Global Approximation Interpretation of Quantum Mechanics (Standard Interpretation)*

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Abstract

Quantum mechanics (QM) is the most glorious and controversial theory of the microscopic world. The interpretation of QM has been fiercely debated ever since its early times. People are still puzzling in the understanding of many quantum behaviors. Physicists have made much progress in understanding the fundamental interactions and elementary particles a few decades after. However, these understandings are absent in QM. To fill the discrepancy, we start from the fundamental theories, i.e., Standard Model (SM), elaborate the global approximation feature of the Schrödinger equation and its physical implications, and interpret QM with no additional assumption. To our surprise, our approach (Global Approximation Interpretation, GAI) leads to intuitive understandings of all formerly puzzled QM concepts and phenomena. GAI can explain the physical meaning of Schrödinger equation and its solutions, the concept of quantum, wave-particle duality, the origin of the probability interpretation of wave function, the role of coherence, the definition of the measurement, the boundary between the classical and quantum world, the emergence of quantization, the properties and the physical pictures of elementary particles, quantum entanglement, quantum eraser experiment, etc. Measurement is the result of interactions, and reality is relative. Formerly contradictory philosophical theories, such as reductionism and holism, idealism and materialism, determinism and indeterminism, reconcile in GAI. The philosophical difficulties posed by Copenhagen Interpretation are all gone.

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1 Introduction

In 1900, to understand blackbody radiation, Planck suggested that energy can only appear in quantized amounts [1]. In 1913, to explain the Rydberg formula of atomic spectral lines, Bohr suggested that electrons can only be located on the "quantized" orbits of atoms and only absorb or release "quantized" energy [2]. In 1923, De Broglie proposed the concept of matter-wave [3]. In 1926, Schrödinger wrote down the Schrödinger equation from the concept of matter waves, [4] explained the spectral lines and covalent bonds of hydrogen atoms. Finally, in 1927, Bohr and Heisenberg formulated the Copenhagen interpretation (CI) of quantum mechanics [5–7] to explain the wave function. Since then, quantum mechanics in the microscopic world is established, and the interpretation of the Copenhagen School is still the orthodox doctrine today [8].

The main principles of CI are: wave-particle duality, all properties of a quantum are in its wave function. The quantum wave function is probabilistic, and measurement causes it to collapse. The wave-particle duality satisfies the principle of complementarity, and the connection to classical physics is the principle of correspondence [9]. Some related physical properties obey the Heisenberg uncertainty principle.

The rise of the CI of quantum mechanics shocked the scientific community and was very successful, but it also met with fierce criticism. For example, Einstein, Schrödinger [10], and others are firm opponents of some of these concepts, such as probability and quantum wave function collapse.

Although many other interpretations have appeared in the past hundred years, such as the pilot wave theory [11], the multiverse theory [12], etc., CI has always been prevailing.

With the progress of Bell experiments since the 1980s, the recognition of CI reached the highest level [13]. In the following decades, although the recognition has declined [14], it remains as the basic interpretation taught in textbooks. Theoretical physicists, such as Feynman [15], Smolin [16,17], t'Hooft [18–21], Weinberg [22] etc., have all expressed their concerns on quantum mechanics and CI.

Quantum mechanics does not answer questions such as "what are elementary particles?" and "what is the interaction?" These issues are the frontiers of subsequent researches. The progress of these studies has dramatically changed our understanding of the world. Although we cannot say that these theories are final, we should put these understandings back into quantum mechanics to solve the problems such as "no one understands quantum mechanics" [15].

We will re-examine the physical implications of the Schrödinger equation and its solution (quantum wave function) based on the pictures of elementary particles and interactions and try to establish a quantum mechanics interpretation based on these fundamental theories.

Many concepts and phenomena in quantum mechanics are quite confusing, and we list some below. Some of them have been heatedly debated [23–25], and some are first proposed in this paper:

1. **Wave-particle duality** Is "particle" a wave or a particle? What is meant by "sometimes behave like a wave and sometimes a particle"? Waves distribute in a space-time continuum, and particles generally have definite sizes and positions.

2. **Measurement problem** Before and after the CI measurement, the process is discontinuous. The transition occurs instantaneously and randomly, which can cause all physical quantities to be discontinuous [26, 27], such as energy and angular momentum, but these quantities should be conserved. In the classical system, the measurement does not affect the state of the system. However, in the quantum system, the measurement causes a sudden, irreversible change of the system [28].

3. **Uncertainty principle** In classical physics, the properties that particles can have at the same time, such as position and velocity, are in principle impossible to be obtained simultaneously

in quantum mechanics. Thus, the more accurate one quantity is, the more uncertain the other quantity must be [7].

4. **The puzzling properties of the elementary particles** For a classic object, we can measure its various physical properties. These properties are self-consistent, with clear physical meaning, understandable, such as size, momentum, mass, angular momentum, etc. However, in quantum mechanics, we have to define the basic properties of elementary particles artificially and regard them as intrinsic ones. They are hard to understand, and there is no physical picture. For example, what is the size of an electron? Its surface may rotate faster than the speed of light [29]. And what is a photon?

5. **Reality** If you don't measure a quantum object, you cannot know its properties, but measurement changes it. So then, before the measurement, does it have an objective state [30]? Einstein thought there was, Bohr thought not, or it is impossible to know. "If I don't look at the moon, will it not exist? [31]" is the exaggeration of this argument.

6. **Quantum entanglement (nonlocality)** Two entangled particles can affect each other instantaneously, even if they are far apart. This image violates the principle of locality [32], but supporters claim that countless experiments have irrefutably proved this phenomenon [33, 34].

7. **Determinism** Classical physics is deterministic in principle. That is, the physical state of the past determines the future. In quantum mechanics, the future can only be possibilities. Quantum mechanics can only tell what could happen in the future. It gives the probabilities of each happening. Of course, there are some other interpretations, such as multi-universe interpretation [12].

8. **Delayed-choice experiment** Quantum interference experiments are confusing enough. In delayed-choice experiment [35, 36], it seems that future choices can change the past paths of the particles. The experiments seem to support the idea of changing the past in the future.

9. **Photon problem** As a particular case where the properties of elementary particles are hard to understand, photons are especially incomprehensible and even theoretically inconsistent. For example, does a photon have specific energy? Each answer has its agreements and contradictions with experiments [37].

Global Approximation Interpretation (GAI): takes advantage of our later understanding of quantum field theory (SM); explains the approximation of Schrödinger equation; investigates the global nature of nonrelativistic QM; discusses measurement from the perspective of interaction; offers an extensive set of interpretation of QM. We can also name it Standard Interpretation (SI) because its theoretical foundation is SM.

Amazingly, GAI (SI) seems to provide a physical picture consistent with cognitive intuition for all the above annoying concepts.

2 Standard worldview

2.1 Elementary theories of the physical world

How does everything work? After thousands of years of hard work by countless thinkers and scientists, we should have almost figured out the fundamental laws of interactions between objects.

The current most recognized theory about elementary interactions is the Standard Model (SM) [38]. It describes the three fundamental interactions in the universe: electromagnetic, weak, and strong interaction, excluding gravity. We can integrate the three kinds of interactions, called Grand Unification Theory (GUT) [39]. If we put gravity in, then it is called Theory of Everything (ToE) [40].

We will not go to the details of these theories, but numerous experiments and reasoning have rigorously tested them. We do not have the final theory yet, and the current one does not necessarily be right in every detail. The theories may subject to change in the future. However, we can still draw some lines of these fundamental laws that govern the physical world. That is, what should our worldview look like under the SM (GUT)?

Contrary to our general concept of concise and graceful physical laws, real-world interactions are extraordinarily complicated and trivial. We can look at a simplified version of the Lagrangian of the SM of particle physics [38]:

$$
\begin{aligned}
L =& -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(W_{\mu\nu}W^{\mu\nu}) - \frac{1}{2}tr(G_{\mu\nu}G^{\mu\nu}) \qquad (U(1), SU(2)\text{ and }SU(3)\text{ term})\\
&+ (\bar{\nu}_L, \bar{e}_L)\bar{\sigma}^{\mu}_{i}D_{\mu}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar{e}_R\sigma^{\mu}{}_{i}D_{\mu}e_R + \bar{\nu}_R\sigma^{\mu}_{i}D_{\mu}\nu_R + (h.c.) \qquad (\text{ lepton dynamial term})\\
&- \frac{\sqrt{2}}{\nu}[(\bar{\nu}_L, \bar{e}_L)\phi M^{e}e_R + \bar{e}_R\bar{M}^{e}\bar{\phi}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}] \qquad (\text{ electron,muon,tauon mass term})\\
&- \frac{\sqrt{2}}{\nu}[(-\bar{e}_L, \bar{\nu}_L)\phi^{*}M^{\nu}\nu_R + \bar{\nu}_R\bar{M}^{\nu}\phi^{T}\begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}] \qquad (\text{ neutrino mass term})\\
&+ (\bar{u}_L, \bar{d}_L)\bar{\sigma}^{\mu}_{i}D_{\mu}\begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar{u}_R\sigma^{\mu}{}_{i}D_{\mu}u_R + \bar{d}_R\sigma^{\mu}{}_{i}D_{\mu}d_R + (h.c.) \qquad (\text{quark dynamial term})\\
&- \frac{\sqrt{2}}{\nu}[(\bar{u}_L, \bar{d}_L)\phi M^{d}d_R + \bar{d}_R\bar{M}^{d}\bar{\phi}\begin{pmatrix}u_L\\ d_L\end{pmatrix}] \qquad (\text{down, strange, bottom mass term})\\
&- \frac{\sqrt{2}}{\nu}[(-\bar{d}_L, \bar{u}_L)\phi^{*}M^{u}u_R + \bar{u}_R\bar{M}^{u}\phi^{T}\begin{pmatrix}-d_L\\ u_L\end{pmatrix}] \qquad (\text{up, charmed, top mass term})\\
&+ \overline{(D_{\mu}\phi)}D^{\mu}\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2 \qquad (\text{Higges dynamical and mass term})
\end{aligned}
\tag{1}
$$

The Lagrangian in quantum field theory represents the dynamics and kinematics properties of the system. It describes the number of degrees of freedom in the system, the energy distribution, and transition rules in and between each degree of freedom. Each particle is a dynamic field distributed in space-time.

The space-time of quantum field theory is a covariant that complies with special relativity, so all the fundamental interactions of the SM have to obey the principle of locality [41], that is, the propagation of any interaction cannot exceed the speed of light.

When calculating actual physical processes, Feynman's rules of path integral are applied [42]. Even for the simplest single-particle case, in principle, there an infinite number of orders of terms. Every next order is much more complicated than the previous one.

Lagrangian, or the terms in the field equations, contain various differential operators. For the differential operator to be valid, the physical quantities must be continuous. All quantities in different degrees of freedom in the field equation must be continuous.

The Feynman rule (Feynman diagram) of quantum field theory calculations [43] addresses the contribution of various possible particle interaction rules to a specific process. Generally, the calculations go well only when the perturbation assumption holds, that is, the higher-order contribution is negligible. In most cases, the perturbation assumption is invalid. Even if the perturbation assumption is valid, the high-order processes may be too complicated.

The formulation, implication, and calculation of the standard model of quantum field theory all show that our physical world is a very complex, intertwined, and nonlinear one [44]. Any elementary process is nonlinear, and even the vacuum itself is infinitely complex and nonlinear [45].

As for the GUT, and the TOE, although we still don't know their specific form, they must include all interactions, and all matter must participate in all fundamental interactions, and they are all coupled together. So their formulation and implications might even be more complicated than the above.

We can give a simple example to illustrate the complexity of interactions between matter, even we only consider the classical electromagnetic interaction. All matter participates in electromagnetic interactions. Even no charge is involved, there is always a spin and magnetic moment. An electron has an infinite range of action, so any charged object will inevitably influence infinity. If it is neutralized, such as hydrogen atoms, will the affected space be tiny? No, its range of influence is still infinite because it has a magnetic moment. According to its internal energy configuration, there are higher-order electrical multipole momentums, and the effective range of action of these momentums is also infinite. If you consider the changes over time, the changes caused by changes, and the actual complexity of the physical world, any precise calculation or measurement is impossible.

2.2 Summation

The physical picture of the world based on the standard model can be called the standard worldview.

Whether starting from elementary physical theory or our common sense, we find that the physical world is highly complex, multi-degree-of-freedom, nonlinear, and possesses infinite objects. As a result, any seemingly simple process is complicated.

Some observations:

- All basic interactions obey the principle of locality, and there is no superluminal interaction [46].
- The mathematical formulation [47] is not the actual physical world. The physical world is inherently complex, and mathematical formulation can only be an approximation from a certain direction to a certain extent.
- The equivalence between matter and energy has profound significance. In the current theoretical framework, matter or energy is the basis for the physical world's existence or observability.
- The Lagrangian, or the laws of physics, are the same for any space-time point. Every point in space-time is equally complex. As long as the conditions are the same, such as energy density or other degrees of freedom, the physical processes are the same.

3 The physical meaning of Schrödinger equation

How did the Schrödinger equation come about? According to Feynman, “It is not possible to derive it from anything you know. It came out of the mind of Schrödinger.” [48]

However, there is a widely circulated “derivation of Schrödinger equation”, which is written on some quantum mechanics textbooks [49]. In which matter-wave is assumed to be in form:

$$\psi(x,t) \sim e^{i(kx-\omega t)}. \tag{2}$$

We write down the one-dimensional stationary Schrödinger equation,

$$E(x,t) = \frac{-\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + V(x)\psi(x,t) \tag{3}$$

And the one-dimensional time-dependent Schrödinger equation:

$$i\hbar\frac{\partial\psi}{\partial t} = \frac{-\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + V(x)\psi(x,t) \tag{4}$$

Usually, we say that Schrödinger equation is a wave equation, but a wave equation should look like (one-dimension):

$$\frac{\partial^2 u}{\partial t^2} = c^2\frac{\partial^2 u}{\partial x^2} \tag{5}$$

u is the wave function, and c is the propagation speed of the wave.

If we ignore the term with V (in free space), the forms of Schrödinger equation (4) and wave equation (5) are different. Schrödinger equation has only first-order time differentiation of the wave function, and the wave equation has second-order time differentiation.

In form, Schrödinger equation is a diffusion equation:

$$\frac{\partial\phi(x,t)}{\partial t} = D\frac{\partial^2\phi(x,t)}{\partial x^2} \tag{6}$$

D is the diffusion coefficient.

From the perspective of equation form, the physical meaning of Schrödinger equation is not a wave equation, but a diffusion equation with an imaginary diffusion coefficient of $\frac{i\hbar}{2m}$.

The physical meaning of the diffusion equation is straightforward. Take thermal diffusion as an example. Once a heat source appears in a medium, the heat will diffuse to the entire medium.

The solution to the stationary Schrödinger equation is a fixed probability distribution without diffusion. The time-dependent Schrödinger equation is usually treated with adiabatic approximation [50], or, as a stationary Schrödinger equation.

What does an imaginary diffusion coefficient mean? The presence of imaginary coefficients in a quadratic differential equation usually means fluctuations.

Therefore, we should take the Schrödinger equation as a wave diffusion equation. What is the physical meaning of the solution to the equation? Since its distribution is no longer changing, we can take it as the final state of the matter-wave after sufficient diffusion. Furthermore, the non-relativistic nature of Schrödinger's equation means that the propagation speed of the action is infinite. That is, complete diffusion does not take time.

Waves are coherent [5], and coherent waves interfere. Therefore, only those with favorable coherence (interference) conditions (frequency) stay if waves sufficiently diffuse.

Therefore, the solution of the Schrödinger equation is the set of all coherence favorable waves in the system, namely, eigenstates or the favorable vibration modes. Moreover, they must reflect all the spatial properties of the system, such as boundary conditions, symmetry, the nature of the potential, etc.

The above arguments are speculations, not proofs.

However, even if we discard the above discussion entirely, the eigenstate argument is still valid. That is, the solution of Schrödinger's equation (quantum wave function) reflects the global nature of space and the potential. The wave nature comes from the assumption of de Broglie matter-wave. The above conjecture and comparison are just for a more intuitive understanding of the physical meaning of the Schrödinger equation.

Due to the equivalence of matrix mechanics and wave dynamics [51], we can infer that all quantum states are global states, non-relativistic, and have an infinitely fast propagation speed. However, these are only mathematical properties implied by the formulation, not actual physical ones.

We should also note that the above discussion refers to ideal conditions. All solutions are distributed in the entire space (except for infinitely deep potential wells, which do not exist).

To sum up, the solution to Schrödinger's equation is a set of waves. They are ideal, global, non-relativistic, preferable modes (eigenmodes). By definition, these are also the properties of a quantum.

For comparison, we can discuss the general solutions to time-dependent differential equations. We need initial conditions, boundary conditions, and the solution is a set of equations that change with time. In normal circumstances, we can not analytically solve the equation in a real-world system. Instead, we have to use numerical methods, such as the computation of fluids, plasmas, electromagnetic fields, etc. However, we hardly use numerical methods to solve Schrödinger's equation. Because, in physics, the problem to be solved is not an initial value problem. Moreover, the spatial and temporal discretization in the numerical calculation means the value on each grid point at the next moment depends only on a certain number of surrounding grids at the previous moment (not including implicit methods). The treatment is only valid for local interactions, but Schrödinger equation is global. Therefore, for eigenvalue problems, numerical methods are very unreliable. Instead, we usually use the matrix method to solve the eigenvalue problem of quantum mechanics [52], which is inherently global.

In principle, to calculate the behavior of any single particle or multiple particles of a quantum system, the Schrödinger equation requires the knowledge of the state of the entire universe because it is a part of the potential. If we consider the particle identicalness complications, it is impossible to calculate a non-relativistic, many-body, ever-changing real system.

Quantum is not a particle. Non-relativistic quantum mechanics do not answer the question of what particle is, only give the global properties of any matter-wave in different situations.

Due to the complexity of the actual system discussed in the previous section, we can also say that the solution to Schrödinger equation is the non-relativistic ideal limit of the system.

4 Quantization as Emergence

The basic definition of quantum is similar to the concept of atom in ancient Greece [53], which is the smallest unit of a particular type of matter or quantity. Quantization refers to the phenomenon that physical quantities that should be continuous in a classical case can only take specific discrete values. For example, the electrical charge is composed of basic unit charges.

In nature, quantization is a common phenomenon, such as individual people, information (bits), molecules, atoms, etc. However, in some fundamental physical quantities, such as energy, momentum, angular momentum, heat, etc., at least in classical situations, we believe they should be continuous. However, in the microscopic world, it may not be valid. This is why Plank [1] assumed the discontinuous change of energy (radiation) in 1900 to solve the problem of black body radiation ultraviolet divergence that plagued physics at that time and won the Nobel Prize in 1918.

With the success of Bohr's atomic model and a large number of experiments in the microscopic world, people believe that quantization is the norm and even the only principle. Charge, angular momentum, atomic energy level, etc., are all quantized.

However, as for Planck's original hypothesis, the definition of energy quantization is not apparent. In 1905, Einstein believed that light is composed of light quantum (Lichtquanta), explained the photoelectric effect [54]. However, Planck does not like the idea and thinks that photons are not what he calls the quanta of energy. Is there a quantum of energy that changes in energy, like in electric charge? Although we treat photons as quantized in later theories, we do not find that energy is quantized. Energy quantization only means energy level discontinuity; rather than energy change must be in a minimum unit.

Energy is not quantized. So how come the energy level quantization [25]?

The atomic electron energy level quantization in the Bohr model is a natural result of the Schrödinger equation in the Coulomb potential [25]. Or, as long as any quantum behaves like a wave in a bound state, its eigenstates are quantized. Thus, energy quantization of quantum states is the result of eigenstates quantization.

The same is true for angular momentum quantization.

Even the energy level and angular momentum are quantized in different atomic eigenstates. However, for the quantum (electron), the energy or angular momentum does not have to be quantized because it can be in any combination of superposed eigenstates.

The observation of quantization in energy level or angular momentum comes from the fact that the eigenstates are the favorable or resonant states of the waves.

However, we do have quantized quantities, such as the electric charge, whether it is an integer (lepton) or a fraction (quark). Moreover, why is the angular momentum of elementary particles quantized? We will answer these questions in the next section, "What are elementary particles?"

In the understanding of GAI and the mathematical formulation basis of SM, all fundamental physical quantities are continuous, and quantizations are emergences [55, 56], which is the discrete manifestation of wave vibration under the combined action of potential and space topology. Just like the frequencies of an instrument are some discrete values (musical notes).

Are the degrees of freedom quantized, or is there a fixed number of degrees of freedom? Is there a correlation between degrees of freedom? Non-relativistic quantum mechanics cannot answer such questions.

There are also phenomena similar to angular momentum quantization in the macroscopic world, such as orbital resonance between stars. The wave eigenstate (dominant vibration) that reflects energy quantization is ubiquitous, such as the resonance of musical instruments, buildings, vehicles, and rockets, etc.

5 What are elementary particles?

In Section 2, we discussed how the real physical world works. The basic conclusion is: the interaction of the physical world is complex, many-body, and nonlinear. It is the same for a single particle, even a vacuum.

In a classical picture, the particle we define is usually a point. To avoid infinity, we imagine the particle as a small ball (there is no reason to assume any other geometric shapes), like a marble ball, a grain of sand, or smaller particles. This image is illogical because it naturally raises the question: what is the material which makes the ball? Are the materials for different particles the same? What are the physical properties of the material? Unfortunately, there is no way to answer these questions.

If the particle is a sizeless point, the material problem is gone. But there is another infinity problem, whether with or without a charge. Because it also has spin and mass.

So the classical point particle picture is unacceptable.

What should elementary particles look like, or what should they be?

Let us return to the standard model Lagrangian in Section 2. The Lagrangian already includes all interactions except gravity, and of course, it must also have all elementary particles except gravitons. Lagrangian exists or acts on every point in space-time. In other words, at any point in space-time, there are all types of interactions. We can also say that all particles exist at any space-time point. What condition determines which particles appear in a small region? It depends on how much energy there is in that region and some other fundamental properties, such as which degrees of freedom the energy is in, what symmetry is present, etc.

Which specific particle appears depends on the energy and other physical properties of the perturbation mode of the space-time point. Some perturbation modes are unstable and will spread out or change to more stable ones, i.e., decay. Some perturbation modes are stable, such as electrons, neutrinos, etc. Some composite modes are stable, such as protons and neutrons, and the components (quarks) are inseparable [58]. If you put enough energy to tear them apart, you can only get more particles that can exist alone.

Every point in space-time in our world has complex interactions. Some interaction patterns are stable and appear as stable particles, and some are unstable and appear as particles that are easy to decay. The translation of these particles in space can be understood as the mode disappearing in one place and then appearing in a nearby location, just like the propagation of a stable wave crest on a rope. The source of these interactions or disturbances to space-time is energy—the higher the energy density, the more degrees of freedom that can be excited, and more stable or unstable interaction patterns may appear, that is, more particles.

Therefore, elementary particles are the stable, or relatively stable disturbance modes, of space-time with a specific energy density and total energy. Usually, there is a somewhat limited spatial range or the main disturbance range (locality).

Although the elementary particles behave as specific types of particles, they still contain all the interactions defined in the Lagrangian. Only some kind of interactions is more significant because different interaction has a different energy range. For example, for low-energy electrons and photons, we only need to calculate the contribution of electromagnetic force (quantum electrodynamics, QED) [43].

However, from the perspective of quantum field theory, each electron is still an extremely complex existence because it affects every space-time point close by and excites an infinite number of "virtual photons [59]". Only when these virtual photons are taken into account can quantum electrodynamics correctly calculate the properties of electrons. In other words, these "virtual" photons have "real" contributions and are the inseparable parts of the electrons [60, 61], or they are real.

From a classic point of view, just like the example we gave in Section 2, every electron is infinite because its range of influence is infinite. Therefore, all particles participating in electromagnetic interaction have the same property.

Let us look into the "intrinsic properties" of elementary particles. Every elementary particle should have a mass, which is the total energy of the perturbation. Generally, we only consider its rest mass. There are two other basic properties: spin and charge. Electric charge is in discrete values (absolute values) such as 1/3, 2/3, and 1, which are all properties of the particle, or space-time perturbation. For a specific particle, the static mass and charge are constant, which is easy to understand.

Spin is a bit different. Although we say that the total spin is also constant, different values will appear in the measurement. Take the electron as an example. When we measure its spin, sometimes it is 1/2, sometimes it is -1/2. If there is no measurement, it is unpredictable. Photon is even stranger. Photons can be polarized, and the spin is any value between -1 and 1. Photons are even more bizarre, and we will discuss them in a dedicated section later.

At least from a classical point of view, we generally think that a particle monopolizes a space equivalent to its size. Other particles can occupy the inextricably "influence" or field part.

The only elementary particle without rest mass is the photon. There is no consensus on the physical picture of the photon. Many people believe that photons, like other elementary particles, have a location and a size. As we are going to discuss photon separately, we only give our key points of view here: at least for low-energy photon (energy lower than X-rays, below the order of hundred electron volts), just like phonon [62], you can take them as quasi-particles, which is still a low-energy excitation within a specific range of space-time, or, a wave, i.e., an electromagnetic wave. As the frequency increases, the energy density increases. The higher energy scale degrees of freedom of space-time can be excited, such as positron-electron pairs. Complex excitation modes with higher degrees of freedom make the photon more like a localized elementary particle.

5.1 Summation

- Elementary particles are not point particles, and each particle has a wide range of influence that is inseparable. If we do not truncate artificially, the influence range of every particle is infinite.
- There are no elementary particles in the classic picture. All particles are complex, with all kinds of nonlinear interactions. The different manifestation is because of the different perturbation energy. Only in low-energy situations can we ignore the participation of high energy scale degrees of freedom.
- The particles in the elementary particle table may be excited by a single component (specific degrees of freedom), be eigenstates, and may not exist independently. Stable or relatively stable particles in nature may be elementary particles, such as electrons, or stable composite excitation modes, such as protons (composite particles).
- For particles with rest mass, the main space range of their mass is tiny, which can be estimated by the uncertainty principle. Its size is what we usually call particle size. The size and location of this particle are localized.
- Low-energy photons are electromagnetic waves that are excited in a wide range. High-energy photons are more particle-like.

We can find that when all the elementary particles are listed, there is none called quantum. Although Einstein once called photon light quantum, the concept of the photon is the most controversial. So, what is quantum?

6 What is a quantum

Quantum mechanics is all about how quantum works. Quantization is the inevitable result of Schrödinger's equation that must meet certain boundary conditions in some potential. Schrödinger's equation is an equation of ideal matter-wave, and its solution is the global limit in non-relativistic approximation.

We stated that elementary particles are specific excitation modes of energy in space-time from SM. Each particle or excitation mode is very complicated. All differential variables are continuous.

According to De Broglie's original assumption, all matter is wave, described by Schrödinger's equation. All objects are quanta, including combinations of particles and even macroscopic objects. All quanta show quantum effects, such as double-slit interference. We have no reason or a limit to determine how macroscopic material will cease to perform double-slit interference [63], but we cannot make small enough slits.

Since all particles are quanta, how do we distinguish between quantum and classical systems? There are no boundaries, and there is only one set of rules. There are only fundamental interactions that we have not yet completely figured out. All physical phenomena are continuous, complex, nonlinear, and interacting, such as discontinuous spectral lines, interference, entanglement, etc., but they appear to be "quantum".

To give another example, if a continuous metal plate is irradiated with X-rays of appropriate wavelengths, a large number of regular diffraction spots can appear [64,65]. These spots are discontinuous and discrete so that we can obtain the metal lattice structure. The discreteness is the result of continuous basic interactions of some periodicity.

As the experimental basis of quantum theory, the discreteness of the atomic spectrum, we should also notice the resonance between many atoms of the same kind. The light at the right frequency is easily absorbed or blocked, and resonance happens among the same type of atoms. If the atomic thermal motion is slow, the resonance will be exceptionally concentrated, and the peak will be very sharp. This sharpness is what the laser or atomic clock hopes to achieve.

6.1 Quantum is wave

All quantum properties, or the discreteness of some physical quantities, wave interference effects, etc., are wave properties. Either they are confined by the potential, boundary conditions, periodicity, and other situations, or be free [66,67]. In other words, quantum is a wave. Hence, de Broglie's matter-wave hypothesis is the most fundamental theoretical basis of quantum theory, not Planck's hypothesis of discontinuity of physical quantities.

So why does matter show the properties of waves? Waves are natural in a system of long-range interactions, such as an electromagnetic system or closely associated systems (such as a medium). Any change in a physical quantity in any part of the system will inevitably propagate in waves. For example, we know that if we do not truncate any elementary particle artificially, its influence is infinite. Its influence is its intrinsic property, which is not separable. Therefore, any change in a particle must also propagate in the form of a wave.

In this case, a quantum particle is no different from a classical particle with a field, such as an electric dipole or a multipole. And we do have some phenomena that only appear under quantum conditions, such as superconductivity. With continuous physical quantity, superconductivity is still understandable, and Cooper's conception [68] is not problematic. The same is true for laser, although we generally describe it as a macroscopic quantum effect. With the understanding of continuous physical quantities, the laser is only the resonance of atomic radiation. Pumping is the drive of the resonance between energy levels.

The properties of waves are valid in whole space or within a specific restricted region. That is, they are global. This globality is the origin of “quantum nonlocality”.

6.2 Quantum is wave function

We have physical pictures of complex fundamental interactions and elementary particles, and waves in space-time. The changes in primary physical quantities are continuous. Then what is quantum?

Let us look at a typical quantum description. The quantum wave function of a photon is a plane wave. The quantum wave function of any free particle is a plane wave, and its energy or momentum can be any positive number. In the infinitely deep square well, the wave function of any particle is also a plane wave, but the energy of the wave is “quantized”. Because of the well (boundary conditions) limitation, only certain fixed energy wave functions can survive, and there is minimum energy, zero-point energy [70], or the energy of the ground state. Other potential wells are more complicated, but the principle is the same. The global wave function is restricted, and the energy cannot be of any value. So quantization is only caused by the potential, not the particle.

The basic description of a quantum is its wave function, which contains all information about the quantum. A quantum can be any particle or its combination. Therefore, we can say that a quantum is its wave function. The wave function, whether in integral (summation) form or vector form, refers to the set of probability wave amplitudes of all possible states of the particle [5, 71]. The possible states can be the discrete eigenstates or a particular physical value (depending on representation) selected arbitrarily, such as coordinates, momentum, energy, etc.

Therefore, quantum becomes a collection of probabilities. However, once we treat the quantum as probability amplitudes, it automatically possesses some strange properties, such as superposition, entanglement, etc. These properties are also from wave ones, and we will discuss quantum entanglement in detail in the next section.

Quantum mechanics is all about the wave function. However, the wave function is not a physically measurable quantity because it is dimensionless. Only its modulus square is a statistical distribution. Any measurement is a destruction of the quantum wave function, and we can not have accurate information about the quantum. We must assume that there are a large number of the same quanta. The same measurement is performed on them so that the total statistical distribution will exhibit the properties of the quanta. If we do not know all the information of a particular quantum in advance, we will not be able to prepare a large number of the identical quantum due to quantum no-cloning theorem [72]. Of course, there are naturally many relatively certain identical or similar quantum states, such as the energy levels of the same kind of atoms.

6.3 The inherent limitations of quantum description

All quantum peculiarities, or properties that we cannot intuitively understand, are properties of waves. All wave functions are global, and it does not take time to measure or collapse. The quantum superposition property comes from the linear property of probability amplitudes, which originates from the linearity of Schrödinger’s equation. In near-ideal cases, such as small-size and large propagation velocity, or the wave itself is close to ideal, with good monochromaticity and long coherence range, non-relativistic Schrödinger equation is a good approximation. Or, as we usually say, it is a quantum system.

Therefore, quantum mechanics is usually applicable to microscopic and low-energy systems. We can treat the propagation speed of the interaction as infinite. However, we must be aware that this is only an approximation, not an accurate description of the interaction. Its violation of the principle of locality is internal and cannot be separated, so there must be “quantum nonlocality”.

On this basis, some quantum descriptions, such as the description of the second quantization of the identical particle system, the creation and annihilation operators, etc., are also subject to the same approximation.

We should be cautious about any nonlocal properties of a quantum system, such as quantum entanglement, because it may not be real.

7 Quantum Entanglement

7.1 Public description of quantum entanglement

Quantum entanglement is one of the most challenging concepts in physics. What is quantum entanglement? We must mention the public description of quantum entanglement.

Why public description? Because you cannot find such a description in the research paper or a textbook. In literature, people will talk about Bell basis, Bell inequality [73], Bell experiment [33, 74–78, 78–88], local realism, hidden variable theory, and non-locality. However, on all public occasions, including professional researcher speakers, they will tell you mysteriously that quantum entanglement is two particularly correlated particles, no matter how far apart. Once you touched (measured) one of them, the other must instantaneously change accordingly. Then he will tell you that he doesn't understand what is going on, but the experiments proved this fact irrefutable.

He can also give seemingly simple but incomprehensible algebraic expressions to illustrate this entanglement relationship and prove quantum entanglement cannot transmit information [89, 90].

Regarding quantum entanglement, two metaphors seem vivid:

Uncle metaphor A man's sister gave birth to a child far away. Although no one told him, he automatically became an uncle. This change is instantaneous and superluminal.

Glove metaphor We randomly put a pair of gloves into two boxes that cannot be detected from outside and sent them to two places far apart. Once you open one of the boxes, you will immediately know the left and right of the glove in the other box, or the state of the other glove is determined.

According to the basic definition of quantum mechanics and other physical laws, we have the following observations [91, 92]:

1. Quantum can be any particle or object so that quantum entanglement can occur between any two objects [93].
2. Quantum entanglement takes no time or happens simultaneously at both points far apart. According to the special theory of relativity, the simultaneousness of two events is relative. So the simultaneousness here violates the special theory of relativity.
3. Quantum entanglement violates the principle of locality [94]; that is, any influence or interaction cannot exceed the speed of light.
4. Quantum entanglement cannot be any known fundamental interaction because SM and General Relativity tell us that no known basic interaction is superluminal.
5. "When one particle of the entangled pair is touched, the other immediately changes accordingly." This description is a causal one. However, all experiments can only prove the existence of correlation, not causality [95].
6. If there is a causality between the changes of two events, it can indeed convey information. However, quantum entanglement cannot transmit information, so there must be no causality.
7. Since quantum entanglement cannot be separated, you will never know whether any object in front of you is entangled with any other object anywhere in the universe. It is also impossible to tell whether its entangled partner caused something that happened to the object or whether its change caused the instantaneous influence on any other objects anywhere in the universe. Such a physical world cannot be reduced or studied.

8. If the speed of light is infinity, the principle of locality problem is gone.

The above descriptions are in contradiction with the existing theories or logically inconsistent. So the publicly described concept of quantum entanglement is doubtful.

However, apart from this public statement, there is no other picture of quantum entanglement.

Countless Bell experiments have only found correlations between entangled particles but have never proved that this correlation is causal [95]. The principle of locality limits causality, not correlation. Therefore, the term "caused" in the public description of quantum entanglement has no experimental evidence.

According to the understanding of Schrödinger equation and quantum provided by the GAI, quantum entanglement is a plain phenomenon like any other global quantum state.

7.2 Quantum entanglement in GAI

The wave function of any quantum is global. If we use the coordinate representation, as long as we find a particle at any point, we immediately know that all other places are empty. If there are only two options, or we divide the space into two sections, then whether a particle is in either of them is "entangled". Once found in one section, the other section must be empty. These two events are instantaneously correlated.

However, this is the nature of measurement in the CI. If we call it entanglement, then any wave function is entangled, and a single particle is also self-entangled (between different measured values or eigenstates [96]).

In other words, entanglement is a measurement property [97] and nothing new. The description of wave function collapse in the CI is inherently timeless and occurs instantaneously in all spaces. That is, any quantum measurement (CI) is global or "nonlocal".

The quantum in quantum mechanics can be any object, as long as it complies with Schrödinger equation. It is not limited to a single particle. If there is an interaction in multiple particles, we should describe it by many-body theory. If there is no interaction, we should use identical particle theory. It is strange that in the discussion of quantum entanglement, people use neither of them but a Bell inequality description that can prove that the two events of the measurement are correlated.

All quanta are waves, and there is a correlation between any two points in any waves. Coherence is the fundamental property of the wave, which means that the values are always correlated, usually differ only by a phase shift.

Therefore, the Bell inequality experiment only proved the most elementary assumption of quantum mechanics: quantum is a matter-wave, and the measurement statistics between different points are correlated. Correlation must be there at any time in the entire space, and there is no information other than the wave itself.

It also suggests an experimental method distinguishing between wave interpretation (GAI) and the spooky quantum entanglement idea. All measurements share the same correlation of the wave in the wave interpretation, and quantum entanglement believes that only two entangled particles are correlated. Therefore, the wave interpretation is more plausible if we find unpaired particle correlation in the Bell experiment. Current Bell experiments deliberately exclude unpaired measurements with the timing method. We can reverse the data collection logic. If we find a correlation, then it is proof of wave interpretation (GAI).

The GAI makes no new assumptions, merely points out the complex nature of elementary particles and interactions, clarifies the physical meaning of Schrödinger's equation and the approximate nature of the theory. From the perspective of GAI, quantum entanglement is not a new phenomenon. Whether called nonlocality or remote instant correlation, it is no more than the fundamental property of matter waves.

So how to understand the numerous quantum entanglement experiments? Or, what is their true nature?

For the polarized-light-entanglement experiment [77,98], the laser irradiates the crystal in the middle to produce a pair of “entangled” photons. The polarization of the “entangled” photons are measured on both sides. Each photon seems to know the polarization of the photon on the opposite side and aligns with it. Entanglement interpretation puts the experiment in a time orderly sequence: the photon pair generation; photons moving to both ends like particles; triggering the recording equipment. In this picture, the measurements on both sides should be independent [98], and it is impossible to understand the correlation.

The understanding of the GAI is: photons are not point particles; they are waves (see Section 8); the polarizers are involved in the generation of photon pairs because they are in the coherence range of the laser. The arrangement of the polarizers affected the production of the photon pair (down conversion). We do not have *three* separate events as understood by entanglement interpretation, but *one* “entangled” global event. When down-converting photon pair develops, it chooses one of the polarizer directions because photons are detected behind the polarizer and must pass through one of the polarizers. The two ends are symmetrical. No matter which end is selected, the correlation is always there [83], as long as the coherence range of the laser covers both ends.

For atom entanglement experiments, such as the “loophole-free” experiment [80,99,100], the “entangling” operation makes two atoms resonate, and the resonant atoms are of course in phase or correlated at all times. Resonance is a fundamental property of the wave.

An “entangled state” is *one* state that collapses after measurement. Usually, we can only measure a quantum state once, but because the entangled state has the energy of two photons, it can trigger two measurement events. The two measurements must be correlated, and the second measurement should give the same distribution. Treating the two measurements of one quantum state as two independent events is the key to the former “spooky” misinterpretation.

In CI, the distance between the measurement equipment is meaningless because the photon’s speed is infinity (non-relativity approximation).

7.3 The problem with the metaphors

The concept of quantum entanglement is unnecessary. The causality in the public statement has no ground. There is no experimental proof, and it is not logically valid.

What are the problems with the metaphors of the uncle and the gloves?

Uncle metaphor In verbal expression, the relationship between someone and his sister is global, independent of time, and does not require information transmission. This relationship has no physical connection. In other words, from a physics point of view, they have nothing to do with each other. The kinship or “of someone” in the language is not a physical connection.

Give another example. I can think that my lucky star is North Star. Anything that happens on “my star” does not affect me. My observation of “my star” is limited by the laws of physics, which is the principle of locality. What is happening now, I can only know after many years. In other words, the nonlocal connection between me and “my star” is non-physical and cannot cause a physical influence.

There is no restriction on this kind of relation. I can turn anything in the universe into “mine”. For example, the galaxy I called M87, the person I like, ... If this relationship is a substantial entanglement connection, then any two objects in the universe are instantaneously entangled.

This universal entanglement picture is a requirement of non-relativistic quantum mechanics because Schrödinger equation requires the knowledge of the potential and boundary condition universally.

The problem with this metaphor is to treat a non-physical relationship of kinship as a physical one.

Glove metaphor The "undetectable assumption" in the glove metaphor is the same as the paradox of Schrödinger's cat, as in all quantum measurements. The collapse occurs globally, but this is an approximate description of the wave function.

Which glove is in the box? We cannot answer this question because we do not know. We did not detect, and the hypothetical premise forbids detection. If you accept the premise, you return to the Schrödinger cat paradox. We do not have to do so. Macroscopically, we can always trace back to how someone put the gloves in the boxes, such as asking the executor or recording.

Even if we cannot detect or trace, we still know which glove is in the box is certain. Opening any box can neither change the state of the glove in this box nor the other one. In other words, this is a pre-determined hidden variable problem.

There is no difference in mathematics between the left-or-right of a glove and the present-or-not of a particle. The glove problem is the measurement problem.

We can only measure any single-particle wave function once. It collapses globally after one measurement. One measurement can only get one state, and one state has no information. Therefore, neither gloves nor quantum entanglement can transmit information because the system has only one state and cannot encode any data.

Therefore, the glove metaphor is a simple measurement problem. The measured nonlocal "entanglement" comes from the global nature of the defined wave function.

7.4 Experiment of proof

Besides the correlation test of non-pairs, we can have more experiments to distinguish GAI and entanglement interpretation of Bell experiments.

GAI believes the correlation comes from the influence of the detectors in photon-pair creation and the coherence range of the photons. The tell-tale experiment would be separating the creation and detection of the pair. We can control the laser pulse duration so that

$$\Delta t < l/c, \tag{7}$$

Δt is the laser pulse duration, l the distance between the crystal and the detector, and c the speed of light.

GAI predicts that the correlation will be gone, but no change according to entanglement theory.

Another approach is to change the illumination light source to a non-coherent monochromatic one, such as arc-light with the right filter. GAI predicts the disappearance of the correlation, and there should be no difference in entanglement theory.

7.5 Summation

The nonlocality of quantum entanglement is an illusion of the global property of the quantum state. It violates the principle of locality unless the speed of light is infinity. We can perform experiments to distinguish entanglement interpretation and GAI understanding of Bell experiments.

8 What is a photon?

8.1 Photon problem

> All the fifty years of conscious brooding have brought me no closer to answer the question, "What are light quanta?" Of course today every rascal thinks he knows the answer, but he is deluding himself. —— Albert Einstein,(1951). [101]

In his later years, Einstein was still confused about photons, so he has the famous saying above. Unfortunately, not many people know it. In one of the most popular optical textbooks in the world, "Optics" by Eugene Hecht [102], when discussing the definition of the photon, he used the above quotation.

In the interpretation of many experiments, such as delayed-choice experiments (quantum eraser) [8, 103], photon entanglement experiments, etc., researchers often understand photons as some point particles.

What is a photon? This question remains unanswered up to date.

Photon is one of the most fundamental quantum or particle. It is an elementary particle with the spin of 1, no rest mass, and its energy is Planck's constant h multiplied by its frequency ν, and then no further information. However, in reality, we have more complicated photons.

The properties of photons are fundamental when we try to understand some quantum mechanics experiments. We need a correct picture of a photon, not like defining a virtual object in a computer language with only one or two data types. The physical concept of photons is the key to understanding most quantum features.

Let us first list some of the characteristics and problems of photons:

1. Let us ignore the gravitational effect. The photon is not charged and moves at the speed of light, so it is uncontainable.

2. In quantum mechanics, photons are free, and the wave function is a plane wave, which extends to the entire universe (whole space). Therefore, the probability of finding the photon anywhere in the universe is the same, which is zero. However, this picture is far from our general understanding of photons. For example, they can be produced from a particular atom and then absorbed by another; or, we can see the trail of a high-energy photon in a cloud chamber.

3. Unlike other elementary particles, which have fixed spins, a real photon can have a spin in various superimposed states. It can have any value between -1 and $+1$, corresponding to different polarization states, including circular (± 1), elliptical, linear (0), etc. We are afraid it is even more complicated, and its spin may exceed 1.

4. From the perspective of electromagnetic radiation, the only difference between high-energy photons and low-energy ones is their frequencies. However, the classic electromagnetic radiation pattern is much more complicated than the concept of polarized photons, mainly due to various multipole radiation and the interaction between complex electromagnetic fields and matter.

   Electromagnetic radiation generally diffuses and propagates in the entire universe. However, photons, particularly high-energy photons, seem to move like particles in one direction at the speed of light, without diffusion.

5. According to the photon definition, the energy of a photon should be a single fixed value, and there should not be an energy distribution, but the photon emitted by an atom has an intrinsic linewidth. The energy level linewidth for different atoms and levels varies, reflecting the significant differences in energy level half-life (energy-halflife uncertainty relationship [104]). The energy distribution of a single photon is hard to understand because we can use prisms to divide photons into different

energies, which contradicts the inseparability property of elementary particles (not considering high-energy processes).

6. In some experiments, the photon's angular momentum seems to be greater than 1, which is difficult to understand. People use the concept of photon orbital angular momentum [105] to describe them. However, photons cannot be constrained. From the perspective of photons, the concept of orbital angular momentum is incomprehensible. The images with orbital angular momentum ±1 and spin ±1 are the same. If the theory of orbital angular momentum holds, the spin concept is not needed. From the electromagnetic field point of view, the wavefront of light has a degree of freedom of helicity, whether it is called spin or orbital angular momentum, but it should have only one name, not necessarily quantized, and can be greater than 1.
7. The atomic energy-level transition is the generation or absorption of photons. Since the photon spin is 1, the angular momentum difference between the two energy levels must be 1. If the angular momentum difference is not 1, the transition should not occur, or this is a forbidden transition [106]. However, forbidden transitions do occur [107]. If we check the photon energy, there is just one single transition. The photon thus produced must have spins other than 1. It can be 2, 3, or even larger. In classical physics, electromagnetic radiation can be multipole, such as electric quadrupole, magnetic dipole, etc. However, it is impossible to understand from the definition of the photon because the maximum spin of photons is 1, and a photon cannot take away more than 1 unit of angular momentum from the atom.
8. Is a photon a point in space or a specific range of distribution? If it is a point, its coherence is difficult to understand. If it is a particular range of distribution, how large is it? What kind of distribution? If different photons have different distributions, the identical particle concept is in danger.
9. Considering the lifetime of atomic energy levels (a few nanoseconds to hundreds of milliseconds), the space distribution range of a photon is quite extensive, from a few meters to tens of thousands of kilometers. Even if the shortest distance of a few meters is far more than tens of billions of times the size of an atom, how does it interact with an atom? In particular, how does the photoelectric effect happen?

Note that the spin problems do not exist in classical electromagnetic theory since we do not require the rotation speed of the electromagnetic vector (wavefront helicity) to be some discrete value in the classical case. The orbital angular momentum (or spin) is not limited to ±1 or other integers.

Regarding the energy level lifetime or the half-life of a transition, there are two perceptions. One is the probabilistic lifetime, such as the γ decay of the nucleus. For each decayed nucleus, a γ photon comes out at a particular time, and it happens instantaneously. The half-life only reflects the intensity of the decay. We can track every photon that decays; the other is the time required for energy level transitions, that is, the duration of each transition. In atomic energy-level transition, we can not ignore the resonance between atoms of the same species because they inevitably influence each other. The results we observe are collective behavior. So atoms have stimulated radiation, but usually, nuclear decay does not.

8.2 Photon in GAI

In section 2, we stated that there is no single standalone "clean" elementary particle. All elementary particles inevitably influence their surrounding space-time. All particles and all interactions are complicated. The same is true for photons, and it involves all fundamental interactions on an infinite number of space-time points.

Photon has no rest mass, so it is pure energy. According to the standard model, energy scale, or energy density, determines the importance of different physical interactions. For high-energy photons (γ

rays), due to the high energy concentration in a small space-time range, other more localized degrees of freedom in SM, such as electron-positron pairs, other high-order interactions, appear. Their contribution is so significant that the high-energy photon is more like a localized particle. High-energy photons do not diffuse or lose energy only through interaction with other particles. Low-energy photons have energy much lower than the mass of the electron, 511 keV, such as photons in optics. Considering its wide spatial distribution, the energy density in any part is very low. Except for electromagnetic interaction, all other degrees of freedom are negligible. Therefore, low-energy photons appear as pure electromagnetic radiation, described by classical electromagnetic radiation theory. Maxwell's equation is a simplified electromagnetic version of SM.

So how to understand the quantum nature of photons? That is, the relationship between the energy of the photon and the Planck's constant and frequency, or in other words, why does the atomic energy level transition emit a photon? Instead of lower energy photons? It concerns the property of the eigenstate, which is the solution to Schrödinger's equation. Eigenstate is the dominant mode. As we said above, the range of a photon far exceeds that of an atom and is hundreds of millions of times of the atomic radius. For the atom, the eigenmode oscillation frequency is the preferred frequency. We should also note that many identical atoms are involved with resonance in optical experiments, such as line spectral measurement.

To be objective, we only see some resonance peaks with relatively concentrated radiant energy frequencies. We did not see atoms emit or absorb photons.

In GAI, all photons are complex and nonlinear. Low-energy photons are linear classical electromagnetic waves with all wave properties, such as superposition and coherence. The spiral nature of the electromagnetic component of the wavefront, namely the spin, is determined by the radiation source.

As the energy increases, the physical composition of the photon is constantly changing. For high-energy γ photons, weak force and strong force comes into play. The effective range of these two interactions is short. As the photon moves at the speed of light, it cannot decay, and it can only lose energy by interacting with other particles.

The photons emitted by atomic electron energy level transitions only involve electromagnetic interaction, while the photons produced by nuclear processes involve higher energy scale interactions.

Except for gravity, electromagnetic interaction is the only long-range low-energy interaction in physics. Therefore, it is natural that electromagnetic processes dominate our daily world. If one calls the energy change process of an atom the generation or absorption of a photon, of course, we can define it that way. However, there are too many kinds of photons like this, and a simple mathematical definition may not be enough.

8.3 Another wave-particle duality

The dispute between the wave and particle nature of photons lasted for centuries. Later, people usually accept that the wave-particle duality explained by quantum mechanics ended the debate. However, Einstein's doubts make us feel that the problem is not so simple [108]. First of all, the behavior of "sometimes like waves and sometimes like particles" described in the wave-particle duality is not well-defined. Secondly, experiments to prove the particle nature of photons are not convincing. It is not so much the particle nature of photons as the particle nature of the detection methods. The particle nature of low-energy photons is an observation effect. A widely distributed wave with the right frequency can sure interact with a localized atom.

Treat all particles as a "pure matter wave" model can explain all the properties of photons and particles with rest mass [109].

GAI's understanding of photons provides another wave-particle duality. As the energy increases or the energy density increases, the photon dominated by electromagnetic interaction gradually becomes dominated by stronger interactions and becomes more particle-like γ photon.

The SM reveals that the interaction behavior of space-time points depends on the energy density, and the wave-like property is natural. Still, it will be more particle-like in high energy density. We can take a basin of calm water as an example. If we drive the water surface slowly and regularly, we can get a series of smooth waves. If different water waves appear in different directions, these waves will be superposed. In some particular places, if the oscillation caused by the superposition of the waves reaches a specific frequency or amplitude, some water comes out of the surface and forms water droplets. The water droplets show particle properties instead of a wave. Throwing a stone into the water means that the energy is more concentrated. In addition to the spreading water ripples, some water droplets will appear. Treating the water surface on a large scale, we can write ideal continuous wave or fluid equations. However, even for water, the interaction that determines its microscopic properties is still highly complex. At different scales, there is surface tension, van der Waals forces, hydrogen bonds, covalent bonds, oscillation, rotation, collective motion, gas-liquid balance, vortex, etc. We ignore these interactions in large-scale wave studies. When water droplets appear, other effects such as surface tension become more significant.

The nature of space-time and energy determines the different physical manifestations of photons in different energy density scales. The large-scale coherence and globality of photons in low-energy experiments is the behavior of waves under certain boundary conditions. Now they are just waves. We can explain all interference experiments with wave coherence property. Quantum entanglement is just a special kind of coherence.

The equivalence of energy and mass can also help understand the different behavior of photons in different energy scales. The lower the energy density, the less likely there will be components such as positive-negative pairs and other high-energy elementary particles within a particular spatial range. The contribution from the high energy scale degrees of freedom will be too small. However, if the energy is more concentrated, the situation is different. The rest mass is the energy contained in a particular relatively stable perturbation mode in space-time.

We can also understand the particle nature of high-energy photons with the theory of special relativity. Suppose low-energy photons are ordinary radial electromagnetic radiation in a reference frame close to the speed of light. In that case, the photon energy will concentrate at the point facing the direction of motion of the frame of reference. In contrast, the energy in other directions is relatively small to be negligible (Headlight effect [110]).

8.4 Summation

Photon, like other particles, is a perturbation mode of energy to space-time. The low-energy photon is a simplified electromagnetic interaction of SM, or electromagnetic waves, with no inherent quantization requirements. Whether spin or energy is quantized is determined by the source of the disturbance. High-energy photons are more like local particles due to the participation of higher energy scale degrees of freedom. The definition of the photon in the elementary particle table is a mathematical definition of a single mode, not a physical reality.

9 Reality

9.1 Debate on objective reality

The reality, or objective reality, is a philosophical concept that refers to the existence and nature of matter, or the objective world, that does not depend on human perception and knowledge. Our perception and knowledge of existence are subjective [111].

In quantum mechanics, the physical system is equal to the existence and measurement perception and knowledge, which is subjective. In quantum mechanics, measurement affects the physical system. That is, subjectivity affects objective reality; the independence of objective reality is under question. We have to answer, does objective reality exist?

The objectiveness of reality is an essential argument in the early days of quantum mechanics [112]. The belief that objective reality still exists is called realism. Einstein was a firm realist, and Bohr was firmly opposed to realism, arguing that it would be meaningless to discuss objective reality without observations [113]. The famous quotation that reflects this difference in understanding is: "If you are not looking at the moon, does it exist? [31]". Only at the philosophical level, there is no obvious answer to this controversy. Einstein believed that, whether you look at it or not, the moon exists. Bohr thinks that if no one sees the moon, there is no point in discussing the moon's existence. Seeing is measuring.

Specific to the measurement process of quantum mechanics, such as the spin of an electron, because a single electron is too fragile, no matter how we measure it, the method will change its state significantly. So does it have a spin state before measurement? Is it the state we measured? There are several possible situations (assuming the measurement is correct) :

1. The measurement does not change the original state of the electron, and the measured value is the original value of the electron spin.

2. The measurement does not change the original state of the electron, and the measurement happens to get this value, and it can get another value.

3. The measurement changes the state of the electron, and the electron turns the original spin direction to the measured value.

4. The measurement changed the state of the electron. The electron had no spin before, and the measurement caused the electron to produce the measured spin.

Unfortunately, although we all agree with the measurement results, we have no way of knowing which of the above situations happened.

There is also a relevant question: whether the measurement changes the object, does the object initially have a specific state? Although we would never know what the state is. Realism believes that it exists, but Bohr believes it is meaningless to discuss the issue [113].

For situations 1 and 2, the measurement does not change the electron state, which is very unlikely. Whether the measurement is a magnetic field or an electric field, it will affect the state of the electron. The electron may happen to be in the right state, but in principle, it has to interact with the measuring device because the device is much more potent than a single electron [114]. No-changing of the electron is also inconsistent with the CI's understanding of measurement. Situation 2 does comply with CI. Measurement causes the electron to collapse, but before the collapse, the state of the electron did not change. Situation 1 is a special case of situation 2.

In situation 3, a standalone electron has a predetermined spin, with its direction unknown. The difference between situations 2 and 3 is whether the electron state has changed during the measurement, such as it aligns with the magnetic field and not just wave function collapse. The probabilistic collapse has a chance to collapse into another value.

Situation 4 means that in the interaction with the measurement equipment (for example, in a magnetic field), the electron's spin degree of freedom selects a direction. The spin arises during the interaction. Or, the quantization in a specific direction emerges during the interaction. It may have no spin when it is alone.

Situation 1 and 2 are probabilistic measurements, and no interaction is involved. Situation 3 and 4 consider the interaction caused by the measurement, and the measurement readings are deterministic.

All four situations conform to realism. Before the measurement, the electron has a predetermined state (including the superposition state), although we cannot know what the state is. Bohr believes that it is meaningless to discuss the pre-measurement state, so he did not deny realism. He thinks that physics should base on measurable or measured properties (instrumentalism) [115].

Another proof for the validity of realism is the calculation of elementary particles. According to the standard model, calculating the fundamental properties of particles, such as electrons, can be very accurate. The basis of the calculation or the numerous Feynman diagrams is not measurable. Still, we have to describe them correctly to produce the right results, which is proof that we know all the details of the electron.

9.2 View of GAI

Purely at the philosophical level, if it is not experimentally verified, the argument is indeed meaningless. After all, the person who argues, or the scientific explorer himself, can only be subjective. Our description of any objective must go through our cognition and measurement. If the measurement itself is not objective, objectivity does not exist. If the object is not measurable or verifiable, different viewpoints are just philosophy, not science.

However, we still want to know what happened after all. What we cannot measure right now does not necessarily mean that we cannot do in the future. We can also guess from known facts.

GAI starts from SM, recognizing the interaction and the complexity of elementary particles.

Situation 1 and 2 in the previous subsection deny the interaction and attribute the result to the special discontinuity of the measurement. We believe that this view of measurement is a rude simplification, derived from the ideal wave limit picture of Schrödinger equation. The instantaneous change from one ideal wave to the next must be discontinuous, but this is not the actual process.

In Section 8, we believe that the spin of a photon is not quantized and can be any value, whether quantized or not depends on the process of photon generation. Situation 4 is equivalent to the idea that the spin of a single standalone electron does not need to be quantized. When interacting, $\pm 1/2\hbar$ are the two eigenvalues of the electron. The spin emerges from the interaction rather than being the "intrinsic property" of the electron.

Considering the interaction between electron and measurement devices [116], unlike the traditional view of Situation 3, GAI favors Situation 4. The arguments are:

1. GAI believes that the global intrinsic behavior of the wave nature is the source of all quantization, so does the quantization of electron spin.
2. The physical picture of 1/2 spin is hard to understand. For example, it changes back to its original state after two complete rotations. As the eigenstate during the interaction, it can be understood similarly to orbital angular momentum quantization.
3. It is challenging to understand the spin of a single standalone electron, at least from a classical perspective.
4. At least there is no experimental evidence to disprove this argument because proof must come from interaction or measurement, which is similar to the situation of Schrödinger's cat paradox.
5. The understanding is consistent with CI.

Since experiments cannot tell us what happened, we can only reason by logic and guess which one is more likely, for example, which view has fewer assumptions.

In Section 4, we argued that the quantization of atomic energy levels and angular momentum are natural emergences, so why can't the quantized angular momentum of elementary particles be the same reason? After all, we believe that elementary particles are some intrinsic or stable energy excitation mode of a complex multi-body process. They do not have to share the same properties when they are standalone. For example, neutrons are unstable when they exist alone but very stable with a proton. The confinement of quarks is also an example.

In conclusion, for realism, GAI recognizes Einstein's realism, but it is not contradictory to Bohr's instrumentalism. However, due to the recognition of local interaction and complexity, we do not agree with CI's measurement theory of probability and wave function collapse. As an extension of the emergent quantization concept, we believe that the spin of elementary particles is also the intrinsic mode that appears when interacting, not necessarily the property of standalone existence. Of course, it is also possible that the particle has its spin when it is alone or can never be alone.

9.3 The relativity of reality

About reality, there is one more point worth discussing. That is, in the context of philosophy or science, reality is relative. We cannot avoid discussing reality from the perspective of subjective cognition and interaction.

We cannot deny that we are the cognitive subjects and cannot rule out the influence of cognitive ability and measurement validity.

Any cognition, or measurement, of the object, is a complex interaction. Generally speaking, the more macroscopic and stable, the closer the space-time distance, the less susceptible to the influence of observation tools, the easier it is to get reliable measurements. For example, whether there is a moon or not, although many people have not seen it and have doubts in their hearts, many people have seen it. If we already have scientific tools, we cannot be affected by the weather and the moon's location. Every one of us can check whether the moon exists; if we know that physical phenomena caused by the moon's gravity, such as tides, exist at any time, we can also find out where the moon is.

If the object and the measuring devices are separated faraway spatially or temporally, or the device is defective, or the observer is biased, the measurements will be less reliable. Therefore, we do not have strong confidence in some ancient historical events, the physical properties of distant celestial bodies, the properties of microscopic objects, the vague memories of witnesses, etc.

Conversely, is there any fact absolutely credible? For example, would we believe that the moon must be there? If someone tells you that the moon is missing or two moons appear in the sky, should you believe him? How about another person tells the same story? Or even more people? People thought that Earth is the center of the universe not very long ago, after all.

In physical measurement, all the values we measured have uncertainty, such as electron mass. Although it is very accurate, there is an inevitable uncertainty, that is, the width of the statistical distribution of experimental measurement.

Generally speaking, quantization means accuracy, no uncertainty, and no distribution width.

The mathematical definition is the same when we define the mass of an object as M or the speed at v, which means that these quantities are accurate, and there is no uncertainty.

Due to the complexity of the interactions in the standard worldview and the influence of external factors added in at any time, it is impossible to obtain a noise-free and accurate measurement. Infinitely precise measurement is impossible.

The uncertainty of physical quantities comes from the relativity of reality. For measuring the spin direction of an unknown electron, the error is of the same magnitude as the measured value, which is very unreliable. Although we believe there is a reality, it is unknowable, which is why Bohr criticized reality.

For certain quantum concepts, such as quantum computing, the relativity of physical reality is ignored. In Shor's algorithm [117], operations like $N + 1$, $N + 2$, $N * M$ are required, where N is a physical quantity representing an integer of at least 1000 binary bits, or about 300 decimal digits. So far, no physical quantity has an accuracy of more than 15 decimal digits. In quantum computing, 3-digit precision is hard to achieve. How to correctly implement $1.01(\pm 2) \times 10^{300} + 1$? We can never implement Shor's algorithm for real large numbers.

The reality based on cognition and measurement is relative. Even for the word "reality", if we ask different people, we will get different answers. We don't even have a unified view of what reality is, and how can anything be absolutely correct or accurate?

9.4 Summation

GAI recognizes both realism and Bohr's instrumentalism. We believe that physical reality is valid before measurement, but due to the influence of instrumentalism, the perceived reality must be relative.

10 Determinism

10.1 Determinism and mechanical determinism

Determinism means that the state of the physical system evolving over time is predetermined [118].

We usually believe that classical physics is deterministic. Newtonian mechanical determinism says, if we have the initial condition of the universe, the future is determined.

According to the relativity of reality discussed in section 9, we know that it is impossible to know the exact physical state of a system at any moment. However, even in classical physics, it is impossible to calculate a complex system's evolution accurately. For example, there is no accurate calculation method in computational fluidal dynamics (CFD), and there is the butterfly effect [119].

10.2 The probabilistic nature of quantum mechanics

In CI, quantum mechanics, including measurement, is inherently probabilistic, that is, indeterministic. In principle, the measurement result is unpredictable. If there are multiple possible outcomes, the probability of each outcome comes from the probability amplitude of its wave function. If it is a one-time process and cannot repeat, it is impossible to predict the result. For example, where the photons irradiated on the screen through the double slits will fall, it is impossible to predict and calculate. Although we can estimate what points are more likely to land, we cannot make any predictions for points with the same probability.

Researchers of quantum field theory, like t'Hooft, infer that the causality and locality of quantum phenomena close to the Planck scale can be restored through a deterministic theory [18].

In section 6, we stated that quantum is the wave function, and the wave function is the probability amplitude of all possible measurements.

The interpretation of quantum as the wave function, or the description of probability amplitude, has the following problems:

1. The wave function is not physical. The probability amplitude is not a physical quantity. We can only measure and verify by large quantity statistics [120].
2. In CI, the measurement causes the wave function to collapse. The collapse of the wave function occurs instantaneously and does not take time. This process cannot be physical [121] because the physical quantity before and after the collapse is discontinuous, and the wave function itself is not a physical quantity.

From the probabilistic nature of quantum mechanics, we know measurement causes unpredictable discontinuous changes. Although there are some theories, such as the multi-universe theory [12, 122], that try to interpret this quantum behavior, in each universe it proposes, every measurement is still discontinuous and causes the universe to split infinitely.

In QM, we cannot predict the result of any measurement. QM is inherently probabilistic and indeterministic.

10.3 Classical probability

The long-term evolution is unpredictable for a classical system with many-body interaction, non-linearity, and rapid evolution. However, we can still describe the system statistically in macroscopic quantities, as in statistical physics. Statistical physics discusses probability distributions.

That is to say, for a classical system, if we cannot track its microscopic evolution, we will also describe it with probability. In other words, the complex classic evolution system that we cannot track the details seems to be probabilistic.

Consider the gas enclosed in a piston expands or compresses adiabatically. Suppose we cannot tract the whole process microscopically. In that case, we will find that the gas velocity distributions in the initial and final states are perfect normal distributions, but the height and width of the distribution function change. The velocity distribution function is global and affects every gas molecule. If we ignore the process of change, the probability distribution of each molecule has undergone a sudden change, which can also be called "collapse" (the concept of collapse here is not the same as that of quantum mechanics, which collapse to a single value). We can assume infinitely slow adiabatic changes for the classical process, and the distribution function will change continuously. If we ignore the process of change, it looks similar to quantum measurement.

The same is true for coin tossing. Suppose we ignore the movement of the coin and the influence of all variables (momentum, direction, mechanical properties of the drop point, changes in airflow, etc.). The head and tail probability distribution is a relatively stable distribution. However, if we track the process, we can predict which face of the coin will land on at least shortly before it stops.

Therefore, even in a classical system, we can only describe it with probability if it is sufficiently complex. And if we can track it, the more information we can have, the more predictable it will be.

10.4 View of GAI

GAI thinks that the wave function or the solution of the Schrödinger equation is an approximation of the ideal wave limit. We did not discuss the physical meaning of the wave function. For the time being, we still use Bohm's probability interpretation.

The measurement changes the quantum to another state or another wave function. The measurement definition in CI is sampling. We tend to believe that the intervention of the measuring device changes the state of the original wave function.

That is, the measurement changes the wave function from one stable distribution to another. Since CI measurement completely ignores the intermediate process of switching from one state to another and only describes the initial and final states, we can only describe the process with probability, just like in the classical situation.

By accepting the probability assumption of the wave function, GAI can understand the indeterminism of CI but believes that its principle is the same as classical physics because it ignores the intermediate physical processes.

So, is the actual physical process deterministic?

GAI recognizes physical reality but thinks it is relative, and we cannot describe it accurately. Therefore, the physical process is deterministic because we know how things interact or evolve. However, we cannot predict or calculate the system accurately because we cannot accurately describe the initial state.

We rephrase the above: Considering the relativity of reality, physical processes are deterministic, but we cannot make an accurate prediction. The more macroscopic the system, and the richer the information we can have, the more we can calculate and predict; the more microscopic, and the more complex the system, the more unpredictable. This concept is consistent with the classical view of determinism.

The future cannot be accurately predicted, but is the future of the physical world predetermined? Random? Or is it chaotic? For example, how to understand the randomness of nuclear decay?

From a physical perspective, the calculation is challenging due to the complexity of the fundamental interaction and nonlinear nature. However, being incalculable does not mean that the micro process is inherently probabilistic. The wave function definition of CI is a mathematical definition to describe statistical properties, not a physical one.

As for the randomness of nuclear decay, although we cannot predict, it seems to be random, but we cannot prove it. It can happen deterministically but appears to be random, like in statistical physics or coin tossing. Of course, phenomenologically, we cannot prove it is deterministic either.

10.5 Free will and fatalism

Although GAI cannot prove or accurately predict, we still believe that the physical process is deterministic. That is, the future is predetermined. This determinism, of course, has critical philosophical consequences, which may severely affect people's worldviews and attitudes to life.

However, GAI's determinism is called agnostic determinism, which is different from agnosticism, determinism, and indeterminism.

If people understand the meaning of this kind of determinism, they will not necessarily be pessimistic or fatalistic.

First of all, looking at it from a cosmic perspective, according to our current understanding of the universe, the fate of the universe is determined.

Secondly, it is impossible to verify whether the future of individuals and human society is predetermined. Each of us can only experience the past and the future once. No one can go back in time, make another choice and compare. Since we can not change, cannot compare, and cannot predict, the future is still uncertain and should not affect anyone's free will. Even if your current free will and thinking are previously determined, you cannot change them. You still have to think that way, have to decide, and bear the corresponding consequences.

Thirdly, can we think that the future is predetermined anyway, and we are obliged to nothing? Can we leisurely eat and sleep and wait for the bright future to come? The problem is that the future, especially your own future, although predetermined, you don't know what it would be, and it may not necessarily be good. You may have a bleak future, which is determined by your doing nothing.

The more macroscopic the system, the more determined its macroscopic properties and the easier it is to predict. We hope that humanity will soon step into the next level of civilization, the stellar civilization. If no major accidents occur, it should be relatively sure, but this requires everyone's efforts. Again, this is not guaranteed. If there are more people doing nothing, human civilization may go downhill. Don't forget the "great filter".

Whether your free will is free or random, you still have to work hard to acquire all kinds of information, think, and make decisions. You are part of the world, part of the future, and your will, decisions, and hopes are also part of the world. You can have and experience full consciousness and freedom, as well as the joy and happiness that you strive for, whether they are determined or created.

10.6 Summation

Determinism does not mean predictability. The relativity of reality and the complexity of calculation indicate that we cannot calculate the future accurately.

The indeterminism in CI comes from its probabilistic interpretation and is not physical.

GAI thinks that the world is deterministic, but it cannot be accurately calculated or predicted. Inability to calculate accurately does not mean indeterminism.

It is necessary to distinguish between agnostic determinism, agnosticism, determinism, and indeterminism.

Determinism does not necessarily mean fatalism or the absence of free will [123].

11 The physical meaning of quantum wave function

As stated earlier, the most precise definition of quantum is its wave function, but what exactly is a wave function?

In the classic wave description, a wave, such as the electric field component (one-dimensional) of electromagnetic waves,

$$E(x,t) = E_0 e^{i(kx-\omega t)}, \tag{8}$$

$E(x,t)$ is a fluctuation of a physical quantity, with dimensions, which can be field strength, pressure, position offset, etc. E_0 is the amplitude of the fluctuation. The square of the amplitude is energy density.

In CI, the amplitude of the quantum wave function is the probability amplitude of the particle's appearance. However, neither probability nor amplitude of probability is a physical quantity because they have no dimension. This interpretation is consistent with experimental statistics. So why is this happening?

Let us first check some clues:

11.1 Schrödinger equation and plane waves

Let's write down the Schrödinger equation (simple form):

$$H\psi(x,t) = E\psi(x,t) = E\psi(x)e^{-iEt/\hbar} = E\psi(x)e^{-i\omega t}. \tag{9}$$

H is the Hamiltonian, and the dimension is energy, which is the same as E on the right side of the equation. E is a constant, which can be understood as similar to the amplitude E_0 in the equation (8). $\psi(x)$ is the spatial part of the stationary wave function. If it is a free particle, the solution of Schrödinger's equation is a plane wave, $\psi(x) = Ae^{-ikx}$, where A is the normalization constant, so we have:

$$\psi(x,t) = Ae^{i(kx-\omega t)}. \tag{10}$$

With the same form as (8).

From Eq. (10), we can see that for free particles or plane waves, the form of the quantum wave function is the same as the classical wave. However, classical wave expression has a clear physical meaning, and the physical quantity of the fluctuation is simple harmonic oscillation over space and time. The quantum wave function, according to CI, is just a probability wave. Since the plane wave extends infinitely, the probability of finding particles in any small area is almost zero. That is, the normalization constant A tends to zero. But in Eq. (8), the amplitude is an arbitrary value. We can eliminate the difference in an infinitely deep well of finite width.

In a finite-wide and infinite-deep well, the quantum wave function is the same as the classical one. Both have discrete wavelengths and are standing waves. The difference is that the amplitude of the quantum wave function is restricted by the normalization requirement, while the classical wave has no restriction. Furthermore, the normalization condition requires the total number of particles to be 1. Thus, for a quantum wave function, the sum of the probabilities of all possible wave modes can only be 1.

We regard the plane wave as a particular case of the wave function and find that the quantum wave function of the photon is consistent with its classical form. However, the classical description has a clear physical meaning with a dimension, but the quantum probability description needs interpretation.

In Eq. (9), if we regard the energy of the particle E as one entity, then the square of its spatial distribution function $\psi(x)$ is the energy density of the particle in space. So the wave function is the energy density distribution.

11.2 Interactions involved in waves

We have explained earlier that only electromagnetic interaction in the standard model is the long-range, low-energy interaction that plays a role in laboratory experiments. Let's carefully analyze all classical wave phenomena, such as sound waves, electromagnetic waves, seismic waves, water waves, etc. We can find that the elementary interaction involved can only be electromagnetic interaction (water waves have gravity but constant).

In real-life applications, the quantum phenomena described by the Schrödinger equation are all electromagnetic. Other potentials are generally hypothetical. Nuclear physics is not discussed here, which involves strong interaction.

In other words, the various quantum phenomena we discuss in condensed matter physics, atomic and molecular physics, optics, chemistry, materials, biology, etc., are all electromagnetic ones.

In a physical system dominated by electromagnetic effects, waves are the most fundamental phenomena.

11.3 Walking droplet experiments

The walking droplet experiment refers to a small oil drop on a vibrating water surface. The vibrating water surface can produce all kinds of wave behavior. Therefore, observing the motion trajectory of the oil droplet can simulate various quantum phenomena. Hence, it is also called hydrodynamic quantum analogs [124].

The walking droplet experiment can simulate double-slit interference [125], tunneling effect [126], quantized orbits [127], Zeeman effect, quantum corral [128], etc.

In the walking droplet experiment, the wave behavior comes from water waves. The similarity between water wave and quantum effect originates from quantum matter-wave. However, the walking droplet experiment can also help us understand the particle nature and the probability amplitude because of the oil droplet tracer. Experiments do many statistics on the trajectory of oil droplets, which show various quantum or wave features.

11.4 The physical origin of the wave function

Quantum mechanics describes physical objects. The wave function embodies all the quantum properties, but the wave function is not physical. Instead, the physical definition of a classical wave is clear. Should quantum wave function have a physical origin or happens to be the expression of specific physical property?

We know that the classical wave amplitude represents the energy density. In the standard worldview, the energy density is the basis of the kind of fundamental interactions space-time shows. The energy density of the wave function is responsible for what happens, such as the photoelectric effect, the reduction of silver ions during film development, etc. Like in the walking droplet experiment, oil droplets are more likely distributed in large amplitude and high energy density areas. In this way, the quantum wave amplitude should be the amplitude of a particular physical quantity, such as the electric field strength.

Thus, the probability amplitude of quantum wave function is the amplitude of a particular physical quantity reflecting the energy density. When we measure the wave function with a material made of particles, we will get a pattern scattered with particles, such as the reducible silver ions in a developing film. The areas with higher energy density are more likely to be developed. The probability value is energy density. The wave function is an energy wave.

In the standard worldview, particles are the perturbation mode of energy to space-time. In quantum mechanics, considering non-relativism, an abstract quantum is its low-energy part, or the electromagnetic interaction part, in the form of energy.

The term probability used here is what we discussed in section 10, that is, it is the physical process that determines the occurrence of an event, but there is no good way to calculate it.

11.5 Summation

The Schrödinger equation is the diffusion equation of matter waves, and electromagnetic interaction is the interaction carrier of matter waves. The similarity between photon quantum wave function and classical electromagnetic radiation wave function implies that quantum wave function is energy wave. We can understand the particle nature of quantum waves from walking droplet experiments. The probability amplitude description of the quantum wave function should have a physical origin. The quantum wave function is the energy density distribution, and the energy density determines the action probability of particle properties. The probability concept in CI happens to depict the energy density characteristics of matter waves.

12 The boundary between quantum and classical world

It is a common idea that the quantum world is different from the classical world, with essential disagreements. The microscopic world is dominated by quantum theory, while the classical world by classical Newtonian theory. However, there is only one world, but the two views are different. How should they be connected?

Traditionally, Bohr's correspondence principle [9], and H. Dieter Zeh's quantum decoherence theory [129] try to answer this question. We discuss them below and put forward the viewpoint of GAI.

12.1 correspondence principle

Bohr described the corresponding principle in 1920 [9, 130], but as early as 1913, when he proposed the atomic Bohr model, he had already used this principle. Correspondence principle refers to: In the limit of the large quantum number, the description of the physical system by quantum theory should conform to that of the classical one.

Bohr's corresponding principle argues that quantization is the essence and is fundamental. The classical theory is only the behavior of quantum theory in the limit of large quantum numbers. We can ignore the effect of quantization because the unit is too small. The analysis of some typical systems, such as hydrogen atoms and harmonic oscillators, can prove that the corresponding principle works.

Planck proposed his version of the corresponding principle. Planck states that when the Planck constant approaches zero, quantum theory returns to classical theory [131].

About the legitimacy of the quantization hypothesis, Bohr or Planck's corresponding principle has to answer, why is the physical world at the microscopic level quantized, but not in the classical macroscopic world? They both believe that quantization is the fundamental principle, but quanta are too small to be observable in classical conditions. They cannot answer why the microscopic world is quantized but take it as a fundamental assumption.

We should note that Bohr and Planck proposed corresponding principles before the De Broglie matter wave hypothesis and the Schrödinger equation [132]. They put forward the quantization hypothesis based only on the existing phenomenon. To solve the contradiction between quantization and classical continuous quantity, they must reconcile to the corresponding principle.

12.2 Decoherence theory

The primary characteristic of the wave is coherence. The change of value or amplitude is within the oscillation range, and there is a fixed phase difference between any two points.

In Section 6, we stated that the quanta in quantum mechanics are ideal waves and are ideal coherent in the whole space. The mathematical treatment adds a wave term containing energy to the wave function after solving the spatial part of the Schrödinger equation. As a result, the oscillating term is equal everywhere in the whole space ($e^{-iEt/\hbar}$).

Such treatment will inevitably lead to idea coherence of the wave function in the whole space. However, this is not what happens experimentally. Thus, quantum coherence is not ideal.

To solve this problem, in the 1970s and 1980s, H. Dieter Zeh proposed the quantum decoherence theory [129, 133, 134], which believed that the interaction between the environment and the quantum system led to the loss of quantum coherence. In mathematical formulation, people treat the environment as a heat bath. Although the initial decoherence theory tried to explain the measurement problem, it seemed not very successful [135].

The decoherence theory does not define the environment clearly. Therefore, one can blame the environment for any unanswerable question.

In non-relativistic quantum mechanics, since the environment is always known, or defined, embodied in the uniqueness of the potential and the boundary conditions, the Schrödinger equation always has solutions. The solution must have specific energy and also a corresponding oscillating term. The oscillating term is equal everywhere in the whole space, or the wave function is ideally coherent.

Mathematically, if the environment is unknown, the equation is unsolvable. Thus, the discussion is meaningless [136].

Therefore, the disappearance of coherence should not exist with the assumption of the ideal wave and Schrödinger equation. We can always specify the environmental conditions, add them to the potential or boundary conditions to obtain new solutions, and establish new ideal coherence.

12.3 View by GAI

GAI is based on the standard worldview, in which the concept of particles is different from the classical ones. However, the image of a particle is not a choice. We have to use concepts from SM. The classic particle concept cannot be the theoretical basis. In other words, the classic particle image is another kind of extreme idealization, that is, extreme localization: all the properties of particles exist on an infinitesimal point, and the interaction passes through an extra, a priori, phenomenological potential-field to describe.

If we use SM particle and interaction pictures, there is no difference between the classical and quantum worlds. Each particle is a complex energy perturbation mode that fills the entire space. Some particles are more concentrated in space, with higher degrees of freedom. Some particles are excited only with low energy degrees of freedom. The Newtonian worldview and the quantum worldview are two extreme descriptions of the same world. The Newtonian worldview is highly local, and the quantum mechanics worldview is highly global and ideally wave-like, but they are both low-energy, low-speed, and non-relativistic.

Low-energy photons are similar to phonons, with low energy, and an extensive range of space-time points and matter contribute.

GAI has explained the natural causes of quantization, so there is no need to distinguish between quantum systems and classical systems. Matter-wave comes from low-energy long-range interaction in the standard model that works in laboratory space-time and energy scale. Even the phenomenon seemly participated by only one particle needs to consider the particle interaction with all surrounding electromagnetic objects, that is, the global influence, such as the double-slit condition, the influence of the measuring device, etc.

Comparing with decoherence theory, GAI believes that quantum waves are no different from classical waves. The effective range of a particular wave depends on its temporal and spatial coherence range. The coherence range cannot be unlimited. Decoherence is not discussed in CI but natural in GAI, as in the classical world.

12.4 Real quantum wave

Classical waves are generally not ideal, with diffusion, attenuation, dispersion, and a lifetime, unless there is an external drive.

In principle, quantum waves should be the same. However, since all fundamental interactions are complex, evolving many-body, and nonlinear, ideal waves do not exist. The non-existence of the ideal wave is also why atomic spectrum lines have intrinsic widths.

Due to the vast number of participating objects and numerous dissipation modes, a classical wave in a medium will surely dissipate and decay. In a vacuum, due to the lack of a dissipation mechanism, electromagnetic waves do not attenuate in traveling, and this is why we can see the end of the observable universe. They are just waves, not particles, which is why we can focus, magnify, and image with telescopes.

GAI seamlessly connects classical and quantum theory. Based on SM, we can see the quantum theory from a more classical perspective and the classical world from a more wave-like (quantum) perspective. The standard worldview elaborated by GAI provides a full range of understanding of the world from microscopic to cosmic.

12.5 Coherence range

For the quantum properties to be significant, the system must be in the coherence range of the characteristic oscillation of the quantum matter-wave, or the space-time range while the wave's energy is not significantly dissipated by the external participating objects yet. Coherence, monochromaticity, signal strength, signal-to-noise ratio, etc., are all descriptions of the soundness of the wave. In microscopic conditions, it is the valid space-time range of quantum properties.

Therefore, for any quantum phenomenon, such as interference, delayed-choice experiment, entanglement, and quantum teleportation, it must be limited by the quantum coherence range [137]. In macroscopic conditions, we can control the coherence range to verifying the influence of coherence on quantum properties, such as entanglement. Manipulating coherence range can also prove that all quantum properties are the behavior of matter-wave under certain conditions.

12.6 Generalized quantization

In the standard worldview, we have explained that fundamental physical quantities, such as space-time, energy, angular momentum, etc., are continuous. Quantization is emergence.

Like our previous description of water waves and droplets, quantization is ubiquitous in the macroscopic classical world. For example, when we talk about a person, a person can only be an entire one. A grain of sand, a cell, an atom, a molecule, a crystal lattice, a snowflake, a day, a week, a dynasty, a star, a star system, a galaxy, etc., are all discrete, quantum concepts. However, we don't feel that classical physics is discontinuous.

A person is a complex biochemical dissipation mode that has gradually evolved from molecules to cells and multicellular organisms. Still, it must exist in the form of a complete life body. There are many life forms. Life is also an emergence, resulting from the self-organization of complex chemical and energy dissipation structures and then continuous interaction and evolution with the environment and ecosystem. If we reduce people to organs, tissues, cells, mitochondria, DNA, genes,..., we will find that the basic biochemical processes that control all life are the same. The basic units are the same until they continue to reduce to atoms, nuclei, elementary particles.

However, atoms and elementary particles, like molecules and DNA, are also composite modes. Only the components that make them are no longer familiar to us, but space-time and energy.

Even on the cosmic scale, we can still find some quantum or wave properties, such as the periodicity of the orbit, the geomagnetic reversal, ice age period, orbital resonance between different planets or satellites, the resonance of Mercury's rotation and revolution, etc. Resonance is a typical wave property.

So quantization is not unique to the microscopic world but is ubiquitous at all scales.

12.7 Summation

Quantum property manifests as the discreteness of physical quantities and the coherence of waves. The traditional correspondence principle thinks that the world is discrete. The decoherence theory believes that the environment will destroy quantum coherence. GAI thinks that quantization is a natural emergence; coherence destruction results from dissipation and weakening of relative influence, as in the classical world. As a particular form of the wave, quantization naturally exists at all scales.

13 Origin of quantum probability

13.1 Causality and logic

Our incomprehension of quantum phenomena comes from the fact that they do not conform to our daily cognition convention and logic. They have contradictory properties, such as wave-particle duality. Wave functions are non-physical. We cannot fully know a quantum (uncertainty principle). Reality could be non-objective. The evolution is unpredictable (probabilistic). Superluminal action (nonlocality [138]). Causality problem (delayed choice experiment, future changes the past), etc.

The difference between causality in quantum mechanics and common sense (principle of locality) is the root of the difficulty in understanding various quantum phenomena, including wave-particle duality, nonlocality, delayed-choice experiment, probability, etc.

The physical definition of causality, or the law of causality, is that the consequence of an event cannot be earlier than its cause. In Einstein's special theory of relativity, the consequence cannot be in front of the light cone of the cause (future). That is, the influence of an event on the surrounding cannot exceed the speed of light. It is another statement of the principle of locality [139].

The law of causality has philosophical and logical connotations and is a basic logical principle. The law of physical causality conforms to logical causality and is also the logical basis for our understanding of the physical world. If an event violates the law of causality, it will cause our logical cognitive problems. Many quantum phenomena violate the law of causality. Therefore, von Neumann et al. [140] believe that we should not interpret quantum events with classical logic but should use another formal logic system—quantum logic—to understand. Quantum logic has developed in logic, philosophy, and mathematics [141].

However, in GAI, we do not need another logic system, nor does it violate the law of causality. However, due to the approximation of quantum theory, causality has been changed into another form.

From the perspective of GAI, quantum properties are the final global state of the system. The system has to reside in the effective range of wave function description and within the scope of instantaneous coherence. All objects, including the final potential and boundary conditions after self-consistent evolution, are the final states of all the iterations, omitting intermediate stages.

Let us first look at the process of eigenstate establishment.

13.2 Establishment of the eigenstates

In quantum theory, there is no discussion about establishing the eigenstates, which are merely mathematical solutions. In classical systems, eigenstates are common, such as the resonance frequencies of architectural structures and musical notes. In broad-spectrum driving, the establishment of eigenmodes needs some time to develop. The energy takes some time to concentrates on the eigenmodes. Take playing the flute for an example. When we block or release a hole, the original note fades away fast because it is no longer the eigenmode—the driving energy of blowing concentrates on the new eigenmode, which is the new note. There is a short time for mode switching and energy reconcentration. The driving frequency of blowing is broad-spectrum, but the vibration mode of non-notes fades rapidly, and the designated note grows. The eigenstate establishment time is approximately the length of the flute air column divided by the speed of sound, which is in the order of milliseconds. Considering the general pitch range is less than 1000 Hz, only one or two oscillation cycles are sufficient to complete the transition and indistinguishable by human hearing.

Other eigenmodes or eigenstates establish similarly. In the quantum realm, in most cases, because the size is small, such as the atomic scale, and the speed of light (corresponding to the speed of sound of a flute) is enormous, the time needed to establish the eigenstate is a few attoseconds ($\sim 10^{-18}$ seconds). We can not diagnose a physical process in such a short time yet. It is possible to analyze the transition between musical notes through high-time-resolution audio analysis technology in the flute case.

As long as the fundamental physical interactions are those we know, i. e., the electromagnetic, weak, and strong forces defined in SM, there are only electromagnetic interactions left in the atomic scale. The propagation speed of electromagnetic interaction is tremendous, and the establishment of the global eigenmode is virtually instantaneous. We can not, and usually not necessarily to, study the eigenstate switching, so we only deal with the conversion probabilities between the initial and final states. Since we cannot track the intermediate processes, the probability description is the only valid mathematic method, just like in a coin-tossing case.

The speed of light is enormous, and the size is small, so the speed of light can be approximated as infinity. This approximation is exactly the non-relativistic one Schrödinger's equation needs.

In the process of establishing a global eigenmode, the law of causality is always in effect. However, If we drop all intermediate stages, causality is lost. For example, usually, we cannot predict the outcome of a coin toss. We can predict before the final landing if we keep tracking the coin states with a high-speed camera. There is no difficulty in understanding the whole process. We can find the cause for each rollover, the law of causality is always working, and there is no need for randomness or probability to step in.

Lacking intermediate processes is the origin of quantum probability, as GAI understands. The negligence of the intermediate processes leads to the loss of the causality, hence the probability description.

From the perspective of Schrödinger's equation, the potential and the boundary conditions work together to get the final eigenstate. It is the final result of all micro-interactions and co-evolutions that do obey the law of causality. When we change the boundary conditions, or a measurement happens, the physical progress from the initial state to the new state comprises all micro-evolutions that keep causality.

The self-consistent field methods, random vector iterative method, and variational method used to solve some problems include or imply the complex processes to reach the final state.

We can analyze some classical processes to understand the establishment of a global mode. For example, if you turn on the lamp in a room, the room will light up immediately, but there is a process from dark to bright. The lamp starts to work, and it takes a little time to reach the rated power. The light emitted by the lamp will be absorbed or reflected on surfaces. There is a certain brightness in places where the lamp cannot directly illuminate. The final state we see is a stable state of absorption and balance after multiple complex reflections. Even though this process is very complicated, with many iterations, reaching the equilibrium is still very fast due to the high speed of light and impossible for the human eyes to notice.

As another example, in a room with mirrors on all sides, we can see ourselves reflected many times in the mirror. It seems that there should be an infinite number of us, and all the copies seem to be in the mirror the moment we enter the room, which takes no time. If we move, the infinite number of our copies in the mirror also move synchronously and "instantly". Similarly, this is because the speed of light is too fast. In a room of a size of a few meters, even if the light reflects hundreds of times, it only takes a few microseconds, and our eyes cannot notice. Usually, we can only see dozens of images in the mirror. No matter how many reflections there are, the light will attenuate, and the angle will be too small, making it challenging to discern too many images.

13.3 Interference experiments

In section 12, we stated that the typical range of quantum effect, or wave effect, is its space-time coherence range. In all interference experiments, including double-slit and delayed-choice experiments (quantum eraser), as long as every device (splitter, mirror, slit, etc.) is in the coherence range, they are all one of the global condition and contribute to the global interference pattern. The final pattern results from continuous feedback and interaction of all devices, light paths, and light sources. We cannot tell the time sequence based on the distance between the devices in the light path and the light source because the latter devices also affect the front. It is not the future decision that affected the light path of the past, but we had neglected the process of pattern establishment. The entire optical path is coherent, so the final interference pattern must carry all the optical path information. Like the development of eigenstates, the final interference pattern is developed, not once-through as we usually think. If we ignore the developing process, we lose causality. The cause and the outcome are entangled. The entire light path is the cause, and the interference pattern is the outcome.

Like the high-speed camera tracking coin toss, we can use the very high time resolution photography technique [142] to investigate the light interaction between the components in the interference experiments.

13.4 Quantum entanglement

Take the entanglement experiment of photon pairs as an example: people generally believed that the process happens in the following sequence [143, 144]:

1. Laser irradiates the crystal to produce entangled photon pairs;
2. The photon pairs fly to the polarizers on both sides respectively;
3. The two photons are detected separately and independently on both sides.

When detecting, it seems that each photon knows the state of the other, so a “spooky” over-distance [145] interaction appears to exist.

GAI understands the process differently. The laser’s coherence range is extensive and covers the detection device, and the detection is part of the global condition. Like the delayed-choice experiment, in the range of coherence, cause and outcome are entangled, or the final state has the participation of all objects in the entire coherent range, including the polarizers used for detection. Therefore, when the “entangled” photon pair looms out, an optimal global state (similar to eigenstate) is selected, which is parallel to the direction of one of the polarizers on the two ends, and we have the occurrence of “seems to know the state of the other.”

The difference between the two mechanisms is that the “spooky” superluminal action has nothing to do with coherence, but GAI thinks it does. We can design an experiment to find out. We can use incoherent monochromatic light as the light source or use an electronic shutter to ensure that the generation and detection of photon pairs are separated in time, to see if there is still that “spooky” correlation, to testify the two mechanisms decisively.

13.5 Summation

GAI thinks that the solution of Schrödinger’s equation is a global approximation, which is the system’s final state. The final state’s development is the result of complex micro-interaction processes that obey the law of causality. Eigenstates, delayed-choice experiments, quantum entanglement, etc., all have similar development mechanisms. Although the complete process of reaching the final state is complicated at the quantum scale, the total time is short, and it is difficult to diagnose or observe. If we ignore the process, causality is lost and can only describe with probability. The coherent quantum evolution is integral, global, and undividable. If we divide a coherent process into separate causal sequences, we will get wrong logical reasoning and thus fail to understand the nature of the experiment.

14 Millennium quantum dispute

14.1 Atom and continuum

In 1900, Planck proposed quantum theory and solved the blackbody radiation spectrum problem [1]. In 1913, Bohr and Rutherford assumed that the atomic angular momentum is quantized and explained the hydrogen atom's energy levels. Since then, quantum theory has flourished and has become the fundamental theory that dominates the scientific community. As a result, some classical approaches, such as gravity, have not yet been successfully quantized, torments physicists.

The philosophical origin of quantum theory is ancient Greek atomism. In Greek, the original meaning of "atom" means indivisible, proposed by Leucippus and Democritus. Another source of ancient philosophy, ancient India, has similar theories. Atomism believes that nature is divided into indivisible atoms and voids.

However, ancient Chinese philosophy does not believe that there is an indivisible smallest unit. Zhuangzi, who was about the same time as Leucippus, said that "a foot long whip, halving it every day, it never ends", or we can divide things forever, which is a continuum view.

From today's point of view, the atom theory is true because we can only decompose to the scale of atoms or elementary particles. The continuity theory is not wrong either because we can still divide elementary particles indefinitely. Only later, the energy of the dividing action itself will produce new matter. The breakdown can continue, but we can obtain no smaller units.

14.2 Reductionism, holism, and quantization

Later on, in the development of science, the west scholars more adopted reductionism [146], which believed that we could describe the complex systems, objects, and phenomena as the sum of their components. At the same time, the Asian philosophers used holism more. They believed that reduction might cause the loss of important information for complex objects, and we cannot correctly understand them. Later, the emergence theory of systems science in modern science is the mend to reductionism. As the scale and the number of participants increase, new physical phenomena will emerge, so the reverse of emergence is also true in the reduction process. That is, the physical phenomena that exist only in the original scale will be lost.

Although the idea of quantum originated from reductionism, Schrödinger's equation is holistic because it requires information of all space. However, people still tend to discuss and conjecture from the perspective of reductionism.

GAI understands quantum theory from the perspective of holism without introducing any assumptions. The integrity and approximation of Schrödinger's equation are also widely recognized by physicists. GAI also discusses SM from the perspective of holism and reinterprets the definitions of elementary particles and interactions. GAI thinks that we should use the holistic elementary particle picture. However, the elementary particle tables listed in textbooks are reductionism ones. We should understand the definition as a particular state of a particle, similar to a space-time point concept. We use space points to describe particles' position, but we know particles cannot occupy an infinitely small space point. Similarly, when we say that a photon's energy is a value, it cannot be that single energy value. GAI extends the same analogy to spin, mass, and other properties, previously treated as single definite values.

However, GAI has not given up on atomic theory and quantum theory. Instead, the concept of quantum has been generalized, and we find many quantized manifestations in the macroscopic world.

GAI thinks that the energy quantum proposed by Planck does not exist, and Bohr's atomic angular momentum quantization is natural emergence, not the fundamental premise. The laser is more a collective behavior of numerous resonating same-type atoms, not the property of single atoms.

14.3 Centennial quantum feud

Einstein and Bohr's feud is a topic of great interest all these years whenever talking about quantum theory [147]. Although people believe that Einstein lost in the feud, he did not think that quantum theory was complete till his death. He did not even accept the photon concept proposed mainly by himself and won him the Nobel Prize.

Bohr's nihilism, or idealism, is summarized as: "The moon does not exist when I don't look at it." It has always been the object of criticism from many people.

Schrödinger and Einstein hated the probabilistic interpretation of wave function and measurement collapse. Einstein's famous saying, "God does not play dice with the universe" [148] is an expression of this position. Although Bohr's answer of "Einstein, stop telling God what to do" is clever and eloquent, but it works for himself too. After all, we have no reason to believe that the world is random. Einstein should not tell God not to play dice, and Bohr can not ask God to play either.

Schrödinger brought about the concept of Schrödinger's cat to mock the idea of measuring collapse. However, many people later used it as a thought experiment to describe and prove the legitimacy of measuring collapse.

Einstein's solution to the incompleteness of quantum mechanics, including the paradox of EPR, was the theory of hidden variables. However, numerous Bell experiments falsified his idea. The Bell experiment also makes people believe the nonlocality of quantum, and it challenges the locality principle made by his special theory of relativity. That is to say, his persistence and challenge not only lost the debate on the completeness of EPR and quantum theory but also threatened his other critical contribution-the special theory of relativity.

Einstein was also puzzled by the "Spooky action" of EPR's entangled photons, and that is why he used the word.

Based on the natural materialism instinct, or reality, John Bell was initially on Einstein's side. He believed that the experiment he proposed should prove the hidden variable theory, and there should be no other way. The results of the experiments devasted him.

Bell's confusion is not a problem of him alone, and most physicists have the same doubts. People quote Feynman famous saying, "I think I can safely say that nobody really understands quantum mechanics" [15], to portray the confusion.

In the "play dice" dispute, we conceptually stand on Einstein's side, but we tend to believe that the result of the "dice playing" is predetermined. At least God should know the outcome. Of course, Bohr's argument still stands. We should not demand how nature works.

As for the "Spooky action", we can tell Einstein: "It is not spooky at all, and there is no action."

14.4 Materialism and idealism

Materialism holds that matter is the fundamental substance of the world, and consciousness reflects the material world. Idealism thinks that consciousness is more critical because reality is meaningless if there is no human perception. Materialism and idealism have been two opposing ideological systems, each with different schools.

For physics, physicists in the Newtonian era were more inclined to materialism, while physicists in the quantum era were confused or opposed in this matter. Bohr represents the idealist [149, 150], who believes that measurement and consciousness have a decisive influence in physics, and most physicists accept his argument. Einstein represented materialism and believed in objective reality.

In section 9 "Reality", we said that GAI accepts both materialistic and idealistic views. The materialistic part is that measurement and human consciousness also matter and interact with the material world. The idealistic part is that we can only manifest the knowledge of the world in consciousness. Without consciousness, there is no subject to discuss the world.

Our standard worldview comes from SM. Elementary particles, or matter, are the perturbation modes of energy to space-time, so there are only energy and space-time, not matter in the classical sense. The non-existence of classical matter is a new problem that materialism needs to face. Suppose we define both energy and space-time as matter. In that case, consciousness is also some modes and must be matter, so the materialistic division of matter and consciousness does not exist. The situation for idealism is the same.

The relativity of reality is an amendment to both materialism and idealism.

14.5 Summation

The concept of quantum originated from atomism. Ancient Oriental and Western understandings of the world's origin are different, but they can all justify themselves. The concept of elementary particles is reductionistic. Schrödinger's equation is holistic. Reductionism and holism complement each other. Idealism and materialism are consistent in GAI. Reality is relative. Millenium debate on discreteness and continuum, reductionism and holism, materialism and idealism, may finally find peace in the global approximation interpretation (standard interpretation) of quantum mechanics.

A A longer abstract

Quantum mechanics (QM) understands the physical world from the perspective of waves. In the context of QM, quantum is an ideal wave, which extends to the entire space and is ideally coherent; that is, the phase difference between any two points only depends on the distance of the points. The full-space property of an ideal wave is its globality. In the real world, there is no perfect quantum, and every matter is an imperfect quantum.

Any primary physical quantity, such as space, time, electric potential, magnetic field, angular momentum, and its components, are continuously changing and differentiable. Continuity is the basis of all basic differential physical equations, including Schrödinger's equation and the Lagrangian.

Particles are not point ones. They are the manifestation of energy in space-time or the disturbance of energy to space-time. Elementary particle tables, and composite particles composed of elementary particles, are some stable or intrinsic perturbation modes, such as electrons. The elementary particles that cannot exist alone, namely quarks, are part of a disturbance, similar to concepts such as the magnetic poles. The properties of particles are the manifestations of the fundamental interactions or the nature of space-time. Any particle is a collective mode in which all space-time points participate, and the properties of all space-time points are the same.

The Schrödinger equation is the diffusion equation of quantum waves. The equation has nothing to do with the fundamental interactions. It only reflects the restriction of the global potential and the boundary conditions on the quantum wave, or in other words, what kind of intrinsic wave the potential and the boundary conditions will produce under specific energy. The state of the whole space all contributes to the formation of the eigenfunction. The fundamental interaction is local and complies with the principle of locality. Schrödinger equation assumes that the interaction propagation does not take time (non-relativistic approximation). In the case of electromagnetic interaction, the assumption suggests the speed of light is infinite. In a real scenario, eigenmodes develop from continuous feedbacks of all restrictions in the whole space. For a broad-spectrum wave source, the eigenmodes prevail, and other frequencies quickly damp out. The solution of Schrödinger's equation is the result of the infinite diffusion of a broad-spectrum wave source at any location or eigenwaves.

The solution of the Schrödinger equation, the quantum wave function, is a real wave, and its amplitude modulus is the energy density.

Eigenmodes (eigenstates) are the dominant modes in all wave systems.

There are no point particles, and the wave-particle duality results from the wave interacting with particle events.

Physical quantity quantization is the emergence of the discreteness of eigenstates. Energy and angular momentum themselves are not quantized. Instead, the eigenstates of the bound system are discontinuous, corresponding to discrete energy levels and angular momentum.

The superposition property of quantum states comes from waves.

All ideal quantum states are global (wave). The Copenhagen measurement of quantum states only shows correlation, not causality. In the development of quantum eigenstates, the causality (principle of locality) of fundamental interactions disappears. The quantum state reflects the global conditions rather than the consequence of a particular instantaneous action (disturbance, signal, measurement, etc.). Naming the global property of quantum waves quantum nonlocality (quantum entanglement) and claiming quantum nonlocality is the true nature of physical particles is a misunderstanding of quantum theory. All quantum states are self-entangled or entangled with global conditions.

In a non-ideal case, quantum properties are only valid in the coherence range of quantum waves.

We cannot separate matter from its background electromagnetic radiation environment.

The measurement defined in the Copenhagen interpretation is a random sampling of the quantum state. The state before and after the measurement is discontinuous. The fundamental physical process of measurement is interaction. Interaction-based measurement will affect the original physical system, so we cannot accurately extract complete information from any entity. Measurement-based reality is relative.

Unlike Newtonian determinism and Copenhagen indeterminism, Global Approximation Interpretation thinks the world is determined but only partially predictable due to the relativity of reality and the lack of precise numerical methods. The more macroscopic, the more predictable, the more microscopic, the more unpredictable.

B Differences between GAI and CI

- Timing

  Quantum mechanics is a theory about the microscopic world, elementary particles, and fundamental interactions.

  When CI came about in 1927, people had very little understanding of the fundamental interactions and elementary particles, so they could only put forward theories phenomenologically. Many theoretical and experimental research in particle physics and high-energy physics have much progress in the following decades. We have understood fundamental interactions and elementary particles, but the knowledge is absent in CI. Even the essential feature of coherence is missing.

  GAI has fully considered the development of modern theories and understandings and naturally includes the discussion of coherence.

- Theory foundation

  CI: quantization assumption, matter-wave assumption, Schrodinger equation, wave function probability description, measurement collapse assumption, uncertainty principle, correspondence principle. Later decoherence theory.

  GAI: The standard worldview based on SM, including the concept of elementary particles. GAI elaborated and expanded the concept of particles in SM, elaborated and demonstrated the physical meaning of the Schrödinger equation and wave functions, and believed that matter waves do not require assumptions and are natural features of fundamental interactions. We made no additional assumptions. Coherence is natural and does not require further consideration.

- Quantization

  CI: One of the basic assumptions.

  GAI: Natural emergence of eigenmodes in a wave system.

- Schrödinger equation

  CI: the wave equation of matter waves. Implied the assumption that all quanta are ideal matter-wave.

  GAI: the diffusion equation of matter waves. The solution is global, including information in the entire space. It is an approximate equation with the interaction propagation velocity being assumed infinity. The eigenstates are the natural dominant vibration modes of the system.

- Wave function

  CI: probability distribution function, the square of its modulus is the probability of the specific value, that is, the number density.

  GAI: energy density, the amplitude of a certain fluctuating physical quantity, such as displacement, electric field strength, etc.

  If the quantum energy is a unity, the GAI's wave function image is consistent with the CI.

- The physical picture of the particle

  CI: point particle with inseparable wave behavior or wave-particle duality.

  GAI: wave, including standing wave, energy disturbance mode in space and time. Usually, it is the eigenstate, i.e., the dominant wave mode.

- The physical picture of the photon

  CI: There is no concept of the photon in the first quantization, wave-particle duality.

  GAI: at low energy density, it is an electromagnetic wave. At high energy density, it is a particle (localized wave). This duality is consistent with the standard worldview, or if the energy scale is different, the physical appearance is different.

- Measurement

  CI: probability sampling, the process is discontinuous.

  GAI: The reading of the interaction between the instrument and the system.

- Quantum entanglement, nonlocality

  CI: no discussion. But the solution of Schrödinger's equation is global, and all physical phenomena are naturally global, that is, nonlocal, including wave functions and measurements. Later, the Bell experiment proved space-like long-distance correlation and believed that quantum is nonlocal, which violates the principle of locality.

  GAI: Space-like correlation is a standard wave coherence property, which is global and needs to establish gradually, and the establishment process does not violate the principle of locality.

  By changing the coherence of the light source, and the separation of photon generation and measurement in time, two interpretations can be attested experimentally.

- Reality

  CI: The objectivity before the measurement is meaningless.

  GAI: There is an objective reality before the measurement, but the measurement may change the system, including measuring the intrinsic properties of particles. Measurement-based reality is relative.

- Determinism

  CI: Wave function and measurement are intrinsically probabilistic. Indeterminism.

  GAI: Agnostic (uncalculable, partially calculable) determinism.

- Delayed choice experiments CI: did not answer, believe they are mysterious; the future can change the past.

  GAI: it is a common coherent phenomenon. As long as all components and paths contribute within the wave's coherence range, it results from all coherence components' gradual feedback. The causality is inter-twained.

- Philosophy system

  CI: generally considered to be idealism, agnosticism, and indeterminism. The concept of quantization comes from classical atomism.

  GAI: the standard worldview of physics. Idealism and materialism are consistent, agnostic determinism is compatible with determinism and agnosticism (indeterminism), and atomism and continuity are not contradictory, though both concepts need slight extensions.

C Epilog

C.1 About the authors

Lei Yian In the fall of 1986, Lei Yian saw the Schrödinger equation for the first time, astonished. He had been trying to find out what it means and all other puzzling quantum phenomena even since. He became the student of the best teacher in quantum mechanics in China, Prof. Zeng Jinyan, and worked as a faculty in the Institute of Theoretical Physics, Peking University. He had to work on other researches, such as nuclear structure theory, plasma physics, nuclear fusion, high-performance computing, etc., to make a living. However, he never stopped thinking about the nature of quantum physics and kept tracking the related research and progress. He translated a few books on quantum physics into Chinese. He was skeptical about many of the concepts, such as quantum entanglement, quantum computing, reality, Schrödinger's cat paradox, etc.

About ten years ago, he thought he had some answers and began to talk. This work is an effort to explain the ideas in one piece.

Liu Yiwen Ph. D. student in School of Physics, Peking University.

C.2 Tentative answers to more problems

There are still more questions to be answered. We have some tentative ones to some as listed below.

- **Vacuum**

  As long as there is one single particle in the universe, there is no absolute vacuum.

- **Cashmir effect and vacuum fluctuations**

  There are no fluctuations in the vacuum itself. All fluctuations come from somewhere, although it is difficult to find out. The Casimir effect is a measurement of the vacuum, that is, the response of vacuum to experimental settings, instead of the fluctuating nature of the vacuum.

- **Photoelectric effect**

  Refer to the oil drop experiment. It is not the reaction of a single photon with a single atom. Instead, there are various electromagnetic radiations around the atom. The incident photon brings a certain frequency of excitation to the radiation bank, and an atom uses the appropriate energy in the bank. The experimental evidence is the efficiency of the photoelectric effect.

- **Zero-point energy**

  The zero-point energy of a particle is the result of the constrained potential field. There is no zero-point energy in free space.

- **Principle of least action**

  The principle of least action is limited by the characteristic coherence range of the wave effect.

- **Heisenberg uncertainty principle**

  The fundamental origin of the principle is that there is no point particle in the classical sense.

- **Schrödinger's cat paradox**

  There is a predetermined reality before measurement (opening the box).

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