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Generalized quantum computing and the problem of randomness origin in quantum mechanics

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Highlights:

- Randomness is not a fundamental property of quantum mechanics.
- The phase of the wave function is a hidden variable.
- Randomness in quantum mechanics may be a consequence of the chaotic dynamics.

Abstract: Randomness is the foundation of quantum mechanics. However, existing theories do not explain its origin. In this paper, a hypothesis is proposed that the phase of the wave function is the sole source of randomness in quantum mechanics. Two postulates of quantum mechanics are proposed. The first postulate states that quantum randomness arises as a consequence of a chaotic scattering process in which wave function phases act as variables. The second postulate asserts that particle phases interact within a topological space, ensuring inherently non-local interactions. The relationship between this model and hidden-variable theories is examined, and experiments to test the postulates are proposed. The proposed theory can serve as a basis for the creation of quantum artificial intelligence on a fundamentally new basis.

Keywords: Born's rule; phase of the wave function; group theory; pseudorandom numbers; discrete mapping; quantum computing

"I find the idea quite intolerable that an electron exposed to radiation should choose of its own free will not only its moment to jump off but its direction. In that case I would rather be a cobbler, or even an employee in a gaming house, than a physicist."

Albert Einstein in a letter to Max Born, 20.04.1924

1. Introduction

As is well known, quantum computing is based on the properties of qubits (quantum particles). Unitary transformations are performed on qubits. Finally, a value is measured, which is the result of the quantum computer's operation. One of the most important properties of quantum particles is that the outcome of a measurement is random and cannot be precisely predicted in advance.

However, we don't fully understand many of the laws of quantum mechanics. It's no coincidence that there are multiple interpretations of quantum mechanics. This lack of understanding hinders the development of quantum technologies, such as quantum artificial intelligence.

The randomness of physical events constitutes the core of quantum mechanics. However, where does this randomness come from? Can its fundamental justification be found? Currently, it is believed that the randomness in quantum mechanics cannot be derived from any source.

We need to take a broader look at the problem: is it possible to somehow further control quantum computing?

A hypothesis on the origin of randomness in quantum mechanics, based on the role of the phase of the wave function, is proposed in this paper.

For example, several studies hypothesized about the special role of the phase of the wave function [1–3]. For instance, one study [2] noted that initial and acquired phases during temporal evolution are usually not part of the final expressions for observable physical quantities. Nevertheless, in many cases, observable physical quantities implicitly depend on phases. Therefore, phases can be considered as hidden variables of quantum mechanics. Neglecting the role of phase makes such peculiar quantum effects as particle interference, Einstein–Podolsky–Rosen correlation, and many others inexplicable. Conversely, considering phases reduces the mysteries of quantum mechanics to simple and obvious trivialities. A previous study [3] proposed that each wave function is multiplied by a separate phase factor $\exp(i\alpha)$ with a phase constant α and represents an individual quantum system. In the ensemble of systems, the phase constants are understood as pseudorandom numbers uniformly distributed in the range of $[0, 2\pi]$. All measurements are based on position measurements. By combining the phase constants of the measured system with the phase constants of special components of the measuring apparatus, a hypothesis is proposed regarding the criterion that determines the occurrence of reduction (collapse), understood as spatial compression, and thus determines the outcome of any individual measurement.

2. Randomness and Born's rule

Born's rule is one of the fundamental postulates of quantum mechanics. It establishes the connection between the probability of finding a particle in a certain location and the wave function. If a quantum system is in a pure state,

$$|\Psi\rangle = c_1|1\rangle + c_2|2\rangle + \ldots = \sum_n c_n|n\rangle ,$$

where $|1\rangle, |2\rangle \ldots$ are eigenstates of some observable A. Then, as a result of measurements, the system will collapse into one of its permissible states, and the probability of finding the observable in a particular state is given by (see, for example, [4]):

$$\Pr ob\left(A_n\right) = |c_n|^2 .$$

At the same time, repeated measurements each time yield a different value of the measured variable, which is not related to the previous value. This is how the randomness in quantum mechanics manifests itself.

Attempts to explain Born's rule based on other principles have not been successful. For example, in [5] it is proposed that the Schrödinger equation is a consequence of a random process for which stochastic equations are written. However, in such a case, the origin of the equations remains unclear. In different interpretations of quantum mechanics, there are different derivations of Born's rule.

3. Postulates of quantum mechanics

There are many theorems in quantum mechanics (see, for example [6,7]. However, the above theorems are explicitly or implicitly based on some axioms. The axioms are formulated differently in different monographs. For example, the following statements can be classified as axioms:

(1) The state of a quantum system is determined by a wave function $\Psi(\vec{r},t)$ that depends on the particle's coordinates ***r*** and time *t*. The product $\Psi^*(\vec{r},t)\Psi(\vec{r},t)d\vec{r}$ represents the probability that the particle lies in the volume element $d\vec{r}$ located at ***r*** and time *t*.

(2) Randomness is at the very core of quantum mechanics and cannot be derived from any deeper principle.

(3) In quantum mechanics, a classical observable quantity is associated with a self-adjoint (Hermitian) operator in a Hilbert space.

(4) In any measurement of the observable associated with operator $\hat{A}$ the only values that will ever be observed are the eigenvalues *a*. These eigenvalues satisfy the equation

$$\hat{A}\Psi = a\Psi .$$

(5) If the system is in a state described by the normalized wave function Ψ, then the average value of the observable corresponding to $\hat{A}$ is given by

$$\langle \hat{A} \rangle = \int_{-\infty}^{+\infty} \Psi^* \hat{A} \Psi d\vec{r} .$$

(6) The wave function or state function of a system evolves in time according to the time-dependent Schrödinger equation

$$\hat{H}\Psi = i\hbar \frac{\partial \Psi}{\partial t}.$$

(7) The total wave function must be antisymmetric with respect to the interchange of all coordinates of one fermion with those of another.

(8) Postulate of measurements. When a quantum system is measured by a macroscopic device, it passes from a pure state to a mixed one, as a result of which it will not be in a superposition of its states, but in some specific state.

It should be noted, however, that the axioms (postulates) put forward are mathematical abstractions and are not directly verifiable by experience. Only certain conclusions from them are verified.

It should be noted, however, that there is no guarantee that these postulates are eternal, especially if we recall that the postulates of physics were completely different just 130 years ago.

Moreover, it is inherently difficult to prove that something cannot exist in nature if it has not yet been observed; perhaps we simply have not performed the appropriate experiment.

Consequently, alternative axioms (assumptions) can be put forward.

4. Phase of the wave function as a control parameter

However, it is possible to provide a simple explanation for the origin of randomness in quantum mechanics. Let us assume that the phase of the wave function plays a crucial role in the emergence of randomness and entanglement.

Let us consider the interaction of arbitrary quantum particles without taking into account their specific interactions. It is known that the solution of the Schrödinger Equation (1) for a particle

$$i\hbar \frac{\partial \Psi}{\partial t} = \widehat{H}\Psi \tag{1}$$

in the general case is given by the function (2)

$$\Psi(\vec{r},t) = \psi(\vec{r})\exp\left(-\frac{iEt}{\hbar}\right)e^{i\varphi}. \tag{2}$$

It is assumed that the wave function is determined up to a phase factor because the probability density is determined by the square of the wave function and well-known equality

$$\left|e^{i\varphi}\right| = 1$$

is satisfied. However, the wave function itself is considered unmeasurable.

It should be noted that the relative phases between different quantum states in a coherent superposition can produce observable effects through quantum interference. A well-known example of this is the Mach–Zehnder interferometer [8].

However, though this phase is not directly measurable in our experiments, it should be taken into account because all quantum particles have different phases. This phase difference can be interpreted as the intrinsic time of the particle, which is not directly measurable.

In this case, postulate 2 from the above list can be reformulated as follows:

Postulate 2: Randomness in quantum mechanics arises from an underlying deterministic physical process. It is not truly random, but rather pseudo-randomness determined by the phases of the particles' wave functions.

If such a scattering process is performed multiple times, the phases of the particles involved in the process, as well as the phases of the particles resulting from the scattering, will be different each time. This property suggests that the specific realization of scattering through a particular reaction channel (which, of course, depends on the specific interaction) is determined by this phase and is deterministic and predictable. In this case, all randomness in quantum mechanics is determined by the uncontrollable phase of the interacting particles.

Then, Born's rule is simply a consequence of the fact that when there are many experiments, we cannot control the phases of particles, and these phases are the source of randomness.

The phase of the wave function is also related to quantum action $S(x,E,t)$:

$$\Psi(x,E,t) = A\exp\left(\frac{iS(x,E,t)}{\hbar}\right), \tag{3}$$

In this case, we can write the quantum analog of the Hamilton–Jacobi equation, where $V(x)$ represents the potential energy:

$$-\frac{\partial S}{\partial t}=\frac{1}{2m}\left[\left(\frac{\partial S}{\partial x}\right)^2-i\hbar\frac{\partial^2 S}{\partial x^2}\right]-V(x), \tag{4}$$

and controlling the phase means controlling the quantum action.

5. Group theory, topological space, and quantum mechanics

Let us formulate one additional important postulate.

Postulate 9: The phases of particles interact within a topological space that is more general than a metric space.

Let us give a definition of a topological space (see, for example, [9]).

Let X be a nonempty set. A set τ of subsets of X is called a topology on X if:

(1) The set X itself and the empty set $\varnothing$ belong to τ.

(2) The union of any (finite and infinite) number of sets from τ belongs to τ.

(3) The intersection of any two sets from τ belongs to τ.

The pair (X,τ) is called a topological space.

Suppose that our metric space is embedded in a topological space. Clearly, our metric space is itself topological, but not vice versa.

It should be noted that our measurement methods do not allow the direct measurement of space and time.

For example, the standard unit of length in the International System of Units (SI) is the meter, defined as the distance traveled by light in a vacuum in 1/299,792,458 of a second. The second itself is defined as the duration of 9,192,631,770 periods of radiation corresponding to the transition between two hyperfine levels of the ground state of a cesium-133 atom. While this issue merits separate discussion, it is important to note that none of our instruments directly measures time or space; instead, they register quantum events associated with the emission or absorption of particles. Our understanding of space and time is therefore always inferred indirectly.

This suggests that the same difficulties encountered in measuring particles may also arise when attempting to measure space itself. It is possible that there are limitations, analogous to the uncertainty principle, which prevent us from determining certain topological properties of space-time.

As a mathematical basis for modeling within the framework of the proposed postulates, group theory is the most suitable (see, for example [10]). This theory also underlies all calculations (generalized calculations).

A group G is a finite or infinite set of elements with a group operation "$\cdot$", which combines any two elements $a,b\in G$ to produce another element c that also belongs to G:

$$a\cdot b=c.$$

In this case, the group operation, commonly referred to as multiplication, must satisfy three conditions.

(1) $p\cdot(q\cdot r)=(p\cdot q)\cdot r$ (associativity).

(2) There is a unique element 1 in the group that satisfies the property $1\cdot x=x\cdot 1=x$ for any $x\in G$.

(3) Each element $x\in G$ has an inverse x^{-1}:

$$x\cdot x^{-1}=x^{-1}\cdot x=1.$$

Let us also consider the complex plane with a unit circle. Then, each point on this circle represents a phase. Consider a complex number z with a unit modulus. Then, interactions between the phases of different particles correspond to certain operations on complex numbers.

The group U(1) (unitary group of order 1) is the multiplicative abelian group of all complex numbers with a unit modulus:

$$\{z \in C : |z| = 1\}.$$

This group is a one-dimensional Lie group and represents a circle. U(1) is a subgroup of SU(2), which consists of rotations in two-dimensional real space.

A ring is a mathematical structure related to a group, and its formalism is likewise suitable for modeling interactions of phases [10].

Group theory is closely related to the concept of symmetry, which is one of the central ideas in physics (see, for example, the classical monograph by Elliot and Dawber, [11]). That work examines numerous applications of group theory, including its role in describing space and time.

However, as is well known, symmetry can be hidden and may not manifest in most measurements; this is the case, for example, for hidden symmetries of dynamical systems [12].

Hidden symmetries are symmetries that are not related to the underlying space-time symmetries. In dynamical systems, hidden symmetry is a profound property: conserved quantities, or integrals of motion, can exist that are not immediately obvious. These quantities are associated with continuous transformations that leave the equations of motion unchanged, but are not directly visible, and they can give rise to complex, chaotic trajectories while still preserving an underlying ordered structure. This hidden order helps explain why a system can behave predictably over the long term.

Hidden symmetries are particularly important in chaotic systems. The problem of randomization, or the emergence of apparent randomness, is the focus of this article.

Suppose that, for an arbitrary interaction of phases, a certain equality holds:

$$(\varphi_1, \varphi_2, \dots \varphi_m)^{out} = \Omega(\varphi_1, \varphi_2, \dots \varphi_n)^{in}. \tag{5}$$

Here, the "*in*" and "*out*" indices correspond to the states of the particles before and after scattering (or measurement). The function Ω represents a deterministic operation on the phases of the interacting particles (Figure 1).

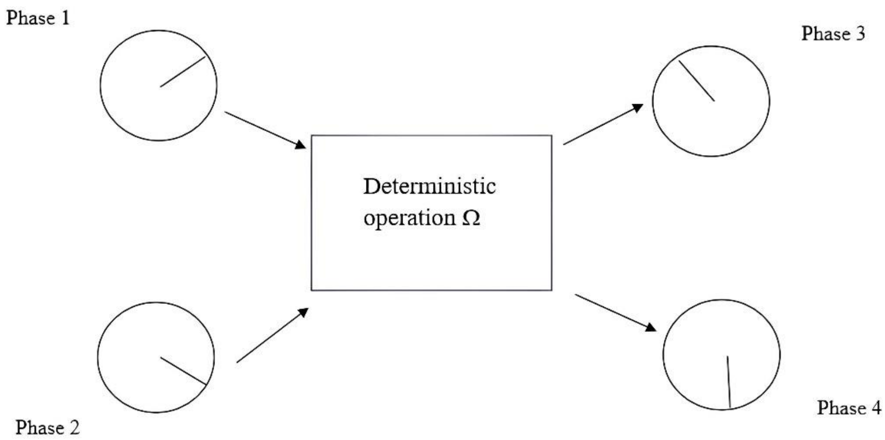

Figure 1. Deterministic transformation of phases.

Additionally, any particle involved in scattering has already undergone previous scattering events. This principle ensures that the phases of the particles participating in the scattering are uncorrelated.

In fact, equality Equation (5) can be interpreted as a multidimensional discrete mapping. Chaotic behavior is typical for a wide class of discrete mappings. For example, even the simplest cubic mapping exhibits chaotic behavior for certain parameter values:

$$x_{n+1} = rx_n\left(1 - x_n^2\right) \tag{6}$$

Mappings such as Equation (6) possess a prediction horizon beyond which the system's behavior becomes chaotic and therefore unpredictable.

Thus, the analysis above suggests that, in reality, the scattering of quantum particles is not truly random, but pseudorandom. Pseudorandom numbers are well known in cryptography, and pseudorandom number generators are widely used. Each such generator is an algorithm that produces a sequence of numbers whose properties closely resemble those of truly random sequences. However, the sequence produced by pseudorandom number generators is not truly random [13].

Algebraic topology (Figure 2) is a field that combines topology and algebra and is one of the most promising disciplines for the development of the proposed ideas.

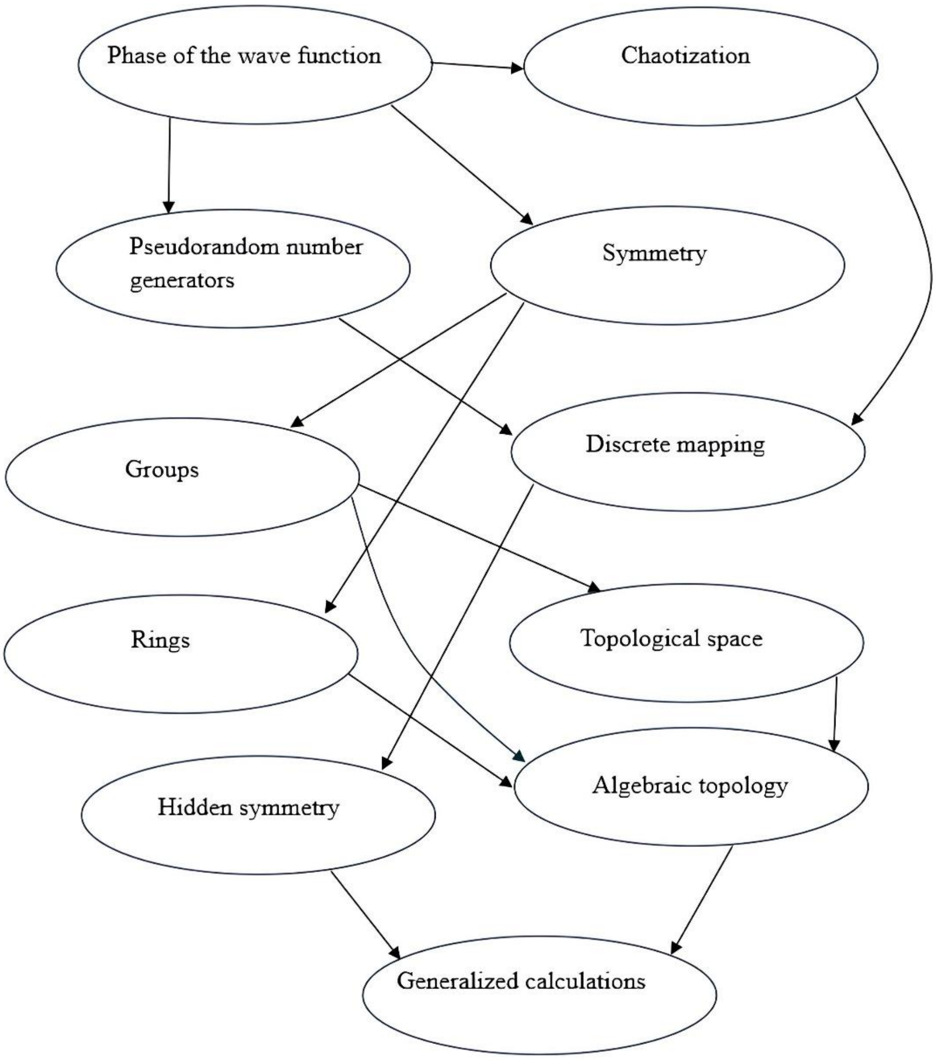

Figure 2. Relationships among some of the areas discussed in this article.

6. The phase of the wave function and hidden parameters, related theories

The phase of the wave function, being immeasurable, is in many ways close in properties to the hidden parameters in quantum mechanics.

The hidden-variable theory is a deterministic model that seeks to explain the probabilistic nature of quantum mechanics by introducing additional, possibly inaccessible, variables.

Historically, the first theory with hidden parameters was the de Broglie-Bohm theory [14].

Many papers have published evidence of the impossibility of maintaining hidden parameters (see, for example, [15,16].

For example, in [17], the authors asked whether it was possible to achieve any improved predictions using any extension of quantum theory. According to the authors, the answer to this question should be negative: no extension of quantum theory can provide more information about the results of future measurements than quantum theory itself.

However, these proofs themselves have significant limitations.

First, it is impossible to prove the absence of hidden variables in all possible cases because the proofs rely on a limited set of known axioms of quantum mechanics.

Second, these proofs are valid only within our usual metric space. Although, Bell’s theorem constrains local causality, this theorem still involves space, since the term “local” refers specifically to our metric space. If the space is extended to a topological one, there is no reason to rule out the existence of hidden variables. A topological space naturally allows for non-local interactions because metric distances play a very different role in such a space.

It is also important to recall that our measurements in quantum mechanics are significantly limited. In a sense, they are coarse because we can only measure the square of the modulus of the wave function. But what does it mean to measure the square of the modulus? It is equivalent to measuring the magnitude of a vector without knowing its direction. This implies that the phase of the wave function may contain a substantial amount of additional, important information. If we cannot measure it directly yet, it may be necessary to accept that we can only infer certain properties of particles indirectly.

The de Broglie–Bohm theory is the approach most closely related to the one under consideration.

The main similarity to the de Broglie–Bohm model is that in both models, quantum mechanics is also deterministic and predictable.

The proposed interpretation is closely related to the Bohmian interpretation, in which the holographic principle is applied to the entire universe. This means that the quantum mechanical laws we deal with are just the beginning, while the rest of the world remains undetected by us. This applies particularly to the topological space.

Bohm postulated [18–20] that each spatiotemporal region of the world contains the entire order of the universe. This includes the past, present, and future. Similar to a hologram, where each segment contains information about the entire recorded object, each perceived portion of the world contains complete information about the structure of the universe or the entire world. In particular, Pribram [21] considered the brain as a holographic structure.

According to Bohm [18], the motion of enfolding and unfolding is a fundamental reality, while the objects, entities, forms, *etc.* emerging in this motion are secondary. Laws of quantum theory, which can be applied to all matter, can describe motion in which there is a continuous enfolding of the whole into each part along with the unfolding of each part back into the whole. Although this process may have many specific forms (some known and some yet unknown), this motion, to our knowledge, is universal. Bohm termed this universal motion of enfolding and unfolding “holomovement.”

Bohm argued that holomovement is the fundamental reality, at least as far as we can comprehend it, and that all entities, objects, and forms, as commonly perceived by us, are autonomous features of the holomovement, much like eddies are features of the current motion of a fluid. Therefore, the fundamental order of this motion is enfolding and unfolding. Thus, we view the universe as a new order, which Bohm termed the “implicate order.”

In the implicate order, everything is enfolded into everything else. However, the entire universe, in principle, is enfolded into each of its parts through active holomovement—just like all its parts. This implies that the dynamic activity is based on the enfolding of everything else, including the entire universe. Of course, each part can unfold the other parts to varying degrees and in various ways. Thus, the parts are not enfolded to the same extent. However, the fundamental principle of enfolding is not negated by this.

Therefore, enfolding is not merely superficial or passive. Each part is internally connected fundamentally in its essential activity with the whole and all other parts.

The author entirely agrees with these ideas.

In fact, in this work, another type of implicate order is proposed, associated with the phase of the wave function.

The proposed ideas are also related, in a sense, to the concept of superdeterminism. A superdeterministic theory is one that violates the assumption of statistical independence, meaning that the distributions of hidden variables are not independent of the measurement settings [22]. However, in this case, phase is a global superdeterministic initial condition, which differs from the case considered in this paper.

Unfortunately, this concept is practically impossible to verify experimentally.

Developing a deterministic version of quantum mechanics could provide a deeper understanding of intelligence.

However, natural intelligence is important not only on its own but also as a guide for building artificial intelligence systems. Conversely, the development of quantum artificial intelligence may help us uncover the underlying patterns of brain function.

Thus, it is possible that quantum mechanics is a deterministic science. However, within the framework of quantum mechanics itself, we do not have the tools to control the specific realizations of the phase of each particle. Nevertheless, this does not mean that such tools cannot exist in principle. It is possible that in strong gravitational fields, certain aspects of quantum mechanics (such as the superposition principle) can be violated. Then, controlling quantum randomness would become possible through phase control.

A recent survey [23] has shown that a significant number of scientists consider the Copenhagen interpretation of quantum mechanics unsatisfactory. Although voting is not a criterion of truth, its results clearly indicate that our understanding of quantum mechanics is far from sufficient. As a result, we also do not fully understand quantum computing.

Currently, the development of quantum artificial intelligence suggests that many technical challenges can be overcome [24–26]. However, understanding the fundamentals of quantum mechanics is essential and could lead to fundamentally new quantum artificial intelligence technologies. In particular, using additional algebraic operations, it is possible to introduce the concept of generalized quantum computing. It can be assumed that additional capabilities for controlling the behavior of quantum particles will enable the creation of quantum AI based on fundamentally new principles.

7. Potential experimental verification of the hypothesis

The following experiments can be proposed to test the hypothesis. It is possible to perform large-scale verification of the outcomes of quantum experiments to examine their randomness. Methods for such testing have already been developed for random number generators. It may turn out that the results of certain quantum experiments are not completely random. Even a small deviation from perfect randomness would represent a significant and important new finding. This would imply that the outcomes of quantum experiments are not truly random, but only pseudorandom.

The smaller the effect, the stricter the requirements for randomness testing and the more challenging the experiment becomes. Nevertheless, such an experiment is feasible.

The experimental outcomes may also vary depending on the quantum phenomena under study. Quantum mechanics in weak fields is well understood, and experiments in such conditions are relatively straightforward. In contrast, strong fields have been studied far less because experiments in these regimes are more difficult to perform. It is precisely in strong fields that deviations from perfect randomness might be observed.

A positive result in such experiments would indicate that randomness is not a fundamental, irreducible property of quantum mechanics, but rather a consequence of deeper underlying patterns.

8. Conclusion and prospects

The uncontrollable phase of the wave function is the source of randomness in quantum mechanics. Randomness in quantum mechanics is simply a consequence of our inability to control the phase of an elementary particle. In this case, quantum randomness is a consequence of an underlying deterministic process, and the resulting outcomes are pseudorandom rather than truly random. It is also proposed that the phases of quantum particles interact within a topological space, which naturally ensures the nonlocality of these interactions.

Experimental approaches are proposed that could confirm or refute the hypotheses.

Quoting Einstein: “I, at any rate, am convinced that [God] does not throw dice.” If by the term “God” we mean the laws of the universe, then this statement is applicable to this article.

Problems such as the measurement problem in quantum mechanics, entanglement, and faster-than-light communication can be viewed as potential avenues for further developing these ideas. Each of these problems may require its own critical experiments and theoretical frameworks. Additionally, continued efforts to model the brain and the processes of thought remain important—not only for understanding natural intelligence, but also for guiding the creation of artificial quantum intelligence.

Based on the proposed formalism, quantum computers on a fundamentally new basis can be created in the future.

Declaration of generative AI and AI-assisted technologies

The author did not use generative AI or AI-assisted technologies. The author takes full responsibility for the content of the manuscript.

Conflicts of interest

Alexey V. Melkikh holds the position of Associate Editor for *Quantum Research* and has not peer reviewed or made any editorial decisions for this paper. The author declares no other conflicts of interest associated with this manuscript.

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