Decoherence is time

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Quantum entities exhibit wave–particle duality as well as complementarity. According to the decoupling theory, the criterion for wave state vs. particle state is the interaction that causes decoherence. When matter is in a state of coherence, it is in a state of superposition with the property of a wave, and when it interacts to cause decoherence, it has the property of a particle. This paper presents an examination of the reason for this phenomenon. It is proposed that decoherence creates time, and this is explained by the space–time discontinuity. In the microscopic world, according to quantum gravity, the variable time cannot be used, and it is argued that time does not exist. In contrast, the variable "time" is used for physical quantities in the macro world. In other words, time is perceived in the macro world and is a definite physical quantity. In this context, the criterion for demarcation of the micro world (in which time does not exist) and the macro world (wherein time exists) is a pertinent question; in this paper, decoherence is proposed as that criterion. In other words, in the state of coherence without interaction, time has no meaning. Complementarity is explained using this concept and the discontinuity of time suggested by the theory of quantum gravity.

Keyword: quantum mechanics, double slit, decoherence

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Every quantum entity has the complementarity of a wave and a particle. According to the theory of decoherence that presents the criterion for the particle state versus the wave state, the state is dependent on the interaction that causes decoherence. When a quantum entity is in a state of coherence, it indicates that the entity is in a state of superposition with the property of a wave, and when it interacts to cause decoherence, the entity has a property of a particle. This paper presents an investigation of the reason for the nature of the decoherence and complementarity. In this paper, it is proposed that decoherence creates time, which is explained in terms of a discontinuity in space–time. According to the theory of quantum gravity, in the microscopic world, it is argued that the time variable cannot be used and time does not exist. In contrast, the time variable is used as one of the physical quantities of the macroscopic world. In other words, time exists in the macroscopic world and is defined as a physical quantity. Then, the criterion for demarcating the microscopic world, with no existence of time, and the macroscopic world, with the existence of time, is a relevant question. In this paper, it is proposed that decoherence serves as the criterion—that is, in the state of coherence without interactions, there is no passage of time and time has no significance, and when decoherence is created by interactions, time is created in the macroscopic world. Based on this concept and the discontinuity of time argued in the theory of quantum gravity, the concept of complementarity is also explained herein.

Keywords: quantum mechanics, double slit, decoherence

Introduction

1. Necessity of Study

Our universe can be classified into microscopic and macroscopic universes.
However, this division only reflects a difference in the viewpoint; the universe is a single entity and must follow a single law of physics whether it is microscopic or macroscopic.
In other words, the laws of physics in the microscopic world cannot be different from those in the macroscopic world.
However, according to various experiments and studies on the microscopic world, that is, the quantum world, phenomena that considerably deviate from the laws of physics in the macroscopic world have been observed, resulting in considerable controversy.
According to the Copenhagen interpretation [1], quantum entities simultaneously have particle and wave properties. For this duality, Zeh proposed a basic framework. According to the decoherence theory [2], which is currently accepted as the orthodox quantum mechanics, in the double-slit experiment, waves create interference patterns in superposed states in the coherence state, and when decoherence [3] occurs, interference patterns cannot be formed but only two lines indicating a particle state are observed. In this case, coherence refers to a state in which a particle does not interact with any other matter in the universe, and thus, the state of superposition that can create interference is maintained [4]. The theory of decoherence is based on the concept in which a simple instance of measurement describes a superposition of states suddenly “collapsing” into one eigenstate, resulting in particle properties in the double-slit experiment of electrons. The theory states that when the quantum entity is not measured by other matter in the universe, that is, it has no interactions, it remains in the state of superpositions of waves. When there are interactions which can lead to decoherence, the superposition of states collapse into one state, resulting in the property of a particle. The important aspect here is that decoherence does not occur in an isolated quantum world; decoherence occurs only when there are interactions between a quantum entity and other quantum worlds.[5][6][7]. The most significant advantage of the decoherence theory is that experimental proof of the theory is possible. If only the state of coherence can be created by maximally limiting the interactions, any atom, molecule, or cell can create the interference patterns of waves in a double-slit experiment. This has been proven to some extent by Zeilinger’s double-slit experiment [8] using fullerene, which consists of 60 carbon atoms connected by single and double bonds forming a shape resembling a soccer ball. This experiment demonstrated that the microscopic state of superposition is collapsed by the interaction alone to have the property of a particle in the macroscopic world. The experiment enabled the determination, although not precisely, the number of interactions that can lead to the collapse of the state of superposition by controlling the concentration of the vacuum state.
Another feature of quantum entities is that they possess particle and wave properties at the same time; as for the characteristics of a wave, it has the probabilistic existence in multiple spaces simultaneously. A typical example is covalent bonds.
It is impossible to know in which space the wave is at a specific instance of time, and the existence can only be expressed as a probability. [9]
With quantum entanglement, it is possible to transmit information at a rate faster than light. [10,11,12,13]

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When the orbit of an electron changes, the electrons move discontinuously in quantum jumps, as in the form of teleportation, and at this time, the movement has simultaneity.[14),15)]
Through various experiments and studies, many different phenomena observed from a microscopic viewpoint have been confirmed to be true; however, these phenomena cannot all be explained by the laws of physics in the macroscopic world.
To date, the origin of these phenomena has not been elucidated.

2. Research methods and limitations

In this study, the causes of the occurrence of various characteristics of quantum entities that are different from the macroscopic world are attempted to be explained through the discontinuity [16)] of time and space. Decoherence is described in the theory of quantum decoherence and the characteristics of time that are different between the microscopic world and the macroscopic world.
Interactions herein refer only to those interactions that can cause decoherence among various types of interactions considered in the quantum decoherence theory.
First, the common aspects of the various characteristics of space–time of quantum entities are examined; these aspects are compared with the concept of space–time in the macroscopic world to identify the differences, and the cause of these differences is explored.
Furthermore, in the theory of quantum decoherence, with decoherence as the reference point, the properties of waves and particles exhibit differences, and various characteristics of space–time are changed. These changes are elucidated herein in terms of the relationship between decoherence and time.
The purpose of this paper is not to explain all aspects of the complementarity of waves and particles. The scope of this paper is to investigate how decoherence can serve as the demarcating criterion for the observation that waves exist simultaneously in multiple spaces and passes through two holes at the same time in the double-slit experiment to create an interference pattern but particles do not have these properties. This is the most significant difference between the waves and particles, and thought experiments and experimental results from previous studies are employed herein.
Moreover, this paper does not aim to provide the complete mathematical formulation of these concepts.

3. Significant Implications of the Study

As aforementioned, this paper does not provide the complete mathematical formulation of the characteristics of quantum entities.
Several interpretations of the quantum world have been formulated, and the Copenhagen interpretation is recognized as the most orthodox one. Furthermore, there are several theoretical explanations for the Copenhagen interpretation, such as the theory of quantum decoherence. However, no clear reason has thus far been presented for the various different characteristics of quantum entities. Among the various explanations for the Copenhagen interpretation and the theory of quantum decoherence, the argument presented in this paper has yet to be established in mathematical terms; however, the ideas herein may have significant implications to serve as a hypothesis.

Main Content of the Study

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According to the laws of physics perceived in the macroscopic world, a single particle cannot exist in multiple locations at the same time and it is impossible to move a particle in the manner of teleportation over space, based on Newtonian mechanics. In addition, one of the generally accepted ideas is that if time can be determined exactly, the exact position of an object can be defined. Further, Einstein's theory of relativity revealed that particles cannot move faster than light.
However, upon close examination of this macroscopic world and observation of the quantum world, phenomena that are very different from the laws of physics of the macroscopic world were discovered, leading to heated debates and controversies.
The following are the representative properties of quantum entities:

1. Quantum entities have properties of both particles and waves at the same time; because of the properties of waves, a quantum entity has the probabilistic existence of simultaneous presence in multiple locations. A typical example is a covalent bond.
2. It is impossible to know the exact location of the quantum entity at a specific time, and its existence can only be represented in terms of probabilities.
3. It is possible to transmit information faster than the speed of light through quantum entanglement.
4. Quantum entities have the properties of a particle and a wave at the same time. If decoherence does not occur in the double-slit experiment, an interference pattern of waves is created; when decoherence occurs, a pattern of a particle is formed.
5. When the orbit of an electron changes, the electron jumps discontinuously in space by quantum jump and moves in the form of teleportation; at this time, simultaneity is exhibited.

Examining these characteristics of the quantum entities, one common aspect emerges—the concept of space and time appears in all the descriptions of these characteristics, and it is remarkably different from the concept of space and time in the macroscopic world.
In other words, the concept of space and time in the macroscopic world should be compared with that of space and time in the microscopic world.
Decoherence has been identified as the criterion dividing the state of a wave and the state of a particle.
In the state of coherence, a quantum entity exhibits superposition and the properties of a wave, and when interactions occur which can cause decoherence, the quantum entity exhibits the properties of a particle in the macroscopic world.
These seemingly irrational properties depending on decoherence are, in fact, based on highly rational and sensible conditions. If one ponders on the idea, there is an exquisite matching that the condition of a wave having the properties of a particle is to have an interaction that can cause decoherence.
In the double-slit experiment of electrons, if a single electron is observed in two holes at the same time, this would be an odd phenomenon. If two electrons are simultaneously observed in the experiment, it would be a clear violation of the law of conservation of energy. Because mass represents energy, the energy from the mass has been doubled in this case.
The statement "the quantum entity has the properties of a particle at the moment of interaction that causes decoherence" can be rephrased as "matter that has the properties of a particle in the macroscopic world cannot have interactions that cause decoherence in two or more locations at the same time."
In other words, a quantum entity can exist in multiple spaces at the same time; however, the interaction that causes decoherence can only take place in a single location at the same time.
Then, the characteristics of space–time in the quantum world can be focused on.
Upon closely observing the aforedescribed phenomena that appear to be highly different, a number of similarities and some associations between them using the space–time concept can be identified.

The concept that when the orbit of an electron changes, the electron moves across space with a quantum jump can be considered in terms of the following two cases. First, let t be the time when the electron exists in the first orbit. When it moves to the second orbit in the form of teleportation, if the time that the electron reached the second orbit is $t + \Delta t$ (i.e., if the electron has disappeared from the first orbit at time t and appears on the second orbit at time $t + \Delta t$), this indicates that the electron has disappeared from the atom during time Δt. In the second case, the electron disappears at time t in the first orbit and appears at time t in the second orbit. Thus, the electron has moved in space with no time passing during the movement, and in this case, it can be expressed that the electron has simultaneity. Modern theories to date have indicated that the latter case is the correct interpretation.
The quantum jump and simultaneous existence in multiple spaces are two different phenomena;

however, they share similar features. If the electron moves from the first orbit to the second orbit at a specific time t in the form of teleportation, it indicates that the electron is simultaneously present in both the first and second orbits at time t. Thus, the phenomenon of a quantum entity moving in space with simultaneity as in the case of quantum jump and the simultaneous existence in multiple spaces may be regarded as similar features when viewed in terms of space and time.

Furthermore, the statement that a quantum entity exists in multiple spaces simultaneously indicates a different phenomenon from the statement that information can be transmitted simultaneously by quantum entanglement. However, when viewed from the perspectives of space–time, these two are highly similar phenomena. When a quantum entity is in the state of coherence and simultaneously exists at a and b, for example, if a single quantum entity is simultaneously present at points a and b in space at 12 o'clock, this indicates that the transmission of information from a to b is possible at 12 o'clock exactly. When the quantum entity is in a state of superposition and is simultaneously present at a and b, that is, in the state of coherence, through the decoherence of observation, as soon as the presence of a particle at a is confirmed, the information that there is no particle at b is generated. Conversely, as soon as the presence of a particle is confirmed at b, the information that there is no particle at a is generated. All this takes place simultaneously.

When the orbit of an electron changes, the statement that the electron moves in space with simultaneity signifies that the electron has moved in the space faster than the speed of light, which corresponds to a similar phenomenon as the statement that information is transmitted faster than light. Furthermore, if a quantum entity exists at a and b at the same time, it cannot be defined as being present at a certain location at a specific time. At 12 o'clock, it can be equivalently stated that the quantum entity exists at either a or at b. The statement that an entity can exist at multiple locations at the same time, in fact, indicates that no precise position can be defined at the same time. The existence can only be represented in terms of probabilities. This has nothing to do with the accuracy of measurement, and from the start, an exact position cannot be defined for a quantum entity in the state of superposition. The concept of teleportation of information, the phenomenon of simultaneous presence at multiple locations, the fact that a precise position of a quantum entity cannot be defined and can only be represented in probabilities, and the phenomenon of quantum jump all appear to be completely different phenomena; however, in some aspects, they are highly similar.

Then, the question arises as to what these characteristics have in common. It is the fact that these take place at the same time. It appears as if there is no passage of time and every aforedescribed phenomenon has taken place in a static state.

In his book titled "*And if time doesn't exist?*," Carlo Rovelli—a researcher on quantum gravity—states, "The idea that time t passes on its own and that everything else changes according to the time no longer fits with the reality. This is because the microscopic world cannot be represented by equations describing changes with respect to time t[17]". In field of quantum gravity, which concerns the microscopic world, the phrase "Time does not exist " is already popular.

Thus, the concept of time may be focused on.

First, to properly understand what time is, the thought experiments can be divided into cases with and without time. This is because, to know what matter is, it would be considerably helpful to understand the matter by dividing it into a case in which matter exists and the other case without the existence of matter.

It is easy to imagine a case in which there is time. We live with the sense of time always in mind. The question then arises as to what if there is no time. The state of "no time" could be considered in two cases. In one case, the time passes extremely fast that the speed of time passage is infinite, and in the other case, time passes extremely slow to infinity. However, as for the case when the speed of time passage is infinite, it would be difficult to consider that "there is no time." Thus, it would be more appropriate to consider the condition of time passing extremely slowly to infinity as the condition of "no time."

The closest condition to "there is no time" would be if time passes extremely slowly to infinity and stands still. Time would have no significance if it does not pass and stop, and in this case, it would not be unreasonable to assume that "there is no time." This expression may represent many errors. However, one has to come up with a definition for the linguistic expression of the invisible microscopic world.

In mathematical terms, this state can be expressed as "$\Delta t = 0$". Accordingly, when time becomes "0", the physical quantity of speed would be meaningless. Speed is equal to "distance/time"; however, when time becomes "0", that is, when the denominator becomes "0", the expression

17) Carlo Rovelli, if time doesn't exist, first edition, samnparkers, seoul, 2021, p. 151

becomes meaningless, and if this needs to be expressed in terms of speed, this state can be expressed as the state of infinite speed. This can be expressed as having simultaneity.
In this paper, the state in which there is no passage of time is expressed as the state of “no time”, and the state of time passage is expressed as the state of “presence of time.”
Rovelli has argued further in his book, “Let us consider the quantum gravity and the meaning of the argument that the 'time does not exist'. The statement that “time does not exist”, to put simply, indicates that the theoretical framework based on Newtonian mechanics does not apply to cases of the microscopic world. Newton's theory provided us with a good strategy, but it is only effective for the macroscopic phenomena taking place in the world we live in. ”[18]

Conversely, let us consider the space and time of the macroscopic world that we perceive in the framework of classical mechanics.
The physical quantity that appears most frequently in the laws of physics in the macroscopic world is speed. Speed is obtained by dividing distance by time. Then, the essential element for the concept of speed to be valid is the passage of time. The concept of speed can exist only when time exists. If $\Delta t = 0$, the concept of speed cannot be valid.
Furthermore, all particles in the state of decoherence do not exist simultaneously at different locations. This is equivalent to the statement that particles need time to move in space. A particle can have interactions only at one location in space at an instance of time and cannot have interactions in multiple locations simultaneously.
Thus, a common aspect in the macroscopic world, as aforedescribed, is the passage of time—that is, the macroscopic world is perceived as the world with the existence of time.
This is contrary to the concept of space–time in the quantum world. The concept of space–time in the quantum world appears as if there is no passage of time, and thus, the quantum world has simultaneity. In contrast, the macroscopic world is perceived as a state in which time exists, and particles in the state of decoherence do not have simultaneity. This leads to the question as to when the concept of time, which does not exist in the microscopic world, starts to have significance in the macroscopic world. It is argued herein that the moment of the occurrence of decoherence[19] may serve as the dividing criterion. In other words, in the state of coherence, time does not exist in the world, and the concept of time is introduced as soon as decoherence occurs.
With decoherence as the reference point, the characteristics of space–time of the quantum world and those of the macroscopic world are divided.[20] The representative characteristic of space–time is the existence or nonexistence of time.
To put the idea in the opposite perspective, the proof that decoherence is time is presented in the double-slit experiment. With decoherence as the dividing criterion, the simultaneity in which the quantum entity can pass through the two holes in the double-slit experiment at the same time disappears. The moment when the characteristic of simultaneity of the quantum entity, which is a completely different characteristic from that of the macroscopic world, disappears is only the moment of the occurrence of decoherence, according to the findings of the experiment. From another viewpoint, an electron, which is a particle, has the property of simultaneous existence in multiple spaces in the same way as the waves in the world without the existence of time.
There are various interactions of different forces; however, in this paper, the interaction only refers to the one that causes decoherence.
There is a scene in a TV drama where the idea of what the interaction really is dawned on the author. This may not make much physical sense but I present the idea for a better understanding of the readers.
Although this type of analogy may not be appropriate in an academic paper, I described the idea to explain the invisible microscopic world. There is an American science-fiction drama called the Lost Room. In this TV series, a series of objects grant special abilities to a person in possession. When a person has these abilities, the person, who can be considered as a particle, may have all the five characteristics of a quantum entity described above. Indeed, the scriptwriter of the drama would not have intended this idea on purpose; however, as the idea provided a hint for this paper, I present the concept herein. It is reiterated that the concept does not make much sense in terms of physics; however, there is a lesson and a valuable insight into the concept.

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18) Carlo Rovelli, if time doesn't exist, first edition, samnparkers, seoul, 2021, p. 151
19) S. Popescu, A. Short, A. Winter, “Entanglement and the foundations of statistical mechanics”, Nature Physics, 754-758 (2006)
20) H. Dieter Zeh, "On the Interpretation of Measurement in Quantum Theory", Foundations of Physics, vol. 1, pp. 69-76, (1970).

That special ability described in the drama is the ability to stop time. This is comparable to the state of superposition in the state of coherence and also to the simultaneity in which there is no passage of time, as in the microscopic world.
The protagonist in the drama can stop time—that is, the person can stop the time from passing. Imagine that this person moved from Busan to Seoul when time stopped at 12 o'clock.
As in the case of a quantum entity, the person can transmit information from Busan to Seoul at 12 o'clock and move in space with simultaneity. Furthermore, just like a quantum entity, the person exists simultaneously in Busan and Seoul at 12 o'clock. Furthermore, the person was present not only in Busan and Seoul, but in all spaces between Busan and Seoul. In addition, the position of this person at 12 o'clock cannot be defined. What can be said is that the person is present with 100% of probability somewhere between Busan and Seoul; however, the information on the precise location can only be represented in the probability distribution. An interesting point here is that the person cannot be engaged in interactions at two locations simultaneously, just like a quantum entity. The drama explains that the reason is that the time of all matter except the time of this person has stopped, and the person cannot have any interaction that can affect other matter. If this person wants to eat an apple at 12 o'clock in Seoul and Busan, he has to decide which of the two apples he wants to eat; then, he must free the stopped time and let the time pass, only then can he eat the apple. If the person eats an apple in Busan at 12 o'clock, that is, if this person interacts with an apple, then he cannot eat an apple in Seoul at 12 o'clock. This is because time passed and 12 o'clock has already become the past. From this story, the person who has stopped time can be compared to a quantum entity in the state of superposition of coherence, and the objects fixed in a state when time has stopped can be compared to a quantum determined by decoherence. This illustration can be considered as an example which explains the coexistence of the world of coherence without time and the world of decoherence with time.
This is why I have explained the concept using the above story. It is not possible for interactions to take place in the state with no passage of time, and the interactions are only possible in the state with the passage of time, that is, with the existence of time. In other words, the essential factor for interaction is time. In this way, other concepts also make sense.
In the world of coherence, everything takes place at the same time as if there is no time. In contrast, the macroscopic world is the world with the existence of time.
The reason that the interaction causing decoherence serves as the dividing criterion between two states is that decoherence creates time, the concept we refer to in the macroscopic world. This is because the moment when simultaneity in the state of superposition disappears and the quantum entity has the properties of a particle without simultaneity is the moment of occurrence of decoherence caused by interaction, as demonstrated by the double-slit experiment.
To sum up, we can infer that time does not exist when there is no passage of time, and the time is created in the moment of interaction that can cause decoherence. Thus, it can be inferred that "in the theory of quantum decoherence, the interaction that produces decoherence is time."
Based on the concept that the interaction that creates decoherence is time, let us consider the theory of relativity and faster-than-light transmission of information by quantum entanglement.
In the Einstein–Podolsky–Rosen paradox (EPR paradox)[21], Einstein argued that, according to the theory of relativity, matter cannot travel faster than light; therefore, it is impossible to transmit information faster than the speed of light. However, through multiple experiments by Anton Zeilinger, it has already been reported that transmission of information faster than light is possible by quantum entanglement [22][23]. Thus, the question arises as to whether this indicates that one of them is wrong. In fact, both the theory of relativity and that of quantum mechanics are correct. According to the theory of relativity, what it states is "There is no speed faster than the speed of light." The key word in this sentence is speed. For speed to exist and to enable the measurement of speed, time is an essential factor. The concept of speed is valid only when time exists—that is, the special theory of relativity requires the concept of time to be created by interaction. The theory of relativity is valid because, in situations in which time exists, nothing faster than the speed of light can exist. However, in a state with no existence of time or no passage of time, the concept of speed itself is not valid. In a state when there is no interaction

21) Einstein, A; B Podolsky; N Rosen, "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?" . Physical Review. 47 (10): 777–780 (1935).

22) X.-S. Ma, T. Herbst, T. Scheidl, D. Wang, S. Kropatschek, W. Naylor, B. Wittmann, A. Mech, J. Kofler, E. Anisimova, V. Makarov, T. Jennewein, R. Ursin & A. Zeilinger, Quantum teleportation over 143 kilometres using active feed-forward, Nature 489, 269–273 (2012).

23) M. Zukowski, A. Zeilinger, M. A. Horne & A.K. Ekert, Event-Ready-Detectors Bell Experiment via Entanglement Swapping, Phys. Rev. Lett. 71, 4287-90 (1993).

and the quantum entity has the properties of waves, it can be regarded as the state without the existence of time; in this state, the concept of speed, which was present when there were interactions, is no longer valid.

In the state of superposition of a wave in which there is no passage of time, everything takes place and is transmitted simultaneously, rather than the concept that the speed of transmission is faster than that of light.

The reason for the occurrence of contradiction between the theory of relativity and quantum entanglement in the EPR paradox is that there were basic assumptions on the existence of time and the passage of time. These assumptions have overlooked the fact that there is a world in which there are no interactions, with no passage of time and existence of time; thus, the concept of speed has no significance. In the theory of relativity, a time delay occurs due to speed and gravity. The concept of time delay is based on the assumption of the existence and passage of time. However, because there is no time in the microscopic world, the author believes that there is a limitation in explaining the microscopic world with the theory of relativity alone.

For the theory of relativity and quantum mechanics to be fully integrated, it is speculated that the existence or nonexistence of time may serve as a deciding factor.

For the notion that there is a state with no passage of time, that is, with no existence of time, and that the time is created at the moment of occurrence of decoherence to be valid, one more condition is required. This condition is that time is not continuous, but it is quantized and discontinuous. The concept of continuous time is not compatible with the concept that time can be stopped. Carlo Rovelli—a researcher on quantum gravity—states in his book, “Time measured by a clock is ‘quantified’. That is, it acquires only certain values and not others. It is as if time were granular rather than continuous”[24]. If time is quantified and, thus, discontinuous, there must be a state with no passage of time. The analogy of the concept can be considered as follows: although the images on TV are viewed as continuous movements, they are in fact, not continuous images but a result of the discontinuous movements of still images. Therefore, these all appear to be continuous images; however, in fact, they are a collection of still images that move discontinuously. If the space–time we live in is also quantified and discontinuous, this indicates that in the smallest unit of time, there is a world with no existence and passage of time.

To put the idea in the opposite perspective, time does not exist in the microscopic world, but the introduction of interactions creates time in the macroscopic world; it can be considered that this change appears as the discontinuity of time.

When the concept of discontinuity in space–time and the concept “Interactions that cause decoherence create time,” are combined, it has been argued that the quantum world is a world without the passage of time and existence of time[25], and when there is no time, a particle can have the state of superposition as in the case of waves. If the state of coherence continues, the state of the entity will continue to remain in the state with no passage of time; however, as soon as the interaction is introduced that can cause decoherence, the time, the concept we understand in the macroscopic world, is created, in which case, the state of superposition disappears and the entity has the properties of a particle.

Thought experiments on time

Our universe presents itself as a mixture of the world of coherence without interactions and the world of decoherence with interactions.

This indicates that the universe is an intermingled presence of a world with the passage and existence of time and the world without.

First of all, time is a highly abstract and difficult-to-grasp concept. It always appears in various equations of physics; however, it is rather difficult to define what time really is. First, time is a man-made concept and is a word defined by humans. However, the words that are frequently used when we mention time are the past, present, and future. Time can be divided into three categories such as the past, present, and future time.

The existence of the past, present, and future time depends on the existence of time. In this case, the concept of the past, present, and future can be considered in terms of the state of superposition in the state of coherence and decoherence due to interactions.

The most significant difference between coherence and decoherence is superposition and determination in the macroscopic world. In the state of coherence, various states are superimposed and can be expressed only in terms of probabilities; however, when decoherence occurs, the states are no longer in the state of superposition but a deterministic state of the

24) Carlo Rovelli, the order of time , first edition 41print, samnparkers, seoul, 2019, p. 90

25) Carlo Rovelli, if time doesn't exist, first edition, samnparkers, seoul, 2021, p. 151

macroscopic world. First, in the time we perceive, is the past time a state of coherence or decoherence? Of course, it is in a state of decoherence. The word superposition indicates a state in which multiple cases are present with a probabilistic distribution—that is, the state is not a determined state. For any particle to have the properties of particles in the macroscopic world, decoherence caused by interaction is required. However, the past has been already determined. No one can be said to have existed in Seoul or Busan at 12:00 noon yesterday in a state of superposition. Yesterday at 12 noon, there was only one interaction and only a single, determined past. Thus, this is a state of decoherence, and not a state of superposition. The same principle applies to all past cases. Let us consider a thought experiment in this case. According to experiments of fullerene diffraction, it is possible to let all matter exist in the state of superposition in the state of coherence. Although the practical implementation, in reality, is nearly impossible, in theory, a cat can also be made into a state of superposition of all constituent atoms without interactions between them. Consider twin brothers who are 20 years old.

Let us assume that the older brother of the twin was made into states of superposition in the state of coherence by removing all interactions on October 30, 2021, at 12:00. The older brother lived in decoherence prior to the point at 12 noon on October 30, 2021.

Let us also consider that the younger brother of the twin continues to live in the macroscopic world of decoherence, with interactions. Fifty years have passed in terms of the time of the younger brother. It indicates that the present time is 12 o'clock on October 30, 2071. The younger brother has a single determined past without superposition of 50 years. At this point, an interaction was introduced with the older brother who has been in the state of coherence, and the older brother is now in the state of decoherence. What would this older brother look like in his appearance? The older brother will look the same as he was 50 years ago. Interaction is necessary for us to think, hear, speak, grow old, and die. Since every constituent atom of the older brother did not have any interactions, the older brother would remain as he was 50 years ago. To this person, what meaning the word “past” would have? The concept of time is the time of the younger brother, and this is, in fact, a concept that has been defined as a rule in human society. For the older brother, there is no such thing as the past from 2021 to 2071 because during that time, the older brother's state was not a determined state of the macroscopic world, but a state of superposition. For this person, it cannot be defined, for example, what this person did in 2022. This is because the person has been in a state of superposition with probabilistic existence.

When we think about this experiment from the viewpoint of the older brother, the past determined by his decoherence is the time before 12:00 on October 30, 2021. From the perspective of the older brother, it would feel that he only blinked an eye at 12:00 on October 30, 2021, but now he is faced with his younger brother looking 50 years older and a completely changed world as if he has teleported. It will be similar to the shock we experience when we, in the macroscopic world, observe quantum motions in the microscopic world.

Then, how we should perceive the “future” of the older brother? At 12 o'clock on October 30, 2021, both the older brother and the younger brother will consider time as their present time. For both of them, the year 2050 was a time of the future. The younger brother with interactions experienced his future in 2050. However, that was not the case for the older brother. The year 2050 was a time of the future at 12 o'clock on October 30, 2021, for the older brother, but in the actual year 2050, the older brother was in a state of superposition, which is not a determined state. Unless the older brother has interactions, he cannot experience the future that was felt and experienced by the younger brother and us. Would it be possible for us to use the word “time” in a world without the past or future as we described above? The future of the older brother is created only when decoherence occurs from the interactions. When the older brother is still in a state of coherence without interactions at 12:00 on October 30, 2071, in terms of the younger brother’s time, the future is not present from the viewpoint of the older brother. Without interactions, then, the older brother is in a state of superposition in which nothing has been determined. No one knows what will happen in the future nor whether what you are doing now will be a success or a failure. However, the future becomes the present as the state of superposition is removed by interaction and becomes a determined state.

The events of the past in time, the usual concept we refer to in a macroscopic world, are all determined. Furthermore, to experience the future, decoherence by interaction is necessary. In fact, our future will not be a state of decoherence when we see it from the viewpoint of the present. This is because the future world is a world without interaction as yet. However, it can be observed that the future becomes the present as the superposition collapses into determined states in the interaction.

In other words, when there are interactions, the present is created; furthermore, the event that

has been the present immediately before becomes a past event. With further interactions, the future becomes the present, and the present becomes the past. In addition, the future cannot exist without interactions.
In this sense, it is inferred in this paper that time, the concept as we understand, can be said to be an interaction that creates decoherence.

It has been stated that "Time does not exist in a state of coherence." However, in the double-slit experiment with electrons, it takes time for the electrons to be emitted and to pass through double slits. In this case, time does not indicate the passage of the electron's time; however, it indicates the time created due to the state of decoherence between the observer who performs the double-slit experiment and the double-slit.
Let us consider another thought experiment; this time, a cat is made into a state of coherence and tossed into the double slits. At this time let us assume that the experimental setup has been made on a gigantic scale such that it takes 10 years (in terms of the observer's time) for the cat to arrive at the double slits. Assume that the present age of the cat is 10 years old, and it has a remaining lifespan of 3 years. On December 30, 2021, a cat in coherence was thrown into the double-slit setup, and the cat had no interactions to maintain the state of coherence. On December 30, 2031, the cat arrived at the end of a slit to form the interference patterns. In this case, 10 years indicate the 10 years that have passed from the perspective of the observer who performed the experiment and has been in the state of coherence for the 10 years. At this point, would the cat be alive or dead? The cat would be alive and have the same appearance as observed in the last point of decoherence 10 years ago. The determination of decoherence by interaction is required for the cat to grow old, die, or become rotten. At this time, we can calculate the speed of the cat. The end-to-end distance of the double-slit setup is divided by 10 years, and we obtain the speed of the cat. In this case, we can use the world, time variable. How can this be possible when we already mentioned that there is no time in the cat's perspective? Here, time "t" refers to the observer's time in decoherence. Therefore, inside the cat, all states have spontaneity and are in superposition; however, from the perspective of the observer, the cat has a speed, which is constrained by the special theory of relativity. Thus, the cat cannot be thrown to the double slit faster than the speed of light. In this case, time is not the time from the perspective of the cat.
When the cat in the state of coherence arrives at the double slit, it has the same appearance as it did 10 years ago; there was no passage of time because the cat was in a coherent state. At this time, there is no time variable from the cat's viewpoint. In other words, when the viewpoint of the observer conducting the experiment with a cat is considered, the variable "time" has significance when explaining the state of the cat; however, when considering only the cat in the state of coherence, excluding the observer in decoherence and the double slit, the time has no meaning.
What can be confirmed at this point once again is that there is a mixed presence of a world in coherence in which time does not exist and in the state of superposition, and a world of decoherence with the existence of time. The strange phenomena of quantum entities occur because the observer in decoherence with the existence of time observes an area of coherence without the existence of time, leading to the observation of difficult-to-understand phenomena such as quantum entanglement and the duality of waves and particles.

Discussion on the uncertainty of the position and "E = hν"

We now focus on de Broglie's concept of matter waves and uncertainty of position.
In matter waves, the uncertainty of matter will be as much as the space of the presence of the matter wave in the state without passage of time regardless of the accuracy of the measurement.
When viewed in one dimension, the lowest value of the uncertainty in the matter wave is the wavelength of the matter regardless of the accuracy of measurement.

$\triangle x = \lambda$

In matter waves, the momentum and wavelength are inversely proportional; however, because momentum is large in the macroscopic world, the wavelength becomes shorter and the smallest unit of uncertainty in the position decreases.

"$E = mc^2$" 과 "$E = h\nu = \frac{hc}{\lambda}$"

Let us consider the above equation from the perspective that "decoherence is time."

The energy of one quantized photon can be obtained as E=hν, and with the application of E=mc^2, we obtain the following relationship:

$$E = mc^2 = h\nu = h\frac{c}{\lambda}$$

$$mc = \frac{h}{\lambda}$$

$$m = \frac{h}{c\lambda}$$

From these equations, because h and c are constants, the frequency of electromagnetic waves and mass are proportional, and mass is inversely proportional to the wavelength.

The aforementioned relationship shows that the frequency of electromagnetic waves is proportional only to the mass.
Consider the above relationship from the opposite perspectives, and let us examine why the energy of electromagnetic waves and matter waves is proportional to the frequency and inversely proportional to the wavelength, while the actual wave energy is proportional to the square of the frequency and the square of the amplitude. Energy is proportional to the square of the frequency and the square of the amplitude in general waves because even if the velocity of propagation of the wave is constant in the same medium, if the frequency is doubled, the actual displacement will be doubled; in the same manner, if the amplitude is doubled, the displacement will also be doubled—that is, the actual velocity is doubled and energy is proportional to the square of the velocity. Thus, the energy is also proportional to the square of the frequency and amplitude. However, this relationship does not hold for electromagnetic waves or matter waves, which are also waves. The energy of these waves is proportional to the frequency only; we argue that this property is also closely related to the fact that time passes only in the state of decoherence described above and there is no passage of time when there is no interaction.
Consider that in the state with simultaneity and with no passage of time, a particle moves from a to b. In this case, from the framework of classical mechanics and not quantum mechanics, this particle is regarded to have moved at an infinite velocity, in which case, energy must be infinite. However, this is not the case in practice. There is no increase in energy for this particle due to the increased velocity.
In the situation in which time has not passed, no matter how a particle has moved or where it is present, it does not indicate that the velocity of the particle has increased, and therefore, it has no effect on the kinetic energy.
In other words, when a particle has the property of a wave, the space in the direction other than the direction of the motion of the particle cannot affect the velocity. Therefore, for quantum entities that travel horizontally in a state with the passage of time, no matter how many of them are present in the vertical direction, their presence is in a state without the passage of time; thus, the existence of these entities in the vertical direction cannot contribute to the increase in the velocity in the case of real waves. In the case of real waves, when the velocity of wave propagation is the same, when the frequency or amplitude increases, there is a proportional increase in the velocity, leading to the value proportional to the square of the frequency or the amplitude. However, in the case of the wave property of a quantum entity, the frequency or amplitude cannot contribute to the increase in velocity.

Then, the increase in frequency in the relationship of "E = hν" of electromagnetic waves has nothing to do with the actual velocity of wave propagation. This is because the velocity in the direction of propagation is c, which is an invariant constant. The distance moved perpendicular to the direction of propagation and the frequency and amplitude that affect the velocity in the perpendicular direction are related to the distance that has been moved in the state without time passage, indicating no effect on the increase in the velocity.
Kinetic energy is proportional to the mass and to the square of the velocity. This does not mean that an increase in frequency or amplitude does not increase energy due to an increase in velocity.
Then, it is inferred that the reason for the proportional increase in energy with the increase in frequency is that in quantum mechanics, unlike real waves, the frequency is associated with mass rather than velocity. Kinetic energy is proportional to the square of the velocity and mass. In actual electromagnetic waves and matter waves, the frequency and mass are directly proportional.
In actual waves, even if the frequency and amplitude change, the velocity in the traveling direction does not change; however, the velocity in the amplitude direction changes according to

the frequency and amplitude to change energy. In the case of electromagnetic waves, the frequency and amplitude do not change the velocity in the direction of wave propagation, and in the direction of amplitude, the energy does not increase with the increase in velocity.
Thus, there is no increase in energy due to velocity changes, and the energy related to the velocity is a constant. It should be considered that this is reflected in Planck's constant h.
If we think about the relationship between the frequency and the rest mass once again, it can be viewed that “mass increases with the increase in the frequency.” However, in the relationship of $\nu = c/\lambda$, the remaining mass increases in proportion with the reduction in the wavelength, and the interpretation and understanding based on this relationship may better reflect the actual underlying principle.

Conclusion

Decoherence is time.
decoherence $\propto$ t

1. A quantum entity has the properties of both particles and waves at the same time, and because of the property of waves, it has the probabilistic existence of simultaneous presence in multiple locations. A typical example is a covalent bond.
2. Defining the exact position of the quantum entity at a specific time is impossible, and the existence can only be represented in terms of probabilities.
3. It is possible to transmit information faster than the speed of light by quantum entanglement.
4. When the orbit of an electron changes, the electron jumps discontinuously in space by quantum jump and moves in the form of teleportation, and simultaneity is exhibited at this time.
5. Quantum entities have the properties of a particle and wave at the same time. In the double-slit experiment, an interference pattern of waves is formed in the state of coherence, and when decoherence occurs, a pattern of a particle is formed.

In the state of coherence, a quantum entity has simultaneity as if there is no passage of time, which is represented as a state of superposition. In this paper, it is inferred that the properties of the quantum entity as described in 1, 2, 3, and 4 above are observed due to the simultaneity with no passage of time.
It is argued in this paper that it is decoherence caused by an interaction that breaks this simultaneity and causes the time-dependent properties of the macroscopic world to be exhibited.
In conclusion, “decoherence is time” is the main argument of this paper.

In this paper, the focus is on the two points, “Is the simultaneous presence in multiple locations possible?” and “Is the simultaneous passing through the two holes in the double-slit experiment possible?,” which are the most distinct differences between a particle and wave. With the concept that the interaction of the decoherence is the time in the macroscopic world alone, the duality of the particles and waves cannot be fully explained. However, the core argument of this paper is the possibility of inference that the interaction of decoherence is one of the reasons why the phenomenon of time has the duality of particles and waves.

From the opposite perspective, the properties of quantum entities discussed by the experiments described above may serve as strong evidence for the argument “decoherence is time”. When the author is asked to present evidence to prove that “decoherence is time,” I would present results of the double-slit experiment with electrons in the state of coherence and those in decoherence as evidence.
Furthermore, when the author is asked to present evidence that time does not exist in the state of coherence, simultaneous information transfer by quantum entanglement and quantum jump of electrons will be presented as evidence.

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