Interpreting the collapse process in terms of new motion of particle

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Aiming at providing an objective picture for the collapse process of wave function during measurement, further analysis about the quantum discontinuous motion [10] is presented, when considering general relativity we show that the new motion is essentially replaced by the quantum jump motion, which naturally results in the collapse process of the wave function. Furthermore, a concrete theoretical model is given to interpret the collapse process quantitatively, and the coincidence between its theoretical prediction and the experimental evidences is also discussed. At last, the possibility to confirm the collapse model is analyzed.

I. INTRODUCTION

In order to provide a complete theory, the founders of quantum mechanics cleverly added a simple projection postulate to its consistent axiom system to account for the measurement process [16], whereas this postulate is evidently a conditional description about the measurement process, it says nothing about how the measurement can and does bring about one definite result, or how the collapse process of the wave function happens during measurement, so the projection postulate needs to be further explained in physics [4] [17] [19].

In recent years many efforts have been made to tackle the so-called collapse problem, and it is well known that in order to bring about the collapse process of the wave function, some kind of randomness should take effect in the normal deterministic evolution of the wave function, but, up to now, the randomness has not been introduced into on a solid basis yet, for example, in the well-known GRWP theory [11] [12] [17] [18] the randomness comes from the special quantum fluctuations of space-time, which is still ill-defined without a consistent quantum theory of gravity; while in Penrose’s proposal of gravity-induced quantum state reduction [19] [20], the origin of the randomness is not touched on at all, in fact, based on the fundamental conflict between the principle of general covariance of general relativity and the principle of superposition of quantum mechanics, what he can conclude in a heuristic way is only that the collapse process should happen when relativistic gravity is considered in the evolution of the wave function, since in the absence of randomness this conflict alone can not provide an answer about how the collapse process happens.

Now, the new motion of particle [10] just provides such a broad framework for objectively studying the microscopic process that it may also help to solve the collapse problem, for example, there may exist many kinds of concrete motion modes among the new motion, and the new motion may display differently in the nonrelativistic and relativistic domains, especially when involving relativistic gravity the new motion of particle may naturally provide the origin of randomness in the collapse process, and further result in the objective collapse process.

The plan of this paper is as follows: In Sect. 2 we first analyze and give the natural origin of randomness in the collapse process. Then in Sect. 3 the possible role of gravity in the collapse process is carefully examined, and the proper existence of local position state is demonstrated. In Sect. 4 we give a strict definition of the quantum jump motion, and its evolution principles are also presented, especially its relation with the collapse process is deeply analyzed. In Sect. 5, as one example, we analyze in detail the collapse process for two-state system using the evolution principles of quantum jump motion, and the concrete collapse time for such system is deduced out. In Sect. 6 we give a general evolution equation of the quantum jump motion, which can be used to account for the collapse process of any wave function. Then in Sect. 7 some experimental evidences supporting our collapse model are discussed, and their coincidence with the prediction of our collapse model is demonstrate. In sect. 8 we give some further theoretical implications on the future theory of quantum gravity. At last, in Sect. 9 we analyze the possibility to confirm our collapse model using present technology.
II. THE NATURAL ORIGIN OF RANDOMNESS IN THE COLLAPSE PROCESS

As we have known, what the wave function objectively describes is the new motion of the particle [10], while the essential discontinuity of the new motion may provide the inherent randomness in the collapse process from the inside. But in case of no gravity this kind of randomness does not appear in the normal deterministic evolution of the new motion state, since even during infinitesimal time interval the particle undergoing the new motion can still move throughout the whole space with a certain position measure density \( \rho(x, t) \), namely the essential discontinuity or randomness is de facto absorbed in the definition of the new motion state such as \( \rho(x, t) \) etc; on the other hand, when the normal deterministic evolution of the new motion is invalidated in some situation, the veiled inherent randomness of the new motion may appear, in the following we will analyze the possible invalidation of normal deterministic evolution of the new motion.

According to the analysis about the new quantum discontinuous motion [10], there are two important preconditions for the normal deterministic linear evolution of the wave function, one is the evolution of the wave function is studied in the nonrelativistic domain, the other is the existence of the nonlocal space-time reference framework.

As to the first precondition, when in nonrelativistic domain the transfer of interaction is instantaneous, thus for the wave function describing the quantum discontinuous motion of particle, its different branches will not interact, this ensures the linear superposition principle of the wave function at an exterior level, when in relativistic domain the transfer velocity of interaction is finite, thus for the wave function describing the quantum discontinuous motion of particle, its different branches will interact through the transfer particle of the interaction including no gravity, for example, in quantum electrodynamics the different branches of the electron wave function will interact through the photon, which is characterized by the interaction term \( \bar{\psi} \gamma^\mu A_\mu \psi \), this interaction between the different branches of the wave function will exteriorly invalidate the linear superposition principle of the electron wave function, but as we have done in relativistic quantum field involving no gravity, this kind of interaction can still be naturally and consistently included in the framework of the normal linear evolution, so there exists no ultimate threat, and the inherent randomness is still veiled in the state definition.

As to the second precondition, the existence of the nonlocal space-time reference framework ensures the linear superposition principle of the wave function at an interior level, since as we have demonstrated [10], its existence will essentially result in the existence of the equivalent nonlocal momentum description of the new motion, which further determines the one-to-one relation between the nonlocal momentum description and local position description, then the most important linear superposition principle of the wave function is deduced out, thus the existence of the nonlocal space-time reference framework is the essential basis of the linear superposition principle of the wave function, or we can say, it ensures the normal deterministic linear evolution of the wave function from the inside, and its nonexistence may essentially result in the breakdown of the normal deterministic linear evolution of the new motion, and the veiled inherent randomness of the new motion may appear. In the following, we will study where the nonlocal space-time reference framework fails to exist, and how the veiled inherent randomness of the new motion appears.

III. THE POSSIBLE ROLE OF GRAVITY IN THE COLLAPSE PROCESS

A. A general analysis

As we have known, according to general relativity there does not exist any nonlocal space-time reference framework at all, then the usual nonlocal momentum eigenstate \( e^{ipx} \) for describing the normal new motion can not be properly defined, and the usual linear superposition principle of the wave function will be broken from the inside, thus the ubiquitous gravity will essentially invalidate the above second precondition of the normal linear evolution of the wave function.

Furthermore, in case of the nonexistence of any nonlocal space-time reference framework, no nonlocal momentum state of the new motion is permitted, and the local position state will be the only proper state, thus the evolution of the new motion, as well as the existence of the new motion, will be extremely different from the normal one, although no complete formulation of quantum gravity is in hand, we can still discuss the essential characters of this kind of new existence and evolution involving relativistic gravity, and give a crude but rational theoretical model to account for the resulting collapse process, in the following discussions we will always call relativistic gravity gravity for simplicity.
On the one hand, when gravity comes into play, the only existence of local position state for the new motion will essentially change the motion mode of the new motion, concretely speaking, during infinitesimal time interval the particle undergoing the new motion can no longer move throughout the whole space with the original position measure density \( \rho(x, t) \), on the contrary, it can only be in a local position state, we suppose the space size of this local position state is \( L_g \).

On the other hand, the discontinuous nature of the new motion requires that during a finite time interval the particle undergoing the new motion can still move throughout the whole space with the original position measure density \( \rho(x, t) \), while in order not to destroy the local spreading law of energy this finite time interval will be terrifically small, during which the usual proper definition of energy, or even time, may not exist, since this time interval provides a time limit of the valid existence of the new motion state, we call this finite time interval the minimal valid existing time \( T_e \) of the new motion state, or wave function describing the new motion, it further means that if the particle stays in a local region much longer than this time interval, then it will collapse into the local state in this region, or we can say, this time interval may also provide a determinant condition for the occurrence of the collapse process; furthermore, the particle will generally stay in a local region \( L_g \) for a time interval much shorter than this time interval, we assume the minimal average staying time in a local region is a universal one, and we will further analyze its deep implications.

C. The implications of the space-time uncertainty

As Karolyhazy et al have denoted [14], when combining quantum mechanics and general relativity the uncertainty of space-time is \( \Delta T^3 = T_p^2 T \) and \( \Delta L^3 = L_p^2 L \), and Adler et al have recently re-demonstrated that the well-known gravitational uncertainty principle \( \Delta x \geq \hbar/\Delta p + L^2 \Delta \rho/\hbar \) is universally valid [2], thus we assume that the above uncertainty relation of space-time is an universal one, and we will further analyze its deep implications.

First, when \( T < T_p \) and \( L < L_p \) we have \( \Delta T > T \) and \( \Delta L > L \), then this result evidently indicates that when \( T < T_p \) and \( L < L_p \) the uncertainty of time and space will be larger than the time and space themselves, and the space-time stage on which everything is defined will fall into ruins, thus the inherent uncertainty of quantum mechanics makes itself invalid within the extraordinarily small Planck time \( T_p \) when satisfying general relativity, and the definition of the wave function in quantum mechanics will be also essentially invalid, or the usual nonlocal state of the quantum discontinuous motion will be also ill-defined and meaningless within the Planck size \( T_p \) and \( L_p \).

Secondly, the above uncertainty of space-time indicates that there exists an absolute minimum uncertainty \( L_p \) and \( T_p \) for the space-time where all particles exist and move, namely the minimum distinguishable size of position and time of the particle are \( L_p \) and \( T_p \), thus in physics the rational existence of the particle is no longer in one position at one instant, but limited in a space interval \( L_p \) during a finite time interval \( T_p \), furthermore, during this finite time interval \( T_p \) the particle can only be limited in a space interval \( L_p \), since if it can move throughout at least two different local regions with separation size larger than \( L_p \), the time interval \( T_p \), then there essentially exists a smaller distinguishable finite time interval than \( T_p \), which evidently contradicts the above conclusion, thus the above uncertainty of space-time essentially results in the rational existence of local position state for the new motion, in which the particle stays in a local region with size \( L_p \) for a time interval \( T_p \), and since the time uncertainty formula \( \Delta T^3 = T_p^2 T \) is irrelevant to the mass of the particle, as well as the concrete form of the wave function, this kind of local position state will be the same for any wave function of any particle, and will be one kind of general existence, we may call such general local position Planck cell state.

Thirdly, since the original new motion state or wave function in quantum mechanics is defined during infinitesimal time interval, the above conclusion will further result in that the proper state which can be consistently defined should be only the local state, and the new motion state or wave function can only be in use for a finite time interval much larger than \( T_p \), during which the particle may move throughout the whole space with the position measure density \( \rho(x, t) = |\psi(x, t)|^2 \) in quantum mechanics.

IV. THE APPEARANCE OF QUANTUM JUMP MOTION

"In essence, it is general relativity that turns the quantum discontinuous motion into quantum jump motion."

Now, according to the above analysis, the quantum discontinuous motion will be naturally replaced by a new kind of motion mode, which is different from both quantum discontinuous motion and classical continuous motion, we call it quantum jump motion.
A. The definition of quantum jump motion

Here we will give a strict definition about the quantum jump motion.

(1). The quantum jump motion state of a particle in space is the local position state, in which the particle stays in a local region with size near $L_p$ for a time interval near $T_p$.

(2). During a time interval much larger than $T_p$, which is still extremely smaller than usual time interval in quantum mechanics, the particle will move throughout the whole space, which average state is described by the position measure density $\rho(x, t) = |\psi(x, t)|^2$ and position measure fluid density $j(x, t)$ as defined for the normal quantum discontinuous motion.

(3). The evolution of the quantum jump motion is determined by both quantum mechanics and general relativity. The visual physical picture for the quantum jump motion will be that during a finite time interval near $T_p$ the particle will stay in a local region with size near $L_p$, then it will still stay there or jump from this local region to another local region, while during a time interval much larger than $T_p$ the particle will move throughout the whole space with a certain position measure density $\rho(x, t)$ as defined in quantum mechanics.

B. A general discussion

First, it is the requirement of general relativity that results in that the quantum discontinuous motion is replaced by the quantum jump motion, while the appearance of quantum jump motion just releases the randomness inherent in the quantum discontinuous motion, thus it will provide the objective origin of randomness or probability in the collapse process.

Secondly, on the one hand, the particle undergoing the quantum jump motion stays in a local region during infinitesimal time interval, this is similar to the property of classical continuous motion; on the other hand, during a finite time interval much larger than $T_p$ the particle will continually jumps from one local region to another local region, and move throughout the whole space with a certain position measure density $\rho(x, t)$, this is similar to the property of quantum discontinuous motion, thus the quantum jump motion is evidently some kind of compromise of quantum discontinuous motion and classical continuous motion, and it will undoubtedly be responsible for the transition from quantum discontinuous motion to classical continuous motion, or from microscopic world to macroscopic world, at the same time, it will be also the origin of the mysterious collapse process of the wave function.

C. The evolution principles of quantum jump motion

As to the quantum jump motion, the particle does stay in a local region for a finite nonzero time interval, and jump from this local region to another local region stochastically, thus the position measure density $\rho(x, t)$ of the particle will be essentially changed by the finite nonzero stay time in a stochastic way related to the stochastic stay region, and the normal deterministic linear evolution of the wave function will be also stochastically changed, in fact, as we will demonstrate, this new element of stochastic evolution just plays an essential role in generating the collapse process.

1. The first principle

As we have demonstrated, the quantum discontinuous motion is some kind of average of the quantum jump motion during a finite time interval much larger than $T_p$, thus the position measure density $\rho(x, t)$ of the particle will be also the average of the position distribution of the particle undergoing the quantum jump motion during this time interval, then it is natural that the stochastic position in which the particle stays will satisfy the position measure density $\rho(x, t)$, which may evolve differently from the normal deterministic linear evolution, namely the stochastic stay position of the particle satisfies the distribution

$$P(x, t) = |\psi(x, t)|^2$$

similar to the assumption in usual dynamical collapse models, the probability of the stochastic stay position, which naturally brings about the noise ad hoc introduced in usual dynamical collapse models, is larger in the regions where the position measure density $\rho(x, t)$ is larger, but here it is not an implausible assumption, but a sound physical principle, which can be naturally deduced out from the objective picture of quantum jump motion.

2. The second principle

Now, according to the original definition of the position measure density $\rho(x, t)$ for the quantum discontinuous motion, the finite nonzero stay time for the quantum jump motion in a local region evidently implies that the position
measure density $\rho(x,t)$ in that region will be increased after this finite nonzero stay time interval, and the increase will be larger when the stay time is longer.

We assume the particle undergoing the quantum jump motion stays in a local region or Planck cell $L_p$ for a time interval $T_p$, then according to the definition of the position measure density its value $\rho_c(x,t)$ in this region will be increased, after normalization it is

$$\rho_c(x,t) = \frac{\rho_c(x,t) + \Delta \rho}{1 + \Delta \rho} \tag{2}$$

where $\Delta \rho = T_p / \Delta t_m$, is the increase of the position measure density $\rho_c(x,t)$ in this region, and $k$ is a dimensionless constant, $\Delta t_m \approx \hbar / \Delta E$, is some average maximum permitted stay time, which evidently results from the dimensional requirement and will be further discussed in the following, in fact, this formula essentially differs with the corresponding ad hoc assumption in usual dynamical collapse models, since here it naturally results from the existence of the objective quantum jump motion, which is physically generated by the combination of general relativity and quantum discontinuous motion.

Then we will further analyze the validity of the formula of $\Delta \rho$, first, according to the original objective definition of the position measure density $\rho(x,t)$ describing the new motion, it essentially describes the real position measure distribution of the particle during a time interval, and its probability interpretation is only a derived exterior concept, thus the change of the position measure density $\rho(x,t)$ resulting from the stay time will be essentially related to the stay time itself, not its square or other forms, especially the increase of the position measure density $\rho(x,t)$ will be proportional to the stay time, when the stay time $\Delta t$ is longer the increase of the position measure density $\rho(x,t)$ in this stay region will be larger.

Secondly, we will analyze the validity of the concrete form of $\Delta \rho$, and the origin and meaning of the average maximum permitted stay time $\Delta t_m$, on the one hand, according to the above general analysis, the existence of gravity will essentially change the structure of space-time, and when combined with the new quantum discontinuous motion this kind of change will naturally result in the discrete quantum jump motion of the particle with average minimum time interval $T_p$, thus it is rational we assume the above time interval $T_p$ in the above formula of $\Delta \rho$.

On the other hand, according to the principle of energy conservation, during a finite nonzero time interval $\Delta t$ the possible change of energy $\Delta E_j$ will be limited by the uncertainty relation $\Delta E_j \approx \hbar / \Delta t$, then the particle can hardly jump from this local region to another local region when the difference of the whole energy $\Delta E$ between these two regions satisfies the condition $\Delta E \gg \Delta E_j$, namely after the stay time $\Delta t$ the position measure density $\rho(x,t)$ will be greatly increased, concretely speaking, it will be nearly one in this local region, and nearly zero in other regions, in fact, the wave function has collapsed into this local region in order to satisfy the requirement of energy conservation, and this situation has also manifested that in order to satisfy energy conservation the quantum jump motion will naturally result in the collapse of the wave function; on the contrary, the particle can more easily jump from this local region to another local region when the difference of the whole energy $\Delta E$ between these two regions satisfies the condition $\Delta E \ll \Delta E_j$, namely after the stay time $\Delta t$ the position measure density $\rho(x,t)$ will be only changed slightly.

In one word, these two extreme situations have indicated that the increase of the position measure density $\rho_c(x,t)$ will relate to both the average minimal stay time $T_p$, which denotes the limitation from the combination of general relativity and quantum mechanics, and the average maximum permitted stay time $\Delta t_m = \hbar / \Delta E$, or the difference of the whole energy $\Delta E$ of the particle between the destination local region and original region, which denotes the limitation from the principle of energy conservation. Furthermore, the increase of the position measure density $\rho(x,t)$ will be proportional to the stay time $T_p$, and reversely proportional to the average maximum permitted stay time $\Delta t_m = \hbar / \Delta E$, thus when considering both the dimensional relation and first order approximation, it is rational that we assume the relation $\Delta \rho = k \Delta t / \Delta t_m$.

3. The third principle In essence, we can not obtain the continuous limit of the above evolution of the quantum jump motion in physics, since according to the above analysis about the space-time uncertainty, there exists a minimum stay time near $T_p$ of the particle undergoing the quantum jump motion in reality, the motion is essentially discrete, although when $T_p \to 0$ we can get the continuous limit formally in mathematics.

V. THE COLLAPSE PROCESS FOR TWO-STATE SYSTEM

In this section, as one example we will first analyze the collapse process for a simple two-state system, and work out the concrete collapse time formula.

We suppose the initial wave function of the particle is $\psi(x,0) = \alpha(0)^{1/2}\psi_1(x) + \beta(0)^{1/2}\psi_2(x)$, which is a superposition of two static states with different energy levels $E_1$ and $E_2$, which are located in different regions $R_1$ and $R_2$ with the same spreading size $L$, and we assume the relation $L \gg L_p$. 
Now, for simplicity but lose no generality, we consider the space of both static states as a whole local region, and only study the quantum jump motion between these two regions, namely we directly consider the difference of the whole energy $\Delta E = E_2 - E_1$ between these two states, we assume the sequence of n jumps as binary bit sequence $[\delta_n] = \delta_1\delta_2...\delta_n$, where $\delta_k = 1$ denotes the particle stays in the region $R_1$, $\delta_k = 0$ denotes the particle stays in the region $R_2$, the probability for this sequence as $P_{[\delta_n]}$, then according to the above principles, if the particle stays in the region $R_1$ for a time interval $T_p$ during the n-th jump, the position measure density in this region will be changed as follows:

$$\alpha_{[\delta_n]1} = \frac{\alpha_{[\delta_n]} + \Delta}{1 + \Delta}$$  \hspace{1cm} (3)

$$\beta_{[\delta_n]1} = \frac{\beta_{[\delta_n]} + \Delta}{1 + \Delta}$$  \hspace{1cm} (4)

where $\Delta = kT_p/\Delta t_m$, and $\Delta t_m = \hbar/\Delta E$; if the particle stays in the region $R_2$ for a time interval $T_p$ during the n-th jump, the position measure density in this region will be changed as follows:

$$\alpha_{[\delta_n]0} = \frac{\alpha_{[\delta_n]} + \Delta}{1 + \Delta}$$  \hspace{1cm} (5)

$$\beta_{[\delta_n]0} = \frac{\beta_{[\delta_n]} + \Delta}{1 + \Delta}$$  \hspace{1cm} (6)

Then similar to the continuous measurement theory for two-state system, we can analyze the collapse process for the above two-state system, first, we will calculate the diagonal elements of the density matrix of the two-state system, according to the definition of the quantum jump motion we have

$$\rho_{11}(n+1) = \sum_{[\delta_n]} (P_{[\delta_n]} \alpha_{[\delta_n]} \alpha_{[\delta_n]1} + P_{[\delta_n]} \beta_{[\delta_n]} \alpha_{[\delta_n]1})$$  \hspace{1cm} (7)

$$\rho_{22}(n+1) = \sum_{[\delta_n]} (P_{[\delta_n]} \beta_{[\delta_n]} \beta_{[\delta_n]0} + P_{[\delta_n]} \alpha_{[\delta_n]} \beta_{[\delta_n]1})$$  \hspace{1cm} (8)

while the definitions of the diagonal elements are

$$\rho_{11} = \sum_{[\delta_n]} P_{[\delta_n]} \alpha_{[\delta_n]}$$  \hspace{1cm} (9)

$$\rho_{22} = \sum_{[\delta_n]} P_{[\delta_n]} \beta_{[\delta_n]}$$  \hspace{1cm} (10)

and the initial conditions are

$$\rho_{11}(0) = \alpha(0)$$  \hspace{1cm} (11)

$$\rho_{22}(0) = \beta(0)$$  \hspace{1cm} (12)

then the discrete evolution equations will be

$$\rho_{11}(n+1) = \rho_{11}(n)$$  \hspace{1cm} (13)

$$\rho_{22}(n+1) = \rho_{22}(n)$$  \hspace{1cm} (14)

when in the continuous mathematical limit, these evolution equations for the diagonal elements will be

$$\dot{\rho}_{11}(t) = 0$$  \hspace{1cm} (15)
\[ \dot{\rho}_{22}(t) = 0 \]  

Now it is evident that the above principles essentially guarantee that the collapse results distribution satisfies the position measure density \( \rho(x, t) \), this is consistent with the prediction of quantum mechanics.

Secondly, in order to work out the concrete collapse time for the above two-state system, we will calculate the non-diagonal elements of the density matrix, similar to the above calculations we can get the discrete evolution equation, namely

\[ \rho_{12}(n+1) = [1 - (\frac{\Delta}{1 + \Delta})^2]^{1/2} \rho_{11}(n) \]  
then the solution will be

\[ \rho_{12}(n) = [1 - (\frac{\Delta}{1 + \Delta})^2]^{n/2} \rho_{12}(0) \approx (1 - \frac{1}{2} \Delta^2 n) \rho_{12}(0) \]  
and the collapse formula is

\[ \nu_c = 1 - \frac{1}{2} \Delta^2 n \]  

Now according to the relation \( \Delta = kT_p/\Delta \tau_m = k\Delta E / E_p \), where \( E_p = \hbar / T_p \), is the Planck energy, \( T_p \) is the average minimum stay time of the particle in one of the two local regions during each jump, and the relation \( n = \tau / T_p \), where \( \tau \) is the whole time interval of the quantum jump motion, the above collapse formula will be

\[ \nu_c = 1 - \tau / \tau_c \]  

where \( \tau_c \approx \frac{1}{2} \cdot \frac{E_p}{\Delta E} \cdot \frac{\hbar}{\Delta \tau} \); is the collapse time.

Then we will further discuss the collapse time formula, first, according to the above general discussions about the collapse process, when \( \Delta E = E_p \), the collapse time will be \( T_p \), then we may simply assume \( k = \sqrt{2} \), and the collapse time will be \( \tau_c = \frac{\hbar}{\Delta E} \); this evidently denotes that the normal quantum evolution of the wave function is invalid at the critical point \( \Delta E \approx E_p \), and in fact the evolution is mainly determined by the collapse process, thus we may call the Planck energy \( E_p \) collapse critical energy; when \( \Delta E \ll E_p \), namely for microscopic objects, we get \( \tau_c \gg \frac{\hbar}{\Delta E} \), this result means that for microscopic objects the collapse time is much longer than the normal evolution time of the wave function, thus quantum mechanics is still approximately valid before the collapse process happens; while when \( \Delta E \gg E_p \), namely for macroscopic objects, we get \( \tau_c \ll \frac{\hbar}{\Delta E} \), which means that for macroscopic objects the collapse time is much shorter than the normal evolution time of the wave function in quantum mechanics, then quantum mechanics will be naturally replaced by classical mechanics. In fact, the border between microscopic objects and macroscopic objects mostly results from the experience and sense of our mankind, thus the above discussion may be improper, the relevant criterion may be that if the collapse time of the objects is small in our sense, say a small section of one second, we may call such objects macroscopic objects, then for macroscopic objects we may assume \( \Delta E \geq 10MeV \).

Secondly, since the above difference of energy \( \Delta E \) is irrelevant to the position measure density \( \rho(x, t) \) of the wave function, the above collapse time is also irrelevant to the initial position measure density \( \rho(x, t) \) of the wave function, in fact, this conclusion essentially results from the existence of quantum jump motion and assumed dynamical continuity of the collapse process.

Thirdly, it can be easily seen that the above collapse formula is just Fivel’s assumed formula resulting from the experimental considerations \[13\], but the meaning of \( \Delta E \) is a little different, here the difference of energy \( \Delta E \) will include all the energy difference obtained from the last unified theory, especially include the possible difference of the gravity energy of the particle in the states, which will essentially result from the complete theory of quantum gravity, while the difference of energy in Fivel’s formula is just the dispersion of the usual energy of the particle in quantum mechanics, the obvious distinction of these two kinds of definitions lies in that the former may relate to the space separation of the wave function, while the latter relates not to the space separation of the wave function, although in general situation the difference of the gravity energy of the particle may be proportional to the dispersion of the usual energy of the particle.

Fourthly, the existence of the above collapse formula will imply the nonexistence of the continuous limit in physics, namely in reality there should exists a nonzero minimum average stay time \( T_p \) for the particle undergoing the quantum jump motion, and this minimum average stay time will also appear in the collapse formula, and determine the collapse time of the wave function, this also results in the appearance of the collapse critical energy scale \( E_p \) in the above collapse formula, in the following, we will further analyze the validity of the formula of the collapse critical energy
\[ E_p = \sqrt{\hbar c^3/G}. \] First, when the new quantum discontinuous motion does not exist, namely \( \hbar = 0 \), this energy scale \( E_p \) will turn to be zero, since the continuous motion has been local, it needs no additional energy to collapse into a local region; secondly, when gravity disappears, namely \( G = 0 \), this energy scale \( E_p \) will turn to be infinite, since the collapse process never happens; thirdly, when in nonrelativistic domain, namely \( c \to \infty \), the collapse process will also never happen, then it is also rational that when \( c \to \infty \) this energy scale \( E_p \) turns to be infinite, thus from the analysis about the constants involved in \( E_p \), the formula of the collapse critical energy \( E_p = \sqrt{\hbar c^3/G} \) is rational, and will be the only one when involving only the above constants in the formula. Furthermore, this conclusion also strongly implies that the Planck energy \( E_p \) will appear in the collapse time formula, thus Penrose’s formula of gravity-induced quantum state reduction may be inappropriate, while the above collapse formula will be more appropriate.

At last, the problem of energy conservation needs to be considered, as Fivel has pointed out [3], the collapse formula \( \tau_c \approx \frac{E_p}{\Delta E} \cdot \frac{2\pi}{h} \) guarantees the principle of energy conservation, now the above collapse model resulting from the continual jump of the particle undergoing the quantum jump motion will be also consistent with the principle of energy conservation, concretely speaking, for any single particle in the state, the energy change during the collapse process lies within the limit of the uncertainty principle, while for the ensemble of the particles in the state the average energy change is evidently zero, since the collapse result is one of the energy eigenstates, and the distribution of the collapse results is just the initial distribution of the energy eigenstates.

Furthermore, we will demonstrate that for a single particle in the state, the energy change during the collapse process lies within the limit of the uncertainty principle, first, during any single jump the collapse critical energy scale \( E_p ( \text{or the maximum permitted energy change} ) \) and the minimal stay time interval \( T_p \) satisfies the energy uncertainty relation \( E_p = \hbar / T_p \), and the principle of energy conservation is naturally satisfied; secondly, when considering the whole collapse process Fivel has demonstrated that the principle of energy conservation is also satisfied [1], here we give some further discussions, since when \( \Delta E < E_p \), we have the relation \( \tau_c \approx \frac{E_p}{\Delta E} \cdot \frac{2\pi}{h} > \frac{\hbar}{E_p} \), this means that the energy change during the collapse process lies within the limit of the uncertainty principle; while when \( \Delta E \geq E_p \), we have \( \tau_c \approx \frac{E_p}{\Delta E} \cdot \frac{\hbar}{E_p} \leq \frac{\hbar}{E_p} \leq T_p \), this relation implies that the collapse process happens within the minimum stay time interval \( T_p \), namely such superposition states with the energy difference larger than \( E_p \) can not exist at all, thus no problem of energy conservation is involved for this situation. In one word, the above collapse model and the resulting collapse formula \( \tau_c \approx \frac{E_p}{\Delta E} \cdot \frac{\hbar}{E_p} \) is consistent with the principle of energy conservation.

**VI. THE GENERAL EVOLUTION EQUATION OF THE QUANTUM JUMP MOTION**

In the following, we will give a general evolution equation of the quantum jump motion, which can be used to account for the collapse process of any wave function describing the quantum jump motion.

For simplicity but lose no generality, we consider a one-dimension initial wave function \( \psi(x) \), whose spreading size is \( L \), and divide the whole size of the wave function \( L \) into many local Planck cells with size \( L_p \), which are denoted by number \( i \), the basic local position state of the particle is limited in one of such local cells, then according to the above analysis, the concrete evolution equation of the quantum jump motion will be essentially one kind of revised stochastic evolution equation based on Schrödinger equation for the wave function, here we adopt the stochastic differential equation ( SDE ), it is

\[ d\psi(x,t) = \frac{1}{i\hbar}HQ\psi(x,t)dt + \frac{1}{2} \left[ \frac{\delta(x-x_N)}{\rho(x,t)} - 1 \right] \frac{\Delta E(x_N,\bar{x}_N)}{E_p} \psi(x,t)dt \tag{21} \]

where \( \delta(x-x_N) \) is the discrete \( \delta \)-function, \( \rho(x,t) = |\psi(x,t)|^2 \), is the measure density, \( \Delta E(x_N,\bar{x}_N) \) is the total difference of the energy of the particle between the cell containing \( x_N \) and all other cells \( \bar{x}_N \), \( x_N \) is a stochastic position variable, whose distribution is \( P(x_N,t) = \rho(x_N,t) = |\psi(x_N)|^2 \). In physics, this stochastic differential equation should be taken as a continuous mathematical description of the discrete evolution equation of the quantum jump motion.

**VII. SOME EXPERIMENTAL EVIDENCES**

Even though we have not directly confirmed the above collapse model up to now, there still exists some experimental evidences which may support the above collapse model, in fact, these coincidences have strongly implied its validity, and confuted other collapse models.

The first experimental evidence is the gravity-induced CP violations discussed by Fivel, as he analyzed in an elegant paper [1], the observed magnitude of CP violation in \( K_L \) meson decay remarkably indicates that the collapse process may happen during the decay and the collapse time satisfies the above collapse formula when we assume \( k \approx 4\sqrt{\pi}, \)
while according to Penrose’s formula, the collapse time will be infinite, since the difference of the gravity self-energy of the states in the superposition is zero, but this result can hardly account for the bizarre coincidence of the observed magnitude of CP violation with the above prediction of collapse time; at the same time, the above collapse model may also provide an economical explanation of the origin of the CP violations, namely all the CP violations just results from the gravity-induced collapse of the wave function of the particle, which has been also demonstrated from other perspectives [3].

The second experimental evidence comes from the avalanche photodiodes devices used for detecting the particles in short time intervals, just as Berg has analyzed [3], even if the time resolutions and energy consumption of these devices can not translate into an immediate estimate of the collapse time, we can still estimate the upper bounds of the collapse time, his calculation indicates that \( b = 2E_p/k^2\Delta E \approx 10^{17} < 3.8 \times 10^{21} \), namely the prediction of the above collapse formula is consistent with the detection property of these measuring devices; on the other hand, according to Penrose’s formula, the collapse time will be \( \tau_c = \frac{bh}{k^2E} \approx \frac{b}{T_p} \), and the equivalent value of \( b \) is \( b \approx 10^{40} \gg 3.8 \times 10^{21} \), thus this result has evidently invalidated Penrose’s formula.

The third experimental evidence comes from the experimental results about the Ramsey fringes in atomic beam spectroscopy, according to Berg’s calculations [3], we get the evident relation \( b = 2E_p/k^2\Delta E \approx 10^{28} > 1.35 \times 10^{11} \), which indicates that the experiments in atomic beam spectroscopy are also consistent with the above collapse formula.

VIII. SOME FURTHER THEORETICAL IMPLICATIONS

Although it may be very difficult to formulate a complete theory of quantum gravity on the basis of the quantum jump motion and resulting collapse process, we can still discuss its direct implications in theory, which will be very valuable for understanding the nature of quantum gravity.

First, the existence of the quantum jump motion naturally results from the combination of quantum mechanics and general relativity, and consistent with the well-known gravitational uncertainty relation [2]; according to which the continuous space-time concept can not be properly used within the Planck scale \( T_p \) and \( E_p \), the local position state will be the only proper state for the quantum motion, in fact, this conclusion is also implied by the fact that a particle with mass larger than \( M_p = E_p/c^2 \approx 10^{-5} \text{gm} \) has a Compton wavelength smaller than its Schwarzschild radius.

Secondly, as Feynman suggested in his Lectures on Gravitation [8], the quantum jump motion just provides the objective reason that gravity need not be quantized, because when involving gravity the linear Schrödinger evolution of the wave function will be broken, and replaced by the nonlinear stochastic evolution, which, as we have demonstrated, will result in the immediate collapse of the wave function at the Planck scale \( E_p \).

Thirdly, since the Planck mass \( M_p \) is essentially macroscopic, the above collapse model based on the quantum jump motion can easily explain the apparent instability and collapse of Schrödinger cat states in which there is dispersion of a macroscopic observable, and will be responsible for the transition from the microscopic world to the macroscopic world, furthermore, the evolution of the quantum jump motion also naturally provides a generalization of the Schrödinger equation that interpolates between linear evolution and collapse, which may unify the descriptions about the microscopic world and macroscopic world.

Fourthly, as to the above collapse model based on the objective quantum jump motion, there does not exist the usual tails problem inherent in other dynamical collapse models at all [1] [1] [1] [1] [1] [1], and arithmetic can still apply to ordinary macroscopic objects [13], since according to our collapse model, the collapse process results from the quantum jump motion, which is essentially discrete, the continuous stochastic evolution of the wave function is just an illusion, especially in the last stage of the collapse process, when the particle stays in one of the branches long enough it will de facto collapse into that branch owing to the limitation of energy conservation, and the ostensible description—wave function also completely disappears in other branches, while this will never happen if the continuous wave function is taken as the last objective description of the quantum process, and the tails will survive forever.

At last, the existence of the quantum jump motion will naturally tackle the well-known time problem involved in formulating a complete theory of quantum gravity [21] [2], since as to the quantum jump motion, the local position state will be the only proper state, and during a finite time interval near \( T_p \), let alone at one instant, the particle can only be limited in a space interval near \( E_p \), namely there does not exist any essential superposition of different positions at all, thus the essential inconsistency of the superposition of different space-time in the theory of quantum gravity will naturally disappear, and the new physical picture based on the quantum jump motion will be that at any instant the structure of the space-time determined by the ostensible superposition state in quantum mechanics is definite or "classical", while during a finite time interval it will be stochastically disturbed by the discontinuous quantum jump motion of the particle in the superposition state, and this stochastic disturbance picture just reflects the real quantum nature of the space-time and matter.
Certainly, the essential nonexistence of the superposition of different space-time structure will also invalidate Penrose's proposal of gravity-induced quantum state reduction [19][20], even though his start point involving gravity is undoubtedly right, since as to the quantum jump motion, there does not exist any essential "fuzziness” of the time translation, in fact, it has been replaced by the stochastic disturbance of space-time resulting from the quantum jump motion of the particle, thus his collapse formula $\tau_c \approx \frac{\hbar}{E}$ will be essentially improper.

IX. SOME FURTHER CONSIDERATIONS ABOUT THE EXPERIMENTAL CONFIRMATION

Although some experiments have been presented to confirm the usual dynamical collapse models and gravity-induced collapse models, it may be very difficult to implement them using present technology, and many efforts need to be made along this direction, here we will further discuss some possible experiments to confirm our collapse model.

At first, we will analyze the general relation between the above collapse process and environment-induced decoherence, since the decoherence process will generally introduce the energy difference among the corresponding decoherence branches of the wave function, and further result in the dynamical collapse process according to our collapse model, at the same time, the decoherence effects will also prevent us from detecting the collapse effects, these two processes are closely interconnected, through a simple mathematical analysis we can find the general relation between the collapse time $\tau_c$ and decoherence time $\tau_d$, it is

$$\tau_c = \left(\frac{\hbar E_p}{k^2}\right) \left(\frac{\tau_d}{\gamma T}\right)^2 \approx 10^7 \left(\frac{\tau_d}{\gamma T}\right)^2$$

where $k$ is Boltzmann constant, $\gamma = 4\varepsilon/(1+\varepsilon)^2$, is the energy transfer factor during a single interaction with the particles in the environment, $\varepsilon = E_i/E$ is the energy ratio, $E_i$ is the energy of the particles in the environment, $T$ is the temperature of the environment.

From this relation between the collapse time $\tau_c$ and decoherence time $\tau_d$, we can see that the decoherence process will generally happen before the collapse process, thus for this situation we can not detect and confirm the existence of the collapse process; on the other hand, if the temperature of the environment is so high, say when $T > 10^{10}$, the collapse process will happen before the decoherence process and can be detected, thus this situation will provide the possible experimental confirmation of our collapse model.

Secondly, we will further analyze the above possibility to confirm our collapse model, on the one hand, it may exist everywhere in the universe, say inside the stars, on the other hand, we had better devise a similar experiment in the earth, as we know, for this situation, in a single interaction the energy transfer will be very large, while the dephasing effect is smaller than the collapse effect resulting from the increased difference of energy, here we consider a trapped neural particle, say a neuron, in a initial superposition state $\psi = \frac{1}{\sqrt{2}}(\psi_1 + \psi_2)$ of different positions with the same energy, and let a high-energy neural atom in state $\varphi$ with energy $E$ collide with one of the neuron states, say $\psi_1$, then the state of the whole system after interaction will be $\omega = \frac{1}{\sqrt{2}}(\psi_1^o \varphi_1 + \psi_2^o \varphi_2)$, then the energy difference between the neuron states $\psi_2^o$ and $\psi_2$ will be approximately $4m_n E/m_a$, and the whole energy difference in the state $\omega$ will be $8m_n E/\gamma m_a$, thus according to our collapse model, this state will collapse into the branch $\psi_1^o \varphi_1$ or $\psi_2^o \varphi_2$ after a collapse time

$$\tau_c = \left(\frac{m_a}{8m_n}\right)^2 \frac{\hbar E_p}{E^2} = \frac{1}{16} \frac{\hbar E_p}{m_n^2 v^2}$$

where $v$ is the velocity of the collision particle, while the dephasing effect of this process will be very small, since the mass of the atom is assumed to be very larger than that of the neuron, and the difference between the states of the atom $\varphi_1$ and $\varphi_2$ will be very small, and not change with time, namely $<\varphi_1|\varphi_2> \approx 1 - 4m_e/m_n$, at the same time, we assume the decoherence effect resulting from the gravitational field can also be omitted, thus one of the direct ways is to keep the last state $\omega$ long enough, then we can easily detect the predicted collapse effect, the concrete relation will be $t > \frac{m_a}{16 m_n} \frac{\hbar E_p}{E^2}$.

From the above relation we can see that, there exists an optimal mass for the collision particle limited by present technology, if its mass is too large, we can hardly generate higher velocity, then the collapse time will be too long and it will be very difficult to keep the last state; while if its mass is too small, its energy $E$ will be also too small, and the collapse time will be also too long.

Now, as one example, we let $m_n/m_a = 100$ and $E = E_n/100 = 9.3 Mev$, which means that the velocity of the atom is approximately $c/100$, then we get the collapse time $\tau_c \approx 10^4 s$, which is in the level of minutes, so if we can keep the last state of the whole system longer than $4m_n/m_a \tau_c \approx 100 s$, we can differentiate the dephasing effect and collapse effect, and confirm the existence of the assumed collapse process.
X. CONCLUSIONS

On the whole, we present a concrete collapse model on the basis of the new quantum discontinuous motion, according to this model, it is the combination of general relativity and quantum mechanics that turns the quantum discontinuous motion into the quantum jump motion, and further results in the collapse process of the wave function, while the resulting quantum jump motion just provides the inherent randomness or probability involved in the collapse process. Furthermore, a crude theoretical model is given to interpret the collapse process quantitatively, and the consistence between theoretical prediction and experimental evidences is also discussed. At last, we analyze the possibility to confirm the collapse model using present technology.

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