve that by raising the frequency of radiation, which is obvious from Planck's equation $E = h \cdot f$ (E is the energy of a photon). Quantum mechanics is also able to explain the threshold frequency. Individual photons of low-frequency radiation simply do not have enough energy to release an electron. Therefore, the photoelectric effect does not occur.

Albert Einstein also derived the equation for calculating the momentum of a photon (λ is the wavelength of the electromagnetic wave in which the photon is located):

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

When an electron absorbs a photon, it obtains all of its energy. Part of this energy is then used to extricate the electron from the atom (the electron must accomplish work W), the rest of the energy is converted into the kinetic energy of the electron. The energy of a photoelectron can thus be calculated using the following equation:

$$\mathbf{E = W + \frac{1}{2}mv^2}$$



Graph showing energy of a photoelectron in relation to the frequency of light it absorbs. The purple circle shows the threshold frequency.

While Young's experiment convincingly demonstrates the wave nature of light, the photoelectric effect sees light as a stream of particles. Therefore, electromagnetic radiation is dual in nature. It has both wave and particle nature.

MATTER WAVE

After a partial clarification of the strange properties of light in the form of the wave-particle duality comes the year 1924 and a young French physicist Louis de Broglie with a very daring hypothesis. According to this hypothesis, duality does not apply only to light but to every single object in the universe. In other words, de Broglie presumed that all objects, including the ones with mass, are surrounded by a kind of wave, similarly to photons. It is not a great surprise that this revolutionary hypothesis was initially not received very well. Opponents of the hypothesis argued that, after all, matter behaves nothing like a wave.

Eventually, however, it turned out that de Broglie had been right and that the so-called matter wave indeed exists. The presence of this wave can be demonstrated with the help of Young's experiment, for instance. When conducting the double-slit experiment with massive particles (electrons, for example), an interference pattern is created, which confirms de Broglie's hypothesis. The relation between the momentum of an object and the wavelength of its matter wave is expressed by the following equation:

$$\boldsymbol{\lambda} = \frac{\mathbf{h}}{\mathbf{p}}$$

The equation above shows that the wavelength of an object's matter wave decreases when the momentum of the object increases. In other words, the more massive the object, the smaller the wavelength of its matter wave. This is why objects from the macroworld do not exhibit wave-like properties. Matter waves of large objects have very small wavelengths, which means that if we wanted to prove the wave nature of a large object using Young's experiment, for example, we would encounter a problem. For diffraction and interference to occur, the size of the slits and the distance between them would have to be significantly smaller than the size of the object itself.

In quantum mechanics, light and matter are dual. Sometimes their wave nature comes to light, other times they show their particle nature. This ground-breaking idea is fundamental to quantum mechanics.

WAVE FUNCTION

Soon after de Broglie introduced his hypothesis to the world, a period which is often referred to as the old quantum mechanics came to an end (1900 – 1925). The basic phenomena of the old quantum mechanics are the quantization of energy and the wave-particle duality. Since 1925 we are dealing with the modern quantum mechanics.

Austrian physicist Erwin Schrödinger in 1925 adjusts de Broglie's inaccurate theory and assigns a so-called wave function to every quantum object. Temporal and spatial evolution of a wave function is described by a complex equation, the so-called Schrödinger equation. A wave function is denoted by the capital or lower-case Greek letter psi:

$$\boldsymbol{\Psi}, \boldsymbol{\psi}$$

The wave function is a complex mathematical function in which all the properties of a given quantum objects (momentum, position, etc.) are stored (this is different from the de Broglie's matter wave, since de Broglie did no assign this property to his wave, moreover, he perceived the wave as a physical object, while Schrödinger's wave function is merely abstract). This set of properties of a quantum object is called a quantum state. Quantum state is denoted as follows:

$$|\boldsymbol{\psi}\rangle$$

The wave function is presumably the most significant idea of quantum mechanics, since most of the phenomena of the modern quantum mechanics are derived from it. Some of these phenomena, especially the principle of quantum superposition, are so different from the ones which are usual for us in the macroworld that it is often very difficult to believe, let alone understand them.

QUANTUM SUPERPOSITION

Already when clarifying the phenomena of the old quantum mechanics, it became clear that the applicability of a certain phenomenon to the macroworld does not necessarily mean the applicability of this phenomenon to the microworld. One of the basic rules of the macroworld is that each object has only one position and one velocity. In other words, it is simply impossible to travel from Germany to the UK at 60 miles per hour while flying from Europe to Australia at eight times that speed. Astonishingly, this rule does not seem to apply to the quantum world, and objects from the microworld may therefore be in many places at once and do many things at once!

When conducting the double-slit experiment, an interference pattern is created only when a wave (wave function) from one slit interferes with a wave that passed through the other slit, as I have already described in the previous chapters. If we were to send waves (whether electromagnetic waves or matter waves) only through one slit, an interference pattern would not be created, of course. Let us imagine a situation where we are conducting the double-slit experiment with massive particles, such as protons, but with one small variation - we are sending only one proton at a time, so the wave functions of individual protons cannot interfere with each other. As strange as it may sound, even in this case, there is an interference pattern.

The entire classical physics is based on the idea of the so-called determinism. The basic principle of determinism is that the future is predictable and that the only thing necessary to predict the future evolution of the universe is having enough information about the present. For example, we can predict the next solar eclipse by having enough information about the motion of the Moon. The entire deterministic physics is based on this condition. Another idea of determinism is that identical conditions lead to identical results. For instance, if we were to shoot two identical bullets from a gun under the same conditions (i.e. in the same direction, at the same temperature, etc.), both bullets would hit the same place. However, the quantum world behaves completely differently. If we were to shoot electrons instead of bullets (from a hypothetical electron gun), each of these electrons could hit a different place and each of them could have a dissimilar velocity, even though the initial conditions were identical.

The strange behaviour of the protons from the second paragraph and the unpredictability of the electrons from the third paragraph are both a consequence of a crucial phenomenon of quantum mechanics – the principle of quantum superposition. Quantum superposition states that an object that is not being observed exists in all possible states at once – it is in a superposition. This superposition is a combination of all the states the object could theoretically be in. This means that a particle which is not observed can have multiple velocities and be at multiple places at once.

This may sound rather strange, but if we take the wave function into consideration, superposition starts to make sense. Consider, for instance, the position of an object. The wave function can be imagined as an abstract mathematical wave surrounding a given object. As mentioned before, the wave function contains all the properties of an object, the position of the wave function thereby determines the position of the object itself. This, however, poses a problem. Recall that a wave is not localized in space but instead tends to spread. This property applies to our wave function as well. It follows that as long as the wave function of an object exists, the position of this object is not fully defined and the object is basically located everywhere where its wave function is located. We say that this object is in multiple eigenstates. For a quantum object to have clearly specified position, the wave function must "disappear". How to achieve that? Simply by observation.

When a quantum object is observed, the so-called wave function collapse occurs. Wave function collapse is the reduction of the wave function to one eigenstate (one position, one velocity). Wave function collapse ensures that one can never observe an object with multiple velocities or positions, since the superposition is destroyed by mere observation. The act of observation thereby does not only identify the properties of a quantum object but also determines them! That basically means that we determine the future of an object purely by observing it (i.e. measuring its properties).

However, there is one important question: How does a quantum object select an eigenstate in which it is located when it is observed? This process is based on probability. The likelihood of a quantum object ending up in a certain eigenstate is determined by its wave function. The wave function is therefore also referred to as the probability wave. From each wave function, a complex number can be extracted, the so-called probability amplitude, which is used to determine this probability. The probability of a quantum object ending up in a certain eigenstate is determined as the square of the absolute value of the probability amplitude. If the probability of a certain process occurring is 50 percent, for instance, the probability amplitude of this process has a value of $\frac{1}{\sqrt{2}}$.

Let us consider a situation where we want to ascertain the velocity of a certain electron. Let us say that this electron is in a quantum state that is a superposition of two eigenstates. The first eigenstate assigns the electron velocity 1, the second eigenstate assigns it velocity 2. This superposition of two velocities can mathematically be written as follows:

$$|\psi\rangle = |\text{velocity 1}\rangle + |\text{velocity 2}\rangle$$

As long as the electron is not observed, it has both velocities. The wave function assigns the electron a probability of ending in each of the eigenstates in case of observation. For illustration, let us assign the electron a 75 percent chance of ending up in the first state with velocity 1 and a 25 percent chance of ending up in the second state with velocity 2. Mathematically we can write this using probability amplitudes:

$$|\psi\rangle = \sqrt{\frac{3}{4}} \times |\text{velocity 1}\rangle + \sqrt{\frac{1}{4}} \times |\text{velocity 2}\rangle$$

If we now try to measure the velocity of the electron, its wave function collapses, and the electron obtains just one velocity. Let us say that in the first measurement, the electron has velocity 1. If we repeat the measurement multiple times using different electrons with the same wave function, we randomly get either velocity 1 or velocity 2. In 75 percent of the cases, the electron has velocity 1, in the remaining 25 percent of the cases, the electron has velocity 2. There is no way of knowing for sure which velocity the electron takes in the next measurement.

A quantum object can be in a superposition of an arbitrary number of eigenstates, and each of these states is assigned a certain probability value. The sum of probability values of all eigenstates of a quantum object in a superposition is equal to one. The probability of finding an object in one of its eigenstates is therefore always equal to 100 percent (in other words, if the object exists, it is always going to be somewhere – even though we may not be able to predict where). Mathematical notation (c_1, c_2, c_3 are probability amplitudes):

$$|\psi\rangle = c_1|\text{state 1}\rangle + c_2|\text{state 2}\rangle + c_3|\text{state 3}\rangle + \cdots$$

$$|c_1|^2 + |c_2|^2 + |c_3|^2 + \cdots = 1$$

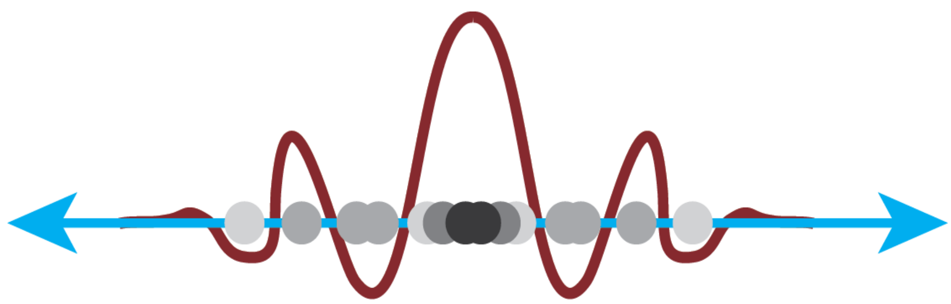
Let us now go back to the second and third paragraph of this chapter to understand what was happening. The proton in Young's experiment is in a superposition, so it actually goes through both slits at once and interferes with itself! If we put a detector in front of the slits and observe which slit the proton goes through, its superposition is destroyed and the interference pattern disappears. The electron fired from a gun (the third paragraph) is in more eigenstates at once, and therefore has multiple velocities and is in multiple places at once. Only after the impact, when the wave-function collapse occurs, does the electron obtain just one position, which, however, does not have to be identical to positions of other fired electrons.

We do not encounter superposition on a daily basis, since objects from the macroworld continuously interact with their environment which acts as an observer, and therefore wave function collapse occurs constantly.

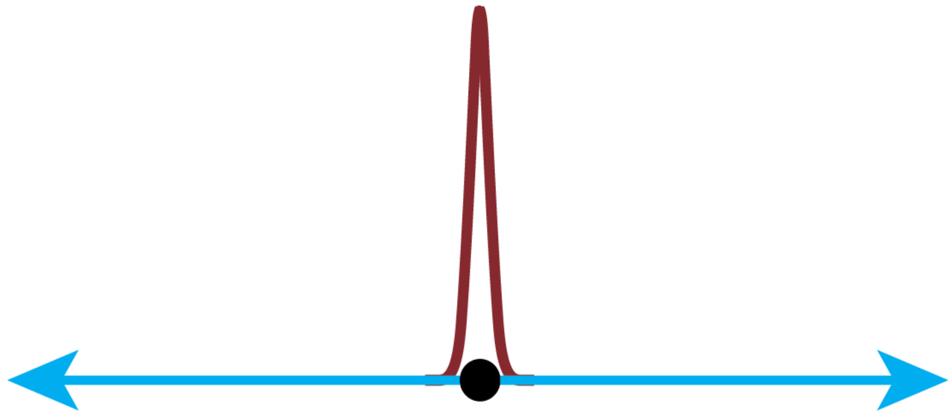
Quantum superposition is an elementary principle of quantum mechanics. It breaks the deterministic perception of the world. In quantum mechanics, future is determined only within probabilities, and the same conditions often lead to utterly different results.

One might think that probability is present in the macroworld as well. However, the opposite is true. Any seemingly random phenomenon from the macroworld, throwing a dice, for instance, is completely deterministic and any “randomness” is caused purely by our insufficient knowledge of the system. In the case of throwing a dice onto a surface, it is the height of the dice above the surface, the speed of the rotation of the dice, the mass of the dice, the surface roughness of the table, and so on. If we had a powerful supercomputer that would be able to take all these factors into consideration, we would know exactly which value the dice would show at any given time.

This, however, is does not hold true in the microworld. In quantum mechanics, instead of the question: “Where is a particle located?” we ask the question: "What is the probability of finding a particle in a certain place?”



An example of a wave function determining the probability of a particle being in various places on the axis. The lighter the shade of a circle, the greater the probability of finding the particle in this place.



In case of observation, wave function collapse occurs, and the exact position of the particle is temporarily determined.

SCHRÖDINGER'S CAT AND INTERPRETATIONS OF QUANTUM MECHANICS

There is no doubt that quantum mechanics is a revolutionary and an exceptionally strange theory. After the establishment of the modern quantum mechanics, physicist divided themselves into several opinion groups. Each of these groups tried to explain the weirdness of the quantum world in a different way, which led to the creation of many interpretations of quantum mechanics. The most acknowledged of these interpretations is the so-called Copenhagen interpretation (this interpretation was used in the previous chapter). Another very interesting interpretation is the so-called many-worlds interpretation. We can demonstrate the difference between these two interpretations on a simple thought experiment.

Let us say we have a box in which an atom of a radioactive element is located. A radioactive element is an element that undergoes decay to lighter elements in a certain period of time. The problem is that one can never know when the decay occurs, since each radioactive atom is described by a wave function that determines only the probability of the atom decaying over time. The probability of the decay occurring increases with time. Thus, the so-called half-life was defined. Half-life is the amount of time after which the probability of an atom decaying is exactly 50 percent. Each radioactive element has a different half-life (ranging from fractions of a second to millions of years). For instance, if we had 100 atoms of an element with a half-life of one year, 50 atoms would have decayed after one year.

Let us go back to our atom in a box. For simplicity, suppose that the half-life of our radioactive element is one day, i.e. if we leave the atom in the box for one day, there is a 50 percent probability of it decaying. However, recall that unless a quantum object is observed, it is in a superposition of all possible states. Therefore, the atom is both decayed and not decayed. In other words, our atom isolated inside of the box is in a superposition of two states – decayed / non-decayed. Only when we open the box and observe the atom, does the wave function collapse occur and the atom "decides" whether it is decayed or not decayed based on the probability given by its wave function (after one day, this probability is 50 percent for both decayed and non-decayed state). Now let us consider a situation where we put a vessel full of poisonous gas and a living cat in the box along with the atom. The whole system is set up so that if the decay occurs, the poisonous gas is released and the cat dies. If the atom does not decay, the gas is not released and the cat stays alive.

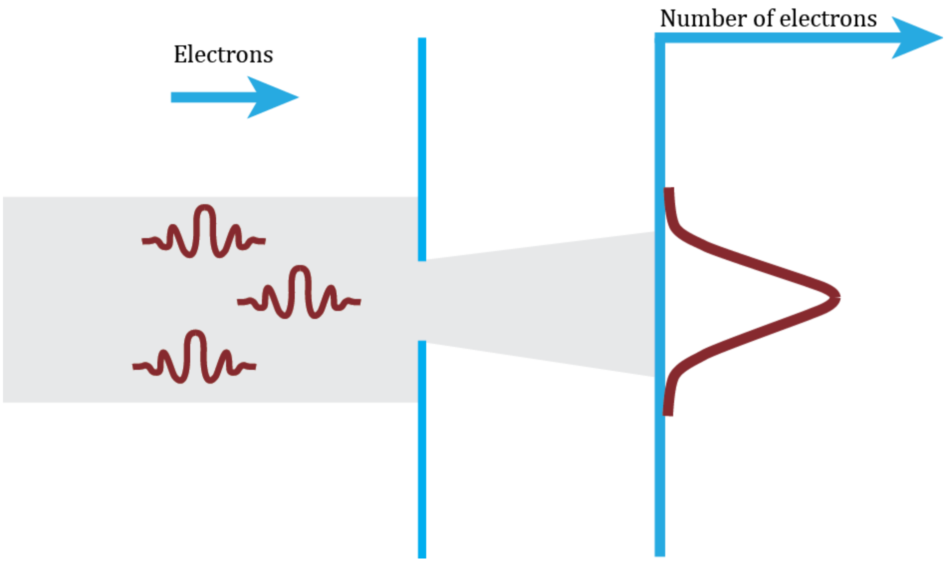
If this thought experiment seems familiar to you, it is because we are dealing with the most famous "paradox" of quantum mechanics. The author of this thought experiment is a famous physicist Erwin Schrödinger, the experiment is therefore often referred to as Schrödinger's cat. With this experiment, Schrödinger wanted to demonstrate the vagueness of the Copenhagen interpretation. It bothered him that the Copenhagen interpretation does not clearly define what it means to "observe" a quantum object. According to him, the Copenhagen interpretation basically says that if an atom is in the superposition decayed/non-decayed, the poison is in the superposition released/not released, which implies that the cat is in the superposition alive/dead until the box is opened. The cat obviously cannot be dead and alive simultaneously. That is why Schrödinger considered the Copenhagen interpretation silly.

However, the authors of the Copenhagen interpretation themselves never saw Schrödinger's cat as a problem, since they reckoned that the fate of the cat is decided long before the box is opened, since atoms in the air around the radioactive atom "observe" (bump into) it and thereby prevent superposition of the cat. Even the cat herself can observe whether the poisonous gas is released or not, therefore preventing superposition.

Each interpretation explains Schrödinger's cat a little differently. For instance, the aforementioned many-worlds interpretation assumes that every time two quantum systems interact, the reality is split into multiple parallel "worlds". The interaction leads to different results in each of these worlds. In other words, everything that can happen does happen in at least one of the worlds. This means that when the box is opened, the whole universe splits into two universes, one of them containing a living cat, the other one containing a dead one!

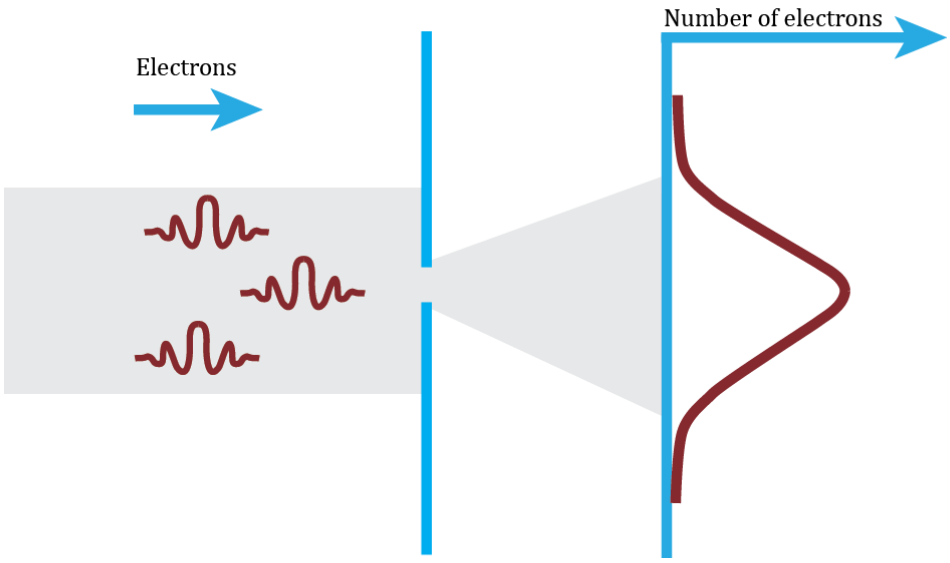
HEISENBERG UNCERTAINTY PRINCIPLE

Let us say we are conducting an experiment where we are sending electrons through a narrow slit. In a certain distance behind the slit, there is a detection plate, which detects the position of individual electrons that strike it. We already know from the previous chapters that we cannot predict where any individual electron ends up on the plate (because of superposition). We can, however, know the probability of an electron ending up in a certain place on the plate if we know its wave function.



Scheme of the experiment – electrons are sent through a narrow slit and strike the detection plate. The graph shows that the vast majority of electrons strike the area directly behind the plate. The grey colour shows the area where the majority of electrons are.

If we make the slit smaller, we probably intuitively expect the electrons to fall into a narrower section on the plate. Let us say we start with a relatively wide opening which we taper gradually. At first, our prediction is correct and the electrons indeed start falling into an increasingly narrower section. At some point, however, the opposite begins to happen. If one continues to make the slit smaller to the point where it is considerably narrow, the electrons start spreading again.



When the slit is narrowed considerably, electrons start to spread on the plate. The majority of electrons now do not end up directly behind the slit.

This phenomenon is a consequence of the so-called *Heisenberg uncertainty principle*, which was introduced by Werner Heisenberg in 1927. The uncertainty principle states that there are pairs of physical properties whose precise values cannot be known simultaneously. The more precisely we know one property, the more uncertainty there is about the other property. The most famous pair of such properties is momentum and position. The uncertainty in the momentum of a given particle multiplied by the uncertainty in the position of this particle is always equal or greater than the value of the reduced Planck constant divided by two:

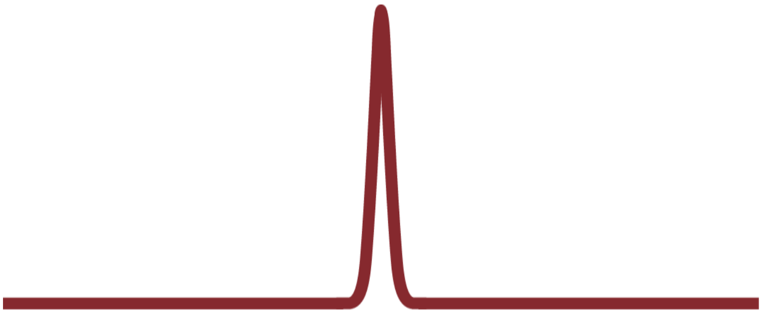
$$\mathbf{\Delta x \cdot \Delta p \geq \frac{\hbar}{2}}$$

$$\left(\hbar = \frac{\mathbf{h}}{\mathbf{2\pi}}\right)$$

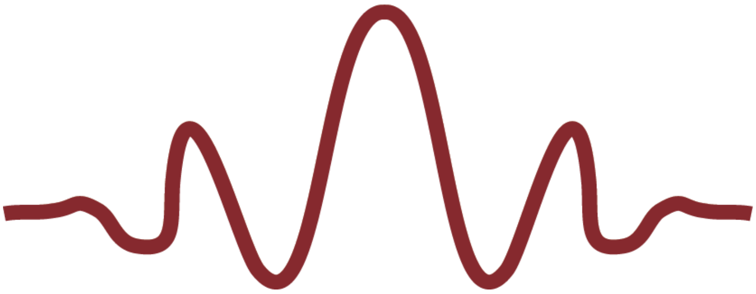
The more accurately one knows the position of a particle, the less information one has about its momentum. Let us go back to the electrons going through a slit. If we make the slit narrower, the uncertainty about the position of the electrons is decreased. Consequently, the uncertainty about their momentum has to be increased. The electrons now have a greater probability of changing their direction (i.e. are deflected sideways) or velocity, leading to them being more spread on the plate.

The Heisenberg uncertainty principle is a mere consequence of the wave function. Let us consider, for example, that we want to measure the momentum of a certain particle as accurately as possible. De Broglie's equation ($\lambda = h/p$) shows that the momentum of a particle depends on the wavelength of its wave function ($p = h/\lambda$). Therefore, if we want to ascertain the wavelength, the wave function cannot be too localized, since the wavelength of a localized wave is not precisely determined. On the other hand, if we want to measure the position of a particle, we need a wave that is as localized as possible. Of course, a wave cannot be both localized and spread simultaneously, which means that when measuring the position and the momentum of a particle at the same time, one has to find a compromise in the form of a wave function that is partially localized and partially spread and as such provides relatively precise values for both position and momentum. Such a wave function is called a wave packet.

An ideal wave function to determine the momentum of an object (spread). The uncertainty regarding the position is huge. Its wavelength is precisely known.



An ideal wave function to determine the position of an object (localised). The uncertainty regarding the momentum is huge. Its wavelength is completely unknown.



An example of a wave packet – the wave function is partially localised and partially spread.

The uncertainty principle is often mistakenly interchanged with the so-called observer effect, which is a phenomenon that occurs every time a physical system is observed. The observer effect states that any time a system is observed, its state inevitably changes. For example, when ascertaining the position of an object using our vision, photons have to bounce off the object into our eyes, so its position is not the same as it had been before the observation occurred. This phenomenon, however, has nothing to do with the uncertainty principle, since the uncertainty in the position and the momentum of a quantum object exists all the time, regardless of the presence of an observer. We can basically say that even the object itself does not "know" its own position and momentum simultaneously. Therefore, explaining the uncertainty principle using the observer effect is wrong.

QUANTUM TUNNELLING

About 150 million kilometres away from us, there is a huge sphere of hot plasma, which we call the Sun. Just like any other star, the Sun makes its energy by colliding lighter atomic nuclei to form a heavier element. This process, called nuclear fusion, is crucial for the existence of every single star in the universe.

However, there is a problem. The colliding nuclei are all positively charged, which means that they repel each other electrically. How do the nuclei fuse, then? There is another force – the strong nuclear force – which brings them together, but only when they are really close to each other to begin with. Therefore, the nuclei must have a huge energy (and thus velocity) in order to approach each other to the point where the attractive nuclear strong force surpasses the repulsive electrical force for nuclear fusion to occur. But when the temperature of the Sun was ascertained by its spectrum, it came to light that it does not even remotely reach the values necessary for nuclear fusion. In other words, the Sun simply should not shine whatsoever. This conclusion is obviously wrong - the Sun evidently shines, for which we owe to a peculiar phenomenon of quantum physics – quantum tunnelling.

Quantum tunnelling is a phenomenon wherein particles or even whole atoms have a certain probability of surpassing a barrier, even though they do not have enough energy to surpass it, which is unambiguously against the principles of classical physics. This phenomenon may not seem that peculiar at first sight, but the opposite is true. It would probably be quite strange if a person who run up against a wall appeared on the other side of the wall or even inside the wall. However incredible it may sound, this is essentially what happens to objects from the microworld during quantum tunnelling.

Quantum tunnelling can be explained using the principle of quantum superposition and the uncertainty principle. How? According to classical physics, the Sun does not have the sufficient temperature for atomic nuclei to approach each other enough for fusion to occur. However, the principle of quantum superposition states that the nuclei can be in more places at once (due to their wave nature), so there is a certain probability of them approaching enough and fusing. According to the Heisenberg uncertainty principle, on the other hand, there is always some uncertainty regarding the momentum of an object, so from time to time, one or both nuclei obtain an immense velocity (momentum) and fuse.

Quantum tunnelling is one of a few phenomena of quantum mechanics whose consequences we can hugely feel in the macroworld as well. The structure of our own bodies, for instance, is determined by the DNA molecule. However, it has been theorised that protons within this molecule can experience quantum tunnelling and therefore change our genetic makeup! These random genetic mutations caused by quantum tunnelling may even be linked to the existence of cancer, but more research is needed. Tunnelling also occurs during radioactive decay or in flash discs.

SPIN

Have you ever wondered how magnets work? How is it possible that some materials, like iron, show magnetic properties, while other materials, like wood, seem to ignore magnetism entirely? It turned out that the answer to these questions lies in a strange property of all particles called spin.

One could say that there are two types of momentum in the macroworld – "classical" momentum, which objects acquire by moving in a certain direction, and angular momentum, better known as rotation. However, objects from the microworld have an additional type of momentum – intrinsic angular momentum or spin. Spin is often compared to classical rotation (hence the name "spin"). However, this comparison is not accurate, since objects with spin do not actually rotate, the rotation is purely "intrinsic".

Spin is typical for elementary particles, composite particles and atomic nuclei. The unit of spin is the reduced Planck constant (ħ). Particles with half-integer spin (1/2 ħ, 3/2 ħ, 5/2 ħ, etc.) are called fermions. Particles with integer spin (1 ħ, 2 ħ, 3 ħ, etc.) are called bosons. We are going to learn more about these particles in the following chapters.

But what is the connection between spin and magnetism? It turns out that particles with spin behave like peculiar tiny magnets by generating weak magnetic fields. That is why objects from the macroworld, which are composed of many of such “small magnets”, are magnetic. But that does not explain why only a handful of materials are magnetic, when all macroscopic materials are made up of these tiny magnets. How is that possible?

The reason is that magnetic fields generated by individual particles (mostly electrons, whose magnetic fields are much stronger than those of protons or neutrons) often cancel out, which in turn makes most materials non-magnetic.

For instance, if an atomic orbital is completely filled, electrons in this orbital have opposite spins, which causes their magnetic fields to cancel out. This means that no atom with filled or almost filled orbitals can be magnetic. For an atom to be magnetic, it must have half-filled orbitals so that the magnetic fields of individual electrons reinforce one another.

However, not all materials made up of magnetic atoms exhibit magnetic properties. This is due to the configuration of individual atoms. Many materials have their atoms arranged so that their magnetic fields cancel out. Only a fraction of materials have the atoms arranged so that their magnetic fields mutually reinforce. This is why magnetic materials are so rare.

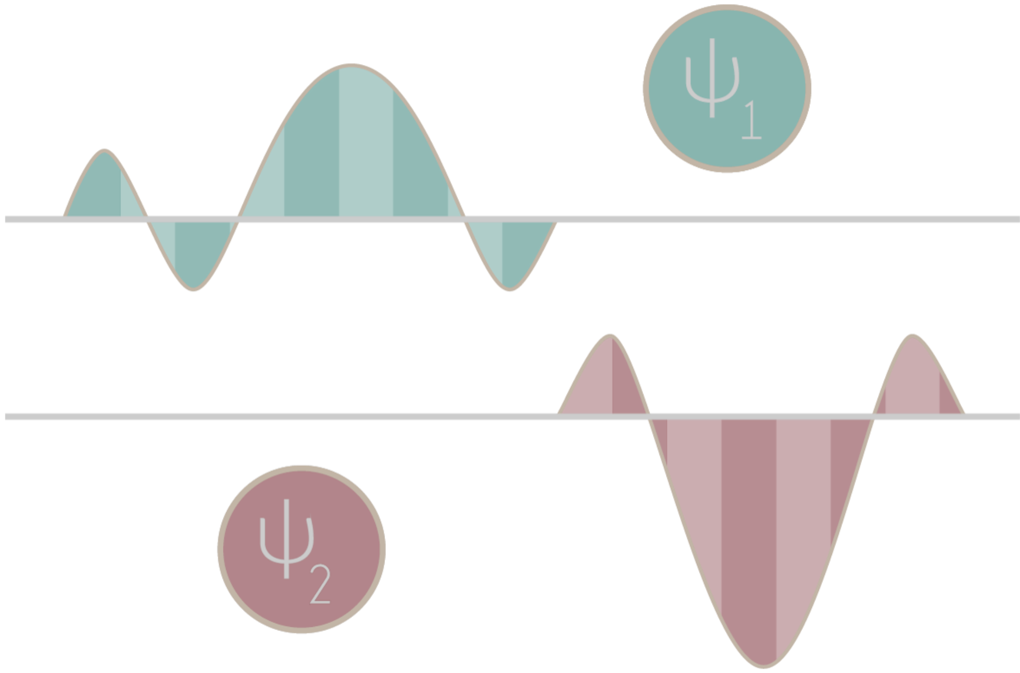
In the previous paragraphs, particles were compared to tiny magnets. However, this comparison is not completely accurate, because magnetic fields created by particles behave rather oddly. We can demonstrate this on a simple experiment. Say we have two axes: x and y, which are perpendicular to each other. Now let us take a particle which has a spin of 1 pointing in the direction of the x-axis (i.e. if we were to measure its spin in the direction of the x-axis, we would get 1). But what happens if we try to measure its spin (magnetic field) in the y-axis? If we took a classical magnet, pointed it in the direction x and conducted the same experiment, we would measure no magnetic field pointing in the y direction, of course (since the x-axis is perpendicular to the y-axis). However, particles behave in a completely different way. If we measure the spin of a particle in the y direction, half the time we get spin 1, the other half of the time we get spin -1. Even if we try to measure the spin in different directions, we always get either 1 or -1. However, the average of the values we get is always equal to the value we would expect to get with classical magnets. We can demonstrate this rule on our particle. The average of the values we got (half the time 1, half the time -1) is equal to zero, which is the value we would get with a normal magnet.

SYMMETRIC AND ANTISYMMETRIC WAVE FUNCTION

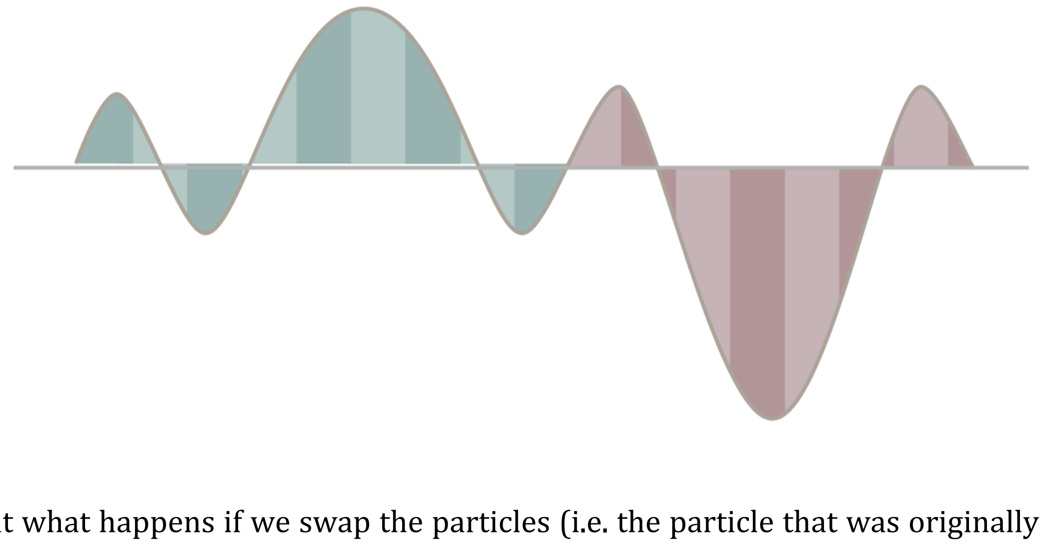
When describing objects from the macroworld, we often use words like "identical" or "same". We could proclaim, for instance, that two mobile phones of the same model are the same. The problem is, however, that no two objects from the macroworld are actually "the same". There is at least a slight difference between any two objects from the macroworld. With the mobile phones mentioned earlier, the difference is not visible at first sight, since it is on a molecular level. In addition, one can always simply differentiate between the phones by marking them (for example, one can paint one of the phones blue and the other one red).

In the microworld, however, the words "identical" or "indistinguishable" have a completely different meaning. Any two electrons (protons, photons, etc.) are absolutely identical and there is no way of telling them apart. One cannot mark them in order to make them different either (it is simply not possible to "paint" an electron, since colour has no meaning in the microworld). It therefore makes no sense to refer to two electrons as "the first electron" and "the second electron", since there is no way of telling which one is which.

Let us consider two identical particles, one of them is described by the wave function $\psi_{(1)}$, the other is described by the wave function $\psi_{(2)}$:



We could describe these two particles by a combined wave function that is a combination of the two original wave functions $\psi_{(1)}$ and $\psi_{(2)}$. This wave function would take a form $\psi_{(1,2)} = \psi_{(1)}\,\psi_{(2)}$:



But what happens if we swap the particles (i.e. the particle that was originally assigned the wave function $\psi_{(1)}$ is now assigned the wave function $\psi_{(2)}$ and vice versa) and describe them by a combined wave function in the form of $\psi_{(2,1)} = \psi_{(1)}\psi_{(2)}$? The particles are indistinguishable, so we should not be able to spot any difference after we swap the particles and the system should look exactly the same as before the particles were swapped. One can achieve that only if the wave function $\psi_{(1,2)}$, which describes the system before the particles are swapped, is identical to the wave function $\psi_{(2,1)}$, which describes the system after we swap the particles, therefore:

$$\boldsymbol{\psi}_{(\mathbf{1},\mathbf{2})} = \pm\boldsymbol{\psi}_{(\mathbf{2},\mathbf{1})}$$

In some cases, however, it may happen that the wave function changes its sign after the particles are swapped. In case this happens, the wave function is considered to be antisymmetric. If the sign remains preserved, it is a symmetric wave function. Bosons are described by symmetric wave functions, antisymmetric wave functions are typical for fermions.

FERMIONS

Fermions are particles with half-integer spin (1/2 ħ, 3/2 ħ, 5/2 ħ, etc.). They serve as the fundamental building blocks of matter. Fermions can be divided into two groups – leptons and quarks. The electron, for instance, is a lepton. The proton and the neutron, however, do not belong to either of the two groups, as they are not elementary particles – both of them are made up of three quarks. Nevertheless, they are still considered fermions. In fact, all composite particles that consist of an odd number of fermions also belong to fermions.

As we have learned in the previous chapter, all fermions have an antisymmetric wave function. This may seem irrelevant, but the opposite is true. Antisymmetric wave functions bring far-reaching consequences in the form of the Pauli exclusion principle.

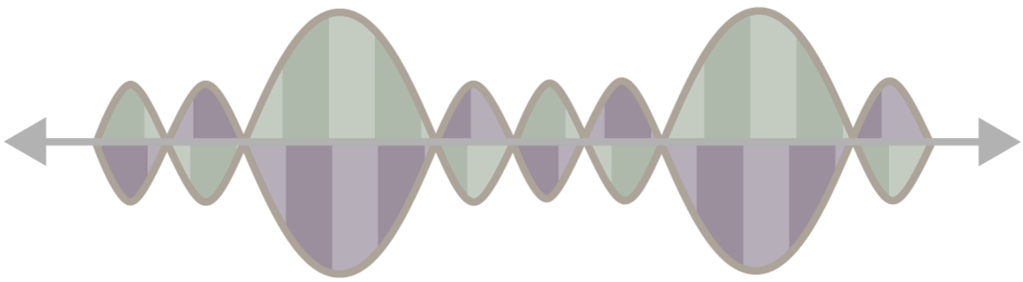
If we take a look at the structure of an atom, we find out that each atomic orbital is occupied by two electrons at most. This is somewhat peculiar, since everything in the universe has a tendency to stay on the lowest possible energy level. We may notice this when observing the behaviour of object in the gravitational field of the Earth – objects fall down to decrease the value of their potential energy. But electrons seem to just ignore this rule entirely – otherwise they would all gather in the orbital with the lowest energy. What prevents them from doing so?

The Pauli exclusion principle states that no two fermions can be in the same quantum state, which means that each fermion must have at least one property (spin, momentum, etc.) different from all the other fermions. Why? The Pauli exclusion principle is associated with antisymmetric wave functions of fermions.

Let us consider two electrons that are described by a combined wave function $\psi_{(1,2)}$. Recall that when swapping the electrons, the sign of the wave function is changed due to its antisymmetric nature: $\psi_{(1,2)} = -\psi_{(2,1)}$. But also recall that any particle can be in all possible states at once due to the superposition principle, which means that if the given electrons can be described by the wave function $\psi_{(1,2)}$ as well as the wave function $\psi_{(2,1)}$, they are in a superposition of both of these wave functions. This superposition looks as follows:

$$\boldsymbol{\psi = \psi_{(1,2)} - \psi_{(2,1)}}$$

However, we can see that if the two wave functions were the same (i.e. if the electrons were in the same quantum state), the equation above would be equal to zero – the electrons basically would not exist! This is not possible, of course. And the Pauli exclusion principle prevents that – it simply ensures that the equation $\psi = \psi_{(1,2)} - \psi_{(2,1)}$ is never equal to zero, since no two fermions will ever be in the same state.



But what does it have to do with electrons inside of an atom? Electrons belong to fermions, the Pauli exclusion principle therefore applies to them. If all electrons gathered in the orbital with the lowest energy, they would violate this crucial principle, as they would all be in the same quantum state. But there is one more crucial fact to be explained – why are there at most two electrons in each orbital and not just one?

This phenomenon can be explained using spin. The spin of an electron can take two different values: $\frac{1}{2}$ or $-\frac{1}{2}$. When electrons are in the same orbital, they have the same amount of energy, but they still have different spins – one of them has a spin of $\frac{1}{2}$, the other one has a spin of $-\frac{1}{2}$. This way, they do not violate the Pauli exclusion principle, as different spins mean different quantum states. However, no other electron can be found in this orbital, because it would inevitably be in the same quantum state with one of the original electrons.

The existence of the Pauli exclusion principle is crucial for stable structures to form. If it did not exist, the universe would be a widely different place. Molecules, for instance, would not form, since atoms would simply not be able to bind to each other.

BOSONS

Bosons are particles with integer spin (1 ħ, 2 ħ, 3 ħ, etc.). They function as particles that transmit interactions, they are therefore often referred to as force carriers. The most famous boson is indisputably the photon. Bosons also include the W and Z bosons, which are accountable for weak nuclear force (the interaction that causes radioactive decay), gluons, accountable for strong nuclear force (the interaction that holds particles inside of the nucleus of an atom together), and the famous Higgs boson.

Bosons do not obey the Pauli exclusion principle, since they are described by symmetrical wave functions, which means that more bosons can occupy the same quantum state. Bosons basically “crave” to be in the same state as other bosons. This property is responsible for the existence of multiple fascinating phenomena.

Let us start with a laser beam. Laser is a device emitting an immensely narrow beam of light, whose photons have the same frequency and are in phase. This is completely different from classical lightbulbs, which produce light of dozens of frequencies in all directions.

Lasers exploit the fact that photons belong to bosons. Within a laser, there are millions of atoms whose electrons are exited from the ground state to a higher energy level using electric current. Some of these electrons consequently emit energy in the form of photons and jump back to the ground state. The emitted photons then fly around the remaining excited electrons and stimulate the emission of other photons, while all of these photons enter the same quantum state (i.e. have the same frequency and are in phase). Once there are enough emitted photons, they leave the laser in the form of a laser beam.

Another mesmerizing instance of bosons in action can be observed when cooling a group of helium-4 atoms to extremely low temperatures – no more than two degrees above absolute zero. Every helium-4 atom is composed of an even number of fermions. This, however, makes the atom itself a boson, which means that it does not obey the Pauli exclusion principle.

All helium-4 atoms therefore behave just like other bosons – they wish to be in the same quantum state. Unfortunately, they cannot achieve that under normal conditions, as their wave functions look nothing alike. Nevertheless, once they reach temperatures just above absolute zero, their wave functions start spreading and overlapping. Eventually, they enter the same quantum state and the wave functions join into a single unified wave function which describes the entire group as a whole. In other words, quantum behaviour starts to transform into the macroworld!

Such a state of matter, in which atoms enter the same quantum state, is called the Bose-Einstein condensate. In some cases, this condensate behaves unlike any other state of matter. For instance, if one fills a vessel with cooled helium-4 atoms, they gradually creep along the walls of the vessel and escape, seemingly defying gravity.

QUANTUM ENTANGLEMENT

Every object around us is made up of massive particles. Collectively, we refer to these particles as matter. However, there is a deeply similar entity in the universe that we do not encounter on a daily basis – antimatter. Antimatter is composed of antiparticles, which have the same mass as their particle counterparts but are oppositely charged. For example, the antiparticle of electron, called positron, is positively charged, while the electron is negatively charged. When a particle comes in contact with an antiparticle, both of them are destroyed while releasing an enormous amount of energy. This process is called annihilation.

Let us imagine a situation where a particle collides with its antiparticle, electron with a positron, for instance, while the electron has a spin opposite to the spin of the positron at the time of the collision, so that their overall spin is zero. Once they collide, annihilation occurs instantly. In this case, the annihilation energy is released in the form of two photons of gamma radiation. Let us label the photons as photon A and photon B.

As mentioned earlier, spin represents the intrinsic angular momentum. That is to say that spin obeys the law of conservation of angular momentum, which states that the total angular momentum of a system does not change over time. In other words, if the total spin of the system of the electron and the positron was zero, the total spin of the photons A, B has to be zero as well. Photon A therefore must have a spin that is opposite to the spin of photon B. For illustration, let us label the spins of the photons as spin 1, spin 2.

However, remember that unless a quantum object is observed, it is in a superposition of all possible states. Photon A is therefore in a superposition of spin 1 and spin 2. The same thing applies to photon B. The spin of neither of the photons is defined, but it is given that the spin of one photon must be opposite to the spin of the other photon.

If somebody observes one of the photons (say, photon A) and tries to measure its spin, its wave function collapses, and the photon obtains only one spin (say, spin 1). To fulfil the law of conservation of angular momentum, immediately after the wave function of photon A has collapsed, the wave function of photon B must collapse as well, so that the total spin of photons A and B stays zero.

In other words, the photons are in a state wherein an observation of photon A immediately influences the state of photon B, regardless of the distance between the photons. This state of a kind of superposition, where observation of one object determines the state of another object, is called quantum entanglement. Mathematically we can write the entangled state of photons A, B with spins 1, 2 as follows:

$$|\psi\rangle = |1_A\rangle|2_B\rangle + |2_A\rangle|1_B\rangle$$

VACUUM FLUCTUATIONS

The Heisenberg uncertainty principle states that there are certain pairs of variables whose values cannot be known simultaneously. As mentioned earlier, an example of such variables is the pair momentum and position. However, this pair is not the only one which obeys the uncertainty principle. Another such a pair is energy and time:

$$\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$$

Let us say, for instance, that we have a measuring device around which we send a photon. We want to measure the energy of the photon and the time in which the photon has passed the measuring device. However, every particle obeys the uncertainty principle for time and energy, so the more precisely we measure the energy of the photon, the greater uncertainty there is about the time it passed the measuring device.

But what happens if we apply this uncertainty to vacuum? Vacuum is by classical physics defined as empty space (space where there are no particles), therefore, its energy should be zero. However, the uncertainty principle for time and energy states that there is always at least a tiny amount of uncertainty regarding the energy of every system, which means that one can never be sure that the energy of vacuum is truly zero. This means that even vacuum itself can obtain non-zero amount of energy for short periods of time. These deviations in the energy of vacuum are called vacuum fluctuations. The question is: What is this temporary energy caused by vacuum fluctuations used for?

It turns out that it is used to create a peculiar new type of particles – virtual particles. These virtual particles of vacuum fluctuations are created spontaneously everywhere in the universe and usually exist for very short periods of time. Each virtual particle may never be created by itself – it is always created in pair together with its antiparticle. As one might expect, they annihilate after a short period of time.

The equation above shows that the greater the uncertainty in energy, the smaller the uncertainty in time. This means that the more energy a given virtual pair "borrowed", the sooner the particles of the pair have to annihilate. When a virtual pair annihilates, no energy is created, the law of conservation of energy (energy cannot be created out of nothing) is thus not violated. Virtual particles and antiparticles simply "borrow" energy which they soon return.

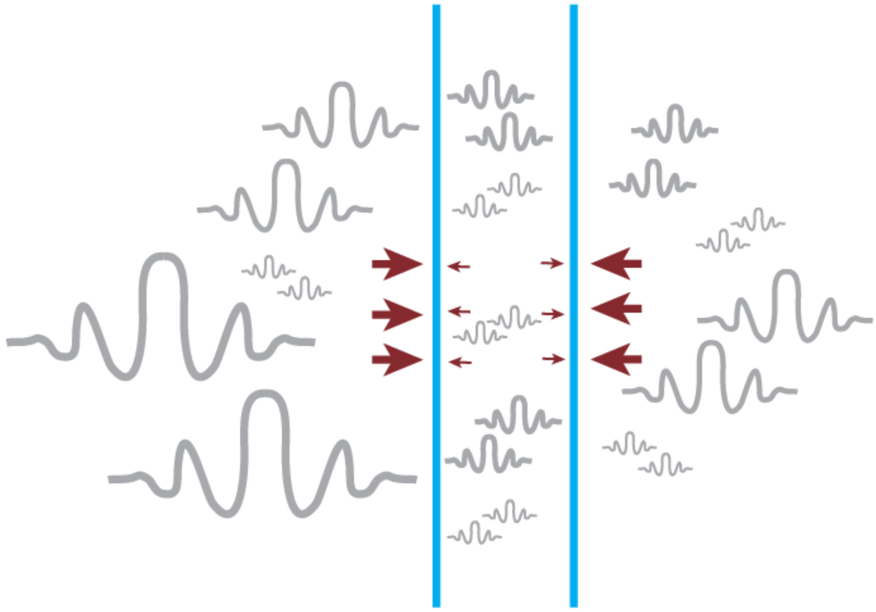
Virtual particles might not always have the same properties as their classical counterparts. A virtual electron, for instance, might not have the same mass as a classical electron. Moreover, virtual particles cannot be observed directly. We can, however, observe their impact on the environment around them. Under certain conditions, they can even be transmuted into classical particles, as we shall see in the following chapters.

CASIMIR EFFECT

The Casimir effect is a physical phenomenon which proves the existence of virtual particles. It was predicted in 1948 by a Dutch physicist Hendrik Casimir based on the uncertainty principle for time and energy.

Casimir correctly assumed that if we put two parallel uncharged plates just a few nanometres apart, they will attract as a consequence of vacuum fluctuations.

As we have learned in the previous chapter, virtual pairs of particles and antiparticles are being created constantly between and around the plates. However, for a virtual pair to be created between the plates, its wave function must have a relatively small wavelength, since greater wavelengths do not fit between the plates. Consequently, less virtual particles are being created between the plates than in other places around the plates, where particles of arbitrary wavelengths can be created. This results in a greater pressure on the outside of the plates, and the plates start drawing closer.



Scheme of the Casimir effect

HAWKING RADIATION

Everybody is presumably familiar with gravity to some extent. Gravity is an omnipresent attractive force that keeps us on the Earth. But it is also the force that keeps the Earth in orbit around the Sun and the force that makes our whole solar system orbit the centre of the Milky Way (the galaxy which we inhabit).

For a long time, people mistakenly believed that gravity acts merely on particles with mass. Later, however, it was revealed that even particles with zero rest mass (photons, for instance) are influenced gravitationally. Light, which is moving through the universe at the greatest possible speed – according to the special theory of relativity – does not significantly feel gravity in most cases. Nonetheless, there are objects of extreme masses within the universe whose gravitational fields are so incredibly strong that even light cannot escape – black holes.

Generally, the closer an object is to a gravitational field, the greater is the gravity acting on it. Therefore, there has to be an area shaped like a sphere around every black hole beyond which the gravity is so immensely strong that even light does not have any chance of escaping. Scientists call this area the event horizon.

When a famous British physicist Stephen Hawking studied quantum mechanical phenomena near the event horizon in 1974, he came up with a fascinating theory – every black hole should constantly emit electromagnetic radiation. Today, his theory is widely accepted, and this type of radiation is known as Hawking radiation.

Let us imagine a pair of virtual photons which is created near the event horizon in such a way that one of the photons appears directly beyond and the other photon directly in front of the event horizon. The first photon is irrecoverably absorbed by the black hole, while the other photon narrowly escapes this fate. However, since it is a virtual particle, it ought to be destroyed immediately. Nevertheless, virtual particles are destroyed purely by annihilation, which cannot occur, since the escaped photon "lost" the other photon inside of the black hole, which means they cannot collide.

The question therefore is: What happens to the escaped photon? Something seemingly impossible – it becomes a classical photon and leaves the surroundings of the black hole as Hawking radiation.

However, there is a problem. Photons cannot be created out of nothing, the law of conservation of energy must be adhered to. One does not have to worry about the law of conservation of energy as long as the photons are virtual, since the "borrowed" energy of vacuum fluctuations to make these photons is returned after a very short period of time.

But in the case of Hawking radiation, annihilation never occurs – the virtual photon has to obtain energy in order to turn into a classical photon. Where does it get the necessary energy? From the black hole itself. This, however, has surprising consequences. As the black hole gives away its energy to every single virtual photon it emits, its mass decreases – the black hole starts evaporating. The smaller the black hole, the faster it evaporates as a consequence of Hawking radiation.

However, this effect is completely negligible for black holes of cosmic sizes, which usually absorb tremendous amounts of matter, steadily gaining energy instead of losing it.

QUANTUM COMPUTERS

Some phenomena of quantum mechanics might have a huge impact on human technology in the future, particularly in the form of quantum computers. A quantum computer is a computer using quantum superposition and quantum entanglement to improve its computing power. How?

In order to understand quantum computers, we first need to take a look at classical computers. The basic unit of information of classical computers is a bit. A bit can take one of two values: 1/0 (yes/no, on/off). Two bits may take one of four values (11/10/01/00), three bits one of eight values, four bits one of sixteen values, and so forth.

Quantum computers use a slightly different unit of information – a qubit (quantum bit). Qubits are similar to bits, but with one significant difference – due to quantum superposition, a qubit may take more values simultaneously! A qubit can thus be in a superposition of values 1 and 0. We could, for instance, create a qubit using an electron's spin. Spin $\frac{1}{2}$ could be assigned the value 1, spin $-\frac{1}{2}$ the value 0 (or vice versa). As long as the electron is not observed, its qubit has both possible values.

However, if we add another qubit, the whole situation becomes even more interesting. Due to quantum entanglement, both qubits enter a superposition of four states. Qubits now take all four possible values (11, 10, 01 and 00) simultaneously. If we add another qubit, the whole quantum system of these three qubits can take eight values at the same time, and so forth. Each time we add a qubit, the number of possible superposed states doubles. The main difference between a classical and a quantum computer is thus in the number of states it takes. While any set of bits can only take one possible value at a time, the same set of qubits can take all of these values simultaneously.

But what is the consequence of this difference? Speed. Quantum computer is capable of solving certain tasks even a million times faster than a classical computer of comparable size – for instance, a quantum computer composed of just twenty qubits can take 1048576 states simultaneously!

This may sound terrific, but there is a downside. Despite its tremendous speed, quantum computers will probably never entirely replace classical computers. The reason is simple – any time a quantum system is observed, the wave function of this system collapses. This means that anytime we tried to use a quantum computer, there would inevitably be an interaction between us and the computer. This interaction would cause the superposition within the quantum computer to collapse, and its qubits would suddenly become mere classical bits.

Unfortunately, quantum computers are only suitable for specific, usually complex computations. During the computation, they must be isolated from their surroundings to prevent the superposition of their qubits from collapsing. A quantum computer basically divides each problem into many simpler calculations, which it then solves in parallel. Once the computation is finished, the computer is observed, which causes its superposition to collapse, and it provides us with just one result.

PARADOXES OF QUANTUM MECHANICS

Ever since its establishment, quantum mechanics has faced attacks of many physicist, who could not accept this theory and therefore tried to prove that it is incorrect. Albert Einstein was, without doubt, the most famous of the physicists who tried to disprove quantum mechanics. Paradoxically, he was one of its founders, since he pointed out the wave-particle duality of light. Einstein did not like the unpredictability which was brought to the world of physics by the wave function, and to show his opposition towards the uncertainty of the quantum world, he uttered the famous sentence *"God does not play dice with the universe"*.

However, quantum mechanics survived all the attempts to refute it. Today, it is one of the best-tested physical theories. Nonetheless, one of the most significant quantum mechanical phenomena, the principle of quantum superposition, is still surrounded with many questions that nobody can answer – as demonstrated by the aforementioned Schrödinger's paradox (Schrödinger's cat). Now, however, we are going to discuss a different well-known paradox of quantum mechanics – the EPR paradox.

The EPR paradox is a thought experiment in which three prominent physicists (Albert Einstein, Boris Podolsky and Nathan Rosen) sought to demonstrate the incompleteness of quantum mechanics. Let us say we create a pair of entangled particles and immediately isolate them from their surroundings, so that the wave function of the pair does not collapse. One of the particles is then transported to the Moon, the other one is left here on Earth. Quantum mechanics states that if one observes either of the particles (the one on Earth, say), the wave function of both particles collapses immediately. This means that the particle on the Moon knows straight away when the particle on Earth is observed.

However, the creators of the EPR paradox did not like this "spooky action at a distance" (in Einstein's own words), since they thought it contradicted Einstein's theory of relativity. According to special relativity, no information can travel through space faster than light. This rule is fundamental to the theory of relativity, and strange things would begin to happen if it were violated – if information travelled faster than light, to some observers it would seem as if it reached its destination before it had even been sent!

The fact that quantum entanglement seemingly violates this rule made the authors of the EPR experiment think that quantum mechanics was wrong. Instead of the uncertainty of the quantum world, they proposed the so-called hidden variables. Einstein assumed that entangled particles always "agree" in advance on which state each of them takes, which would eliminate the unlovable "spooky action at a distance". If this hypothesis were true, it would mean that the basic principles of quantum mechanics, like quantum entanglement or quantum superposition, are merely an illusion.

A few years later, a physicist John Stewart Bell came with a relatively complex experiment that could prove whether particles actually communicate faster than light, or whether hidden variables exist, as proposed by Einstein. This experiment includes measuring the spins of entangled particles in various directions by two measuring devices. To the satisfaction of physicist fighting for quantum mechanics, the experiment confirmed that no theories that include hidden variables can replace quantum mechanics. This proved that the authors of the EPR paradox were wrong.

However, if quantum entanglement is real, how could we explain the seeming contradiction with special relativity? The trick is that it is actually impossible to transmit information through entangled pairs, since entanglement is based on probability.

Let us say we have an entangled pair of photons with opposite spins which we want to use to transmit information at a speed that is greater than the speed of light. We agree with the receiver of our message in advance how the message would be encoded – one of the spins could be assigned the value YES (1), the other spin could be assigned the value NO (0). Then, we split the photons – we keep one photon and send the other one to our receiver. In case our photon is observed, the combined function of both photons collapses and the message is automatically sent. Say we want the receiver's photon to show the value YES, which means that we must influence the spin our own photon (in this case our photon must have the value NO). The problem is, however, that there is no way of determining the spin of our photon, remember that wave function collapse is completely random. This basically means that if we sent the message, the receiver has a 50 percent chance of receiving the value YES and a 50 percent chance of receiving the value NO. Obviously, such communication does not make any sense.

FREE WILL DEBATE

It is undoubtable that quantum mechanics has dramatically changed the world of physics and greatly influenced many other fields as well — including biology, chemistry, and computer science. But besides that, it has expanded outside the realm of science by posing interesting philosophical questions.

The goal of science and philosophy is actually very similar – they are trying to provide answers to fundamental questions. However, they adopt widely different approaches to reach these answers. Whereas philosophy only utilises rational argumentation and critical thinking, science relies on observable evidence and the rigour of the scientific method. To demonstrate that, I am going to use one of the oldest philosophical questions as an example: What is the world made of? Philosophers had been trying to answer this question for centuries, but without much success. Many of them thought they knew the answer – Thales, for instance, argued that everything was made of water. He was wrong — just like many other philosophers of that time — because philosophy is inherently bad at answering such questions.

Today, we know the answer due to modern physics — every object around us is made up of quarks and electrons. And even though this may not be the final answer — string theory proposes even smaller building blocks — there is no doubt that science has made more progress in unravelling the nature of our universe in a few decades than philosophy has in centuries. When it comes to studying nature, the scientific method is by far the best tool we have.

This certainly does not mean that philosophy is unimportant or redundant in today's world. In fact, the opposite is true. While science is much better at providing correct answers, it cannot make sense of its own discoveries. Thanks to science, we know that humans have evolved in the process of natural selection or that the universe is going to come to an end, but we still need philosophy to decide what to make of these discoveries. Every scientific discovery brings forth a multitude of questions which can only be answered by philosophical discourse, not by conducting more experiments. For instance, biologists have discovered that you could theoretically create your exact copy — or thousands of such copies — by the process of cloning, but it is up to each of us to decide how we feel about that.

But this chapter is not about quarks, electrons, or the relationship of science and philosophy. Instead, I would like to talk about a particular philosophical question, which remains open to this day — the question of free will. Free will is usually defined as the ability to consciously control one's actions. For instance, let us imagine that you have a day off and decide to go for a trip. Most people would argue that this decision was completely voluntary — you could have just as well decided to stay home. There is no reason to think that you were somehow predetermined to decide this way. We assume to have free will because we naturally feel that way. But is it really the case?

Initially, this issue was purely philosophical. But just like with the question of the fundamental substance, it has eventually expanded into the domain of science, which first contributed to the free will debate with the arrival of Newtonian physics. As you may recall from early chapters, classical physics states that the universe is inherently deterministic. In other words, it presumes that we can, in theory, gather all information about the present state of the universe and use it to predict the future with absolute certainty.

This so-called "clockwork universe" was a crucial factor in the development of the debate, as it makes free will impossible. Your decision to go for a trip was inevitably caused by the specific arrangement of molecules in your brain, which was predetermined at the beginning of the universe just like everything else that has ever happened. Every action has a predictable reaction, and your decisions are mere consequences of a huge chain of actions going back all the way to the Big Bang. Any voluntary decision that is not based on anything that came before it would violate the laws of Newtonian physics, as it would create a new, independent chain of actions and reactions. Such a universe would be both boring and unimaginably frightening. Anybody possessing enough information about the current state of the cosmos would be able to predict all of your future decisions with absolute certainty. All events in the universe would simply play out according to a precisely written script. (Some philosophers, called "compatibilists", argue that determinism and free will are still compatible. This belief is caused by the fact that they use a different definition of free will than the one people are used to.)

Luckily, quantum mechanics brings liberation from the clockwork universe. How could we predict the future position of a particle when we are not even able to precisely know its current position? In our universe, one can only use probabilities to make assertions about the future. The non-determinism of quantum mechanics is often viewed negatively, as it undermines the simplicity of Newtonian physics. However, only in a probabilistic universe is the future a mystery.

Some physicists even went so far as to use the uncertainty principle as undeniable evidence of free will's existence. However, that is nothing more than wishful thinking. While it is true that quantum mechanics could perhaps allow for free will to exist — certainly more than Newtonian physics — we know far too little to make any definite conclusions. As of today, we are left with two equally valid options:

The first option is quite straightforward — in spite of the uncertainty principle, our brains are still purely deterministic. One may say that, after all, quantum phenomena only apply to much smaller objects than the brain's neurones or synapses, so why should they have any significant effect on the way we think? While this could be true, it is certainly not a conclusive argument. Quantum effects are exclusive to the microworld, but that certainly does not mean they have no effect in the macroworld. For instance, in Schrödinger's thought experiment, the decay of a single nucleus — which is governed purely by probabilities — is scaled up to the macroworld, so that it affects whether the cat dies or lives.

This brings us to the second option, which is a lot more interesting than the first one. Consider for a moment that quantum mechanics really does play a significant role in decision making. What would it mean for the notion of free will? You could assign a certain probability value to all of your future decisions. For example, just before you decided to go for a trip, there was a 60 percent probability that you were going to decide this way, and a 40 percent probability that you were going to stay at home. (Of course, this is a huge oversimplification. Every decision could have hundreds of possible options with constantly varying probability values.) This would make your decisions non-deterministic and therefore completely unpredictable. But is this really free will? Would these decisions be truly “yours”? After all, quantum mechanics is completely random, and is randomness synonymous with freedom?

These questions have no definite answers — at least not yet. We have no idea whether quantum mechanics plays a crucial role in our brains, and if so, nobody knows what to make of it. Right now, it is simply up to each of us to decide what we believe and whether this question even matters to us. However, one thing is certain — thanks to quantum mechanics, the free will debate remains open to this day.

TEST 1

1. Quantum mechanics describes the motion of objects:

A) Moving at very high speeds

B) Of very small sizes

C) In strong gravitational fields

D) Of macroscopic sizes

ANSWER:
Quantum mechanics deals with objects of very small proportions, such as atoms or subatomic particles.

---

2. Quantum mechanics dates back to the year:

A) 1850

B) 1950

C) 1800

D) 1900

ANSWER:
Quantum mechanics dates back to the year 1900, when Max Planck proposed the idea of quantization of energy.

---

3. For an electron to jump to an orbital with higher energy, it must:

A) Emit a photon

B) Emit an electron

C) Absorb a photon

D) Absorb an electron

ANSWER:
For an electron to jump to an orbital with higher energy, it must absorb a photon.

4. Which of these particles is responsible for the existence of spectral lines?

A) Photon

B) Proton

C) Neutron

D) Electron

ANSWER:
Spectral lines are caused by electrons, which absorb only photons of specific frequencies when jumping from one orbital to another.

---

5. Electrons which jumped to a higher energy level by absorbing a photon are called:

A) Excited electrons

B) Bohr electrons

C) Orbital electrons

D) Energy electrons

ANSWER:
Electrons which are on an energy level that is higher than their original level are called excited electrons.

---

6. Which of these physicists proposed the idea of quantization of energy?

A) Niels Bohr

B) Albert Einstein

C) Max Planck

D) Ernest Rutherford

ANSWER:
The idea of quantization of energy was first proposed by a German physicist Max Planck in 1900.

7. What is the energy of one quantum of light with the frequency of 10000 hertz?

($h \approx 6{,}626 \cdot 10^{-34}$ Js)

A) $6{,}626 \cdot 10^{-30}$ J

B) 6,626 J

C) 10 J

D) $6.626 \cdot 10^{-34}$ J

ANSWER:
According to Planck's equation $E = h \cdot f$, the energy of a quantum of light with the frequency of 10000 hertz is equal to $6{,}626 \cdot 10^{-30}$ J.

---

8. When two waves strengthen each other, we are talking about:

A) Destructive interference

B) Destructive diffraction

C) Constructive interference

D) Constructive diffraction

ANSWER:
When two waves strengthen each other, we are talking about constructive interference.

---

9. Diffraction is a phenomenon in which:

A) Two waves interfere

B) Three waves interfere

C) Interference pattern is created

D) Waves bend

ANSWER:
Diffraction is a phenomenon in which a wave bends. Diffraction occurs when a wave passes through a narrow slit.

10. The original version of the double-slit experiment proves the:

A) Particle nature of light

B) Duality of light

C) Wave nature of light

D) Wave nature of matter

ANSWER:
The original version of the double-slit experiment proves the wave nature of electromagnetic radiation.

---

11. Which of these physicists clarified the photoelectric effect?

A) Albert Einstein

B) Louis de Broglie

C) Max Planck

D) Ernest Rutherford

ANSWER:
The photoelectric effect was first explained by Albert Einstein in 1905.

---

12. In the photoelectric effect, light is perceived as a:

A) Wave

B) Particle

C) Set of particles

D) Set of waves

ANSWER:
In the photoelectric effect, light is perceived as a set of particles. These particles are called photons.

13. The photoelectric effect is a phenomenon in which:

A) Photons turn into electrons

B) Light turns into particles

C) Light turns into a wave

D) Electrons are released from atomic orbitals

ANSWER:
The photoelectric effect is a phenomenon in which electrons are released from atomic orbitals as photons strike them.

---

14. What is the momentum of a photon whose wave has a wave length of 1 meter?

($h \approx 6{,}626 \cdot 10^{-34}$ Js)

A) 1 Ns

B) $6{,}626 \cdot 10^{-34}$ Ns

C) 10 Ns

D) Cannot be determined

ANSWER:
The momentum of a photon is determined by the equation $p = h/\lambda$. In this case, the photon has a momentum of $6{,}626 \cdot 10^{-34}$ Ns.

---

15. Objects from the macroworld do not exhibit wave properties, since:

A) They do not have a wave nature

B) They do not have enough energy

C) The wavelength of their matter wave is too small

D) The wavelength of their matter wave is too big

ANSWER:
Massive objects from the macroworld do not exhibit wave properties, since the wavelength of their matter wave is too small.

TEST 2

1. Which of these physicists assigned a wave function to all quantum objects?

A) Erwin Schrödinger

B) Louis de Broglie

C) Albert Einstein

D) Max Planck

ANSWER:
A wave function to all quantum objects was assigned by an Austrian physicist Erwin Schrödinger in 1925.

---

2. When did the period of modern quantum mechanics begin?

A) 1900

B) 1925

C) 1950

D) 1975

ANSWER:
The period of the modern quantum mechanics began in 1925, when Erwin Schrödinger assigned a wave function to all quantum objects.

---

3. The wave function is denoted:

A) Ψ

B) λ

C) h

D) $\hbar$

ANSWER:
The wave function is denoted by the capital or lower-case Greek letter psi – Ψ or ψ.

4. Quantum superposition is a consequence of:

A) The photoelectric effect

B) Quantization of energy

C) The wave function

D) Schrödinger's cat

ANSWER:
Quantum superposition is a consequence of the wave function.

---

5. Quantum superposition, among other things, allows quantum objects to:

A) Cease to exist spontaneously

B) Have a wave function

C) Become waves

D) Be in many places at once

ANSWER:
Quantum superposition allows quantum objects to be in many quantum states at once. As a consequence, they can be in many places at the same time.

---

6. A reduction of a wave function to one quantum state is called the:

A) Wave function destruction

B) Wave function collapse

C) Wave function reduction

D) Wave function localization

ANSWER:
A reduction of a wave function to one quantum state is called the wave function collapse.

7. Quantum state is denoted:

A) $\hbar$

B) $|\psi\rangle$

C) Ψ

D) λ

ANSWER:
Quantum state (the set of all properties of a quantum object) is denoted $|\psi\rangle$.

---

8. The wave function of a given quantum object collapses:

A) When the object is observed

B) Spontaneously

C) When the eigenstate of the object is reduced

D) When the object is created

ANSWER:
The wave function of a given quantum object collapses when the object is observed.

---

9. Why is quantum mechanics a nondeterministic theory?

A) Because of many interpretations

B) Because of energy quantization

C) Because of quantum superposition

D) Quantum mechanics is deterministic

ANSWER:
Quantum mechanics is nondeterministic (i.e. based on probability) because of the principle of quantum superposition.

10. Quantum object which is not observed can:

A) Have an infinite amount of wave functions

B) Be in only one eigenstate

C) Cease to exist

D) Be in many eigenstates at once

ANSWER:
Quantum object that is not observed can be in many eigenstates at once due to the principle of quantum superposition.

---

11. The probability amplitude is a:

A) Type of wave function

B) Probabilistic value

C) Number which determines the height of a wave function

D) Complex number which determines the probability of a process

ANSWER:
The probability amplitude is a number which determines the probability of a process occurring. This probability is determined as the square of the absolute value of the probability amplitude.

---

12. The probability amplitude of a process has a value of 1. What is the probability of the process occurring?

A) 1 %

B) 100 %

C) 10 %

D) 50 %

ANSWER:
If the probability amplitude of a given process has a value of 1, the probability of the process occurring is 100 percent.

13. The probability amplitude of a process has a value of 1/2. What is the probability of the process occurring?

A) 100 %

B) 75 %

C) 50 %

D) 25 %

ANSWER:
If the probability amplitude of a given process has a value of 1/2, the probability of the process occurring is 25 percent.

---

14. Which of these phenomena led to the development of many interpretations of quantum mechanics?

A) Matter wave

B) Photoelectric effect

C) Quantum superposition

D) Quantization of energy

ANSWER:
The principle of quantum superposition led to the development of many interpretations of quantum mechanics.

---

15. Which of the interpretations of quantum mechanics is the most recognised?

A) The Copenhagen interpretation

B) Decoherence

C) Many-worlds interpretation

D) De Broglie-Bohm interpretation

ANSWER:
The most recognised interpretation of quantum mechanics is the Copenhagen interpretation.

TEST 3

1. Quantum tunnelling can be explained using:

A) Quantum superposition

B) Quantization of energy

C) The photoelectric effect

D) Special relativity

ANSWER:
Quantum tunnelling can be explained using quantum superposition or the Heisenberg uncertainty principle.

---

2. Quantum tunnelling is a phenomenon in which:

A) Nuclei of lighter elements collide to form a heavier one

B) Nuclei repel electrically

C) Objects pass through an impermeable barrier

D) A heavier atom divides into two lighter elements

ANSWER:
Quantum tunnelling is a phenomenon in which objects pass through a barrier which, according to classical physics, should be impermeable.

---

3. The uncertainty principle applies to:

A) Energy and momentum

B) Velocity and position

C) Momentum and position

D) Energy and position

ANSWER:
The uncertainty principle applies to the position and the momentum of a quantum object. It also applies to energy and time.

4. The ideal wave function to determine the momentum of a quantum object is:

A) As spread as possible

B) As localised as possible

C) In the form of a wave packet

D) Small

ANSWER:
The ideal wave function to determine the momentum of a quantum object is as spread as possible, since the wavelength of such a wave is accurately determined.

---

5. Quantum tunnelling does not occur:

A) In flash discs

B) In stars

C) In bodies of living organisms

D) In electrons

ANSWER:
Quantum tunnelling takes place in flash discs as well as in stars during nuclear fusion and in living organisms during random DNA mutations.

---

6. The uncertainty in the momentum of an object is $5 \cdot 10^{-31}$ Ns. What is the minimal uncertainty in its position? ($\hbar \approx 10^{-34}$ Js)

A) $6{,}626 \cdot 10^{-34}$ meters

B) $5 \cdot 10^{-31}$ meters

C) 10^{-4} meters

D) 10^{-34} meters

ANSWER:
Based on the equation $\Delta x \cdot \Delta p \geq \hbar/2$, the uncertainty in the position of the object is roughly 10^{-4} meters.

7. What is the cause of uncertainty in the position and the momentum of a quantum object?

A) The wave function

B) Quantization of energy

C) Schrödinger's cat

D) Observer effect

ANSWER:
The cause of uncertainty about the position and the momentum of a quantum object is the wave function of the object.

---

8. What is spin?

A) Rotation

B) Intrinsic rotation

C) A magnet

D) Wave function symmetry

ANSWER:
Spin presents intrinsic rotation (intrinsic angular momentum). It occurs in elementary particles, composite particles and atomic nuclei.

---

9. Which of these interactions is caused by intrinsic angular momentum?

A) Weak interaction

B) Strong interaction

C) Magnetism

D) Gravity

ANSWER:
Intrinsic angular momentum (spin) is responsible for the existence of magnetism.

10. Which particles are described by antisymmetric wave functions?

A) Fermions

B) Bosons

C) All particles with spin

D) All particles without spin

ANSWER:
Fermions are described by antisymmetric wave functions. Bosons are described by symmetric wave functions.

---

11. Which of these particles may not share quantum states?

A) Fermions

B) Bosons

C) Particles with integer spin

D) All particles

ANSWER:
Fermions cannot be in the same quantum state, since the Pauli exclusion principle prevents them from doing so.

---

12. Atoms are composed of:

A) Gluons

B) Photons

C) Bosons

D) Fermions

ANSWER:
Atoms are composed of fermions, which can form stable structures as a result of their antisymmetric wave functions.

13. Which of these phenomena is most responsible for the existence of atoms?

A) The uncertainty principle

B) The Pauli exclusion principle

C) Quantum tunnelling

D) Spin

ANSWER:
Atoms exist due to the Pauli exclusion principle, which forbids fermions from sharing quantum states.

---

14. The consequences of which of these phenomena do we greatly feel in the macroworld?

A) Quantum superposition

B) Quantum tunnelling

C) The uncertainty principle

D) Quantization of energy

ANSWER:
In the macroworld we greatly feel the consequences of quantum tunnelling, especially in the form of energy from the Sun.

---

15. Photons in a laser beam:

A) Have zero spin

B) Are described by an antisymmetric wave function

C) Have half-integer spin

D) Are in the same quantum state

ANSWER:
Photons in a laser beam are in the same quantum state – they are in phase and have the same frequency.

TEST 4

1. When an observation of a particle affects the state of a different particle, we are talking about:

A) Quantum tunnelling

B) Quantum entanglement

C) Annihilation

D) Casimir effect

ANSWER:
A phenomenon where an observation of a particle changes the state of a different particle is called quantum entanglement.

---

2. Which of these phenomena is responsible for the existence of vacuum fluctuations?

A) Quantum entanglement

B) The uncertainty principle

C) Pauli exclusion principle

D) Annihilation

ANSWER:
The uncertainty principle is responsible for the existence of vacuum fluctuations.

---

3. Hawking radiation is formed:

A) Inside black holes

B) In vacuum

C) Inside singularities

D) Near the event horizon

ANSWER:
The photons of Hawking radiation are formed in the vicinity of the event horizon.

4. Virtual particles cease to exist:

A) Spontaneously

B) When their wave function collapses

C) Near the event horizon

D) By annihilation

ANSWER:
Virtual particles cease to exist when they collide with their virtual counterpart. This process is called annihilation.

---

5. The basic unit of information in quantum computers is called:

A) Spin

B) A bit

C) A qubit

D) A qubyte

ANSWER:
The basic unit of information in quantum computers is a qubit (quantum bit).

---

6. Which of these quantum mechanical phenomena causes most disputes among physicists?

A) Quantum superposition

B) Quantum tunnelling

C) The uncertainty principle

D) Vacuum fluctuations

ANSWER:
The most controversial phenomenon of quantum mechanics is the principle of quantum superposition, which is still surrounded by many questions.

7. Quantum computers use:

A) Quantum superposition and quantum entanglement

B) Quantum entanglement and the uncertainty principle

C) Quantum tunnelling and quantum entanglement

D) Quantum superposition and the uncertainty principle

ANSWER:
To improve their computing power, quantum computers use the principle of quantum superposition and quantum entanglement.

---

8. The antiparticle of the electron is called:

A) Fermion

B) Gluon

C) Quark

D) Positron

ANSWER:
The antiparticle of the electron is called the positron. Unlike electrons, positrons are positively charged.

---

9. The Casimir effect is a consequence of:

A) Hawking radiation

B) Quantum entanglement

C) Vacuum fluctuations

D) Quantum tunnelling

ANSWER:
The Casimir effect is a consequence of vacuum fluctuations, which arise due to the uncertainty principle.

10. Which of these physicists was among the authors of the EPR paradox?

A) Albert Einstein

B) Hendrik Casimir

C) Stephen Hawking

D) Erwin Schrödinger

ANSWER:
Albert Einstein belonged among the authors of the EPR paradox. He was one of the greatest opponents of quantum mechanics.

---

11. Compared to classical computers, quantum computers are:

A) More reliable

B) Faster

C) More accurate

D) Bigger

ANSWER:
Compared to classical computers, quantum computers are much faster due to the principle of quantum superposition.

---

12. Which of these phenomena greatly limits the utility of quantum computers?

A) Quantum superposition

B) Wave function collapse

C) Quantum entanglement

D) Quantum tunnelling

ANSWER:
The usefulness of quantum computers is greatly limited by the fact that the wave function of their qubits collapses anytime somebody interacts with them.

13. The uncertainty principle applies to:

A) Position and energy

B) Momentum and energy

C) Momentum and time

D) Time and energy

ANSWER:

The Heisenberg uncertainty principle applies to time and energy. It also applies to the position and the momentum of an object.

---

14. A phenomenon where two uncharged plates approach due to vacuum fluctuations is called:

A) The Casimir effect

B) The Hawking effect

C) The Einstein effect

D) Hawking radiation

ANSWER:

A phenomenon where two uncharged plates approach due to vacuum fluctuations is called the Casimir effect.

---

15. Which of these phenomena is seemingly in conflict with Einstein's theory of relativity?

A) Vacuum fluctuations

B) The Casimir effect

C) Entanglement

D) Hawking radiation

ANSWER:

Albert Einstein believed quantum entanglement to be in contradiction with his theory of relativity, which states that no information can travel through space-time faster than light.