Does true randomness exist in the universe?

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Abstract: This article explores the existence of true randomness in the universe, challenging traditional mechanistic and deterministic viewpoints. The article begins by demonstrating the random waviness of electrons without external forces through the double-slit experiment in quantum mechanics, as well as the random distribution when individual electrons are imaged on a screen. It then discusses the theory of hidden variables, which suggests that there are undiscovered variables that could explain the deterministic motion of particles. However, experimental results from Bell's inequality have refuted this theory, proving the correctness of quantum mechanics. The article also mentions nonlinear systems in the macro world, such as the three-body problem in chaos theory, illustrating the uncertainty in the macro world. Finally, the article further explains the counterintuitive and random behavior of particles in quantum mechanics through anti-reflective film and delayed-choice experiments, emphasizing that randomness is ubiquitous even in the macro world. The article concludes that although the universe is full of randomness, this does not mean it is unknowable; humans can still understand and control these random phenomena through probability theory.

Keywords: Randomness, Quantum Mechanics, Nonlinear Systems, Three-Body Problem, Macro World, Probability Theory

1. Introduction

In the exploration of the universe, humanity has always yearned to uncover its most fundamental operating principles. Traditionally, many philosophers and scientists have inclined to believing that the universe is deterministic, meaning that every event has a definite cause and effect, thus constituting a predictable universe. However, with the advancement of science, especially the birth of quantum mechanics, this notion has faced an unprecedented challenge. Quantum mechanics has revealed the peculiar behavior of matter at the microscopic scale, among which the most striking is the existence of randomness. This article will lead readers to delve into the randomness in quantum mechanics, from the double-slit experiment of electrons to quantum entanglement, and then to the chaos theory in the macro world. We will gradually unveil the mystery of randomness in the universe. Through these explorations, we will not only understand the role of randomness in nature but also discuss how it affects our understanding of the essence of the universe. Ultimately, we will realize that although the universe is full of uncertainty, it is not unknowable but follows a set of probabilistic laws that we can gradually master.

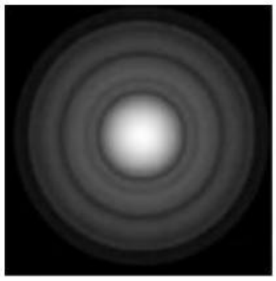
2. Guantum mechanics and wave-particle duality

This perspective originates from the mechanistic philosophical thoughts, and masters like Descartes also believed so. However, today, there is some very clear scientific evidence that negates this philosophical view.

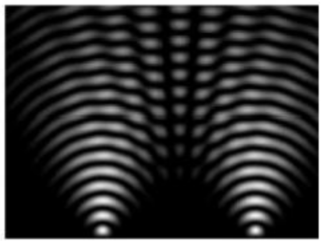
The first is quantum mechanics. Do you think that if electrons are not bound by a field, they will move in a straight line? Previous scientists also thought so, which is why they believed that electrons in atoms follow circular or elliptical orbits. The reality is not the case. Quantum mechanics has discovered that all matter has wave-particle duality, and the motion of an electron is also significantly affected by its wave nature. The simplest experiment is the single-slit diffraction and double-slit interference experiment, similar to optical experiments. When an electron beam is passed through a very narrow slit and projected onto a screen behind it, according to classical theory, the electron either hits the barrier and thus cannot reach the screen, or it

https://doi.org/10.62852/csa/2025/113

passes through the slit and thus hits the screen in a straight line. Therefore, there should be a spot on the screen the same size as the slit. But in reality, a very obvious diffraction pattern is produced on the screen, and the area far exceeds the size of the slit. If the single slit is changed to a double slit, the screen will also display very beautiful interference fringes (Figure 1).



(a)single-slit diffraction



(b)double-slit interference

Figure 1: Diagram of Light Diffraction and Interference Experiment

3. The randomness and wave-particle duality of electrons

The concept of wave-particle duality itself is not problematic; light also exhibits this property, and no one considers light to be random. The issue lies in the fact that electrons are individual particle entities. Although a beam of electrons hitting a screen produces a pattern, what about a single electron? A single electron will only produce a single dot on the screen. This creates a phenomenon where each individual act is irregular, but the collective behavior follows statistical laws. We can only describe this phenomenon as the motion of electrons having randomness, and the randomly distributed probabilities exhibit wave-like behavior.

How should we explain this result? Proponents of mechanistic theory might argue that this randomness is not necessarily inherent to the electrons themselves. It could be due to different initial conditions at the time of electron emission, followed by interactions between the electrons and the slits, causing changes in the electron trajectories. If an electron passes close to the slit, it will deviate outward slightly; the closer it gets, the more it deviates, appearing as if diffraction has occurred. Is this explanation perfect, bringing our electrons back to the track of determinism and mechanistic theory?

4. The double-slit experiment and hidden variable theory

Let's continue to examine the issues with the double-slit experiment. In the double-slit experiment, according to classical theory, an electron can only pass through one slit at a time, so the final pattern observed should be the superposition of two diffraction patterns. However, what is actually seen are interference fringes. If one of the two slits is blocked, the pattern immediately becomes a diffraction pattern. This cannot be explained by the electrons being disturbed by the slits; how could an electron be influenced by a slit it did not pass through?

Proponents of mechanistic theory might argue that perhaps the electron passing through one slit is affected by the electron passing through the other slit, causing the pattern to change. Unfortunately, this hypothesis still does not hold up. Now, let's reduce the rate at which electrons are emitted from the source to such a low level that it is almost impossible for another electron to be emitted before one hits the

https://doi.org/10.62852/csa/2025/113

screen. That is, each electron is imaged on the screen individually. This time, there can be no interference from other electrons, right? As you might have guessed, after a long period of imaging, an interference pattern is still obtained.

This illustrates an astonishing fact: electrons pass through both slits simultaneously in the form of waves, reach the screen in the form of waves, and then appear at different positions on the screen according to probability. Mechanistic theorists, of course, are not so easily convinced, as this is not just a scientific issue but also a philosophical one.

Finally, mechanistic theorists proposed the ultimate proposition: no matter how particles move, no matter how much their motion appears to be random fluctuations, how can you prove that it is truly random? Perhaps there are some hidden variables that we have not yet discovered, and with these hidden variables, the motion of particles would no longer be random but determined?

This view is known as the hidden variable theory, and Einstein was one of its advocates. For a long time, everyone thought this was a philosophical dispute that could not be tested by scientific methods. However, it is ironic that it was the theory of relativity proposed by Einstein himself that ultimately discredited this theory.

5. Quantum entanglement and relativity

Suppose there is a particle with spin 0 that suddenly splits into two particles with spin angular momentum, flying off in opposite directions. It is not necessary to understand the concept of spin; in any case, it is a type of angular momentum. According to the law of conservation of angular momentum, the components of the angular momentum of these two particles in any direction are equal in magnitude and opposite in direction. Both quantum theory and hidden variable theory yield such results.

However, what if these two particles have flown very far apart, say several light-years? When these two particles are measured simultaneously, their angular momenta remain equal in magnitude and opposite in direction. According to relativity, the speed of information transmission cannot exceed the speed of light, so it is impossible for the two particles to reach an agreement instantaneously.

The explanations for this phenomenon are different: Hidden variable theory posits that from the moment the particle splits, the future angular momentum of the particles is already determined, which may be fixed or may change according to a determined law, but the two particles change independently, and due to the initial conditions, no matter when they are measured, their angular momenta are equal in magnitude and opposite in direction. In contrast, quantum mechanics explains that no matter how far apart these two particles are, they remain a single entity (known as a quantum entangled state). Therefore, measuring one of these particles at any time is equivalent to measuring the same entity, no matter how large the span of this entity, so there is no issue of information being transmitted faster than the speed of light.

6. Bell's inequality and the confirmation of randomness

When measurements are made in the same direction, both explanations are tenable. If measurements are made in a direction that is perpendicular, the two measurement results are completely unrelated, and both explanations still hold. However, what if the two measured directions are neither the same nor perpendicular, but at some other angle, such as 45°? The angular momentum in the 45° direction is clearly a combination of the x and y components, and therefore has some correlation with the x component. A scientist named Bell discovered through calculations that under hidden variable theory, this correlation has an upper limit, while the prediction given by quantum mechanics exceeds this limit. Thus, by examining the actual correlation coefficient, it is possible to determine which of the two theories is correct.

Interestingly, Bell actually believed in hidden variable theory and was confident that he could prove quantum mechanics wrong. However, the experimental results showed that the correlation coefficient matched the predictions of quantum mechanics precisely, far exceeding the upper limit of hidden variable theory. This means that hidden variable theory cannot be correct.

Up to this point, humanity has finally reached a conclusion: God does indeed play dice, and there is indeed true randomness in the universe. Or rather, the universe is permeated with true randomness.

https://doi.org/10.62852/csa/2025/113

7. The uncertainty of the macro world

Proponents of mechanistic theory might take some comfort in the idea that the macro world does not seem to have the uncertainty found in quantum mechanics; everything runs precisely according to the laws of physics. Perhaps as long as we do not explore the world of atoms and electrons, we can live in a deterministic world. However, this view was quickly shattered by chaos theory.

Mathematicians have discovered a class of nonlinear problems. Although the physical laws for each step of deduction are deterministic, due to the high degree of nonlinearity in the system, the system exhibits extreme sensitivity to initial values. A classic example is the three-body problem in astrophysics. In a simplified version, there are two large masses, such as the Earth and the Moon, orbiting around their center of mass; there is also a small mass, such as an artificial satellite, launched into a position near the two celestial bodies. What happens? This artificial satellite sometimes orbits the Moon, then suddenly returns to Earth's orbit, then flies to the Moon after a while, and even gets flung out of the Earth-Moon system into the solar system by a gravitational slingshot. If two satellites are launched side by side with only a slight difference in orbital parameters, they will initially run side by side, but later the distance between them increases, and after a period of time, they end up in completely different orbits.

The bad news is that almost all real-world problems are nonlinear models, such as celestial motion, solar activity, weather, life, ecosystems... These systems continuously amplify the details in the initial conditions, which is what people often refer to as the "butterfly effect." Following the chain of causality to seek these subtle initial conditions is ultimately blocked by the "uncertainty principle" of quantum mechanics. This shows that the uncertainty of quantum mechanics is ultimately amplified by macro nonlinear systems, making the macro world full of uncertainty.

So, in summary, there is true randomness in the universe, and randomness is everywhere. The clouds we see in the sky are a fractal system, every detail of which can ultimately be traced back to quantum-level activity; the coastline we see, with its undulating hills, is also random; our life activities, our thoughts, our destiny, and future, all are random.

8. Randomness and regularity

Does randomness signify the triumph of another philosophical "agnosticism"? Although the world we see is random, randomness does not mean that there are no patterns. Probability distributions, expectations, and variances are all real patterns that humans can grasp and control. Therefore, the world is uncertain yet controllable by humans. If God exists, he must indeed be a skillful craftsman.

Let's add an example to further illustrate the huge difference between the world in quantum mechanics and our intuitive understanding. Bell's inequality is essential but not easy to understand. The example we use now has many applications, but analyzing it can be astonishing.

We know that the surface of glass has a certain reflectivity, which allows us to vaguely see our reflection in front of a window. This reflection affects the proportion of light transmitted through the lens, affecting optical performance. So, if we coat the lens with a layer of film, which is also transparent, photons will reflect off the surface of the film and again at the interface between the film and the lens. Normally, thinking about this problem, photons have two chances to reflect, and the total reflection probability should be greater, so less light would pass through. However, when we control the thickness of the film to be exactly one-quarter of a wavelength, the phases of the waves formed by these two reflections are opposite and cancel each other out. The result is that photons pass through the film and the lens surface with a probability of almost 100%!

9. The challenge to determinism

This is quite awkward for determinism. According to determinism, once a photon has encountered the first interface, it has already determined whether or not to reflect. How could a subsequent reflection change the probability of the previous reflection? Of course, supporters of determinism might argue that perhaps light has a special mechanism to determine the situation behind the reflective surface before the reflection, such as a precursor wave that scouts the situation behind the reflective surface before deciding whether to reflect or not.

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There is a specific experiment targeting this hypothesis, known as the delayed-choice experiment, and the following describes a variant of it. Photons are still allowed to encounter a half-transparent and half-reflective mirror, which means the photons may pass through or may reflect, splitting into two beams of waves, just like the effect when photons pass through the first anti-reflective coating.

As shown in Figure 2, after appropriate reflection by two flat mirrors, the photon will reach one of the two detectors, 1 and 2, and which one it reaches is random. Then, imitating the situation that occurs with the anti-reflective coating, a second half-transparent and half-reflective mirror B is inserted, allowing photons from path 1 to reflect with a certain probability and superimpose with path 2 (note that this diagram is often mistakenly thought to show both paths of light hitting B, but that is not the case; only one path hits B, while the other does not pass through B).

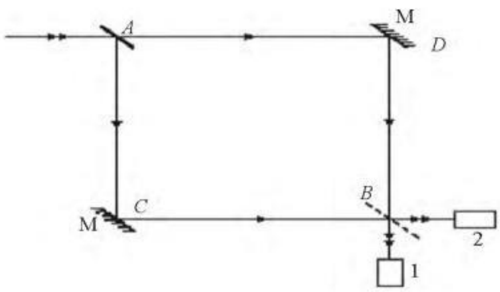

Figure 2: Schematic Diagram of the Delayed-Choice Experiment

When the position of mirror B is appropriate, the light from path 1, after being reflected by B, and path 2, have a path difference of exactly half a wavelength, and thus they cancel each other out due to opposite phases, leaving only path 1. When the photon encounters the two semi-transparent and semi-reflective mirrors, it always passes through A and then through B before arriving at detector 1. When B is removed, the situation reverts to where the photon reaches detectors 1 and 2 in a certain proportion. This is similar to the phenomenon in the anti-reflective coating. So, the proponent of determinism might once again invoke theories like the pilot wave to counterargue.

Now, a shutter is installed for the incident light, which opens for a very short interval and then closes quickly, allowing control over the timing of the emitted photons. Then, the distance of this device is extended sufficiently to let the photon fly around for a while. A very sensitive switch is installed for B, allowing us to quickly insert or remove B. After opening the shutter, let the photon fly until it has passed A but has not yet passed B, and then decide to insert or remove B. When B is inserted, the photon will definitely come along path 1; otherwise, when B is removed, the photon will probabilistically arrive at either path 1 or path 2. It can be seen that whether the photon is reflected at A can actually depend on a decision we make afterward. For quantum mechanics, this is not new; the issue has already been discussed when analyzing double-slit interference, where electrons or photons pass through both slits simultaneously, and here they undergo transmission and reflection at the same time. However, what is novel is that the ratio of transmission to reflection can be determined by future actions. This cannot be explained by a deterministic worldview. It can only be considered that both histories of photon transmission and reflection occur simultaneously, and then, the experimental device can erase one of these histories, leaving only the other. This also illustrates that a definite past does not exist.

10. Conclusion

After exploring the randomness of the universe, we must come to accept a fact: randomness is one of the fundamental characteristics of the universe. From quantum entanglement to the chaos of the macro world, randomness is everywhere present. However, this does not mean that the world is incomprehensible or uncontrollable. On the contrary, through probability theory and statistics, we can reveal the patterns behind

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random events and make predictions and decisions accordingly. The existence of randomness, while challenging the traditional deterministic worldview, also provides us with a richer and more diverse perspective on the universe. In this uncertain world, our wisdom and creativity are given greater value, as we have the ability to seek order amidst randomness and create meaning out of chaos.

https://doi.org/10.62852/csa/2025/113