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Quantum field theory

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What do we understand by the word quantum? The word "quantum" in physics refers to the discrete, granular nature of certain physical quantities and the associated principles and phenomena that arise at the quantum level, right so quantum the word itself is a very huge topic on its own, a small wonder Nobel laureate Richard Feynman supposedly said: “If you think you understand quantum mechanics, you don't understand quantum mechanics.” Not that physicists have stopped trying to know more about quantum theory, but what we are talking about here is a theory that is relatively small compared to the ‘quantum’ theory but merely a small fractional part of it.

In basic words, the Quantum field theory is one that explains how the simple and fundamental forces and partiality of nature work, and in other words Quantum Field Theory mostly referred to as the ‘QFT’ is a theoretical framework that combines quantum mechanics with special relativity to describe the behaviour of quantum fields and particles. It is a powerful and mathematically sophisticated framework that provides a unified description of fundamental particles and their interactions.

Quantum Mechanics

Wave-particle duality

If we want to understand wave particle theory starting from the beginning is crucial for understanding this concept.

Historical context and background

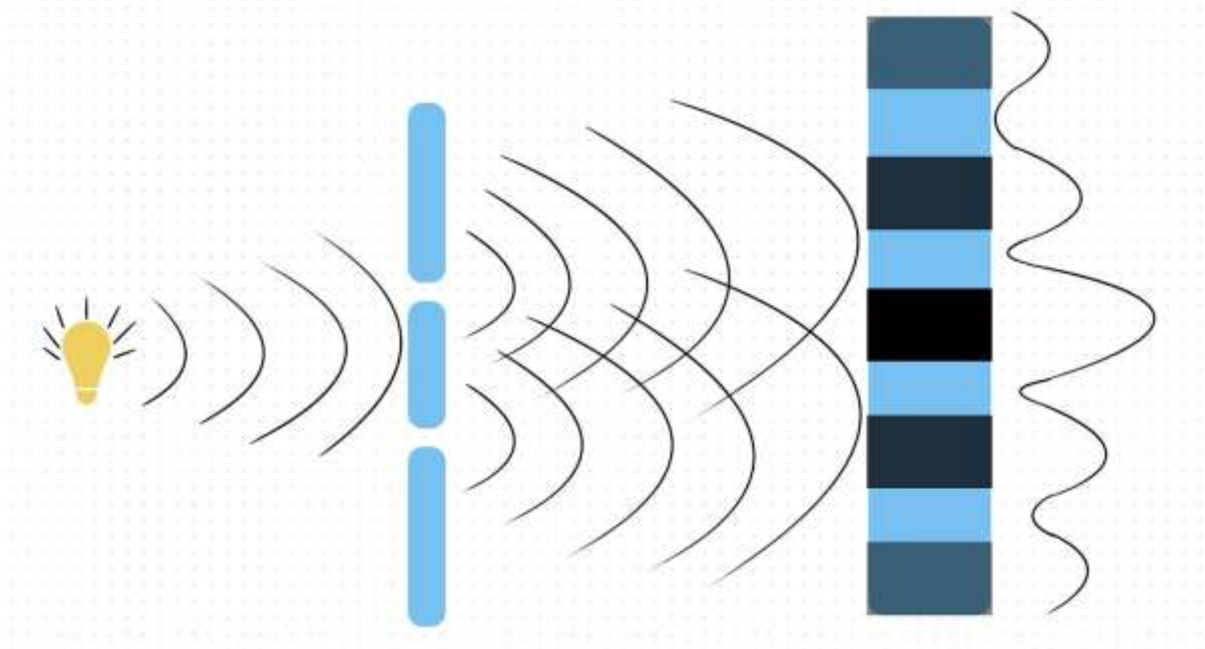
For just a basic example we can see waves in the water when a rock is thrown in a pond, as an example of particles the wave-particle states that they sometimes exhibit the same behaviour now we won't just mash both of the things and say that we have proven this they right? It all started when the wave theory of light was introduced in the 17th century it says that light in standard quantum mechanics, particles are often described or shown by wave functions (these are mathematical functions that assign a complex number to every point in space and time), now this happens because particles are not localised at specific points but are instead described by a probability amplitude that is spread out over a range of positions. The wave function evolves in time according to the Schrödinger equation, which determines how the probability distribution changes over time. It's crucial to remember that this interpretation of the wave function uses mathematics to describe how quantum mechanical particles behave. Although it provides a strong and effective framework for projecting the results of investigations on the atomic and subatomic scales, it does not imply that particles are "waves" in the traditional sense. Wave-particle duality is a concept in quantum physics where particles have both wave-like and particle-like characteristics, to add on this information was given after the theory of light was proposed by Sir Issac Newton, this simple theory was the start of the central idea of quantum mechanics and one of the most beautiful theories, the wave-particle theory and this simple theory or idea was proposed by Louis de Broglie, he said that light has properties of both a particle and a wave, after proposing this idea he was not happy.

There was one more theory that had concluded into the Modern-day wave-particle theory, the first person to suggest the dual nature of light was Albert Einstein in 1905 but he picked up the earlier idea of Max Planck, Planck explained the different colours of light emitted by objects at different temperatures like the filament in the bulb but to make it work he needed to explain, thus he said that the object was made up oscillators that could only emit light in discrete chunks, units of energy that depend on the frequency of the light, Einstein picked up this idea and used it, he applied Planck's idea to light itself and said that light, that everyone knew was a wave, made up of photons, particles of light each with a specific amount of energy. Einstein himself said that this could be the most revolutionary idea he ever had. It also says that small particles such as electrons and photons behave like both waves and particles.

Introduction and a general idea of the theory

At its core, QFT is based on the principles of quantum mechanics, which describe the behaviour of particles at the subatomic level. In quantum mechanics, particles are described by wave functions, and observables are represented by operators. Quantum Mechanics (QM) is a fundamental theory in physics that describes the behaviour of matter and energy at the atomic and subatomic scales, so it provides a mathematical way to understand particles and is the basis of much modern physics theory, there are many theories in QM but One of the central concepts in QM is the wave-particle duality of matter.

Particles, such as electrons and photons, can exhibit both wave-like and particle-like properties, depending on the experimental setup. The wave-like behaviour is described by wave functions, while the particle-like behaviour is represented by localised states, so in my opinion wave particle duality in simple terms, means that particles such as electrons and photons can behave like waves depending on how we observe them, like when in the double slit experiment when you shoot light through 2 openings on certain places the light bends and spreads out for instance let's take a real life example everyone reading this text knows or has a specific and general amount of knowledge about light even while reading this text light is being emitted somewhere near you or even from the device you are reading from now light can behave as particles but on the other hand it can also behave like a wave to prove this we have to go back to reading about the double slit experiment so when you shoot light form 2 openings it it spears and thus behaves like a wave but this is not whole thing the interesting thing is the in this experiment it forms a certain kind of pattern like dimmest ,dimmer, bright,again dimmer,dimmes.

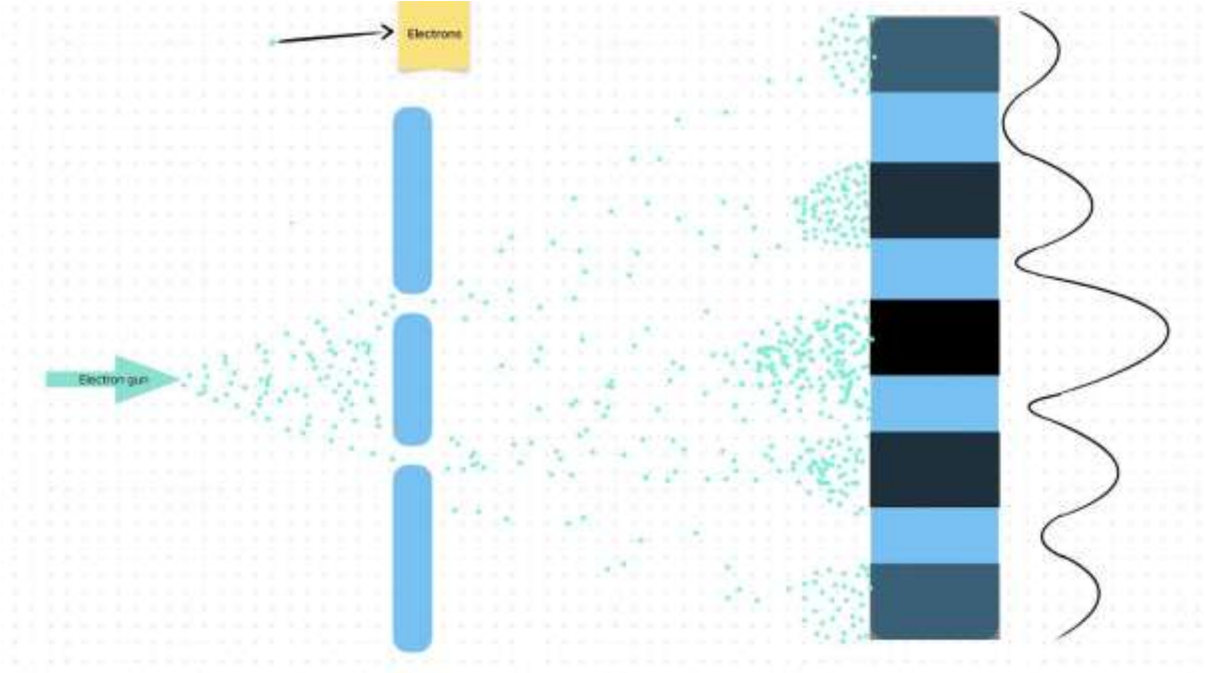


We can see interference in action if we shine light through two slits onto a screen. Explore Young's Double Slit experiment, a cornerstone in understanding light as a wave. Discover how light waves spread out, overlap, and create patterns of constructive and destructive interference. Uncover the rules of wave interference in two dimensions, and how path length differences lead to these intriguing patterns.

What you see happening here is constructive interference. Constructive interference happens when two waves overlap in such a way that they combine to create a larger wave. Destructive interference happens when two waves overlap in such a way that they cancel each other out. Wave interference also depends on the relative phase of the two waves, as this video shows through examples of path length differences and pi shifts. Created by David SantoPietro.

Diffraction, in this particular case diffraction, is the speeding of the waves when passing through a narrow gap or in this case a slit, due to the slit or gap being narrow the wavefronts curve around the edges of the gap producing a circular wavefront, represented by the curved lines that can be seen if the silts would not have been narrow or would have had a greater distance between the two edges the wavefronts would have curved from the edges only and rather than spreading like when the slit id narrow the wavefronts would have curved a little at their two endings and wouldn’t have made much of a difference.

If we redo this experiment with particles such as electrons the electrons when shot through the gaps create the same pattern shown in this experiment and stack up on each other like shown in, the dim sides symbolise the smaller amount of electrons on each other whereas the bright side symbolises the highest amount of electrons thus this proves that particles not on electrons, photons or even neutrons and protons but also atoms and molecules have wave-like properties and sometimes in many precise conditions, the particles behave like waves, this not only increases our understanding about the particles, but also in some way or other affects our concepts about all the particles in existence, the cosmos, and more, when this experiment was done with electrons and they show the same patterns like waves and create the same wave like the in this picture above, you can see this by comparing the pictures below and above.



(These images might not be as precise or accurate) In these images the things that symbolise each other are the number of electrons and the brightness of light in the image above, moreover, here the electrons (particles) behave like waves because of wave-particle duality,this fundamental principle in quantum mechanics, to add on The particles' behaviour can be described by a probability wave function, which gives the likelihood of finding the particle at different positions. When these probability waves pass through the two slits and interfere, they create an interference pattern on the screen behind the slits, similar to what you'd expect with waves. This phenomenon highlights the unique behaviour of particles at the quantum level.

Young's double slit experiment's equation is a way to derive the precise factors and characteristics that might be able to understand wave-particle duality more. Deriving a formula that relates all the variables in Young's double slit experiment as we explore Young's Double Slit Equation. Uncover how light's path length difference relates to the angle of incidence, and how this leads to constructive and destructive interference. Applying this knowledge to the world of wave patterns, trigonometry, and the wonders of diffraction, the derivation of this formula is Young's double-slit experiment involving light waves passing through two closely spaced slits, creating an interference pattern on a screen. The equation describing this pattern can be derived using basic principles of wave optics.

Assumption of Coherent Sources:

- Let S1 and S2 be the two slits.
- Assume a monochromatic light source illuminating both slits.

Wave Nature:

- Each slit acts as a new source of secondary waves.
- Consider S1 as the reference point. The electric field E1 from S1 and E2 from S2 combine to produce the resultant electric field E at a point on the screen.

Path Difference:

- The path difference Δx between S1 and S2 to a point p on the screen is crucial it can be calculated as $\Delta x = d\sin\theta$, where d is the slit separation and θ is the angle of observation.

Interference Condition:

- For constructive interference, the path difference Δx must be equal to an integer multiple of the wavelength λ :
- Δx=mλ (where m is an integer).

Resultant Electric Field:

- The total electric field E at point P is the sum of E1 and E2, considering their phase relationship due to the path difference.

Intensity Calculation:

- Intensity (I) is proportional to the square of the amplitude of the resultant electric field:
- I∝|E|2.

Intensity Pattern Equation:

Combining the interference condition and intensity calculation, you get the equation for the intensity pattern on the screen:

- I(θ)=I(o is the subscript)o cos^2(πdsinθ/λ)

where:

- I(o is the subscript)o is the maximum intensity, d is the slit separation, λ is the wavelength of light, and θ is the angle of observation.

This equation represents the bright and dark fringes observed in Young's double-slit experiment due to constructive and destructive interference.

The interconnection between superposition and wave-particle duality

Wave-particle duality and superposition are interconnected concepts in quantum mechanics, describing the dual nature of particles and their ability to exist in multiple states simultaneously, the correlation of these theories is that these concepts tell us about the dual nature of particles such as, the theory of wave particles duality tells us about how electrons can exhibit wave like behaviour in some conditions such as in the double slit shown above, in a image above that how the behaviour exhibited by the the electrons from the electron gun make a congruent pattern like the waves in the other image make a similar pattern such as the image above with the light bulb builds the pattern shown in the image leaving some blind spots on the screen where the waves do not reach and light is not exhibited there similarly the electrons from the electron gun are not on every single spot of the screen and like the waves of the light bulb leave some blind spots in a similar way and the pattern of the the different images matches and thus showing us that how waves and particles show or exhibit similar or congruent or even different behaviour in different conditions and also depending on different factors and criterias the particles or the waves are in, on the same side superposition refers to the ability of quantum systems to exist in multiple states simultaneously.

This means that a particle, such as an electron or photon, can exist in multiple positions or states at the same time until it is measured. A famous example is Schrödinger's cat, where the cat is considered to be both alive and dead until someone observes it, thus showing how a particle like the cat can exist in two or more states, for example, Schrödinger's cat exists in two states dead and alive, similarly like the famous example of the wave-particle duality, young's double slit experiment which is shown above, in the double slit experiment the particles exhibit wave-like behaviour the forming congruent patterns, now this experiment also helps us prove superposition as when not observed, the particles exhibit an interference pattern as if they are passing through both slits simultaneously, suggesting a superposition of states. However, when observed, the particles behave as if they went through one slit or the other, and the interference pattern disappears.

This experiment highlights the concept of superposition by showing that particles can exist in multiple states at once, displaying wave-like behaviour, until a measurement is made, causing the system to "collapse" into one of the possible states, furthermore imagine an electron being shot towards a single slit between a piece of cardboard the electron is only passing through the single slit present there yet when we talk about this same concept in terms of a double slit the electrons overtime form a pattern a pattern that we saw above, just like the one formed by waves passing through a double slit, and if we keep repeating this process while keeping track of all the individual detections, we understand the this pattern is a result of an electron going through both slits at the same time the electron in its specific position is not choose to go left or right but left and right simultaneously.

Superposition is a fundamental principle in quantum mechanics and is closely related to the wave-particle duality of quantum entities. It challenges classical intuitions, as particles don't have well-defined properties until measured, and their behaviour is described by probability distributions. Superposition plays a crucial role in quantum computing, where quantum bits (qubits) can represent multiple states simultaneously, allowing for parallel computation, in simpler words a particle in superposition is in all possible positions at the same time.

The interconnection between quantum entanglement and Wave-particle duality

Like we have seen through out of the whole paper that wave particle duality is the theory which tell us about the dual nature of particles how they can act like waves or waves can act like particles in some conditions, and like how superposition was interrelated with wave particle duality,so basically quantum entanglement is majorly related to superposition, as, for example you bought two pair of shoes one for you and one for your friend and thus the design of the shoe is same but the colour is different one of them is blue and one of them is red both of them where in separate boxes and both the boxes where kept in your car's trunk after you go back to your car's trunk to take the shoes you have no idea which one is blue and which is red so at that exact moment when you pick one of them that shoe is blue and red at the same time (superposition), but the moment you open one of them you know the colour of oth the shoes as their possibilities are entangled if one is red it is certain that the other will be blue , quantum entanglement is almost exactly this, in other words it is similar to this, it is just that the shoes that you bought are particles wide spread in space and the colour of the shoe symbolises , any other criteria they might be related in, thus if there are only two of those criteria's possible and if the particle shared entanglement.

Single Slit Interference

In simple words what all we have talked about is wave-particle theory that statue or tells us that some particles behave like waves in certain conditions and this changes our understanding about a lot of this in the universe such as mainly the realm of the whole quantum mechanics but also the great classical physics as this theory clearly states that particles such as photons and electrons can show both wave-like and particle-like behaviour depending on how they are analysed this theory has implications and changes in the subjects of physics including each and every theory about particles, chemistry and even technology, as it directly challenges classical notations of how the particles behave and interact at a quantum scale, continue to explore the phenomenon of single slit interference. See how there's actually constructive (rather than just destructive) interference at some points on the screen. single slit interference, a complex phenomenon in light physics. Learn about the mathematical reasoning behind destructive points and why it doesn't apply to constructive points, and relate this to diffraction gratings, phase differences, and the challenge of finding exact locations of constructive points.

So furthermore when observed in a certain way particles like electrons behave like particles like they have discrete properties like position and movement thus they also have different velocities and so different forces of attraction in addition photons and electrons are particles so they display particle like behaviour but why do they display wave like behaviour in some certain conditions ,like when observed as waves they show or exhibit wave like behaviour like interference or diffraction these are typical wave behaviour like waves of sound and light , now the question in all your minds should be how can the particles exhibit typical wave patterns, now the explanation to this question is not very simple, so imagine a particle when in a superposition of states(meaning they can exist in multiple states simultaneously),their wave function can interfere constructively or even destructively , thus leading to patterns being created like waves of water and light , now again taking help from the double slit experiment we can easily understand the interference phenomenon demonstrated , when the particle like taking an example of a electron they pass through the slits and create an interference pattern on a screen behind the slits. The pattern suggests that the particles exhibit wave-like behaviour for example waves interfering with themselves and creating patterns of high and low probability of detection and the same patterns were made by the particles (electrons in the images above).
Now this is an example of waves exhibiting particle-like properties but what about particles showing wave-like properties?

To add on particles also show wave-like behaviour and one of the major examples of this is Photons are particles of light. While they are often described as particles, they also exhibit wave-like properties. Photons can interfere with each other, diffract when passing through small openings, and exhibit properties of both particles and waves in various experiments like in experiments involving quantum entanglement, Photons exhibit non-local correlations in quantum entanglement studies that are difficult to explain without taking into account their wave-like characteristics. When the properties of two entangled photons are measured, it is discovered that they are instantly correlated even when separated by vast distances. This phenomenon shows that photons behave like waves and exist in a superposition of states. There are many more examples of particles showing wave-like behaviour, looking over a one that you can relate in day to day life is an example involving neutrons, neutrons are subatomic particles that are found in the nucleus of an atom it has a neutral charge as the name suggests and are present there to stabilise the nucleus, relating this to x-ray diffraction if we apply the same thing to neutrons, we can see that neutron diffraction is possible by crystalline materials and, thus proving that neutrons exhibit wave-like behaviour in certain and specific conditions.

How wave-particle duality affects other theories and concepts.

In addition, imagine the effects on our understanding of merely everything this theory affects an almost infinite amount of concepts, if some particles like photons and electrons exhibit wave-like behaviour then our understanding of finding the minuscule wavelengths associated with the electrons, now that because of the wave-particle theory in electron microscopy, the minuscule wavelength associated with the electrons can be utilised to observe objects that are far smaller then what visible using visible light, this is one of the effects of wave-particle duality and even the application or in other words uses of the theory moreover there are many other applications of the wave-particle theory like by understanding wave-particle theory has led to the. Development of technologies like the electron microscope and the development of quantum mechanics, which has numerous practical applications in Morten electronics and materials science.

Now looking more deeply into this concept we also see that while often associated with mostly electrons wave-particle duality applies to all particles, including atoms and even molecules even large molecules like Buckyballs have been shown to display this behaviour, these observations have led to making wave-particle duality theory even more vastly extended, and here the word 'extended' means something so vast that this concept can also be applied to theories beyond our understanding and knowledge and this concept has already helped in many theories such as Matter-Wave Interferometry: Wave-particle duality has practical applications, such as matter-wave interferometry. It is used in precision measurements, including determining fundamental constants and testing the equivalence principle in general relativity, Quantum Electrodynamics (QED): QED is a quantum field theory that describes the interaction of electrons and photons. It relies on wave-particle duality to explain how these particles interact via the exchange of virtual photons, contributing to a highly accurate and successful theory, and also nanotechnology is also a crucial area where wave-particle theory has played its role as This knowledge is applied in the design of nanoscale devices, such as transistors, sensors, and quantum dots.

A short summary of the text

Wave-particle duality is like an engine for a car as without it the acceleration would not happen, and it is a very crucial component of quantum mechanics and helps us understand more about the quantum field theory, thus wave-particle duality in simple words is the analysis tellings us how sometimes in specific and certain conditions some particles like photons and electrons act like waves and sometimes wave exhibit particle-like behaviour, one of the biggest examples of this is young's double slit experiment, thus This text explores the concept of wave-particle duality in quantum mechanics. It highlights how particles, like electrons and photons, exhibit both wave-like and particle-like behaviours depending on observation methods. The double-slit experiment is discussed, illustrating interference patterns and the unique behaviour of particles at the quantum level. The text delves into the implications of wave-particle duality on various scientific theories and concepts, emphasising its impact on physics, chemistry, and technology. It concludes by noting practical applications, such as in electron microscopy, quantum mechanics, and nanotechnology.

My thoughts and perspective on the theory

In my opinion, the wave-particle duality theory is one of the most beautiful theories out there as just thinking about how It must have been discovered is phenomenal as someone with great critical thinking ability and microanalysis skills must have observed and analysed the behaviours of wave and particles and how they would have thought of similarity between the two is simply fascinating and one of the most interesting parts of this theory is subatomic particles, like electrons and photons, can exhibit both waves like and particle-like properties depending on how they are observed or measured. This phenomenon challenges our classical understanding of physics and this also affects most of the concepts out there about subatomic particles and forces as this theory tells us or changes our views on the behaviour of the particles and also the behaviour of the waves and how they interconnect or relate to each other, thus this theory is the podium that quantum mechanics is standing on and is so much more than just a mere understanding of the behaviour of different types of particles and waves, it’s a way of describing the similarities of waves and particles and help us understand or better a lot of concepts some of which are ahead of our time and are not discovered or understood by the current scientific society, thus, in conclusion I think that the wave particle duality theory affects each and almost theory about particles be subatomic particles or large molecules, so this theory can help us understand more about them. It's fascinating how this fundamental principle challenges traditional notions and has far-reaching implications in scientific fields, from particle physics to technology development.